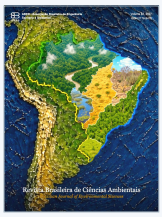
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Zinc phytostabilization potential of the native species *Lantana fucata*

Potencial de fitoestabilização de zinco pela espécie nativa *Lantana fucata*

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Abstract

Soil contamination by metals poses a risk to the environment. Although zinc (Zn) is an essential micronutrient, it can bioaccumulate in living organisms, in addition to exhibiting environmental persistence. Phytoremediation has therefore emerged as a sustainable alternative for removing contaminants from soil. This study therefore evaluated the potential of the Brazilian native species *Lantana fucata* to remediate zinc-contaminated soils. Five treatments were tested (mg Zn · kg^{-1} soil): a control (no Zn added), 75, 150, 300, and 450. The plants were cultivated for 90 days under controlled conditions. After the cultivation period, Zn concentrations in the soil, roots, and shoots were determined by flame atomic absorption spectrometry (FAAS). These data were used to calculate the bioconcentration factor (BCF) and the translocation factor (TF), and the tolerance index (TI) was estimated from total dry biomass. The results demonstrated that *L. fucata* accumulated significantly more zinc in its roots than in its shoots. A BCF > 1 indicates a high capacity for metal uptake and retention, whereas a TF < 1 indicates limited mobilization of zinc from the roots to the shoots. Despite the high Zn concentrations in the soil, the plant remained tolerant, with no statistically significant reduction in biomass production. It is concluded that *L. fucata* has high potential for zinc phytostabilization, immobilizing the metal in the roots and reducing its dispersion in the environment.

Keywords Phytoremediation · Analytical Chemistry · Flame Atomic Absorption Spectrometry

Resumo

A contaminação do solo por metais representa um risco ao ambiente. Embora o zinco (Zn) seja um micronutriente essencial, ele pode bioacumular-se nos organismos vivos, além de apresentar persistência ambiental. Assim, a fitorremediação, enquanto técnica de remediação ambiental, surge como uma alternativa sustentável para a remoção de contaminantes do solo. Nesse sentido, este estudo teve como objetivo avaliar o potencial da espécie nativa brasileira *Lantana fucata* na remediação de solos contaminados com zinco. Foram testados cinco tratamentos (mg Zn kg^{-1} de solo): 75, 150, 300, 450 e um controle (sem adição). As plantas foram cultivadas durante 90 dias sob condições controladas. Após o período de cultivo, as concentrações de Zn no solo, nas raízes e na parte aérea das plantas foram determinadas por espectrometria de absorção atômica com chama (FAAS). Com base nos teores obtidos, calcularam-se o fator de bioconcentração (FBC) e o fator de translocação (FT), enquanto o índice de tolerância (IT) foi estimado sobre a biomassa seca total. Os resultados demonstraram que a espécie acumulou significativamente mais zinco nas raízes do que na parte aérea. O FBC > 1 indica elevada capacidade de absorção e retenção do metal, enquanto o FT < 1 evidencia a limitada mobilização do zinco das raízes para a biomassa aérea. Apesar das altas concentrações de Zn no solo, a planta demonstrou tolerância, sem redução estatisticamente significativa na produção de biomassa. Conclui-se que a *L. fucata* possui um alto potencial para a fitoestabilização de zinco, imobilizando o metal nas raízes e reduzindo sua dispersão no ambiente.

Palavras-chave Fitorremediação · Química Analítica · Espectrometria de Absorção Atômica com Chama

1 Introduction

Environmental contamination resulting from anthropogenic activities can cause significant imbalances in ecosystems. Among the different types of pollutants, metals pose an additional concern because, unlike many organic compounds, they are not biodegradable and can bioaccumulate along the trophic chain (Soliman et al., 2024; Mustapha et al., 2026). The present study focuses on zinc, an essential plant micronutrient that becomes potentially toxic at high concentrations (Sharma et al., 2025). Zinc occurs naturally in soil, derived from the parent rock, but anthropogenic activities can increase its concentration in the environment (Sharma et al., 2025).

In regions of intensive pig farming, such as southern Brazil, one of the main causes of increased soil Zn concentrations is the systematic application of liquid pig slurry. This practice, common in agricultural fertilization, can result in excessive accumulation of potentially toxic elements, which are present at high concentrations in the slurry (Lemos et al., 2025). This scenario is associated with the addition of supranutritional doses of zinc and other metals to pig feed to prevent disease and promote growth (Kunz, 2024). However, approximately 70% of this zinc is excreted, as it is not absorbed by the animal's organism (Kunz, 2024). Although the use of pig slurry adds organic matter to the soil, its successive and indiscriminate application can unbalance the system and lead to the chronic accumulation of potentially toxic elements (Ferreira et al., 2022; Florentino et al., 2025).

Beyond slurry application, increased zinc concentrations in soil may be associated with the agricultural use of the element, whether as a micronutrient in fertilizers or as a component of crop protection products (Alloway, 2012). Contamination can also originate from industrial activities involving zinc, such as galvanizing. This sector generates metal-rich residues, such as sludge, which represent a considerable environmental risk factor (Mustapha et al., 2026). Added to this is atmospheric deposition, mainly from smelters and vehicles (Alloway, 2012). Given these and other sources of soil contamination, it is necessary to establish regulatory limits for monitoring this environmental matrix, which is of great importance to human life.

To establish guidelines for monitoring and assessing the levels of metals added to different environments, the Brazilian National Environment Council (CONAMA) defined reference values for the total concentration of zinc in soil. These values correspond to 300 $mg \cdot kg^{-1}$ as the prevention value and 450 $mg \cdot kg^{-1}$ as the investigation value for agricultural areas, 1,000 $mg \cdot kg^{-1}$ for residential areas, and 2,000 $mg \cdot kg^{-1}$ for industrial areas (Brazil, 2009). Exceeding these limits indicates potential environmental risk, making the adoption of remediation strategies for these soils necessary.

Traditional soil recovery approaches involve physical, chemical, and physicochemical techniques. Physical methods include soil excavation, followed by removal of the contaminant or disposal of the contaminated soil at a suitable site (Xu et al., 2024). Chemical treatments employ chelating agents or adsorbents, such as zeolite and activated carbon. These techniques, however, degrade the soil and the local biodiversity, creating collateral environmental problems (Xu et al., 2024). Physicochemical techniques combine physical processes with chemical reactions, such as electrokinetic remediation, which applies an electric current to mobilize and extract metal ions from the soil matrix (Naseer et al., 2025). Although effective, these techniques are environmentally invasive and generally costly, which justifies the interest in sustainable alternatives such as phytoremediation.

Phytoremediation is a sustainable option because it is less harmful to the environment and to soil biota (Morsch et al., 2024). It is a technique that uses plants to extract, stabilize, degrade, or volatilize contaminants present in the soil. Its use to reduce the bioavailability or concentration of zinc in contaminated soils is therefore more cost-effective and has a lower environmental impact than other remediation methods (Wei et al., 2021). The efficiency of this technique, however, depends directly on the availability of the metal in the soil. Zinc uptake by the plant is affected by soil conditions such as organic matter, microbial biomass, and, above all, soil pH, which is the factor that most influences bioavailability, since plants take up zinc preferentially in its ionic form (Zn^{2+}), which predominates in soils with acidic pH (Alloway, 2012).

As a result of the greater availability and uptake of the metal in contaminated environments, plants develop tolerance and homeostatic regulation mechanisms. These mechanisms include the production of antioxidant enzymes to reduce oxidative damage, the release of root exudates, and the transport of the metal to vacuoles or its sequestration by proteins and ligands (Wei et al., 2021). Together, these processes help mitigate the effects of the element at toxic levels.

Based on their tolerance mechanisms and on the distribution of metals in their tissues, metallophyte plants are classified as excluders, indicators, or hyperaccumulators (Baker, 1981; Sharma et al., 2025). Hyperaccumulators concentrate metals in the shoots at high levels, whereas excluders restrict their translocation, accumulating them mainly in the roots, a trait that makes excluders suitable for phytostabilization. Indicators, in turn, exhibit tissue concentrations proportional to those in the soil, reflecting the level of environmental contamination (Baker, 1981; Sharma et al., 2025). For phytoremediation to succeed, species selection is fundamental, with priority given to native plants because of their adaptation to local conditions and lower risk of biological invasion (Morsch et al., 2024).

Several plants capable of remediating metal-contaminated soils have been described in the literature, notably species of the family Verbenaceae, such as *Lantana camara*, a cadmium hyperaccumulator and a phytostabilizer of lead and zinc (Liu et al., 2019; Xie et al., 2021), and *Lippia lupulina*, capable of accumulating nickel (Reeves et al., 2007). In addition, *Verbena hybrida*, belonging to the same family, is suited to chromium phytoextraction (Batool et al., 2025), as is *Lantana fucata* to copper phytostabilization (Batista et al., 2025).

Given this botanical group's consistent record of species with phytoremediation potential, *Lantana fucata* was chosen for the present study on zinc. This choice is justified because copper and zinc are both essential micronutrients that can be toxic at concentrations exceeding those considered adequate (Raza et al., 2022). Moreover,

the two metals behave similarly, with low mobility in soil, and, according to Kunz (2024), both are present in a common contaminant: liquid pig slurry.

Despite existing studies on species of the family Verbenaceae and prior results for copper, information on the behavior of *L. fucata* in zinc-contaminated soils remains scarce. This study therefore evaluated metal uptake, translocation, accumulation, and tolerance of L. *fucata*, seeking to verify its potential for application in phytostabilization processes.

2 Materials and methods

2.1 Experimental design and cultivation

The experiment was initially conducted in a greenhouse at the Federal University of Fronteira Sul (UFFS). *L. fucata* seedlings were obtained from cuttings, using indolebutyric acid as a rooting agent, planted in a mixture of soil, sand, and substrate (1:1:1), and watered daily for 30 days (Batista et al., 2025). According to the Embrapa (2018) classification, the soil used in the experiment is a typic Dystroferric Red Latosol (Oxisol); it was collected in the university's experimental area, sieved, and artificially contaminated with zinc sulfate heptahydrate solutions at increasing levels across the five treatments (0, 75, 150, 300, and 450 mg·kg^{-1}). Each treatment was then turned and sprayed with distilled water over 30 days to incubate the metal in the soil (Batista, 2020).

After the incubation period, uniform seedlings were transferred to plastic pots containing 1 kg of dry soil, following a completely randomized design (CRD). The pots were kept in a growth room under an automated 12-h photoperiod provided by LED lamps. A total of 75 plants were used: five treatments with five replicates each and three plants per replicate (one plant per pot). Pest control was performed using neem oil (1.2 g·L^{-1}) to avoid exogenous sources of metals and to prevent insecticide-induced phytotoxicity (Carvalho et al., 2008). Irrigation was manual, according to water demand, and fertilization was carried out every 30 days (CQFS-RS/SC, 2016). At the end of the 90-day cultivation period, the plant material was collected.

2.2 Soil analysis

For the soil analyses, Mehlich-1 extractant solution (0.05 mol·L^{-1} HCl and 0.0125 mol·L^{-1} H_2SO_4) was used to determine the available zinc content (Embrapa, 2009). The soil was oven-dried for 76 h at 65 °C and sieved to 1.7 mm. Portions of 5 g of soil were weighed and transferred to snap-cap flasks, to which 25 mL of Mehlich-1 solution was added. The flasks were shaken at 100 rpm for 5 min and then left to stand for approximately 16 h so that the soil could settle and the supernatant could be collected (Embrapa, 2009). The blank consisted of the extractant solution only and underwent the same procedures as the samples. To determine the pH, 10 g of dry soil and 25 mL of distilled water were placed in a beaker. After stirring, the suspension was left to stand for 1 h (Embrapa, 2009), and the pH was then measured with a combined glass-electrode pH meter (HI 2221, Hanna).

2.3 Plant tissue analysis

The collected plants were separated into leaves, stems, and roots. The shoots were washed with distilled water; the roots were washed with running water, subjected to an ultrasonic bath (BIOBASE) for 5 min, and then rinsed again with distilled water (Batista, 2020). Both shoots and roots were placed in kraft paper bags and dried in a forced-air circulation oven at 60 °C for 72 h. After drying, the plants were weighed for dry mass determination and then ground. The plant samples were prepared according to Embrapa (2009), with adaptations, using a 4:1 mixture of HNO_3 and $HClO_4$. To each digestion tube were added 0.5 g of sample, 8 mL of HNO_3 (65%), and 2 mL of $HClO_4$ (70%). The samples were left to stand in the fume hood for 30 min. They were then subjected to a heating ramp in a digestion block (TE-007MP, Tecnal), remaining for 1 h at each of the following temperatures: 80 °C, 120 °C, 150 °C, and 180 °C, followed by a further 30 min at 190 °C (Batista, 2020). The extracts were brought to a final volume of 15 mL with ultrapure water. An analytical blank, consisting of a digestion tube containing only the acid mixture, accompanied each batch.

2.4 Zinc determination and analytical validation

Zinc was quantified using a flame atomic absorption spectrometer (SavantAA, GBC) with a Zn hollow-cathode lamp (213.90 nm). The slit width was 0.50 nm, with an integration time of 3 s and a 10-cm laminar-flow burner. For zinc determination, an air/acetylene mixture was used at flow rates of 12 and 2 L·min^{-1}, respectively, for soil samples, and 10 and 2 L·min^{-1} for plant samples. The burner height was adjusted to obtain maximum absorbance with a 5 mg·L^{-1} Zn standard. A deuterium lamp was also used for background correction.

To verify that the methods were fit for purpose, several analytical parameters were evaluated, including precision, accuracy, linearity, linear working range, limit of detection (LOD), and limit of quantification (LOQ), following Inmetro (2020) guidelines. Linearity was verified by external calibration curves ($R^2 > 0.99$). For soil, the working range was set at 0.25 to 9.00 mg·L^{-1}, with the stock standard solution diluted in Mehlich-1 extractant. For plants, the working range was 0.20 to 4.00 mg·L^{-1}, and the standards were diluted in ultrapure water containing 0.2% nitric acid and 0.05% perchloric acid. Precision was expressed as the coefficient of variation (CV%), and accuracy was assessed by recovery assays, spiking the samples at two concentration levels: 2 and 4 mg·L^{-1} for soil, and 0.5 and 2 mg·L^{-1} for plants. The limits were calculated using Equations 1 and 2 (Inmetro, 2020):

$$LOD = (3\,s) / a \quad (1)$$

$$LOQ = (10\,s) / a \quad (2)$$

Where: s = standard deviation of the blank measurements
a = slope of the analytical curve

2.5 Phytoremediation indices and statistical analysis

To describe the zinc phytoremediation capacity of *L. fucata*, the following parameters were used. The bioconcentration factor (BCF) was calculated using Equation 3 (Morsch et al., 2024; Batista et al., 2025):

$$BCF = Zn\ roots / Zn\ soil \quad (3)$$

Where: Zn roots = Zn concentration in the roots;

Zn soil = available Zn content in the soil after cultivation.

The second parameter evaluated was the translocation factor (TF), which expresses whether the plant is able to move the absorbed zinc from the roots to the shoots, calculated using Equation 4 (Borah et al., 2023).

$$TF = Zn\ shoots / Zn\ roots \quad (4)$$

Where: Zn shoots = Zn concentration in the shoots;

Zn roots = Zn concentration in the roots.

Finally, the tolerance index (TI) was determined using Equation 5 (Borah et al., 2023; Batista et al., 2025).

$$TI = (total\ plant\ dry\ mass\ in\ Tn / total\ plant\ dry\ mass\ in\ T0) \times 100 \quad (5)$$

Where: Tn = treatment of interest;
T0 = control treatment.

Excel and RStudio (R Core Team, 2024) were used for the statistical analysis of the data and the preparation of the results. The data were first subjected to normality (Shapiro–Wilk) and homoscedasticity tests. Data meeting these assumptions were analyzed by analysis of variance (ANOVA), followed by Tukey's test for the comparison of means, at a 5% significance level. Data that did not meet the assumptions were evaluated by the nonparametric Kruskal–Wallis test, followed by Dunn's multiple comparison test.

3 Results and discussion

3.1 Method validation

Table 1 presents the parameters evaluated for the validation of the zinc determination method by FAAS.

Table 1. Validation parameters of the methods used for zinc determination

	Soil	Plant
Working range (mg·L^{-1})	0.25 - 9.00	0.20 - 4.00
a (n=3)	0.1187 ± 5.8595 × 10^{-3}	0.3921 ± 4.2579 × 10^{-2}
b (n=3)	0.01126 ± 1.7444 × 10^{-3}	0.00659 ± 6.2414 × 10^{-3}
R^2 (n=3)	0.9995 ± 2.8867 × 10^{-4}	0.9987 ± 8.5440 × 10^{-4}
LOD (mg·L^{-1})	0.0520	0.0113
LOQ (mg·L^{-1})	0.1732	0.0376

Note: *a* = slope, *b* = intercept, and R^2 = coefficient of determination.

The working range was defined based on linearity, which, according to Harris and Lucy (2023), is the analyte concentration range over which the response is proportional to the concentration. For the plant samples, the linear range was established up to 4.00 mg·L^{-1}. Linearity was assessed using the coefficient of determination (R^2), with values closer to 1 indicating a better fit of the linear model. In addition, the external calibration curves were prepared with the same reagents used in sample preparation, reducing systematic errors and increasing analytical precision, since standards and samples were analyzed under equivalent conditions.

For both the plant and the soil matrices, the LOD and LOQ values were adequate, given that the working range begins at concentrations above the LOQs. A comparison of the two curves shows that the calibration curve for the plant samples exhibited better analytical conditions. Although its coefficient of determination (R^2) was slightly lower, the higher slope indicates greater method sensitivity. The lower intercept also suggests less background signal interference. The LOD and LOQ were likewise lower, reinforcing the method's greater detection capability for this matrix (Inmetro, 2020; Harris and Lucy, 2023). Precision and accuracy were evaluated by recovery assays, the results of which are presented in Table 2.

Table 2. Accuracy and precision of the method

Concentration (mg·L^{-1})	Recovery (%)	CV (%)
Soil		
2	87	3.28
4	98	4.19
Plant		
0.5	106	7.68
2	94	10.71

Note: n=3 for all measurements.

Accuracy is defined as the closeness of the measured value to the true value and is assessed through recovery, whereas precision indicates the reproducibility of the analysis and is expressed as the coefficient of variation (CV). The acceptable recovery range is 80% to 110%; both the plant and the soil analyses therefore show good accuracy, and the coefficient of variation falls within the acceptable limit of 11%, demonstrating good precision (Inmetro, 2020; Harris and Lucy, 2023).

3.2 Zinc bioavailability and uptake

The chemical analysis of the soil, performed before contamination and cultivation, yielded the following results: organic matter content 3.9%; clay content 63%; pH in water (1:1) 5.4; SMP index 5.8; CEC base saturation 64.8%; CEC Al saturation 1.0%; exchangeable Al 0.1 cmol$_c$·dm^{-3}; exchangeable Ca 7.2 cmol$_c$·dm^{-3}; exchangeable Mg 1.9 cmol$_c$·dm^{-3}; H + Al 5.5 cmol$_c$·dm^{-3}; P 8.7 mg·dm^{-3}; K 393 mg·dm^{-3}.

The soil analysis results over the course of the experiment indicate that the pH remained in the acidic range (4.5 - 4.8) in all treatments. Although these values are below the range recommended for most crops, 5.5 to 6.0 (CQFS-RS/SC, 2016), no significant variation

was observed among treatments. The difference in pH between the collected soil and the soil after experimental preparation can be attributed to the addition of zinc sulfate and to biological processes associated with the cultivation of the species, such as the release of root exudates. As a native plant, *L. fucata* is adapted to the region's acidic soils, which demonstrates its hardiness. On the other hand, acidic conditions increase the bioavailability of the metal in the soil, with a predominance of the free ionic form (Zn^{2+}), which can intensify toxicity to plants (Alloway, 2012).

The strong linear correlation shown in Figure 1, relating the available Zn concentrations before and after cultivation, validates the contamination method employed and confirms that the samples were exposed to increasing concentrations of the metal. However, the available concentration (Mehlich-1) was lower than the total dose added. In T4, for example, the 450 mg·kg^{-1} added resulted in 367.7 mg·kg^{-1} available. This difference indicates that part of the metal is in the unavailable fraction, specifically adsorbed to iron and aluminum oxides and clay minerals, or complexed with organic matter (Alloway, 2012). At the end of cultivation, a reduction to 288.75 mg·kg^{-1} (T4) was observed, reflecting the uptake of the metal by the plant. This uptake may have shifted the soil's chemical equilibrium, promoting the gradual desorption of zinc from the solid phase into the soil solution to replenish the metal absorbed by the roots.

It is important to emphasize that artificial soil contamination, frequently employed in experimental studies, does not fully reproduce the conditions found in real contamination scenarios. Metal bioavailability is influenced by factors such as its initial chemical form, its residence time, and the soil properties. In this context, chemical aging is responsible for gradually altering contaminant availability. Francisco et al. (2025) observed that different forms of zinc application result in distinct plant uptake rates, while Wang et al. (2024) demonstrated that newly added metal is more labile than metal associated with historical contamination. The data presented in this study therefore represent a condition of high zinc lability and bioavailability, resulting from the use of a readily available source of the metal in the soil (Francisco et al., 2025). Moreover, the incubation time (30 days) is too short for the complete redistribution of the metal among the soil fractions (Wang et al., 2024).

Turning to the plant results, *L. fucata* showed preferential accumulation in the root system (Figure 2). The increase in Zn concentration across treatments raised the metal contents in both the shoots and the roots. Accumulation, however, was significantly greater in the roots. In the highest-concentration treatment (450 mg·kg^{-1}), the mean Zn concentration in the roots reached 3,369 mg·kg^{-1}, while in the shoots of the same treatment it peaked at 339 mg·kg^{-1}. Overall, in all treatments, the Zn concentration in the roots was significantly higher than that in the shoots ($p < 0.05$).

The statistically significant difference between root and shoot uptake suggests that this species acts as a metal excluder. This behavior indicates the activation of physiological defense mechanisms. Retention of the metal in the roots generally occurs through immobilization in the cell wall (binding to pectins) or sequestration in the vacuoles of root cells, which restricts transport via the xylem to protect the photosynthetic tissues from oxidative toxicity. This compartmentalization mechanism is a key strategy of tolerant plants for surviving in metal-rich soils (Wei et al., 2021; Raza et al., 2022).

When accumulation was analyzed across treatments, a significant difference in mean shoot concentrations occurred only up to treatment 2 (150 mg·kg^{-1}). For the roots, only T0 differed, with stabilization in the subsequent treatments. Similarly, stabilization occurred at T3 and T4 in the shoots. The results suggest the existence of a possible saturation limit for zinc accumulation in both the shoots and the root system. This points to a homeostatic regulation mechanism, since even when the available dose was doubled, no major changes occurred in the uptake and accumulation of the metal. The purpose of this mechanism is to restrict excessive metal uptake or to saturate the root binding sites at extreme toxicity levels (Cozma et al., 2025).

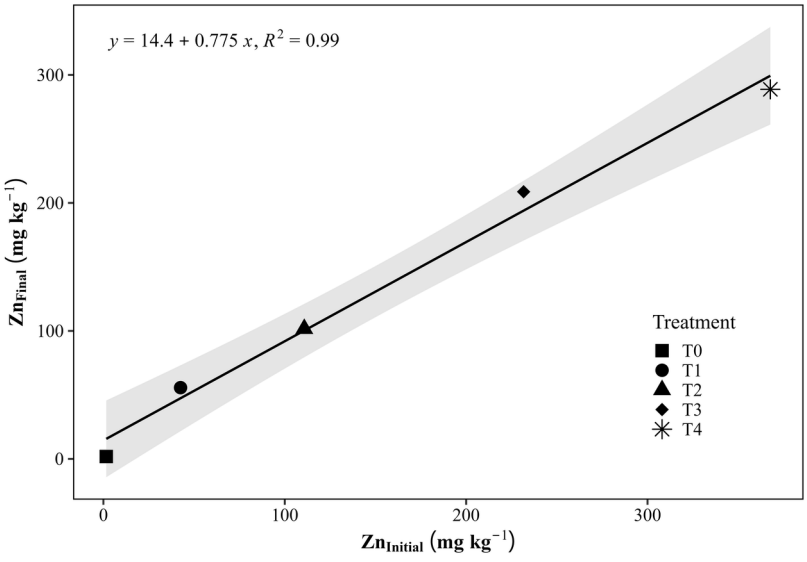


Figure 1. Correlation between available zinc in the soil before and after cultivation

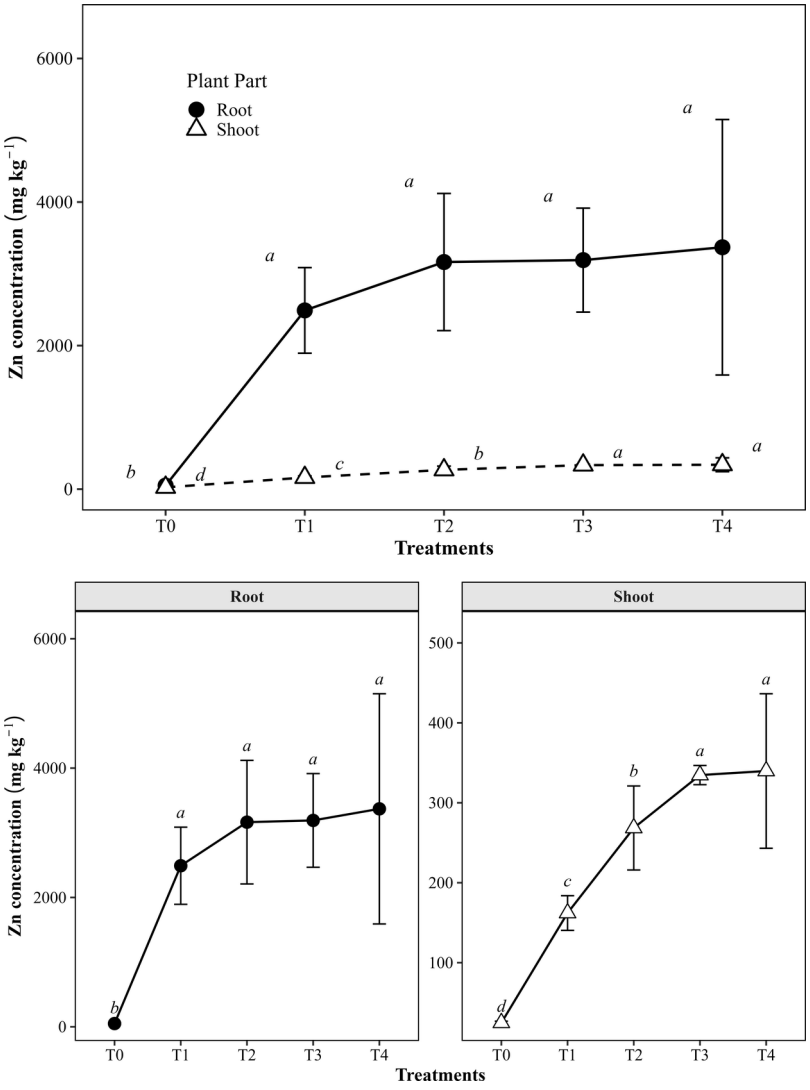


Figure 2. Comparison of metal concentration in the roots and shoots

3.3 Phytostabilization potential

Based on the phytoremediation indices, *L. fucata* was categorized according to its relationship with the metal. Root BCF values greater than one (BCF > 1) combined with TF values lower than one (TF < 1) characterize the process as phytostabilization; if both values were greater than one, this would indicate metal extraction. The TF values were consistently below 1 in all zinc-amended treatments, ranging from 0.068 to 0.1328. The BCF, by contrast, was always above 1, reaching a maximum value of 44.93 in T1 (Table 3 and Figure 3). According to the criteria established by Baker (1981), this profile classifies the species as a phytostabilizer.

The BCF response was not linear: it reached its maximum value (44.93) in T1 and decreased progressively in the more concentrated treatments. This behavior suggests a saturation effect of the root uptake mechanisms or a physiological regulation in response to metal excess. These results parallel those of Batista et al. (2025), who used the same species in copper-contaminated soils, suggesting that *L. fucata* has a conserved physiology for the immobilization of cationic metals in the rhizosphere. Comparatively, the species differs from others of the same genus, such as *Lantana camara*, which exhibits hyperaccumulation behavior (TF > 1) for cadmium (Liu et al., 2019). Compartmentalization, however, occurs similarly in the two species under zinc stress (Xie et al., 2021).

Unlike phytoextractors, which accumulate metals in their leaves and require complex biomass disposal, the stabilization strategy of *L. fucata* offers an ecological advantage: by retaining zinc mostly in the roots, the plant acts as a green barrier, reducing the mobility of the contaminant in the soil (Wei et al., 2021; Sharma et al., 2025). Despite the low TF, the concentration in the shoots was still high, exceeding 300 mg·kg^{-1} of dry mass. Although zinc retention in the roots reduces its mobility in the environment, leaf senescence and the formation of metal-rich litter may favor its reintroduction at the soil surface (Alloway, 2012). The use of the species under field conditions therefore requires management techniques, such as periodic pruning, to minimize recontamination risks (Cozma et al., 2025).

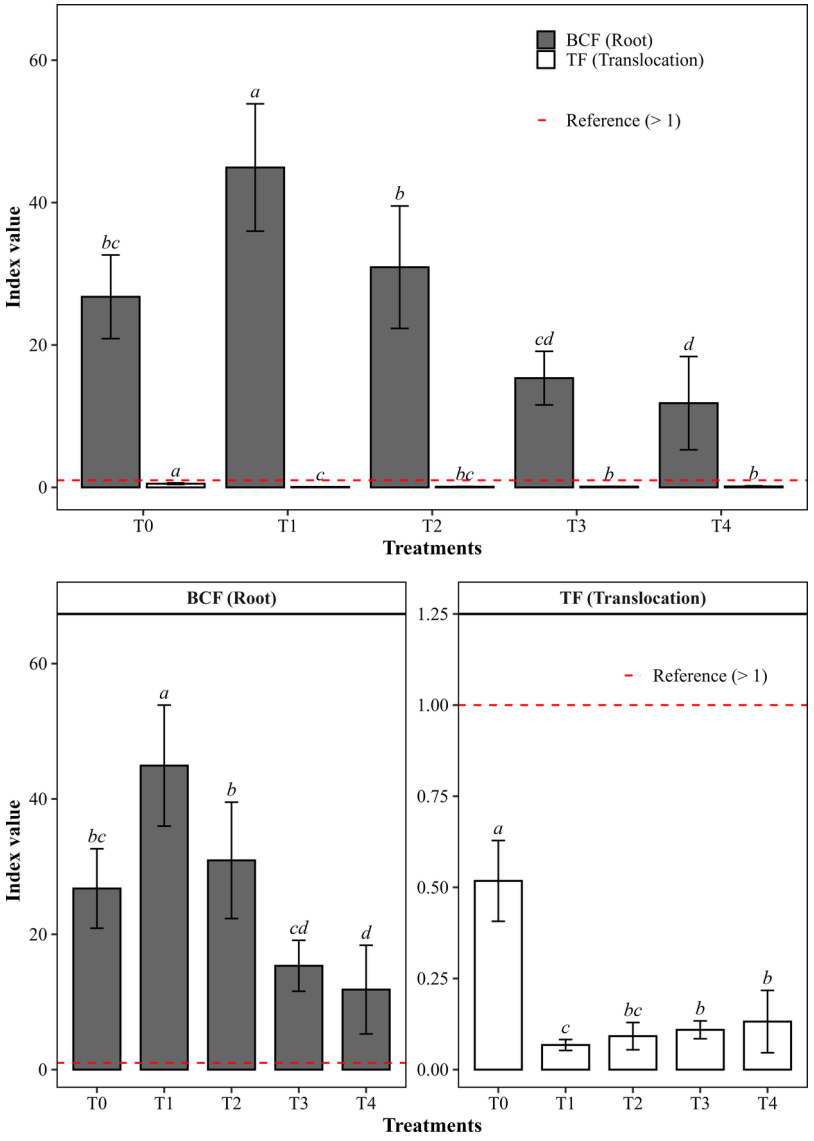


Figure 3. Graphical comparison of the phytoremediation indices with the reference value

Table 3. Metal concentration in the plant, TF, and BCF per treatment

	Zn added to soil ($mg \cdot kg^{-1}$)	Zn available in soil ($mg \cdot kg^{-1}$)	Zn in root system ($mg \cdot kg^{-1}$)	Zn in shoots ($mg \cdot kg^{-1}$)	TF	BCF
T0	0	1.86^{a}	50.16^{a}	24.79^{a}	0.52 ± 0.11^{a}	26.77 ± 5.87^{a}
T1	75	55.67^{b}	2490.23^{b}	162.1^{b}	0.068 ± 0.015^{b}	44.93 ± 8.94^{b}
T2	150	101.67^{c}	3164.02^{b}	268.5^{c}	0.092 ± 0.037^{b}	30.92 ± 8.60^{a}
T3	300	208.71^{d}	3190.96^{b}	334.68^{c}	0.11 ± 0.024^{b}	15.34 ± 3.76^{ac}
T4	450	288.75^{e}	3369.92^{b}	339.76^{c}	0.13 ± 0.085^{b}	11.83 ± 6.55^{c}

Note: The indices are presented as mean ± standard deviation of the 5 replicates. Different lowercase letters indicate mean values that differ significantly at the 5% significance level by Tukey's or Dunn's test.

Finally, environmental factors may influence this metal uptake efficiency in a real-world application. Morsch et al. (2024) point out that seasonality affects metal translocation in native species of the Pampa. It can be hypothesized that the remediation potential of *L. fucata* may also vary under field conditions, especially in scenarios of multiple contamination and across different times of the year. Such differences may also influence whether barriers or repellents against herbivores are needed. These aspects reinforce the need for further studies under natural conditions.

3.4 Tolerance and biomass production

The analysis of the total dry biomass and of the tolerance index (TI) revealed the species' hardiness toward the contaminant. Although there was a visual trend of decreasing dry mass (Figure 4) and TI (Figure 5) with increasing Zn dose in the treatments, the analysis of variance indicated no statistically significant difference ($p > 0.05$) between the control and the metal-contaminated treatments. This demonstrates that *L. fucata* is able to maintain its basic metabolic functions even at a zinc concentration of 450 mg·kg^{-1}, which corresponds to the investigation value (IV) for agricultural soil according to CONAMA Resolution No. 420/2009. The IV is the concentration of a substance in the soil above which there is a potential risk, direct or indirect, to human health, requiring a more in-depth assessment of the site.

A wide range in the growth data was nevertheless observed within each treatment, reflected in the high standard deviations. In treatment 4, this variation was extreme: while four of the 15 individuals in this treatment underwent senescence, the remaining plants developed fully. Such heterogeneity is expected in populations of non-domesticated native species, which naturally have greater genetic diversity than commercial cultivars (Sharma et al., 2025). Although the observed variability may be associated with the species' natural genetic diversity, specific studies are needed to confirm this hypothesis and to identify individuals with greater zinc tolerance. If this variability is confirmed, more tolerant individuals could be selected and propagated, enhancing remediation efficiency in the field and exploiting the local adaptation provided by native species (Cozma et al., 2025).

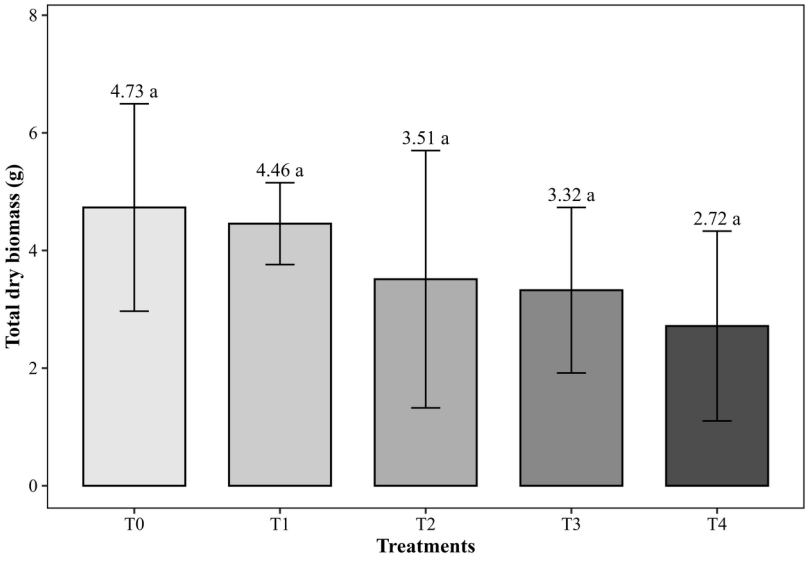


Figure 4. Mean total dry biomass produced in each treatment. There is no significant difference among the means at the 5% significance level.

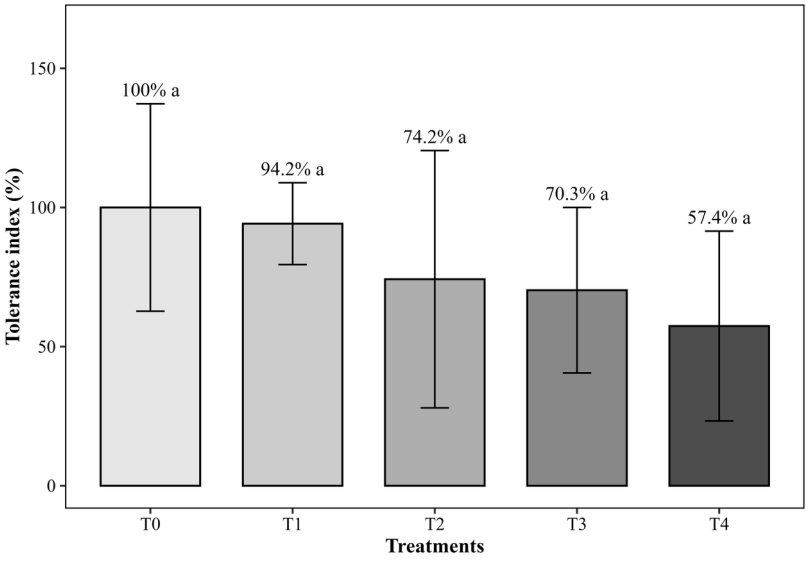


Figure 5. Tolerance index for each treatment. There is no significant difference among the means at the 5% significance level.

Compared with the literature, the TI values obtained for *L. fucata* are consistent with the findings of Batista et al. (2025), who obtained high tolerance indices (> 100%) for the species exposed to copper. The discrepancy in biomass production between the studies (approximately 1 to 6 g for Zn in the present work versus 50 g for Cu), however, can be attributed to the distinct experimental conditions. The copper study was conducted in a greenhouse with larger pots, favoring root and shoot development; that experiment was carried out under natural light and with an automated irrigation system. The present zinc experiment, in contrast, took place in a growth room set up in the laboratory, under greater spatial restriction (1 kg of soil), which limited full plant growth; the lighting used was artificial and watering was manual.

Considering that copper and zinc are micronutrients essential to plants and behave similarly in the soil and in biological systems, with toxic effects when present at high concentrations, the physiological response observed in this study indicates that the species has efficient metal tolerance mechanisms. The absence of a significant reduction in mean biomass reinforces the hypothesis that the species possesses efficient physiological mechanisms of root compartmentalization, preventing toxicity in the metabolically active tissues of the shoots (Xie et al., 2021). This set of characteristics, combined with the fact that it is a native species, highlights its potential for application in long-term remediation strategies.

4 Conclusion

This study was motivated by the need to identify sustainable strategies for the remediation of metal-contaminated soils. In this context, it aimed to evaluate the phytoremediation potential of a Brazilian native plant, *L. fucata*, by determining the Zn taken up by the species, which was exposed to different concentrations of the metal, generating data on tolerance, uptake, and translocation of the contaminant.

The results indicate that *L. fucata* behaves as an excluder plant and demonstrate its potential for application in phytostabilization strategies. Its capacity to absorb and accumulate high concentrations of zinc in the root system, while limiting transport to the shoots, makes it a promising tool for remediation strategies aimed at immobilizing the metal contaminant, reducing the associated environmental risks. In addition, the species has ornamental potential, which may contribute to the aesthetic requalification of degraded areas during the environmental recovery process.

Regarding the applicability of the species, field studies are needed to confirm the results obtained under controlled conditions and to assess the influence of factors such as seasonality, soil characteristics, microbiota, and the simultaneous occurrence of other contaminants on the phytoremediation potential of *L. fucata.* Long-term experiments may also contribute to understanding the stability of phytostabilization and the persistence of zinc retention in the soil-plant system.

Authors' Contributions

Santos, M.V.: Project administration; Supervision; Validation; Funding acquisition; Roles/Writing – original draft; Writing – review & editing; Harms, M.L.: Conceptualization; Data curation; Methodology; Writing – original draft; Pelegrin, C.M.G.: Conceptualization; Data curation; Methodology; Roles/Writing – original draft; Dartora, N.: Conceptualization; Data curation; Methodology; Roles/Writing – original draft; Cassol, F.: Conceptualization; Data curation; Methodology; Roles/Writing – original draft; Schinvelski, N.M.: Data curation; Methodology.

Conflicts of interest

The authors declare no conflicts of interest.

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Declaration on the use of generative artificial intelligence

During the preparation of this manuscript, the authors used Gemini (Google) for spelling, grammar, and punctuation checking, error identification, and assistance in drafting the R scripts used for figure generation in RStudio. The tool acted solely by providing suggestions, without directly modifying the text or scripts, which were then evaluated and accepted or rejected by the authors. After using this tool/service, the authors reviewed and edited the content as necessary and take full responsibility for the content of the published article.

5 References

Alloway, B.J. (Ed.), 2012. Heavy metals in soils: trace metals and metalloids in soils and their bioavailability. 3rd ed. Springer Science & Business Media, 612 p.

Baker, A.J.M., 1981. Accumulators and excluders: strategies in the response of plants to heavy metals. Journal of Plant Nutrition, v. 3 (1-4), 643-654. https://doi.org/10.1080/01904168109362867.

Batista, L.S., 2020. Absorção de cobre e potencial fitorremediador de *Lantana fucata* (Verbenaceae). Dissertação, Mestrado em Ambiente e Tecnologias Sustentáveis, Universidade Federal da Fronteira Sul, Cerro Largo.

Batista, L.S.; Pelegrin, C.M.G.; Cassol, F.; Dartora, N.; dos Santos, M.V., 2025. *Lantana fucata* Lindl. is tolerant and grows in copper-enriched soils. Ciência e Natura, v. 47, e87925. https://doi.org/10.5902/2179460X87925.

Batool, R.; Hadayat, N.; Khalid, N.; Raza Shah, S.M.; Aqeel, M.; Zaman, Q.U.; Alotaibi, M.O.; Alotaibi, N.M.; Al-Mutairi, M.; Noman, A., 2025. Phytoremediation potential of *Calendula officinalis L.* and *Verbena hybrida* for chromium detoxification in tannery wastewater. International Agrophysics, v. 39 (4), 489-504. https://doi.org/10.31545/intagr/209448.

Borah, P.; Rene, E.R.; Rangan, L.; Mitra, S., 2023. Phytoremediation of nickel and zinc using *Jatropha curcas* and *Pongamia pinnata* from the soils con-

taminated by municipal solid wastes and paper mill wastes. Environmental Research, v. 219, 115111. https://doi.org/10.1016/j.envres.2022.115055.

Brazil. Conselho Nacional do Meio Ambiente (CONAMA), 2009. Resolução CONAMA n. 420, de 28 de dezembro de 2009. Diário Oficial da União, Brasília.

Carvalho, G.A.; Santos, N.M.; Pedroso, E.C.; Torres, A.F., 2008. Eficiência do óleo de nim (*Azadirachta indica* A. Juss) no controle de *Brevicoryne brassicae* (Linnaeus, 1758) e *Myzus persicae* (Sulzer, 1776) (Hemiptera: Aphididae) em couve-manteiga. Arquivos do Instituto Biológico, v. 75 (2), 181-186. https://doi.org/10.1590/1808-1657v75p1812008.

Comissão de Química e Fertilidade do Solo - RS/SC (CQFS-RS/SC), 2016. Manual de calagem e adubação para os Estados do Rio Grande do Sul e de Santa Catarina. 11. ed. Sociedade Brasileira de Ciência do Solo - Núcleo Regional Sul, Porto Alegre.

Cozma, P.; Roșca, M.; Minuț, M.; Gavrilescu, M., 2025. Phytoremediation: A sustainable and promising bio-based approach to heavy metal pollution management. Science of the Total Environment, v. 1001, 180458. https://doi.org/10.1016/j.scitotenv.2025.180458.

Empresa Brasileira de Pesquisa Agropecuária (Embrapa), 2009. Manual de análises químicas de solos, plantas e fertilizantes. 2. ed. rev. e atual. Embrapa Informação Tecnológica, Brasília.

Empresa Brasileira de Pesquisa Agropecuária (Embrapa), 2018. Sistema brasileiro de classificação de solos. 5. ed. rev. e ampl. Embrapa, Brasília.

Ferreira, P.A.A.; Ceretta, C.A.; Lourenzi, C.R.; Conti, L.; Marchezan, C.; Girotto, E.; Tiecher, T.L.; Palermo, N.M.; Parent, L.; Brunetto, G., 2022. Long-term effects of animal manures on nutrient recovery and soil quality in acid typic hapludalf under no-till conditions. Agronomy, v. 12 (2), 243. https://doi.org/10.3390/agronomy12020243.

Florentino, R.W.; Kummer, A.C.B.; Bednarz, J.A.; Martins, K.G., 2025. Influence of liquid swine slurry on soil quality and water infiltration. Revista Brasileira de Ciências Ambientais, v. 60, e2301. https://doi.org/10.5327/Z2176-94782301.

Francisco, M.; Ortiz, R.; Obrador, A.; Gonzalez, D.; Gascó, G.; Almendros, P., 2025. The effect of complexed, nanosized, and conventional zinc sources applied at varying rates to an acidic mediterranean soil on two successive lettuce crops. Agronomy, v. 15 (4), 896. https://doi.org/10.3390/agronomy15040896.

Harris, D.C.; Lucy, C.A., 2023. Análise química quantitativa. 10. ed. LTC, Rio de Janeiro.

Instituto Nacional de Metrologia, Qualidade e Tecnologia (Inmetro), 2020. Orientações sobre validação de métodos de ensaios químicos: DOQ-CGCRE-008. 9. rev. Inmetro, Duque de Caxias.

Kunz, A. (Ed.), 2024. Gestão dos resíduos da produção animal: gestão e tratamento dos dejetos na suinocultura. Embrapa, Brasília; Sbera, Concórdia.

Lemos, A.P.; Freitas, D.A.F.; Adeyemo, A.J.; Oliveira, D.M.S., 2025. Evaluating potentially toxic elements under prolonged application of pig manure in Brazilian soils. Discover Applied Sciences, v. 7 (11), 1373. https://doi.org/10.1007/s42452-025-07048-4.

Liu, S.; Ali, S.; Yang, R.; Tao, J.; Ren, B., 2019. A newly discovered Cd-hyperaccumulator *Lantana camara L.* Journal of Hazardous Materials, v. 371, 233-242. https://doi.org/10.1016/j.jhazmat.2019.03.016.

Morsch, L.; Marques, A.C.R.; Trentin, E.; Oliveira, F.N.; Andreolli, T.; Barbosa, J.G.P.; Ferreira, M.M.; Moura-Bueno, J.M.; Comin, J.J.; Loss, A.; Lourenzi, C.R.; Brunetto, G., 2024. Diversity and botanical composition of native species in the Pampa biome in vineyards cultivated on soils with high levels of copper, zinc and manganese and phytoremediation potential. Chemosphere, v. 349, 140836. https://doi.org/10.1016/j.chemosphere.2023.140819.

Mustapha, L.S.; Obayomi, O.V.; Obayomi, K.S., 2026. A comprehensive review on potential heavy metals in the environment: Persistence, bioaccumulation, ecotoxicology, and agricultural impacts. Ecological Frontiers, v. 46 (2), 434-449. https://doi.org/10.1016/j.ecofro.2025.10.009.

Naseer, U.; Du, Z.; Ahmad, A.; Farooq, S.; Yousaf, M.; Yue, T., 2025. Advanced Electrode Materials in Electrokinetic Technology for Remediation of Heavy Metal-Contaminated Soil: Recent Progress and Challenges. Advanced Sustainable Systems, v. 9 (8), 2500197. https://doi.org/10.1002/adsu.202500197.

R Core Team, 2024. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/.

Raza, A.; Tabassum, J.; Zahid, Z.; Charagh, S.; Bashir, S.; Barmukh, R.; Khan, R.S.A.; Barbosa, F.; Zhang, C.; Chen, H.; Zhuang, W.; Varshney, R.K., 2022. Advances in "omics" approaches for improving toxic metals/metalloids tolerance in plants. Frontiers in Plant Science, v. 12, 794373. https://doi.org/10.3389/fpls.2021.794373.

Reeves, R.D.; Baker, A.J.M.; Becquer, T.; Echevarria, G.; Miranda, Z.J.G., 2007. The flora and biogeochemistry of the ultramafic soils of Goiás state, Brazil. Plant and Soil, v. 293 (1), 107-119. https://doi.org/10.1007/s11104-007-9192-x.

Sharma, S.; Kumar, T.; Das, D.K.; Mittal, A.; Verma, N.; Vinod, 2025. Phytoremediation of heavy metals in soil-concepts, advancements, and future directions. Journal of Soil Science and Plant Nutrition, v. 25 (1), 1253-1280. https://doi.org/10.1007/s42729-024-02199-6.

Soliman, M.; Al-Akeel, R.; Al-Ghamdi, M.; Almadiy, A.; Rawi, S.; Zhang, W.; Dhafer, H.A.; Mohamed, A.; Al Naggar, Y.; Salem, A.M., 2024. Trophic transfer of heavy metals across a food chain in a wastewater-irrigated agroecosystem. Environmental Monitoring and Assessment, v. 196 (11), 1082. https://doi.org/10.1007/s10661-024-13179-9.

Wang, G.; Cissé, G.; Staunton, S., 2024. Changes in the chemical fractionation of copper and zinc in soil as a function of incubation moisture content and organic matter amendments. Chemosphere, v. 351, 141198. https://doi.org/10.1016/j.chemosphere.2024.141198.

Wei, Z.; Gu, H.; Van Le, Q.; Peng, W.; Lam, S.S.; Yang, Y.; Li, C.; Sonne, C., 2021. Perspectives on phytoremediation of zinc pollution in air, water and soil. Sustainable Chemistry and Pharmacy, v. 24, 100550. https://doi.org/10.1016/j.scp.2021.100550.

Xie, Y.; Zhang, M.H.; Xiong, R.; Li, T.; Pu, Y.L.; Xu, X.X.; Li, Y.; Zhang, S.; Jia, Y.X., 2021. Study on the tolerance and detoxification mechanisms of *Lantana camara* under the combined stress of cadmium, lead and zinc. Journal of Ecology and Rural Environment, v. 37 (9), 1209-1217. https://doi.org/10.19741/j.issn.1673-4831.2020.1027.

Xu, L.; Zhao, F.; Xing, X.; Peng, J.; Wang, J.; Ji, M.; Li, B.L., 2024. A review on remediation technology and the remediation evaluation of heavy metal-contaminated soils. Toxics, v. 12 (12), 897. https://doi.org/10.3390/toxics12120897.