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Environmental Chemistry

Lantana fucata Lindl. is tolerant and grows in copper-enriched soils

Lantana fucata L. é tolerante e cresce em solos enriquecidos com cobre

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ABSTRACT

Phytoremediation is a technology that uses the capacity of plants to absorb, accumulate, metabolize, volatilize, or stabilize contaminants present in the environment, including metals. Thus, the goal of this research was to evaluate the tolerance, absorption, and accumulation of copper (Cu) by the native species from the Brazilian flora, *Lantana fucata*, in soil. The experimental outline was completely randomized and conducted in the greenhouse with a 100-day cultivation cycle. Cu was added to the soil at concentrations of 70, 140, 210, 280, 420, 630, 840 mg kg^{-1} and control (without addition). The parameters evaluated were: translocation factor (TF), bioconcentration factor (BCF), metal extraction rate (MER), tolerance index (TI) and dry mass. *L. fucata* showed good tolerance (TI>100%) in all treatments when compared to the control. It was also observed that efficiency in retention of this metal, mainly in the roots, obtained TF<1 for all treatments and a BFC range from 0.18 to 7.41. MER showed an average variation of 2.5%, being less effective in the treatment with the highest dose of Cu. Thus, in this work we show for the first time the potential phytoremediation capacity of *L. fucata*, through a phytostabilization mechanism, when the soil presents contamination of up to 140 mg kg^{-1}.

Keywords: Phytoremediation; Translocation; Bioconcentration; Native plant

RESUMO

A fitorremediação é uma tecnologia que utiliza a capacidade das plantas de absorver, acumular, metabolizar, volatilizar ou estabilizar contaminantes presentes no meio ambiente, incluindo metais. Assim, o objetivo desta pesquisa foi avaliar a tolerância, absorção e acúmulo de cobre (Cu) pela espécie nativa da flora brasileira, *Lantana fucata*, no solo. O delineamento experimental foi inteiramente casualizado e conduzido em casa de vegetação com ciclo de cultivo de 100 dias. Cu foi adicionado ao solo nas concentrações de 70, 140, 210, 280, 420, 630, 840 mg kg^{-1} e controle (sem adição). Os parâmetros avaliados foram: fator de translocação (FT), fator de bioconcentração (FBC), taxa de extração de metal (TEM), índice de tolerância (IT) e massa seca. *L. fucata* apresentou boa tolerância (IT>100%) em todos os tratamentos, quando comparado ao controle. Observou-se também eficiência na retenção deste metal, principalmente nas raízes, obtendo FT<1 para todos os tratamentos e faixa de FBC de 0,18 a 7,41. A TEM apresentou variação média de 2,5%, sendo menos eficaz no tratamento com maior dose de Cu. Assim, neste trabalho mostramos pela primeira vez potenciais características fitorremediadoras de *L. fucata*, através de um mecanismo de fitoestabilização, quando o solo apresenta contaminação de até 140 mg kg^{-1}.

Palavras-chave: Fitorremediação; Translocação; Bioconcentração; Planta nativa

1 INTRODUCTION

Environmental pollution by metals from anthropic activities causes imbalances in nature. Products and waste containing copper (Cu) are present in various urban, industrial and agricultural activities, all with great potential for soil and water contamination (Andreazza et al., 2013; Alaboudi et al., 2018). In soils for agricultural use, one of the main factors related to the increase in Cu content at the toxic effect level is the excessive use of copper fungicides (Pietrzak & Mcphail, 2004; Schmitt et al., 2020).

Unlike what occurs with organic contaminants, Cu, like most metals, does not undergo microbial or chemical degradation. Consequently, metals not only accumulate in the soil and can infiltrate into groundwater, but also into the food chain through crops that grow in contaminated areas, and consequently affect human health (Guo et al. ,2006; Alaboudi et al. 2018; Schmitt et al., 2020). In this sense, the Conselho Nacional do Meio Ambiente (CONAMA), aiming at the need to create legislation and parameters for monitoring and evaluating the levels of metals added to different environments and in areas exploited by agriculture, stipulated reference values based on the total concentration of Cu in the soil, being 60 mg kg^{-1} of soil for prevention and 200 mg kg^{-1} for investigation.

In order to minimize the harmful effects of metals in the soil, when these are in excess, remediation can be applied. Remediation is divided into physicochemical and biological methods. The physicochemical forms involve techniques such as washing with chelating and strong acids, the use of adsorbents, soil replacement, and in some cases they can be environmentally destructive and degrade local biodiversity, soil structure and fertility (Alaboudi et al., 2018; Ghazaryan et al., 2019). Biological forms involve absorption and biosorption of contaminants by microorganisms, among them the use of phytoremediation (Alaboudi et al., 2018).

Phytoremediation is a technique that consists of using plants to remove contaminants from the environment by absorbing, accumulating or transforming the pollutant in its plant mass, as well as stabilizing and degrading it in the rhizosphere (Andreazza et al., 2013; Ghazaryan et al., 2019).

For the use of plants in phytoremediation, it is necessary for them to be tolerant to the metal to be remedied (Yadav et al., 2018). Tolerance varies according to the species and the mechanisms that the plant expresses to the metal, for example, root exudates can interrupt metal absorption; or when metal is absorbed, it can be stored in less functional tissues, reducing its toxicity (Antoniadis et al., 2017).

The absorption of metals by plants is influenced by soil characteristics such as pH, organic matter content and cation exchange capacity (Yoon et al., 2006). Cu is preferentially absorbed in inorganic form where the Cu^{2+} ion coordinates with water molecules, being classified as a free species (Kabata-Pendias & Pendias, 2010; Printz et al., 2016). The formation of Cu species complexed by binders or ionic pairs, exuded by plants, reduces the amount of free Cu^{2+}, decreasing the contaminant toxicity, characterizing as a tolerance mechanism of the species. Such mechanisms depend on the physiological and biochemical response of the species, controlling the absorption, accumulation and translocation of the contaminant in the plant (Souza et al., 2011; Yadav et al., 2018).

In addition to tolerance, another important characteristic for phytoremediation is accumulation. Several hyperaccumulators species have already been described in the literature for accumulating a high concentration of metals in their plant mass, which specifically in the case of Cu is up to 1000 mg kg^{-1}. Although plants with this characteristic are already known, they are not suitable for all regions, and it is important to test native plants for this purpose, as they tend to be better in terms of survival, growth and reproduction under stress conditions when compared to introduced plants from another environment (Yoon et al., 2006; Ghazaryan et al., 2019).

In this context, the hypothesis that *Lantana fucata* has tolerance to metals in the soil is considered, since there are records of its occurrence in ferruginous rocky outcrops in the State of Minas Gerais, Brazil (Schettini et al. 2018). *L. fucata* is an evergreen and ruderal shrub, extremely tolerant, being able to survive in poor and shady soils (Lorenzi, 2008). It belongs to the Verbenaceae family, the same family as *Lantana camara*, which showed good adaptability to adverse soil conditions contaminated with Pb, Cd, Ni and Cr and phytoremediation potential (Waoo et al., 2014; Alaribe & Agamuthu, 2019; Liu et al., 2019; Waoo et al., 2019). However, there is little information about the behavior of *L. fucata* when cultivated in soil with high contents of Cu and about the possibility of this plant to be used in the phytoremediation of this metal.

Therefore, this study aimed to evaluate the phytoremediation potential of *L. fucata* plants in soils contaminated with Cu.

2 MATERIALS AND METHODS

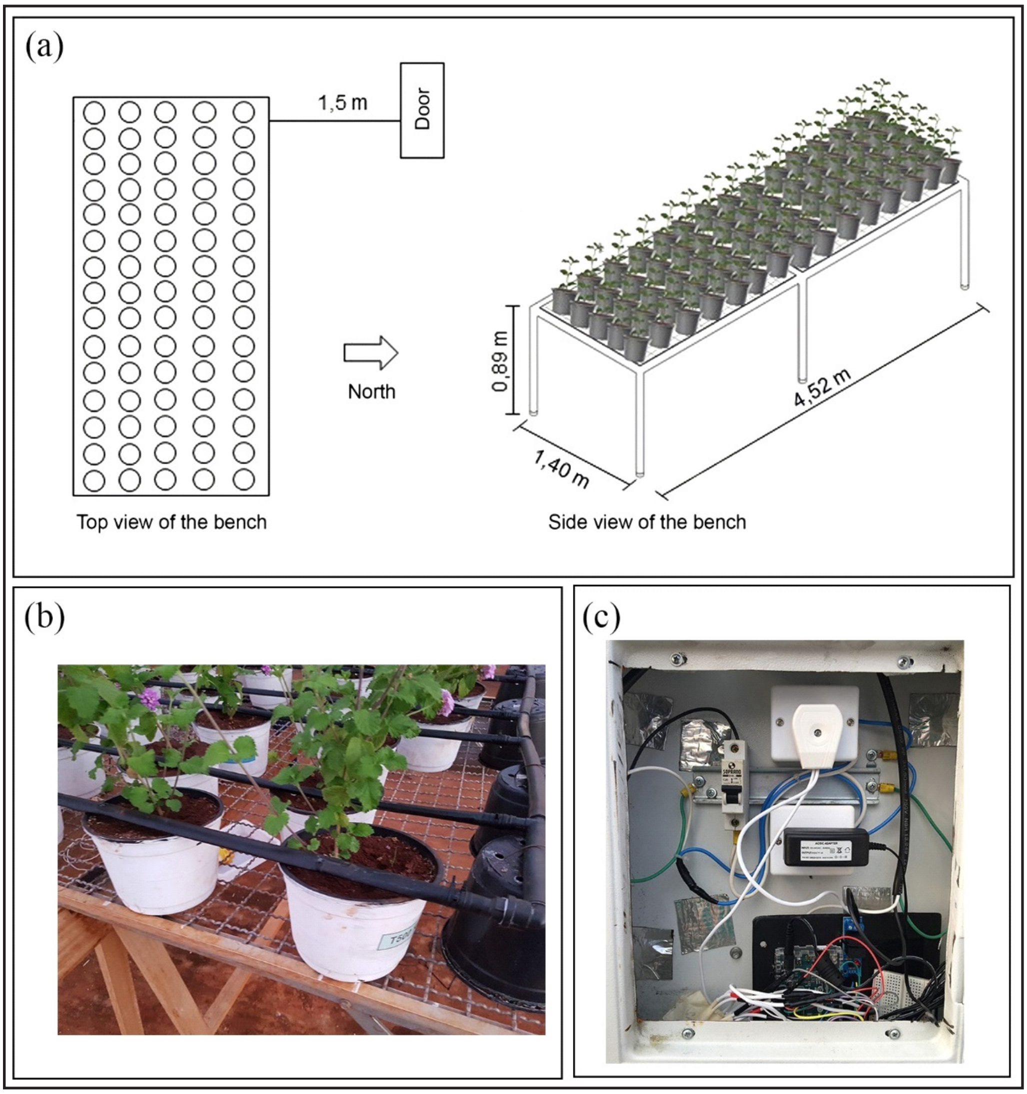
2.1 Soil preparation and pot experiments

The experiment was carried out in a greenhouse in the experimental area of the Federal University of Fronteira Sul, campus Cerro Largo, RS (28°08'31.8"S and 54°45'41.7"W), in a completely randomized design (DIC), composed of five replications and seven treatments with additions of penta-hydrated copper sulfate solution ($CuSO_4{\bullet}5H_2O$) to the soil that resulted in Cu concentrations of 70, 140, 210, 280, 420, 630 and 840 mg kg^{-1} and the control (no addition of Cu, with 5.74 mg kg^{-1}).

The soil used in the experiment is classified as Typical Dystroferric Red Latosol (Oxisol). The chemical analysis of the soil carried out before cultivation showed the following results: organic matter 3.9%; 63% clay; pH_{water} (1:1) 5.4; SMP index 5.8; SAT from CTC Bases

64.8%; SAT of CTC Aℓ 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}.

Figure 1 – Implementation of the experiment, (a) sketch of the experiment, (b) installation of the irrigation system in experiment and (c) installation of the Arduino Uno microcontroller (c)



Source: Authors (2024)

Lantana fucata seedlings were prepared by manual collection of the apex of young branches of naturally occurring matrices in the region (28°07’54.4”S and 54°52’17.3”W; 28°07’08.9”S and 54 °50’37.5”W; 28°07’09.0”S and 54°49’02.2”W). The propagation of the seedlings was carried out by means of cuttings, containing from 3 to 4 nodes, with application of indolebutylic acid (IBA) in the form of powder and inserted in tubes, containing substrate for planting, arranged on a board inside the greenhouse, with daily irrigations. After complete rooting, they were transplanted to plastic pots (Ø 16 cm x 12 cm) containing the aforementioned treatment or control. These were placed on a board in the greenhouse (Figure 1a).

The experiment was conducted for 100 days and during this period the soil moisture and drip irrigation (Figure 1b) were controlled by programming an Arduino Uno microcontroller (Figure 1c), which every 30 min read the moisture sensors of soil humidity installed in the vases. The irrigation system was set up to be activated at intervals ranging from 3 to 5 h. Each activation turned on the hydraulic pump, providing irrigation for 1min.

The plants were monitored daily and, weekly, received 40 mL, per pot, of nutrient solution composed of KNO_3 (0.290 g L^{-1}), KH_2PO_4 (0.450 g L^{-1}), $Ca(NO_3)_2$ (0.260 g L^{-1}) and $MgSO_4$ (0.210 g L^{-1}). To ensure equal sunlight exposure across treatments, the positioning of the pots was modified by drawing every 14 days.

2.2 Sample preparation and analysis

After 100 days of planting, the plants were collected, in ascending order of treatment. In this procedure, a clean canvas was spread on the floor of the greenhouse and the pots were individually placed on the canvas in order to allow the soil/plant separation.

Subsequently, the plant was divided into shoot and root system, the first was cleaned with distilled water. While the roots were cleaned with running water and in an ultrasonic cleaning (BIOBASE) for 5 minutes and rinsed with running water. The process was repeated three times, the last washing being with distilled water (Cuske et al., 2014).

After cleaning, the shoot and the roots were placed, separately, in kraft bags and dried at 60 ºC for 72 hours in an oven with circulation and air renewal. After drying, the plants were weighed to check the dry mass.

The dry samples (shoot and root system) were ground separately and the 0.5 g mass of each individual plant part was digested in a digester block (TE-007MP, Tecnal) with

10 mL of the nitro-perchloric mixture 4:1 (v/v) with application of a temperature ramp: 80, 120, 150, 180 ºC for 1 hr and 190 ºC for 30 min (Neto & Barreto 2011; Liu et al. 2019).

On the day of collection, the soil from each pot was transferred to separate plastic bags. Afterwards, they were shaken twice a day, for three days, for complete homogenization. Afterwards, 500 g of soil were collected from each treatment for drying at 105°C for 48 h in an oven with circulation and air renewal. From these, 5g were weighed and Cu was extracted with 25 mL of the Mehlich-1 solution (HCℓ 0.05 mol L^{-1} + 0.0125 mol L^{-1}) H_2SO_4 under shaking at 120 rpm for 5 min on shaking table for soil (SL-184, SOLAB) and then left to rest overnight (Teixeira et al., 2017; Santana et al., 2018).

To determine the pH of the soil, a pH meter with a combined glass electrode (HI 2221, Hanna) was used, 10 g of dry soil and 25 mL of distilled water were added in a beaker, the mixture was stirred with a glass rod for 60 s and left to stand for 1 h (Teixeira et al., 2017).

The concentration of metal present in the soil and in the plant was determined using a flame atomic absorption spectrometry (SavantAA-GBC). The method was validated by evaluating linearity, detection limit (DL) and quantification limit (QL), precision and accuracy. As instrumental parameters were used: hollow Cu cathode lamp, wavelength 324.7 nm, slit width of 0.50 nm and integration time of 3 s, in a 10 cm laminar flow burner. For the soil, the flame was formed by mixing air/acetylene at flow rates 15.0 L min^{-1} and 2.20 L min^{-1}, respectively, and for the air/acetylene plant at flow rates 10.10 L min^{-1} and 2.00 L min^{-1}, and also the background correction by using a deuterium lamp.

2.3 Phytoremediation Potential

To evaluate the phytoremediation potential of *Lantana fucata*, the root bioconcentration factor (BCF_{root}), the translocation factor (TF) (Yoon et al., 2006; Alaribe & Agamuthu, 2019; Ghazaryan et al., 2019), the tolerance index (TI) (Silva et al., 2015) and the metal extraction rate (MER) (Mertens et al., 2005) were calculated.

BCF_{root} can be used to evaluate the metal's bioconcentration capacity in the roots, being calculated by Equation 1, and the plant's ability to translocate metals from the root system to the shoot is evaluated using the TF, which is calculated using Equation 2, where CuRS is the metal concentration in the root system, CuSH is the metal concentration in the shoot and CuS is the concentration of Cu available in the soil after cultivation.

$$BCF_{root} = CuRS / CuS \tag{1}$$

$$TF = CuSH / CuRS \tag{2}$$

The metal extraction rate (MER) was calculated using Equation 3 and the tolerance index (TI) according to Equation 4, where CuP is the concentration of metal in the plant dry mass, CuS is the concentration of available Cu present in soil after cultivation, MR is the mass of the volume of soil rooted by the species, DM is the total dry mass of the plant, T_n is the treatment of interest and T_0 is the treatment without addition of Cu (control).

$$MER = (CuP \times DM) / (CuS \times MR) \tag{3}$$

$$TI = (DM_{Tn} / DM_{T0}) \times 100 \tag{4}$$

The results were submitted to analysis of variance (ANOVA) and when this was significant, the Tukey test was applied at 5% probability. Pearson's linear correlation test was also applied. Statistical tests were performed using the R® software.

3 RESULTS AND DISCUSSION

3.1 Method validation

Table 1 presents the figures of merit of the methodology studied for determination of Cu in plant and soil.

Linearity refers to the method's ability to generate results linearly proportional to the analyte concentration, within a specific analytic range. This parameter can be demonstrated by the coefficient of determination (R^2), which the closer to 1, the more it represents a true linear adjustment (Harris, 2013).

The DL represents the lowest concentration of the analyte under study that can be detected and the QL represents the lowest concentration of the analyte that can be quantified in acceptable reliability and precision (ICH, 2005; Inmetro, 2020). Values were calculated using the average of the slopes of the curve. As it can be seen in table 1, the R^2, DL and QL for the developed procedure were adequate for the determination of Cu in both samples.

Precision represents the variability of the results, among themselves, and accuracy represents the proximity of the results, to the value accepted as true, and it can be determined through the recovery test (ICH, 2005; Inmetro, 2020). Accuracy can determine the lack of analyte levels due to the losses or contamination during sample preparation, and matrix interferences during the measurement step (Ertas & Tezel, 2004).

Table 1 – Methodology validation merit figures

	Plant		Soil	
Analytic range (mg L^{-1})	0.25 - 6		1 - 10	
a*	$0.0911 \pm 7.51 \times 10^{-4}$		$0.0685 \pm 5.86 \times 10^{-4}$	
b*	$0.0036 \pm 7.64 \times 10^{-4}$		$0.0132 \pm 1.01 \times 10^{-3}$	
R^2	$0.9998 \pm 1.53 \times 10^{-4}$		$0.9987 \pm 1.51 \times 10^{-3}$	
DL (mg L^{-1})	0.0202		0.0237	
QL (mg L^{-1})	0.0674		0.0789	
Spike (mg L^{-1})	**Recovery (%)**	**CV (%)**	**Recovery (%)**	**CV (%)**
1	106	10.2	-	
2	-		100	2.4
3	107	2.6	-	
6	-		98	2.3

Source: Authors (2024)

Note: a = angular coefficient of the line; b = linear coefficient of the line; R^2 = coefficient of determination; * (n=3); cv= coefficient of variation

As it is shown in Table 1, it can be observed that the coefficients of variation were lower than 11%, so it can be said that the proposed method for determination of Cu is accurate. The recovery determination was carried out by spiking technique of soil and plant samples, and the resulting spiked samples were measured, calculated, and compared to the known value of standard solutions added. As suggested by ICH (2005), the analytical steps were performed in three different levels of analyte concentration, with three replicates for each level of concentration. Both samples showed recoveries within the acceptable range of 80-110% (Inmetro 2020).

3.2 Cu content in soil

Table 2 – Soil pH and available Cu contents (mg kg^{-1}) before and after planting

Cu added to soil (mg kg^{-1})	Cu in soil before planting *	Cu in soil after planting*	pH in soil before planting	pH in soil after planting
0	5.74 ± 0.07	2.58 ± 0.25	5.23	5.91 ± 0.10
70	41.51 ± 1.68	27.07 ± 2.85	5.48	5.86 ± 0.07
140	88.94 ± 4.16	43.57 ± 4.80	5.41	5.76 ± 0.05
210	149.93 ± 2.24	78.25 ± 3.28	5.37	5.77 ± 0.06
280	172.12 ± 3.55	116.27 ± 12.89	5.30	5.59 ± 0.09
420	286.65 ± 5.89	243.75 ± 3.40	5.05	5.38 ± 0.12
630	430.15 ± 6.68	386.88 ± 6.89	4.90	5.27 ± 0.05
840	602.11 ± 3.85	546.95 ± 7.49	4.86	5.24 ± 0.14

Source: Authors (2024)

Note: Data are presented as averages ± standard deviation (n = 5)

Cu is an element that occurs naturally in the soil and interacts with the functional groups of organic matter, forming stable complexes, in such a way that it is retained in the solid phase of the soil, which reflects a low free Cu^{2+} content in the soil solution and low availability of this element for plants, as they readily absorb Cu in ionic form (Girotto et al., 2010; Kabata-Pendias & Pendias, 2010; Printz et al., 2016). The availability and mobility of metals in the soil depend on the chemical composition, the amount added, being mainly related to organic matter and pH. With the decrease in pH, there is a change in balance between the phases, increasing the metal ion content in the liquid phase (Bissani et al., 2008).

The pH (water) values determined (Table 2) demonstrate the acidity of the soil used in the experiment, which favors the release of Cu^{2+}, increasing the availability of the ion to the plant (Yoon et al., 2006). This is evidenced by the reduction of Cu after planting, a consequence of absorption by *L. fucata* (Table 2, third column). Where there is a greater absorption of copper for the smallest treatments (up to 280 mg kg^{-1} of soil).

The difference in Cu available in the soil before and after planting was presented as the theoretical value absorbed by the plant. However, these values, for both experiments, were lower than the total found in the plant (experimental). This can be explained by the fact that micronutrients are found in balance between the solid phase and the liquid phase of the soil and as the plant absorbs the Cu available in the liquid phase, the balance is shifted to compensate for the loss (Drozdova et al., 2019).

3.3 Response of plants to Cu concentration

The evaluation and selection of plants for phytoremediation purposes depends entirely on translocation factor (TF) and bioconcentration factor (BCF) values (Wu et al., 2011). The BCF is used to evaluate the ability to accumulate metal in the root and is defined as the relation between the metal concentration in the roots and that of the soil. With TF, the translocation of metal from the root system to the shoot is evaluated, defined as the ratio of the concentration of metal accumulated in the shoot by the root system (Yoon et al., 2006; Yadav et al. 2018; Ghazaryan et al., 2019). Thus, plants with TF and BCF greater than one (TF> 1, BCF>1) have potential for use in phytoextraction. Plants with TF less than one and BCF greater than one (TF<1, BCF>1) have the potential for phytostabilization. A hyperaccumulator plant must have BCF>1 and TF>1, as well as total Cu accumulation greater than 1000 mg kg^{-1} (Bini et al., 2012).

Lantana fucata accumulated Cu in the dry mass in the range of 29.46 to 114.31 mg kg^{-1} (sum of the root system with the aerial part, Table 3), a quantity lower than a hyperaccumulator plant, but considered higher than the amount found in most plants, which is 2 to 20 mg kg^{-1} Cu in dry mass (Kabata-Pendias

& Pendias, 2010). Despite the high content of Cu in the root system, *L. fucata* translocates little of this metal to the shoot, as can be seen from the TF (Table 3) (Kabata-Pendias & Pendias, 2010).

TF values were lower than one (TF<1), indicating low Cu translocation from the root system to the shoot, which limits its use in phytoremediation by the phytoextraction mechanism. However, when evaluating the BCF values, it was found that *L. fucata* presents values greater than one (BCF>1) for Cu contents in the soil from 5 mg kg^{-1} to 140 mg kg^{-1}, indicating that this species is phytoremediator using the phytostallization mechanism for treatments with lower amounts of Cu (Table 3).

Table 3 – Cu concentration in the plant and factors. CuSH is the metal concentration in the shoot, CuRS is the metal concentration in the root system, TF is the translocation factor, BCF is the root bioconcentration factor and MER is the metal extraction rate

Cu Added to soil (mg kg^{-1})	**CuSH (mg kg^{-1})**	**CuRS (mg kg^{-1})**	**TF**	**BCF**	**MER (%)**
0	10.38	19.08	0.56 ± 0.098^{a}	7.41 ± 1.351^{a}	12.98 ± 1.967^{a}
70	13.37	37.22	0.36 ± 0.018^{b}	1.40 ± 0.274^{b}	2.15 ± 0.329^{b}
140	14.38	54.83	0.26 ± 0.012^{c}	1.28 ± 0.240^{bc}	1.95 ± 0.370^{b}
210	14.43	71.93	0.20±0.010^{cd}	0.92 ± 0.083^{bcd}	1.34 ± 0.175^{bc}
280	12.67	82.97	0.15 ± 0.024^{cd}	0.73 ± 0.168^{bcd}	0.99 ± 0.154^{bc}
420	13.75	71.01	0.19 ± 0.013^{cd}	0.29 ± 0.028^{cd}	0.26 ± 0.025^{c}
630	15.80	79.27	0.20 ± 0.010^{d}	0.21 ± 0.035^{d}	0.16 ± 0.027^{c}
840	16.57	97.74	0.17 ± 0.032^{d}	0.18 ± 0.030^{d}	0.14 ± 0.014^{c}

Source: Authors (2024)
Note: Data are presented as the means ± standard deviation (n = 5). Different lower case letters in each column indicate that average values are significantly different between treatments at 5% significance according to Tukey's test. TF and BCF values >1 are in bold. * Available Cu in the soil after planting

The BCF results varied inversely proportional to the increase in the Cu content in the soil (Table 3). Each treatment contained increasing amounts of the metal and the maximum absorbed by the *L. fucata* roots was 97.74 mg kg^{-1} (Table 3). Thus, it is inferred that even the plant accumulating increasing amounts of metal in the root system, directly proportional to the increase in Cu content in the treatments, the amount of Cu remaining in the soil after planting reflects the BCF index lower than one for concentrations above 140 mg kg $^{-1}$ Cu in the soil.

Low TF values were also calculated by Zancheta et al. (2011), when working *Sorghum bicolor, Pennisetum glaucum, Crotalaria juncea* and *Canavalia ensiformis* in nutrient solution with increasing concentrations of Cu and by Yoon et al., (2006), when analyzing eight plants growing in soil contaminated by metals, including Cu, only three plants (*Sesbania herbacea, Rubus fruticosus* and *Phyla nodiflora*) presented TF>1 and four (*Gentiana pennelliana, Rubus fruticosus, Stenotaphrum secundatum* and *Plantago major*) BCF values<1. The smallest translocation to the aerial part (TF<1) simultaneously with stabilization in the root system (BCF>1) is considered a mechanism of plant tolerance to excessive concentrations of the metal (Zancheta et al., 2011).

Cu is a metal that has an affinity for hard plant tissue binders, being retained mainly in the epidermal and cortical cells of the roots, which contributes to the phytostabilization mechanism in the plant's root system, however, it limits phytoextraction with translocation to the aerial part (Kabata-Pendias & Pendias, 2010; Zancheta et al., 2011; Kopittke et al., 2014).

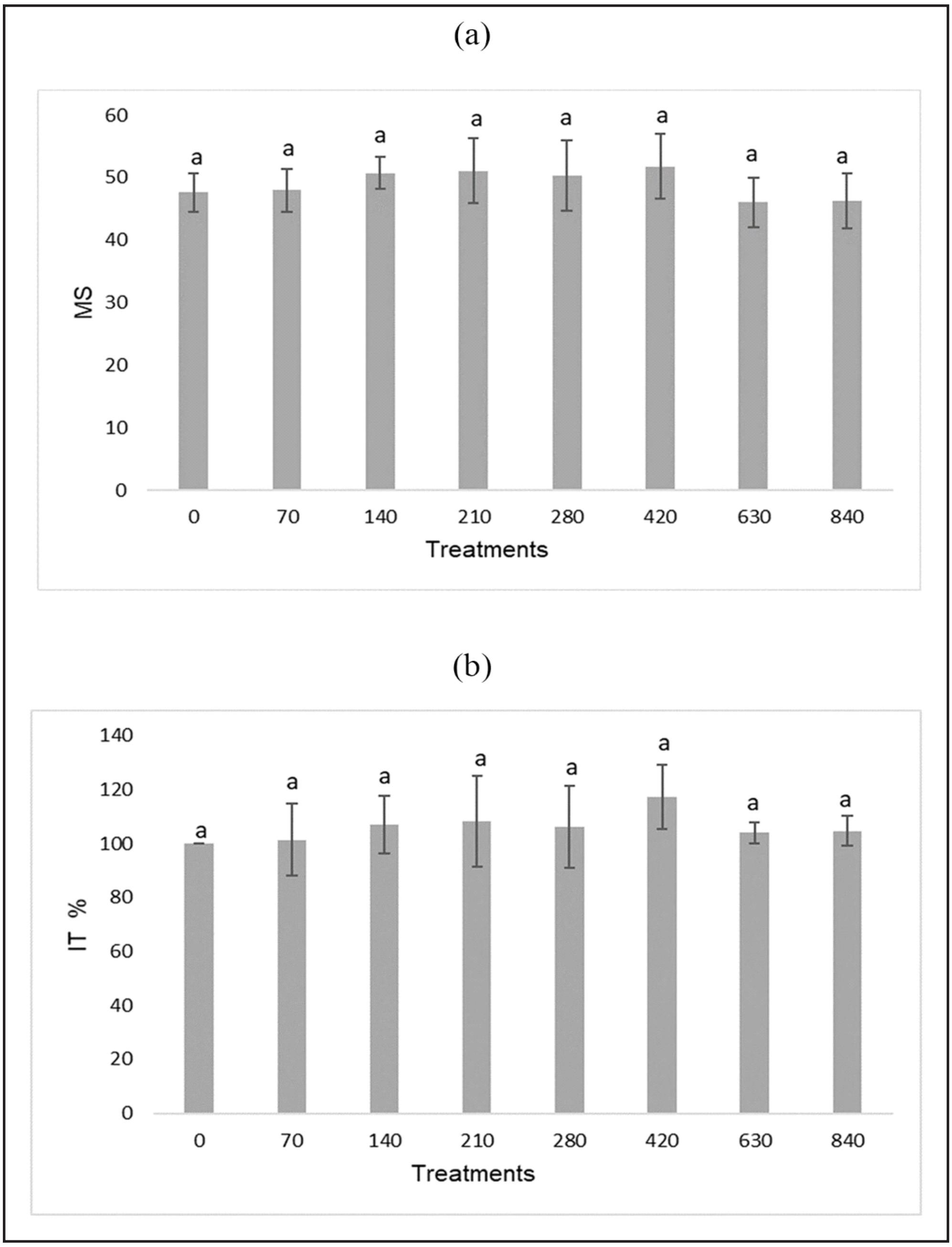
L. fucata was tolerant to the tested amounts of Cu. Moreover, this can be observed by the TI, which measures the capacity of plants to grow in environments with high metal concentrations and is calculated through the relation between the dry mass of the plant in the treatment of interest and the dry mass of the control (Silva et al. 2015).

This result is consistent with the observation that dry mass production is directly related to the plant' s tolerance to metals (Menegaes et al., 2017), since tolerant species develop biochemical adaptations capable of controlling the absorption, accumulation, and translocation of metals at toxic levels in tissues, allowing them to grow under such conditions (Silva et al., 2015).

In line with this, there was no significant difference ($p<0.05$) between treatments for dry mass production and TI (Figure 2a), which reinforces the indication that *L. fucata* is tolerant to Cu at the concentrations studied.

Specifically, the treatment with the highest TI (117.23%) was 420 mg kg^{-1}, which also presented the highest dry mass production (Figure 2b). This outcome further corroborates the established relationship between dry mass and plant tolerance to metals.

Figure 2 – Total dry mass (DM) (a) and Tolerance index (TI) (b) in *Lantana fucata* plants grown in copper-contaminated soil



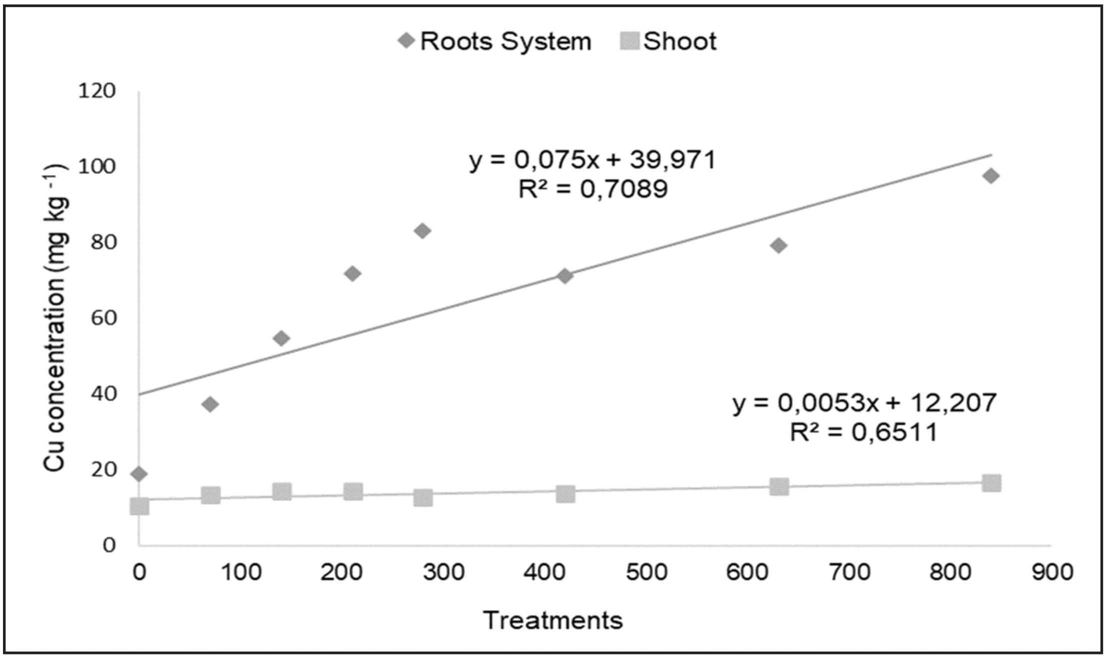
Source: Authors (2024)

Note: Averages (n=5) followed by different lowercase letters on each bar indicate that mean values are significantly different between treatments at 5% significance according to Tukey's test

Therefore, it is confirmed that *L. fucata* demonstrated tolerance to Cu at the studied concentrations, since all treatments, when compared to the control (TI = 100%), showed good tolerance to the metal (TI > 100%) (Silva et al., 2015).

Complementarily, the last calculated index, the metal extraction rate (MER), provides additional information regarding the plant's performance. MER expresses, in percentage, the plant's capacity to extract metal from the soil as a function of its dry mass and considers the volume of soil rooted by the plant. In other words, an MER value of 10% indicates that 10% of the metal present in the soil can be removed in a single harvest (Mertens et al., 2005).

Figure 3 – Copper (Cu) concentrations present in the root system and shoots



Source: Authors (2024)

It can be observed that the MER (Table 3) decreased as the concentration of Cu added to the soil increased, significantly differentiating from the control ($p<0.05$). The MER for the control treatment was 12.98%, decreasing with the increase of Cu concentrations in the treatments, reaching the lowest extraction 0.14% in the 840 mg Kg^{-1} Cu treatment. The results indicate high MER for *L. fucata*, when compared to *Solanum nigrum*, described as a hyperaccumulators plant for Cd and As, maximum MER of 1.07 and 0.007%, respectively (Sun et al. 2008). The MER results were also higher than the ones found for *Helianthus annus L.*, showing 0.94% for an uncontaminated soil and 0.30% for a Cu-contaminated vineyard soil (Andreazza et al., 2015).

Furthermore, it can be observed that the largest amount of Cu present in the plant is located in the RS, and this can be attributed to the fact that the plant developed an adaptation mechanism in response to metal toxicity, such as the immobilization of excess of Cu in the root system and therefore low translocation of the metal to the shoot (Yruela 2009; Kabata-Pendias & Pendias, 2010; Silva su., 2015).

4 CONCLUSIONS

In order to remedy the excess Cu in the soil, the present study evaluated the phytoremediation capacity of *Lantana fucata*, a native plant in Brazil. The species had good plant development, showed tolerance to cultivation in contaminated soil (TI>100%), as well as absorbed metal in greater amounts in the roots (up to 97.74 mg kg $^{-1}$) and less in the shoots (up to 16.57 mg kg $^{-1}$, levels higher than those normally found in plants - 2 to 20 mg kg $^{-1}$).

Therefore, this species has the potential to be cultivated in areas contaminated with Cu. It can be used for phytoremediation by the phytostabilization mechanism, since its BCF indexes were higher than one (BCF>1) for concentrations up to 140 mg Cu kg $^{-1}$ soil.

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