CULTIVATION OF LUDWIGIA PERUVIANA IN SOIL WITH HIGH LEVELS OF NICKEL

CULTIVO DE LUDWIGIA PERUVIANA EM SOLO COM ALTOS NÍVEIS DE NÍQUEL

CULTIVO DE LUDWIGIA PERUVIANA EN SUELO CON ALTOS NIVELES DE NÍQUEL

https://doi.org/10.56238/edimpacto2025.080-010

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ABSTRACT

This study evaluated the cultivation of Ludwigia peruviana in soil contaminated with nickel (Ni), a heavy metal (HM) micronutrient that is toxic in high concentrations. Excess nickel poses risk to both human health and the environment. Five conditions were evaluated using different proportions of contaminated soil and substrate (0:100, 25:75, 50:50, 75:25, and 100:0), with ten replicates per treatment and one plant per pot. The cultivation period lasted

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14 weeks in a greenhouse under controlled temperature and humidity conditions. Throughout the experiments, plant growth and chlorophyll content were monitored weekly, while flower production was recorded daily. At the end of the experiment, root length, total dry mass, and metal concentrations in different plant tissues were analyzed. Results indicated that L. peruviana exhibited low Ni uptake, accumulating only small amounts in the roots under lower Ni contamination levels. Additionally, exposure to excess Ni negatively affected plant growth, sprouting, chlorophyll content, total dry mass, root length, and reproductive development. These findings suggest that L. peruviana is not suitable for the phytoremediation of Ni-contaminated areas. However, due to its ability to thrive in compacted and nutrient-poor soils, this species may still be valuable as a bioindicator and for revegetation programs in degraded areas.

Keywords: *Ludwigia Peruaviana*. Nickel. Phytoremediation. Heavy Metals.

RESUMO

Este estudo avaliou o cultivo de Ludwigia peruviana em solo contaminado com níquel (Ni), um micronutriente classificado como metal pesado (MP) que se torna tóxico em altas concentrações. O excesso de níquel representa riscos tanto à saúde humana quanto ao meio ambiente. Foram avaliadas cinco condições, utilizando diferentes proporções de solo contaminado e substrato (0:100, 25:75, 50:50, 75:25 e 100:0), com dez repetições por tratamento e uma planta por vaso. O período de cultivo foi de 14 semanas em casa de vegetação, sob condições controladas de temperatura e umidade. Ao longo dos experimentos, o crescimento das plantas e o teor de clorofila foram monitorados semanalmente, enquanto a produção de flores foi registrada diariamente. Ao final do experimento, analisaram-se o comprimento das raízes, a massa seca total e as concentrações de metais em diferentes tecidos vegetais. Os resultados indicaram que L. peruviana apresentou baixa absorção de Ni, acumulando apenas pequenas quantidades nas raízes sob menores níveis de contaminação. Além disso, a exposição ao excesso de Ni afetou negativamente o crescimento das plantas, a brotação, o teor de clorofila, a massa seca total, o comprimento das raízes e o desenvolvimento reprodutivo. Esses achados sugerem que L. peruviana não é adequada para a fitorremediação de áreas contaminadas por Ni. Entretanto, devido à sua capacidade de se desenvolver em solos compactados e pobres em nutrientes, essa espécie pode ser valiosa como bioindicadora e em programas de revegetação de áreas degradadas.

Palavras-chave: *Ludwigia peruviana*. Níquel. Fitorremediação. Metais Pesados.

RESUMEN

Este estudio evaluó el cultivo de Ludwigia peruviana en suelo contaminado con níquel (Ni), un micronutriente clasificado como metal pesado (MP) que resulta tóxico en altas concentraciones. El exceso de níquel representa riesgos tanto para la salud humana como para el medio ambiente. Se evaluaron cinco condiciones utilizando diferentes proporciones de suelo contaminado y sustrato (0:100, 25:75, 50:50, 75:25 y 100:0), con diez repeticiones por tratamiento y una planta por maceta. El período de cultivo fue de 14 semanas en invernadero, bajo condiciones controladas de temperatura y humedad. A lo largo de los experimentos, el crecimiento de las plantas y el contenido de clorofila se monitorearon semanalmente, mientras que la producción de flores se registró diariamente. Al final del experimento, se analizaron la longitud de las raíces, la masa seca total y las concentraciones de metales en diferentes tejidos vegetales. Los resultados indicaron que L. peruviana presentó una baja absorción de Ni, acumulando solo pequeñas cantidades en las raíces bajo niveles más bajos de contaminación. Además, la exposición al exceso de Ni afectó negativamente el crecimiento de las plantas, la brotación, el contenido de clorofila, la masa seca total, la longitud de las raíces y el desarrollo reproductivo. Estos hallazgos sugieren que

L. peruviana no es adecuada para la fitorremediación de áreas contaminadas con Ni. No obstante, debido a su capacidad para desarrollarse en suelos compactados y pobres en nutrientes, esta especie puede ser valiosa como bioindicadora y para programas de revegetación en áreas degradadas.

Palabras clave: *Ludwigia peruviana*. Níquel. Fitorremediación. Metales Pesados.

1 INTRODUCTION

By 2050, the global population is projected to reach 9.7 billion, significantly increasing the demand for natural resources (SADIGOV, 2022). However, since the Industrial Revolution, rapid industrialization, urbanization, and intensive agriculture have substantially contributed to soil contamination, posing challenges for future generations, particularly in terms of food security and human health (BOUIDA et al., 2022, RAJENDRAN et al., 2022; SARAVANAN et al., 2024).

Among major environmental pollutants, contamination by heavy metals (HMs) represent one of the most pressing environmental, economic, and social issues of the 21st century. It is estimated that approximately 16% of the planet's arable land is contaminated with HMs (XU et al., 2021; KUMAR et al., 2021). Heavy metals are non-biodegradable contaminants with a density greater than 5 g.cm-1, including lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), cobalt (Co), and manganese (Mn), among others (WAHID et al., 2021; AZHAR et al., 2022; JHA et al., 2024).

Soils play a fundamental role in sustaining life and ensuring environmental well-being. Although HMs naturally occur in soils at low concentrations, human activities have significantly increased their levels (GODÉRÉ et al., 2023; WAHID et al., 2021; RASOULI et al., 2023). Nickel, for instance, is a micronutrient essential for plants in small amounts, as it participates in enzymatic synthesis, nitrogen uptake, and photosynthesis (KUMAR et al., 2021; ALTAF et al, 2021). However, excessive Ni levels can interfere with the absorption of essential nutrients such as calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), and Mn, leading to nutritional deficiencies, impaired photosynthesis, and, in severe cases, necrosis (GHAZANFAR et al., 2021; VISCHETTI et al.,2022; RASOULI et al., 2023).

Nickel contamination can occur naturally through rock weathering and volcanic eruptions or result from anthropogenic sources such as industrial effluents, landfills, electroplating, and paint manufacturing (KUMAR et al., 2021; EL-NAGGAR et al., 2021). In China, 4.8% of agricultural soils are contaminated with Ni (DING et al., 2022). In humans, the primary route of Ni exposure is through the ingestion of contaminated food, which can lead to serious health issues, including cancer, allergies, and respiratory disorders (EL-NAGGAR et al., 2021).

The safe concentration range for Ni in agricultural soils varies between 20 mg.kg-1 and 60 mg.kg-1, with values exceeding 75 mg.kg-1 being toxic to certain plants, especially in soils with a pH below 6, where Ni is more bioavailable and thus toxic (EL-NAGGAR et al., 2021; ROCCOTIELLO et al., 2022). Various soil remediation techniques are available, including soil removal, washing, chemical precipitation and flocculation, chelating agent application, electrochemical processes, and bioremediation. Among these, phytoremediation has gained attention as a sustainable approach, utilizing plants to remove contaminants while being more economical and environmentally friendly compared to conventional methods (CUI et al., 2023; RASAFI et al., 2023; UGRINA; JURIĆ, 2023). Additionally, phytoremediation aims to restore soil quality and functionality by improving parameters such as pH, texture, cation exchange capacity (CEC), microbial diversity, and by reducing erosion and leaching (KAFLE et al., 2022; SABREENA et al., 2022). Plants employ various mechanisms to mitigate HM contamination, including phytoextraction, phytomining, rhizofiltration, and phytostabilization (MOCEK-PLÓCINIAK et al.2023; WANG; DEVALAR, 2023).

Several plant species have been successfully used for Ni phytoremediation, including Odontarrhena chalcidica (Janka), Brassica napus, Lavandula angustifolia L., Iris sibirica L., and Chrysopogon zizanoides L. (DURANT et al., 2023; NAWAZ et al., 2022; RASOULI et al., 2023; WAN et al., 2021; NUGROHO et al., 2021). Additionally, some plant species can serve as bioindicators. These species are adapted to specific environments and exhibit changes in physical characteristics or coloration, which can help classify environmental conditions. Examples include Silene suecica (Loidd.) Greuter & Burdet, which exhibits Cu resistance and grows near mines; Pteridium aquilinum, which thrives in aluminum (Al)-rich environments; and Ruppatorium sp., which is associated with molibdenium (Mo)-rich or Mo-contaminated soils (TOMCHINSKY; SIQUEIRA, 2020; OLIVEIRA; FREIRE; AQUINO, 2004; LEITE; MEIRA,2024, CAKAJ et al., 2024).

In this context, aquatic macrophytes such as Ludwigia peruviana (L.) H.Hara have shown promise for phytoremediation due to their ability to absorb and accumulate HMs, along with other advantageous characteristics such as rapid growth, tolerance to adverse conditions, and well-developed root systems (EID et al., 2020; ULAGANATHAN et al., 2022). L. peruviana is a native species of wetlands in South, Central, and Caribbean America, adapted to flooded environments such as riverbanks and streams (BARUA, 2010; USDA, 2023; ANYINKENG et al., 2020). Beyond its potential for phytoremediation, this species has been explored for its antimalarial properties (CHINSEMBU, 2015; DIKE; OBEMBE; ADEBIYI, 2012), as well as its use in treating liver pain, diuretic and kidney disorders (TENE et al., 2007). Additionally, its biomass has been investigated as an organic fertilizer alternative to phosphate-based fertilizers (POVEDA, 2023; SHUKLA et al., 2020; SHUKLA et al., 2021). The phytoremediation potential of L. peruviana has been studied for various metals, including

Cu, Zn, Cd, Pb, Al, Ag, Cr, Ga, and Sr (ANYINKENG et al., 2020; AVEIGA et al., 2023). However, to date, no studies have evaluated its effectiveness in specifically Ni-contaminated soils. Therefore, this study aims to assess the cultivation of L. peruviana in Ni-contaminated soil to determine its potential for phytoremediation.

2 METHODOLOGY

The soil used in this experiment was collected in the municipality of Arroio do Meio, in the state of Rio Grande do Sul, Brazil, at coordinates 29°24’33’’S 51°58’02’’W in June 2023. After collection, the soil was air-dried at room temperature and sieved using a mesh 6 sieve, a process conducted in loco. The experiment consisted of five treatments, in which the contaminated soil was mixed with a commercial substrate (composed of peat, vermiculite, and dolomitic limestone) in different contaminated soil:substrate (v/v) ratios: 0:100, 25:75, 50:50, 75:25, and 100:0, respectively. These treatments were identified as T 0%, T 25%, T 50%, T 75%, and T 100%.

For each treatment, the physicochemical properties of the soil were assessed, including pH, organic matter content, total nitrogen, available phosphorus, and cation exchange capacity (CEC), following the methodology described by Teixeira et al. (2017). The particle size distribution was determined according to the ABNT NBR 7181 (2016) standard, while the specific mass of grains and porosity were evaluated following ABNT NBR 6458 (2016). The contaminant content was analyzed by microwave digestion, followed by inductively coupled plasma-atomic emission spectroscopy (ICP-OES, ICAP PRO Series), as described by Song et al. (2022).

L. peruviana specimens were collected from the margins of the Taquari River in the municipality of Forquetinha, Rio Grande do Sul, Brazil, and propagated by stem cuttings in Carolina Soils substrate. The cuttings were maintained in a greenhouse until they reached approximately 10 cm in height. Each treatment was then set up in 3.6 L plastic pots, with 10 pots per treatment, each containing one L. peruviana seedling. The plants were cultivated for 14 weeks in a greenhouse at the University of Vale do Taquari (Univates), under an average temperature of 23.2 °C ± 5.0 °C and relative humidity of 84.3% ± 12.5%.

Figure 1

Cultivation of L. peruviana

Source: From the author.

Throughout the cultivation period, weekly assessments were conducted, including the length of the longest shoot (measured with a measuring tape) and the total number of shoots per plant. Chlorophyll A, B, and total chlorophyll content were measured using a portable chlorophyll meter (Clorofilog CFL 2060, Falker). For the 7th week onwards, the number of flowers per treatment was recorded daily (TENG et al., 2022; HASNAOUI et al., 2020; MADANAN et al., 2021; CAPOZZI et al., 2020).

At the end of the cultivation period, the plants were harvested, and root length was measured with a ruler. The samples were then separated into shoot, stem, and root, and dried in an oven (MA035, Marconi) at 40 °C for one week. After drying, the dry biomass was determined using an analytical balance. Subsequently, the material was ground using a knife mill (MA880, Marconi), digested in a microwave system (Multiwave PRO, Anton Paar), and analyzed via ICP-OES, following the methodology described by Song et al. (2017). The metal content analyses were performed by an external laboratory.

The obtained results were subjected to analysis of variance (ANOVA) and Tukey's Test at a 95% confidence level for normalized data. For non-normalized data, the Shapiro-Wilk test was applied. Statistical analyses were performed using Microsoft Excel 2016 (Microsoft) and PAST software (HAMMER; HARPER; RYAN, 2023). All experiments were conducted in triplicate.

3 RESULTS

3.1 PHYSICOCHEMICAL PARAMETERS

Table 1 presents the physicochemical parameters of the different treatments. The T 0%, T 25%, and T 50% treatments exhibited statistically similar soil pH values and organic matter content. In contrast, T 75% and T 100% displayed comparable pH values but distinct organic matter content. The cation exchange capacity (CEC), an index that evaluates soil nutrient retention capacity and is influenced by factors such as pH, moisture, and organic matter, was approximately five times higher in T 100% compared to T 0%. Similarly, the availability of essential nutrients (K, P, Ca, and Mg) was highest in T 100%, showing statistically significant differences from other treatments. The concentration of Ni was approximately four times higher in T 100% compared to T 0%, with T 100% being the only treatment where Ni content was significantly higher than in other treatments.

Organic matter directly influences soil physical quality, as higher organic matter content reduces soil density and enhances water and air circulation, thereby improving root development and, consequently, plant growth (PORTO et al., 2024; WITZGALL et al., 2021; MAURYA et al., 2020; VOLTR et al., 2021). Additionally, CEC is associated with water and nutrient retention, making the soil more fertile as these values increase (TEXIERA et al., 2017; AMPONG; THILAKARANTHNA; GORIM, 2022; MAURYA et al., 2020).

Table 1

Physicochemical parameters of the different treatment ratios in which L. perviana was cultivated

Parameter	T 0%	T 25%	T 50%	T 75%	T 100%
pH	6.40 ± 0.05 a	6.49 ± 0.03 a	6.31 ± 0.04 a	5.90 ± 0.14 b	5.80 ± 0.05 b
Organic Matter (%)	11.03 ± 0.17 a	13.37 ± 0.33 a	16.52 ± 0.96 a	26.97 ± 2.46 b	50.36 ± 4.31 c
CTC	21.28	24.83	29.7	37.44	101.29
Density (g/cm^3)	0.87 ± 0.07 a	0.77 ± 0.04 a	0.55 ± 0.03 b	0.35 ± 0.03 c	0.11 ± 0.01 d
Porosity	67.37	68.04	74.27	81.04	93.13
Total N ($g.kg^{-1}$)	5.36	5.27	5.05	4.56	4.10

Available P ($mg.kg^{-1}$)	28.08 ± 0.46 a	62.10 ± 3.07 b	98.37 ± 2.08 c	108.97 ± 3.10 d	220.31 ± 0.02 e
Available K ($g.kg^{-1}$)	0.12 ± 0.01 a	0.17 ± 0.01 a	0.27 ± 0.01 a	0.59 ± 0.01 b	2.17 ± 0.10 c
Available Ca ($mg.kg^{-1}$)	609.19 ± 22.67 a	655.47 ± 10.78 a	650.71 ± 22.44 a	590.23 ± 32.68 a	788.91 ± 44.41b
Available Mg ($mg.kg^{-1}$)	0.52 ± 0.02 a	0.75 ± 0.03 a	0.86 ± 0.03 a	0.67 ± 0.04 a	2.83 ± 0.11 b
Total Ni ($mg.kg^{-1}$)	106.99 ± 2.50 a	121.09 ± 29.08 a	150.95 ± 5.12 a	187.59 ± 4.64 a	426.76 ± 45.69 b

Identical lowercase letters indicate statistically similar values. Different lowercase letters indicate statistically different values.

Brazilian soils are generally poor in available P, with average levels around 1 mg.kg-1 (Melo, 2021). However, an adequate level of available P should exceed 26 mg.kg-1 (Sobral et al., 2015). Thus, P availability was not a limiting factor in any of the treatments.

According to Silva et al. (2021), the optimal level of available K in the soil should exceed 104 mg.kg-1. Consequently, no K deficiency was observed in any of the experiments.

Sobral et al. (2015) state that the adequate level of available Ca in the soil should be above 156 $mg.kg^{-1}$. Therefore, Ca availability was also not a limiting factor in any of the treatments. However, for Mg, the adequate level should be above 21 $mg.kg^{-1}$, indicating that all five treatments were deficient in available Mg.

Ni is an essential micronutrient that plays a role in several biological functions, partially responsible for normal plant growth, development, and photosynthesis (ALTAF et al, 2021). However, concentrations between 75 mg.kg-1 and 150 mg.kg-1 may be toxic to plants (KUMAR et al, 2021). In this study, the soil in the T 100% treatment contained 2.8 times more Ni than the maximum level that plants typically tolerate. Additionally, T 50% and T 75% also exceeded this threshold, whereas T 0% and T 25% remained within acceptable levels for some plant species.

3.2 GROWTH AND DEVELOPMENT OF LUDWIGIA PERUVIANA UNDER DIFFERENT SOIL CONDITIONS

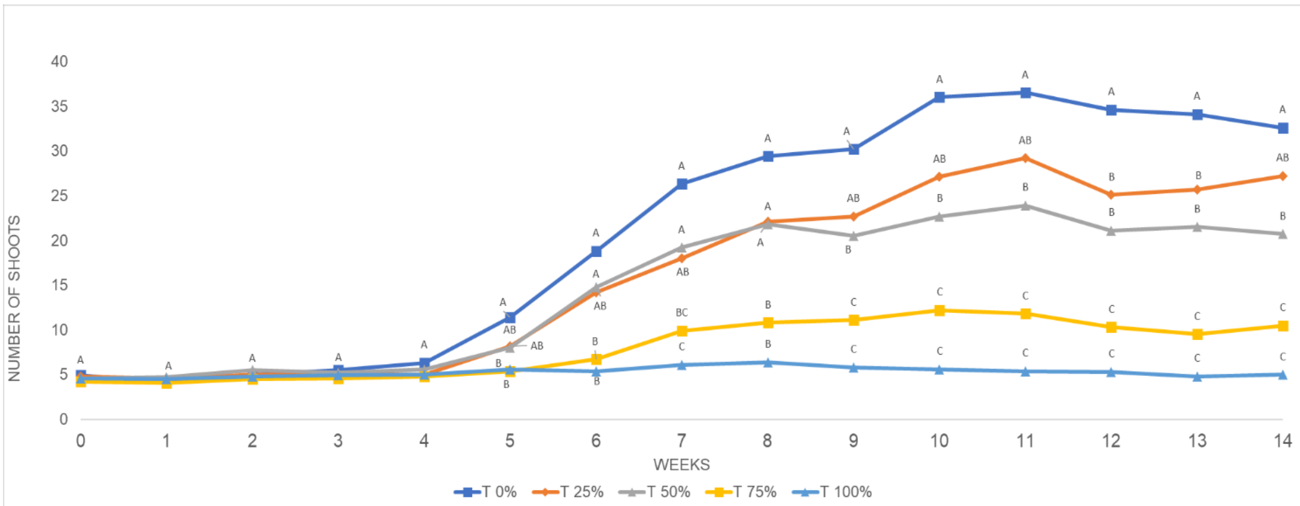
Figure 2 presents the shoot development of L. peruviana over 14 weeks across the five different treatments. Until the fifth week, the number of shoots was statistically similar among all treatments. The T 0% treatment exhibited the highest number of shoots, showing a statistically similar pattern to T 25%. In contrast, T 75% and T 100% displayed the lowest shoot production, with no statistical difference between them. This parameter is novel for this species in particular, as no studies correlating these findings were found in literature.

However, studies by Kumar et al. (2021) and Ghazanfar et al. (2021) report that excess Ni negatively affects shoot development. Thus, the high Ni concentration in T 75% and T 100% likely hindered shoot formation. Throughout the 14 weeks, the length of the longest shoot was measured (Figure 3). Until the fourth week, all treatments exhibited similar shoot lengths. However, from this point onward, T 0%, T 25%, and T 50% showed greater shoot development, with no statistical differences among them. Conversely, T 100% exhibited the poorest growth, showing statistically significant differences from the other treatments. This assessment is also unprecedented for the genus Ludwigia and will therefore be compared with other plant species. Once again, the reduced growth observed in T 100% is likely associated with the high Ni concentration, as Ni contamination is known to hinder plant growth (Kumar et al., 2021; Ghazanfar et al., 2021).

In a study by Parera et al. (2023), the phytotoxic effects of arsenic (As), Ni, Cd, and mercury (Hg) were evaluated on two species: Adesmia pinifolia Gillies ex Hook & Arn and Adesmia subterranea Clos. For both species, Ni exposure reduced growth by more than 90% compared to the control. Similarly, Nawaz et al. (2022) found that exposing two varieties of Brassica napus seeds to Ni reduced plant height by approximately 20%. In another study, Khair et al. (2020) observed that Ni exposure led to an ~80% reduction in the growth of Mentha piperita (L.).

Figure 2

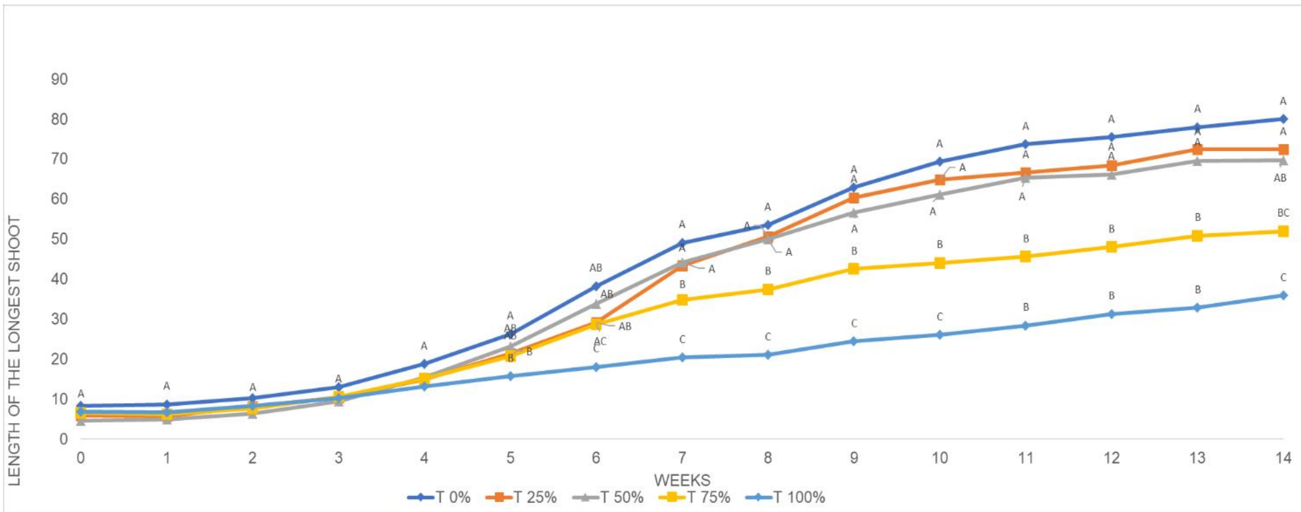
Number of shoots of L. peruviana over 14 weeks, evaluated under different treatments



Lowercase letters indicate statistically similar values, whereas different lowercase letters indicate statistically different values.

Figure 3

Length of the longest shoot of L. peruviana over the cultivation period under five different treatments

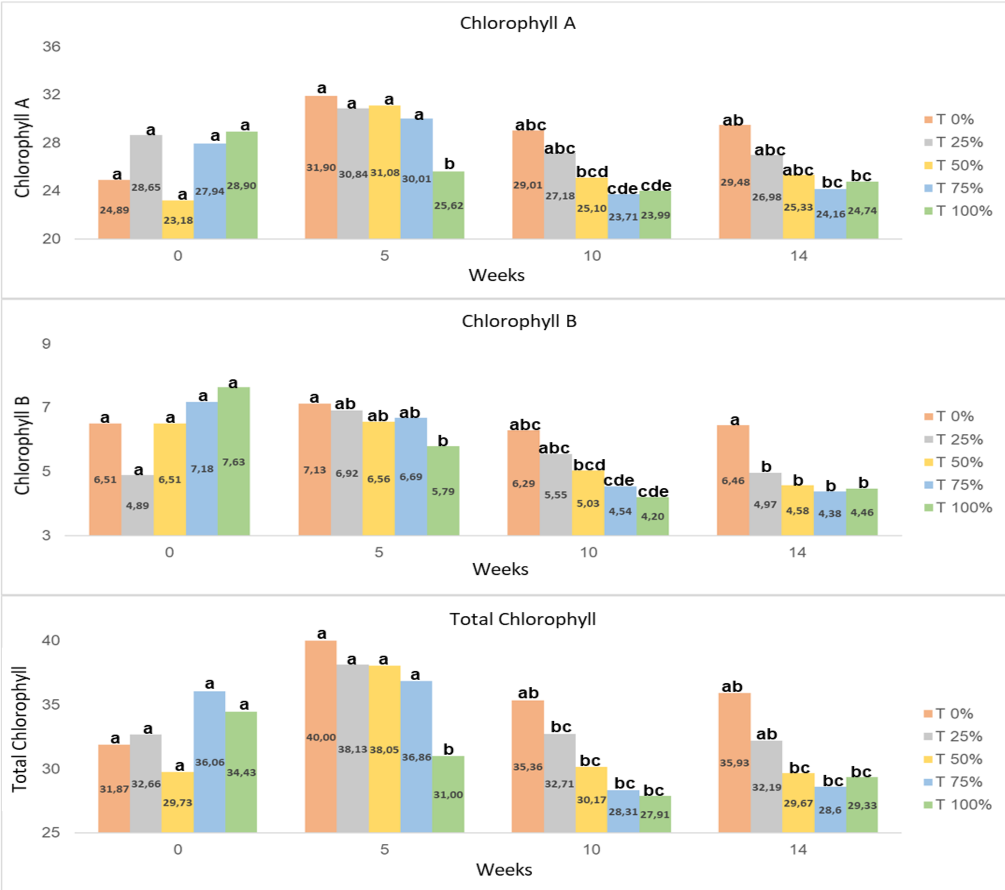


Lowercase letters indicate statistically similar values, whereas different lowercase letters indicate statistically different values.

The chlorophyll A, B, and total chlorophyll contents are presented in Figure 4. Chlorophyll levels remained stable across all five treatments until the 5th week. After this period, T 100% began to show statistically different chlorophyll content in comparison with all other treatments. From the 10th week onward, T 75% also exhibited lower chlorophyll levels compared to T 0%, T 25%, and T 50%. By the end of the cultivation period, T 0% had the highest chlorophyll A, B, and total chlorophyll content. The decrease in chlorophyll levels, particularly in T 100% and T 75%, is likely related to competition between Ni and Mg ions, especially because the pH values in these treatments was below 6, which increases the solubility of the contaminant in the soil (GHAZANFAR et al., 2021; VISCHETTI et al.,2022; RASOULI et al., 2023). Similar reductions in chlorophyll levels have been observed in other plant species exposed to Ni contamination, such as M. piperita (Khair et al., 2020), B. napus (Nawaz et al., 2022), and Zea mays (Malik, 2022).

Figure 4

Chlorophyll A, B, and total chlorophyll content in L. peruviana cultivated for 14 weeks under five different treatments

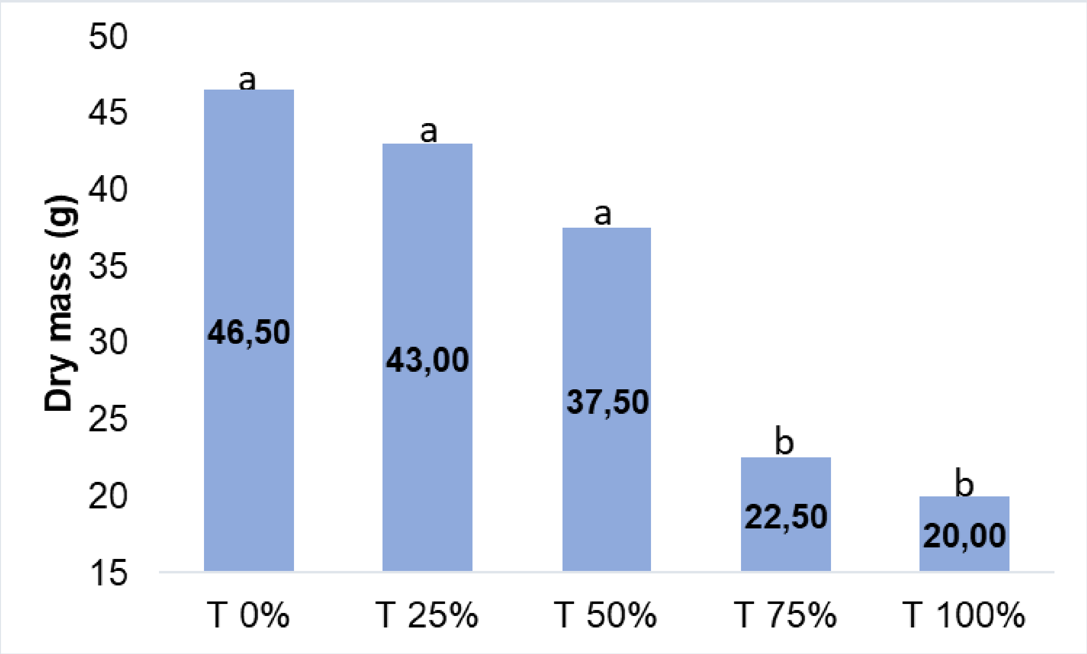


Lowercase letters indicate statistically similar values, whereas different lowercase letters indicate statistically different values.

Figure 5 presents the dry mass of L. peruviana. The T 0%, T 25%, and T 50% treatments exhibited the highest dry mass values, with 46.5 g, 43.0 g, and 37.5 g, respectively. In contrast, T 100% showed a more than 50% reduction in dry mass compared to T 0%. The decrease in dry mass observed in T 100% and T 75% may be associated with delayed plant development due to Ni toxicity. Similar results have been reported in other studies, such as the work of Nawaz et al. (2022), where exposure to 30 $mg.kg^{-1}$ of Ni contamination in two seed varieties of B. napus resulted in a 40% reduction in dry mass for the Con-II variety and 50% for the Oscar variety.

Figure 5

Dry mass of L. peruviana after 14 weeks of cultivation in different soil conditions

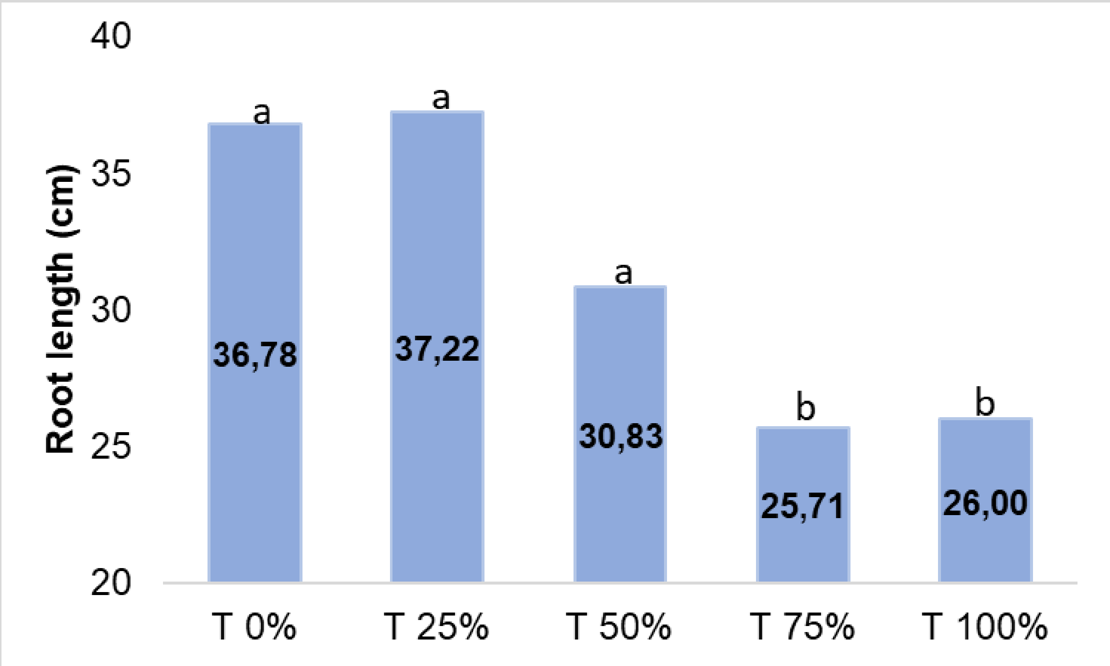


Lowercase letters indicate statistically similar values. Uppercase letters indicate statistic differences between values.

Figure 6 presents the root length of L. peruaviana at the end of the cultivation period. The T 0%, T 25%, and T 50% treatments exhibited the greatest root length, while T 75% and T 100% showed reduced root development. Since this study is novel for this species, comparisons were made with studies on other plant species. According to Kumar et al. (2021), Ni contamination leads to root shortening. Similarly, in the study by Chen et al. (2022), Ni contamination reduced the root length of Medicago sativa L. Additionally, Tipu et al. (2021) reported a 19.4% reduction in Zea mays root length in the presence of Ni. In the study by Visioli et al. (2014), six plant species were tested, all of which exhibited root shortening as Ni contamination increased.

Figure 6

Root length of Ludwigia peruviana after cultivation in five different soil conditions

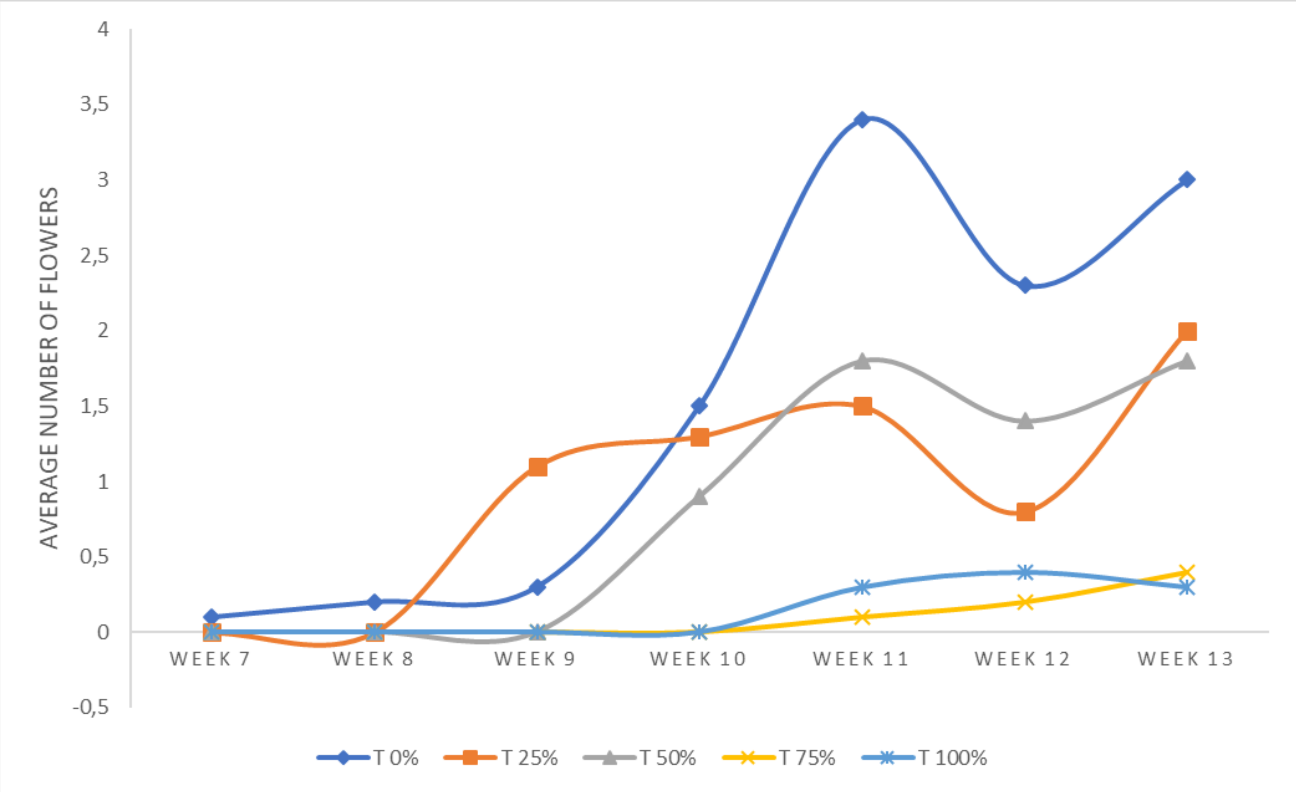


Lowercase letters indicate statistically similar values, whereas different lowercase letters indicate statistically different values.

Figure 7 presents the average number of flowers per week for each soil treatment. 0% treatment entered the reproductive stage two weeks earlier than T 25%, three weeks earlier than T 50%, and four weeks earlier than T 75% and T 100%. This suggests that increased Ni levels cause a delay in the reproductive development of L. peruviana. However, there are few studies linking Ni contamination to this specific aspect of plant development. In the study by Meindl and Ashman (2013), no significant difference in flower number was observed when Streptanthus polygaloides was exposed to 200 $mg.kg^{-1}$ of Ni contamination.

Figure 7

Average number of flowers per week in L. peruviana cultivated in five different soil treatments



Source: From the author.

3.3 NICKEL UPTAKE AND FATE

After the cultivation period, the plants were dried, separated into different parts, ground, digested, and analyzed by ICP-OES. Ni accumulation was detected only in the roots of the T 0% and T 25% treatments, while no Ni accumulation was observed in other plant parts or soil treatment conditions. The results are presented in Table 2.

Table 2

Ni uptake by L. peruviana in five different soil treatments

	Leaves (mg.kg^{-1})	Stem (mg.kg^{-1})	Root (mg.kg^{-1})
T 0%	<0.001	<0.001	0.018 a
T 25%	<0.001	<0.001	0.020 a
T 50%	< 0.001	<0.001	<0.001
T 75%	<0.001	<0.001	<0.001
T 100%	<0.001	<0.001	<0.001

Lowercase letters indicate statistically similar values, whereas different lowercase letters indicate statistically different values.

In the study by Khair et al. (2020), an increase in Ni concentration in the environment led to lower accumulation in the roots of M. piperita. Similarly, Nawaz et al. (2022) reported that B. napus was able to accumulate approximately 20% of the Ni contamination when grown in pots. In the study by Malik (2022), Zea mays also demonstrated the ability to absorb and accumulate Ni.

4 CONCLUSION

At the end of this study, we conclude that Ludwigia peruviana is not suitable for the phytoremediation of Ni soil contamination, as it was unable to absorb this contaminant during the cultivation period and exhibited signs of Ni toxicity when exposed to higher Ni concentrations. At elevated levels, the metal negatively affected growth, development, and chlorophyll production, in addition to delaying the reproductive phase and reducing dry biomass. However, under the conditions of this experiment, L. peruviana can still be used as a bioindicator in environments with high Ni concentrations.

Despite this, L. peruviana demonstrated low nutritional requirements, successfully growing in soils with low CEC and reduced levels of certain nutrients. This suggests that this species may be useful for restoring native vegetation in protected areas with degraded soils. Furthermore, the plant showed no impairment in root development in soils with lower porosity and higher density, indicating potential for use in areas with high soil compaction. Future studies could explore different types of soil, the chemical binding states of Ni in the soil, and longer exposure period for adult plants.

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