REVISTA DCS
FUNDADA EN 2000

TOLERANCE AND GROWTH OF BRACHIARIA (*Urochloa brizantha*) ASSOCIATED WITH ARBUSCULAR MYCORRHIZAL FUNGI TO DOSES OF ZINC AND NICKEL – PERSPECTIVE OF DECONTAMINATION OF POTENTIALLY TOXIC METALS ZN (II) AND NI (II) IN AGRICULTURAL SOILS

TOLERÂNCIA E CRESCIMENTO DA BRACHIARIA (*Urochloa brizantha*) ASSOCIADA A FUNGOS MICORRÍZICOS ARBUSCULARES A DOSES DE ZINCO E NÍQUEL – PERSPECTIVA DE DESCONTAMINAÇÃO DE METAIS POTENCIALMENTE TÓXICOS ZN (II) E NI (II) EM SOLOS AGRÍCOLAS

TOLERANCIA Y CRECIMIENTO DE BRACHIARIA (*Urochloa brizantha*) ASOCIADA A HONGOS MICORRÍZICOS ARBUSCULARES A DOSIS DE ZINC Y NÍQUEL – PERSPECTIVA DE DESCONTAMINACIÓN DE METALES POTENCIALMENTE TÓXICOS ZN (II) Y NI (II) EN SUELOS AGRÍCOLAS

Emilly de Souza Costa[1], Aurea Catarine Brandão de Souza[2], Ramiro Cabral de Meneses[3], Ivaneide de Oliveira Nascimento[4], Jorge Diniz de Oliveira[5]

DOI: 10.54899/dcs.v23i89.5004
Recibido: 19/03/2026 | Aceptado: 23/03/2026 | Publicación en línea: 02/04/2026.

ABSTRACT

The indiscriminate contamination of the environment by potentially toxic metals (MTPs) due to human action poses socioeconomic and environmental problems. Phytoremediation is a sustainable technique used for soil decontamination, using plants capable of absorbing and accumulating PTMs in their tissues. The present study aimed to evaluate the tolerance and development of Brachiaria (*Urochloa brizantha*) as a phytoremediator of the metals Nickel (Ni^{+2}) and Zinc (Zn^{+2}), through analysis of translocation factors (FT) and bioaccumulation (FBC), and to compare the phytoremediation potential in symbiosis with arbuscular mycorrhizal fungi (FMA). The study was conducted in a greenhouse, in a completely randomized design, with a 6x2x3 factorial system, with 6 doses of the metallic species incubated in the soil (0, 10, 20, 40, 60, and 80 mg kg^{-1}), with inoculation of FMA and absence, with 3 repetitions each, resulting in 36 experimental units. The determination of the percentage of organic matter (MO) was done via the volumetric method using potassium dichromate. Physicochemical parameters, height and

[1] Graduating in Agronomic Engineering, Universidade Estadual da Região Tocantina do Maranhão (UEMASUL), Imperatriz, Maranhão, Brazil. E-mail: emillycosta.20200002871@uemasul.edu.br
Orcid: https://orcid.org/0009-0000-1985-8646
[2] Master student in Environmental Sciences, Universidade Estadual da Região Tocantina do Maranhão (UEMASUL), Imperatriz, Maranhão, Brazil. E-mail: aurea.souza@uemasul.edu.br Orcid: https://orcid.org/0009-0001-6566-0398
[3] Graduated in Chemistry, Universidade Estadual da Região Tocantina do Maranhão (UEMASUL), Imperatriz, Maranhão, Brazil. E-mail: ramirocdemeneses@gmail.com Orcid: https://orcid.org/0009-0008-1934-6024
[4] PhD in Agroecology, Universidade Estadual da Região Tocantina do Maranhão (UEMASUL), Imperatriz, Maranhão, Brazil. E-mail: ivaneide@uemasul.edu.br Orcid: https://orcid.org/0000-0001-7095-7092
[5] PhD in Chemistry, Universidade Estadual da Região Tocantina do Maranhão (UEMASUL), Imperatriz, Maranhão, Brazil. E-mail: jorgediniz@uemasul.edu.br Orcid: https://orcid.org/0000-0001-9421-0524

chlorophyll index were determined. DTPA extracting solution was used to determine MTPs. The data were subjected to analysis of variance using the software AgroEstat and the means was compared using the Tukey test at 5 % probability. The MO concentration was 16,03 mg kg^{-1}, characterizing a soil that retains negative charges. Ni^{+2} and Zn^{+2} had FT <1, making Brachiaria a phytoextractor, while FBC presented results >1, making it a hyperaccumulator. Treatments with FMA were more efficient. The grass showed good development in contaminated soil at different MTPs dosages.

Keywords: Absorption. Phytoremediation. Symbiosis. Environmental.

RESUMO

A contaminação indiscriminada do ambiente por metais potencialmente tóxicos (MTPs) pela ação antrópica oferta problemas socioeconômicos e ambiental. A fitorremediação é uma técnica sustentável, utilizada para descontaminação de solos, utilizando plantas capazes de absorver e acumular MTPs em seus tecidos. O estudo teve como objetivo avaliar a tolerância e desenvolvimento da braquiária (*Urochloa brizantha*) como fitoremediadora dos metais Níquel (Ni^{+2}) e Zinco (Zn^{+2}), através de análise dos fatores de translocação (FT) e bioacumulação (FBC), comparar o potencial fitorremediador em simbiose com fungos micorrízicos arbusculares (FMA). O trabalho foi conduzido em casa de vegetação, em Delineamento Inteiramento Casualizado, sistema fatorial 6x2x3, com 6 doses das espécies metálica incubadas no solo (0, 10, 20, 40, 60,e 80 mg kg^{-1}), com inoculação de FMA e ausência, com 3 repetição cada, resultando 36 unidades experimentais. A determinação da percentagem de matéria orgânica (MO) foi feita via método volumétrico pelo dicromato de potássio. Foram determinados parâmetros físico-químicos, altura e índice de clorofila. Utilizou-se solução extratora de DTPA para determinação de MTPs. Os dados foram submetidos a análise de variância via software AgroEstat e a comparação das médias a partir do teste Tukey a 5 % de probabilidade. A concentração de MO foi de 16,03 mg kg^{-1}, caracterizando um solo que retem cargas negativas. O Ni^{+2} e o Zn^{+2} tiveram o FT <1, tornando a braquiária fitoextratora, já o FBC apresentou resultados >1, tornando-a hiperacumuladora. Os tratamentos com FMA tiveram maior eficiência. A gramínea apresentou bom desenvolvimento em solo contaminado nas diferentes dosagens dos MTPs.

Palavras-chave: Absorção. Fitorremediação. Simbiose. Ambiental.

RESUMEN

La contaminación indiscriminada del medio ambiente por metales potencialmente tóxicos (MTPs) debido a la acción humana plantea problemas socioeconómicos y ambientales. La fitorremediación es una técnica sustentable utilizada para la descontaminación del suelo, utilizando plantas capaces de absorber y acumular MTPs en sus tejidos. El presente estudio tuvo como objetivo evaluar la tolerancia y desarrollo de Brachiaria (*Urochloa brizantha*) como fitorremediador de los metales Níquel (Ni^{+2}) y Zinc (Zn^{+2}), mediante el análisis de factores de translocación (FT) y bioacumulación (FBC). Comparar el potencial de fitorremediación en simbiosis con hongos micorrízicos arbusculares (HMA). El trabajo se realizó en invernadero, en un Diseño Completo al Azar, sistema factorial 6x2x3, con 6 dosis de las especies metálicas incubadas en el suelo (0, 10, 20, 40, 60 y 80 mg kg-1), con inoculación de FMA y ausencia, con 3 repeticiones cada uno, resultando 36 unidades experimentales. La determinación del porcentaje de materia orgánica (MO) se realizó mediante el método volumétrico utilizando dicromato de potasio. Se determinaron parámetros fisicoquímicos, altura e índice de clorofila. Se utilizó la solución de extracción DTPA Para determinar los MTPs. Los datos fueron sometidos a análisis de varianza mediante el software AgroEstat y la comparación de medias se realizó mediante la prueba de Tukey al 5% de probabilidad. La concentración de MO fue de 16,03 mg kg^{-1}, caracterizando un suelo que retiene cargas negativas. Ni^{+2} y Zn^{+2} presentaron FT <1, convirtiendo a Brachiaria en un fitoextractor, mientras que FBC presentó resultados >1, convirtiéndolo en un hiperacumulador. Los tratamientos con FMA fueron más eficientes. El pasto mostró un buen desarrollo en suelo contaminado a diferentes dosis de MTPs.

Palabras clave: Absorción. Fitorremediación. Simbiosis. Ambiental.

INTRODUCTION

Physical, chemical, and biological remediation techniques used to remove metalloids and potentially toxic metals (PTMs) from soils are effective in reducing their presence in the environment resulting from anthropogenic activities. However, these methods require high financial investment and often alter essential soil properties (Asharaf et al., 2019). Therefore, alternative strategies are sought that minimize such impacts and contribute to mitigating this environmental issue.

Phytoremediation is a decontamination method that employs plants capable of removing or immobilizing organic or inorganic contaminants from the soil. These processes are categorized as phytostabilization and phytoextraction. This technique is a low-cost, easily applicable, socially acceptable, and more sustainable alternative compared with chemical extraction techniques for PTMs (Shah & Daverey, 2020).

Due to their beneficial effects on plant growth under stressful conditions, arbuscular mycorrhizal fungi (AMF) have been used to enhance the rehabilitation of soils contaminated with PTMs (Leal et al., 2016). This symbiotic association between plant roots and AMF mycelia improves the efficiency of nutrient uptake and may enhance the phytoextraction capacity of plants in removing PTMs (Leudo et al., 2020).

Urochloa brizantha (commonly known as brachiaria grass) (Embrapa, 1999) exhibits remarkable tolerance to soils contaminated with high levels of Mn, maintaining normal growth without adverse effects on its anatomy or morphology (Caione et al., 2023).

Arbuscular mycorrhizal fungi are effective in reducing PTM contamination in soils. According to Boorboori et al. (2022), the symbiotic association between plants and AMF improves tolerance to various metals. AMF not only survive under these conditions but also assist plants in mitigating metal-induced phytotoxicity. The efficiency of mycorrhizal colonization depends on the plant–fungus–metal interactions (Raklami et al., 2022).

Zinc is an essential micronutrient for plants and acts as an enzymatic activator in tryptophan synthesis, a precursor of indole-3-acetic acid (IAA), which plays a critical role in plant growth. Zinc is also important for metabolic pathways associated with RNA formation, cell membranes, ribosomes, and lipid and protein production, as well as for auxin structure (Mengel & Kirkby, 1989). Zinc deficiency results in reduced protein synthesis, ribosomal disorganization, and increased RNAase activity, ultimately decreasing cell multiplication due to RNA hydrolysis.

Nickel is an activator of urease and is essential for nitrogen metabolism in plants, particularly in the hydrolysis of urea into carbon dioxide and ammonia. It also participates in the activity of several enzymes, including urease, acetyl-CoA synthase, and RNAase-A. Like other nutrients, nickel can become adsorbed onto soil colloids, and its availability is pH-dependent: soils with pH below 5.5 exhibit higher availability of this element (Veloso, 1992). Plants absorb nickel in its divalent form.

This study aims to evaluate the performance of the grass *Urochloa brizantha* as a phytoextractor of potentially toxic metals, specifically Zn and Ni, in artificially contaminated soils. Additionally, the research seeks to expand knowledge on the effectiveness of *U. brizantha* associated with arbuscular mycorrhizal fungi in removing these potentially toxic metals from regional soils.

METHODOLOGY

The present study was conducted in a greenhouse at the Center for Exact, Natural and Technological Sciences (CCENT) of the State University of the Tocantina Region of Maranhão (UEMASUL). Soil samples were obtained from the sample bank derived from preserved areas in the municipality of Imperatriz, Maranhão, as part of the project *Evaluation of native plants from the Maranhão Cerrado with phytoremediation potential in soils contaminated by manganese, nickel, zinc, chromium, and lead*, developed by the Environmental Chemistry Research Group (GPQA) of the Environmental Chemistry Laboratory (LQA) at CCENT/UEMASUL. The

Brachiaria seeds used in the experiment were commercially acquired in the city of Imperatriz, Maranhão.

Experimental Design and Treatments

The experiment was carried out using a 6 × 2 × 3 factorial design, consisting of six doses of metallic species and two AMF inoculation conditions (with and without AMF), arranged in a completely randomized design (CRD) with three replicates, totaling 36 experimental units. The soils were incubated with the investigated metallic species in the form of analytical-grade salts at doses of 0, 10, 20, 40, 60, and 80 mg kg^{-1}, following the methodology proposed by Costa et al. (2008).

The experiment was conducted in a greenhouse using pots prepared from polyethylene terephthalate (PET) bottles with a total volume of 2 dm^3. The bottles were cut approximately in half, and the upper portion was used as a pot to accommodate the soil. Each pot was filled with 1.5 kg of substrate composed of a sand-to-soil mixture (1:2), previously autoclaved at 121 °C for 1 hour over two consecutive days to ensure that only the inoculated AMF influenced the system.

Throughout the experiment, the pots were irrigated with distilled water without exceeding 70% of the soil's field capacity. At weekly intervals, each pot received 50 mL of nutrient solution.

Plant development parameters were assessed every 14 days after planting (DAP). Plant height was measured using a metric tape graduated in centimeters, and chlorophyll content was determined using a SPAD 502 Plus chlorophyll meter.

At 55 DAP, plants were harvested, and biomass was separated into shoot and root components. Samples were placed in pre-labeled paper bags and dried in a forced-air oven at 75 °C until constant weight. Subsequently, shoot dry matter (SDM) and root dry matter (RDM) were determined. The dried material was ground using a mill at the Environmental Chemistry Laboratory (LQA). After grinding, the samples were stored in polyethylene containers under refrigeration at 27 °C until analysis of the concentrations of Zn(II) and Ni(II) phytoextracted by the plants.

Extraction of AMF Spores

AMF spores were extracted from the soil following the wet sieving method (Gerdemann & Nicolson, 1963) combined with sucrose centrifugation. A total of 50 g of dry soil was weighed and soaked in water for 3 minutes, then passed through a 53-µm sieve. The soil was washed repeatedly until the rinse water became clear. The material retained on the sieve was transferred to centrifuge tubes and centrifuged for 5 minutes at 300 rpm. The supernatant was discarded, and a 45% sucrose solution was added to the tubes. The material was then subjected to a second centrifugation for 3 minutes at 3000 rpm. After centrifugation, the supernatant was poured through a 53-µm sieve, where the AMF spores were retained, and washed with water to remove excess sucrose. The material was subsequently transferred to Falcon tubes and stored until inoculation into the plants.

Inoculation of AMF in Plants and Staining and Counting of Colonized Roots

The plants were inoculated with AMF as soon as they developed a root system, with the inoculum applied near the plant roots. The AMF solution added to the soil corresponded to the extract obtained from 50 g of soil for each pot. Root colonization was determined according to the methodology described by Phillips and Hayman (1970). After root collection, the samples were washed to remove solid residues, cleared with 5% KOH, and stained with 0.05% trypan blue. Mycorrhizal colonization was then quantified using the gridline intersection method, following the procedure of Giovannetti and Mosse (1980).

Extraction of Metals in Soil Before and After Planting, and in *Brachiaria*

For the determination of bioavailable metals, approximately 10 g of dry soil were weighed into polyethylene conical flasks. After weighing, 20 mL of DTPA extractant solution (0.005 mol L^{-1} DTPA + 0.1 mol L^{-1} TEA + 0.01 mol L^{-1} $CaCl_2$, pH 7.3) were added. The mixture was then shaken for two hours at 220 rpm on an orbital shaker. After agitation, the suspension was filtered through filter paper (Tavares, Oliveira & Salgado, 2013).

All analyses were performed in triplicate. Determination of Ni(II) and Zn(II) in soil and *Brachiaria* samples was carried out using Flame Atomic Absorption Spectrometry (FAAS) equipped with a deuterium background corrector. Standard solutions used for instrument calibration were prepared from aliquots of a 1000 mg L^{-1} stock solution.

Statistical Analysis

The results were subjected to analysis of variance, and the means were compared using Tukey's test at the 5% significance level, performed with the AgroEstat software. Statistical analyses of metal concentrations were conducted using the mean values obtained from the measured metal contents in soil and *Brachiaria* samples.

RESULTS AND DISCUSSION

According to Meurer (2010), the hydrogen potential (pH) represents the concentration of H^+ ions present in the soil solution. As shown in Table 1, the pH value obtained indicates a soil with moderate acidity, according to the classification proposed by Silva et al. (2017), within the range of 5.1–6.0. Costa et al. (1999) state that cation exchange capacity (CEC) represents the amount of negative charges present on soil colloids that retain cations of similar valence. The soil CEC value was 0.3 cmolc kg^{-1}, which, according to Prezotti and Guarçoni (2013), characterizes a soil with low CEC.

The organic matter (OM) content (Table 1) was 16.03 mg kg^{-1}. According to Mamedes (2017), OM contributes to the retention of cations by providing negative charges, increasing CEC, and consequently enhancing the soil's buffering capacity. The pH variation (ΔpH) indicates that the soil is predominantly negatively charged (–1.22).

Table 1. Average values of the physicochemical parameters of soils from the municipality of Imperatriz, MA. pHH2O_{H2O}H2O; pHKCl_{KCl}KCl; ΔpH: pH variation; OM: Organic Matter (mg kg^{-1}); CEC: Cation Exchange Capacity (cmolc dm^{-3}).

	pH (in H_2O)	pH (in KCl)	ΔpH	PCZ	C.T.C (cmol$_c$ kg^{-1})	M.O (mg kg^{-1})
Arable soil	5,23	4,01	-1,22	2,79	0,3	16,03

Source: Costa, 2025

According to the Environmental Technology and Sanitation Company (CETESB, 2021), indicative concentration values are established for soils considered at the quality limit. The reference values for soil quality (VRQ) are 13 mg kg^{-1} for Ni^{2+} and 60 mg kg^{-1} for Zn^{2+}. For soils with concentrations considered harmful to the environment, known as the prevention value (VP), the limits are 30 mg kg^{-1} for Ni^{2+} and 86 mg kg^{-1} for Zn^{2+}. The agricultural intervention value (VIA) corresponds to concentrations harmful to human health, soil, and groundwater, with VIA values of 190 mg kg^{-1} for Ni^{2+} and 1900 mg kg^{-1} for Zn^{2+}. The concentrations incubated in the soil exceeded the VIA for both PTMs, with maximum values of 1,330.2 mg kg^{-1} for Zn^{2+} and 1,682.9 mg kg^{-1} for Ni^{2+}.

As shown in Table 2, the effect of PTMs on *Brachiaria* at 15 DAP was not significant. The same trend was observed in the second analysis (Table 3), indicating that *Urochloa brizantha* maintained its development in soil contaminated with PTMs at 30 DAP, regardless of treatments with or without AMF, and across Ni^{2+} and Zn^{2+} doses ranging from 0 to 80 mg kg^{-1}. The plants showed no visible signs of PTM toxicity.

Table 2. Analysis of variance for plant height in the first assessment.

Effects	GL	SQ	QM	F
Factor A	1	12,48	12,48	0,48 NS
Factor B	5	56,83	11,36	0,44 NS
Interaction A × B	5	125,08	25,01	0,97 NS
CV(%)	35,26			

*Means followed by the same letter do not differ statistically from each other, while means followed by different letters differ statistically according to Tukey's test at 5% probability.
Factor A: With and Without AMF; Factor B: Doses; Interaction: With and Without AMF versus Doses; CV (%): Coefficient of variation; DF: Degrees of freedom; SS: Sum of squares; MS: Mean square.
Source: Costa, 2025

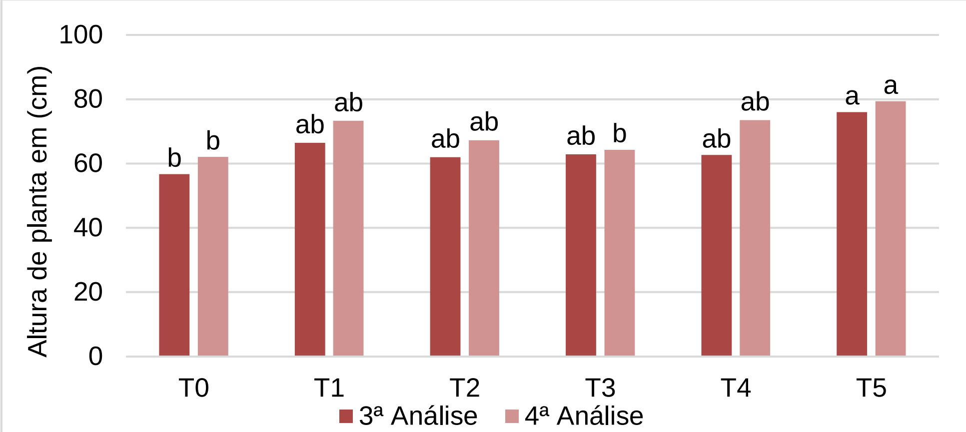
Table 3. Analysis of variance for plant height in the second assessment.

Effects	GL	SQ	QM	F
Factor A	1	30,43	30,43	0,30 NS
Factor B	5	667,74	133,54	1,33 NS
Interaction A × B	5	107,99	21,59	0,21 NS
CV(%)	5,79			

*Means followed by the same letter do not differ statistically from each other, while means followed by different letters differ statistically according to Tukey's test at 5% probability.
Factor A: With and Without AMF; Factor B: Doses; Interaction: With and Without AMF versus Doses; CV (%): Coefficient of variation; DF: Degrees of freedom; SS: Sum of squares; MS: Mean square.
Source: Costa, 2025

According to studies on zinc and cadmium in maize cultivation, Cunha et al. (2008) observed visual Zn toxicity at higher doses, causing leaf necrosis as well as interveinal and marginal chlorosis. In the present study, such symptoms were not observed. As shown in Figure 1, regarding plant height, the grass tolerated the highest PTM concentrations, with a statistically significant difference between the highest and lowest dose treatments. This can be explained by the plant's mechanism to absorb the metal and utilize it in its metabolism, supporting its growth.

Figure 1. Analysis of variance for the third and fourth assessments of shoot height of Brachiaria at different doses.



Source: Costa, 2025

As shown in Table 4, chlorophyll content in the first, second, and fourth assessments did not differ statistically. However, variation was observed in the third assessment, with T4 showing the highest significance among the treatments. In the final assessment, no statistically significant differences in chlorophyll content were observed. It is noteworthy that the genus *Urochloa* has a high capacity to tolerate and absorb PTMs even under stress, without impairing its normal development (Santos et al., 2005; Martinez et al., 2012).

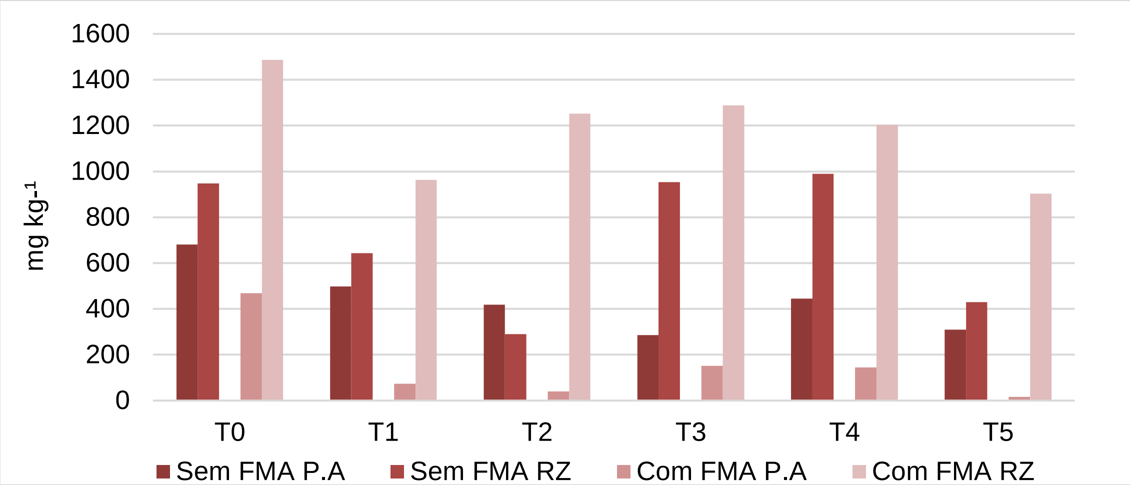
Table 4. Analysis of variance for chlorophyll index.

Treatment	1ª assessment	2ª assessment	3ª assessment	4ª assessment
T0	24 a	29,40 a	21,20 ab	19,88 a
T1	20,01 a	26,36 a	22,73 ab	24,23 a
T2	19,11 a	26,88 a	26,63 a	23,46 a
T3	18,73 a	23,01 a	22,40 ab	23,36 a
T4	15,56 a	22,35 a	17,43 b	20,93 a
T5	19,58 a	30,45 a	21,56 ab	19,43 a
DP	5,07	5,51	5,11	3,73
CV(%)	35,26	20,89	23,26	17,07

*Médias seguidas pela mesma letra não diferem estatisticamente entre si, enquanto médias seguidas por letras diferentes diferem estatisticamente pelo teste de Tukey a 5% de probabilidade.
Fator A: com e sem FMA; Fator B: doses; Interação: com e sem FMA versus doses; CV (%): coeficiente de variação; DP: desvio-padrão; GL: graus de liberdade; SQ: soma dos quadrados; QM: quadrado médio.
Source: Costa, 2025

The concentrations of Ni^{2+} in the shoot, as shown in Figure 2, were higher in the treatment without AMF when compared to the treatment with AMF. This may be explained by the plant's ability to adapt to the toxicity of the element present in the soil. However, it is evident that T4 showed higher values than the lower-dose treatments. According to Martinez et al. (2012), in an evaluation of *Brachiaria* and Indian mustard for use in phytoremediation, *Brachiaria* grass is capable of accumulating higher concentrations of Ni^{2+}, as well as other elements such as chromium and lead. In their study, *Brachiaria* was able to remove more than 80% of Ni^{2+} from the system.

Figure 2. Mean concentrations of Ni^{2+} in Brachiaria plants (mg kg^{-1}).

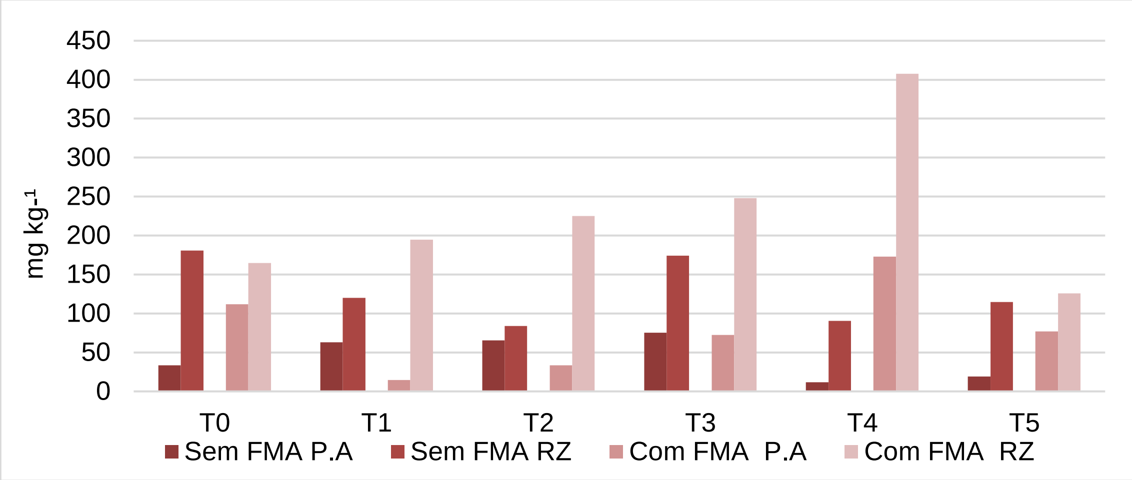


Source: Costa, 2025

The concentrations of Ni^{2+} in the roots were higher than those in the shoots for both treatments (Figure 2). It can be inferred that the reduced concentration of Ni^{2+} in the shoot compared with the root zone may be due to a plant defense mechanism against metal toxicity. The higher values accumulated in the treatment with AMF may have been influenced by the fungus's tolerance to PTMs. In the study by Berton et al. (2006) with common bean inoculated with AMF, the authors observed a reduction in symbiosis due to the high concentration of Ni^{2+} in the soil. However, this effect was not observed in the present study, likely because the grass species has a natural capacity to tolerate PTMs (Martinez et al., 2012). Fernandes et al. (2011) also reported lower Ni^{2+} concentrations in the shoot, with greater accumulation in the root system. According to Mariano and Okumura (2012), retention of the metal in the root is an indication of plant stress caused by PTMs.

As shown in Figure 3, Zn^{2+} concentrations in the shoot were higher in the treatment with AMF, and the plant gradually increased Zn accumulation across treatments, except at the highest dose. Zn concentrations in the roots were also higher in the treatments with AMF, except for the final treatment. When comparing metal concentrations in different plant tissues, the root system exhibited the highest values, indicating a limitation in Zn^{2+} translocation from root to shoot and preferential accumulation in the root zone.

Figure 3. Mean concentrations of Zn^{2+} in Brachiaria plants (mg kg⁻¹).



Source: Costa, 2025

According to Broadley et al. (2007), Zn^{2+} can form complexes with organic ligands in the soil, making it less available for plant uptake. Considering the CEC of the soil in this study, which was 0.3 cmolc kg^{-1}, and the organic matter content of 16.03 mg kg^{-1} (Table 1), it can be inferred that these factors contributed to metal adsorption in the soil, limiting its absorption by the plant. As reported by Awkummi et al. (2015), soils within the observed pH range influence PTM dynamics between soil and plant, affecting availability, solubility, and leaching. This phenomenon was also observed by Freitas et al. (2019) in a phytoremediation study using *Schinus terebinthifolius*, where metal accumulation increased proportionally with different Zn^{2+} concentrations and remained adsorbed in the soil. According to Raij (1991), soil texture may also play a role, as the element is strongly adsorbed onto the mineral fraction of the soil.

Table 5. Translocation factor of Ni^{2+} in *Brachiaria* (Urochloa brizantha) in soil without and with AMF.

Ni^{2+} translocation factor						
	T0	T1	T2	T3	T4	T5
Without AMF	0,71	0,75	1,44	0,29	0,44	0,72
With AMF	0,31	0,07	0,03	0,11	0,12	0,02

Source: Costa, 2025

Table 6. Translocation factor of Zn^{2+} in ***Brachiaria*** (Urochloa brizantha) in soil without and with AMF.

Zn^{2+} translocation factor						
	T0	T1	T2	T3	T4	T5
Without AMF	0,18	0,52	0,77	0,43	0,13	0,16
With AMF	0,67	0,07	0,14	0,29	0,42	0,61

Source: Costa, 2025

Table 7. Bioaccumulation factor of Ni^{2+} in *Brachiaria* (Urochloa brizantha) in soil without and with AMF.

Ni^{2+} bioaccumulation factor						
	T0	T1	T2	T3	T4	T5
Without AMF	6,23	5,34	3,99	9,60	13,93	5,98
With AMF	32,23	17,81	10,95	30,72	11,62	5,57

Source: Costa, 2025

Table 8. Bioaccumulation factor of Zn^{2+} in ***Brachiaria*** (Urochloa brizantha) in soil without and with AMF.

Zn^{2+} bioaccumulation factor						
	T0	T1	T2	T3	T4	T5
Without AMF	3,38	2,80	2,31	3,76	1,44	1,88
With AMF	4,35	3,22	120,2	52,32	59,29	16,25

Source: Costa, 2025

The translocation factor (TF) indicates the movement, that is, the transfer of the metal through plant tissues from the roots to the shoots. Therefore, TF reflects how much the plant translocates the metal for its nutrition and to support its metabolism. The bioaccumulation factor (BAF) represents the intrinsic relationship between the metal concentration in plant tissue and its concentration in the soil. A TF < 1 and BAF < 1 indicate the plant's efficiency in phytostabilizing the metal, whereas a TF > 1 suggests that the plant is promising for phytoextraction. Values of BAF > 1 indicate that the plant is a hyperaccumulator.

The TF for different doses of Ni^{2+} (Table 5) and Zn^{2+} (Table 6) in *Brachiaria* was more efficient with and without AMF across all doses, characterizing *Brachiaria* as a phytostabilizer of Ni^{2+} and Zn^{2+}, as all treatments showed values below 1.

The BAF was >1 in treatments with and without AMF across different doses of Ni^{2+} (Table 7) and Zn^{2+} (Table 8), exhibiting the same behavior, indicating that the plant acts as a hyperaccumulator of Ni^{2+} and Zn^{2+} in both treatments.

CONCLUSION

Plant productivity remained constant in both treatments, as the metals are important for plant metabolism, and plant development was normal throughout the experiment. The symbiosis with AMF influenced the plant in the presence of metals. The use of AMF was effective for phytoextraction and hyperaccumulation of metals in *Brachiaria*. *Brachiaria* acts as a phytoextractor of Ni^{2+} and Zn^{2+} and also as a hyperaccumulator of both elements, regardless of symbiosis with AMF.

REFERENCES

ASHARAF, S., ALI, Q., ZAHIR, Z., ASHARF, S., & ASGHAR, H. N. (2019). Phytoremediation: **Environmentally sustainable way for reclamation of heavy metal polluted soils.** *Ecotoxicology and Environmental Safety, 174*, 714–727.

AWKUMMI, E. E., IBIGBAMI, O. A., ASAOLU, S. S., ADEFEMI, O. S., & GBOLAGADE, Y. (2015). Sequential extraction of heavy metals from soil samples collected from selected cocoa farmland in Erijiyan, Ekiti State, Nigeria**. *International Journal of Environmental Protection***, *5*(1), 52–56.

BERTON, R. S., et al. (2006). Nickel toxicity in bean plants and effects on soil microbiota. ***Pesquisa Agropecuária Brasileira***, *41*, 1305–1312.

BOORBOORI, M. R., & ZHANG, H.-Y. (2022). Arbuscular mycorrhizal fungi are an influential factor in improving the phytoremediation of arsenic, cadmium, lead, and chromium. ***Journal of Fungi***, *8*(2), 176.

BROADLEY, M. R., WHITE, P. J., HAMMOND, J. P., ZELKO, I., & LUX, A. (2007). Zinc in plants. ***New Phytologist***, *173*(1), 677–702.

CAIONE, G., et al. (2023). Tolerance of marandu grass to excess iron and manganese. ***Revista de Agricultura Neotropical***, *10*(1), e7027.

CETESB. (2021). Update of soil and groundwater guideline values. Available at: https://cetesb.sp.gov.br/wp-content/uploads/2021/12/DD-125-2021-E-Atualizacao-dos-Valores-Orientadores-paa-solo-e-aguas-subterraneas.pdf. Accessed: **December 14, 2024.**

COSTA, A. C. S., TONIRO, C. A., & RAK, J. G. (1999). Cation exchange capacity of organic and inorganic colloids in Oxisols of Paraná State. ***Acta Scientiarum***, Maringá, PR.

CUNHA, K. P. V., et al. (2008). Availability, accumulation, and toxicity of cadmium and zinc in maize grown in contaminated soil. ***Revista Brasileira de Ciência do Solo***, *32*, 1319–1328.

EMBRAPA, Serviço Nacional de Levantamento e Conservação de Solos. (1979). ***Manual of soil analysis methods*.** Rio de Janeiro, Brazil.

FERNANDES, E., et al. (2011). Behavior of *Cistus ladanifer* L. and *Cistus monspeliensis* L. regarding trace elements in soils in the Chança mining area. ***Revista de Ciências Agrária**s, 34*(2), 57–67.

FREITAS, D. A., ALVARENGA, A. C., & DURÃES, A. F. S. (2019). Phytoremediation potential of the tree species *Myracrodruon urundeuva* in soils contaminated by zinc**. *Brazilian Journal of Animal and Environmental Research***, *2*(5), 1768–1775.

GERDEMANN, J. W., & NICOLSON, T. H. (1963). Spores of mycorrhizal *Endogone* species extracted from soil by wet-sieving and decanting. ***Transactions of the British Mycological Society,*** *46*, 235–244.

LEAL, P. L., VARÓN-LOPEZ, M., PADRO, I. G. O., SANTOS, J. V., SOUSA SOARES, C. R. F., SIQUEIRA, J. O., & SOUZA MOREIRA, F. M. (2016). Enrichment of arbuscular mycorrhizal fungi in a contaminated soil after rehabilitation. ***Brazilian Journal of Microbiology***, *47*, 853–862.

LEUDO, A. M., CRUZ, Y., MONTOYA-RUIZ, C., DELGADO, M. P., & SALDARRIAGA, J. F. (2020). Mercury phytoremediation with *Lolium perenne*-mycorrhizae in contaminated soils. ***Sustainability***, *12*, 2–13.

MAMEDES, I. M. (2017). Influence of improper disposal of urban solid waste on soil: case study of the Várzea Grande-MT landfill. ***Revista Gestão de Sustentabilidade Ambiental,*** *5*(2), 327–336.

MARTINEZ, M. S., CRUVINEL, D. F. C., & BARATTO, D. M. (2013). **Evaluation of phytoremediation of metal-contaminated soils by brachiaria grass and Indian mustard**. *Revista DAE, 191*, 30–37.

MENGEL, K., & KIRKBY, E. A. (1987). **Principles of plant nutrition**. Bern: International Potash Institute, 525–536.

MEURER, J. E. (2010). ***Fundamentals of Soil Chemistry*** (4th ed.). Porto Alegre: Yangraf Ltda.

OLIVEIRA, G. F. (2017). **Chemical indicators of soil under different uses and management in lot 31 of the Veneza settlement project in southeastern Pará**. *Agroecossistemas, 9*(1), 227–235.

OKUMURA, R. S., & DE CINQUE MARIANO, D. (2012). Agronomic aspects, human use, and phytoremediation mechanisms: a review. ***Revista em Agronegócio e Meio Ambiente,*** *5*(2 Special).

RAIJ, B. V. (2001). ***Chemical analysis for the evaluation of tropical soil fertility***. Campinas: Instituto Agronômico.

RAKLAMI, A., et al. (2022). Plants–microorganisms-based bioremediation for heavy metal cleanup: **Recent developments, phytoremediation techniques, regulation mechanisms, and molecular responses.** *International Journal of Molecular Sciences, 23*(9), 5031.

SANTOS, F. S., AMARAL SOBRINHO, N. M. B., NASCIMENTO, V. S., HOFFMANN, R., & MAZUR, N. (2005). **Phytoremediation by *Brachiaria humidicola* of a hazardous waste disposal site.** *Floresta e Ambiente, 12*(1), 22–29.

SHAH, V., & DAVEREY, A. (2020). Phytoremediation: **A multidisciplinary approach to clean up heavy metal contaminated soil.** *Environmental Technology & Innovation, 18,* 100774.

SILVA, K. R., PONTES AMARAL, E. T. O., OLIVEIRA, A. N., MELLO, A. H., TAVARES, S. R. de L., OLIVEIRA, S. A., & SALGADO, C. M. (2013). **Evaluation of plant species in phytoremediation of soils contaminated with heavy metals.** *Holos, 5*, 80–97.

VELOSO, C. A. C., et al. (1992). **Effect of different materials on soil pH**. *Scientia Agrícola*, *49*, 123–128.