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Alterations in macro and micronutrient uptake by Jambu (*Acmella oleracea* (L.) R.K. Jansen) exposed to cadmium

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Abstract

The Jambu, an herbaceous plant widely consumed in the Amazon in typical dishes and in natura, is also found in Central America, Asia, and even in Europe. Its behavior when exposed to heavy metals is unknown and, being Cd one of the most phytotoxic metals, the objective is to elucidate how Cd influences nutrient uptake by jambu. The experimental design was entirely randomized with five treatments and six repetitions, in a hydroponic culture system. Four doses of Cd (1, 3, 6 and 9mg/L), plus a control were used. At the end of the experiment, chemical analyses were performed to quantify the content of K, Mg, Ca, Fe, Zn, Mn and Cu in the leaf, stem, inflorescence and root. The results were submitted to ANOVA and regression analysis and show a significant increase in K, Mg and Ca, up to a dose of 6mg/L of Cd. The micronutrients Fe, Zn, Mn and Cu also showed a significant increase in the absorption, until the dose of 6mg/L. The difference in uptake ranged from 23.02% for Cu to 151.9% for Ca in relation to the uptake of the nutrients by the control plants. The dose of 9mg/L, produced an antagonistic effect, with a reduction in the uptake of the nutrients, with the exception of Ca. In general, Cd in small doses produced in the jambu a stimulant effect and in larger doses, a toxic effect. This behavior indicates a hormetic effect of jambu against Cd.

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Introduction

Cadmium (Cd) is considered one of the metals that more represents ecotoxic effects to human beings, animals and plants, with high adverse potential to the environment and food quality (Kabata-Pendias, 2010). It naturally occurs associated with sedimentary and igneous rocks, forming minerals as the greenochite (Cds) and octative ($CdCO_3$). Due to its geochemical affinity with phosphorus, sulfur and carbon, the increase of its concentration are related to the higher presence of these elements inn rocks (Alloway, 2013).

The industrial appliance of Cd are linked to the production of Ni-Cd and Ag-Cd batteries, however, the main source is the refining of zinc (Zn), as a byproduct. Nevertheless, the Cd is also used in the fabrication of pigments, plastic, electric circuit plates, fertilizers and in addition to its presence on fossil fuel (Alloway, 2013; Shanmugaraj *et al.,* 2019). In addition, the metal can reach the environment through the intensive use of phosphate fertilizers, sewage sludge on agriculture, pesticides, and so on (Alloway, 2013; Rai *et al.,* 2019).

According to Shanmugaraj *et al.* (2019) and Qin *et al.* (2020), the plant exposition to Cd can provoke damage to the photosynthetic apparatus, clorosis, necrosis and even total loss in some species. The presence of the metal acts negatively in the nutrient absorption, because cadmium competes with calcium (Ca) and magnesium (Mg) for having similar chemical properties (Khan *et al.,* 2015). Cadmium can also affects the nitrogen metabolism (N) and severely reduce the phosphorus and potassium content, harming the growth of plants contaminated with the metal (Khan *et al.,* 2016).

According to Naeem *et al. (*2019) and Khan *et al. (*2016), Cd interfere in the micronutrient absorption as cooper (Cu), iron (Fe), zinc (Zn) and manganese (Mn). The influence of Cd in relation of micronutrients occurs mainly with the reduction in the translocation of these mineral elements to the plant leaves. In relation of Fe, the reduction of Cd concentration promotes the decreasing of ferredoxins, affecting the photosynthetic apparatus (Taiz *et al.,* 2017). These effects, however, are related with the capacity of some plants have to adapt or not with the metal presence. For some species of plants named accumulators and hyperaccumulators, the levels of Cd accumulated in its tissues exceed the toxicity limits of most vegetable species without showing adverse effects (Sytar *et al.,* 2016). On other plants, the metal in low concentration provoke stimulant effect of growth, however, in high concentrations it shows toxicity signs. This phenomena is known as hormesis and its characterized by the binary effect, with stimulant and inhibitory response of organism to stress (Calabrese and Blain, 2009; Ray, *et al.,* 2014; Pincelli-Souza *et al.,* 2020).

In analysis of the phytoremediation potential of *Acmella oleracea (L.) R.K.* Jansen*,* Hungria *et al.* (2019), observed that the plant cultivated in contaminated soil with 9mg/kg of Cd showed low sensibility to the metal, without toxicity signs.

Acmella oleracea (L.) R.K. Jansen, also known as jambu, is largely used in Amazon culinary, composing traditional dishes, cooked or in natura. Widely utilized in pharmaceutical industry for producing alkaloid called espilantol and in the cosmetic industry. Jambu as a vegetable consumed not only in the Amazon region but in several parts of the world, needs to be better studied, especially with regard to the ability to tolerate heavy metals, including Cd (Dubey, *et al.,* 2013; Lalthanpuii, *et al.,* 2017; Uthapala and Navaratne, 2021).

In this sense, this survey aims to demonstrate how the presence of Cd can influence the uptake and efficient use of nutrients by jambu.

Material and Methods

Experimental procedures

The experiment was conducted between February and March 2020 at the greenhouse of the Agrarian Science Institute (ASI), from the Rural Federal University of the Amazon- UFRA (1° 27' 13,70" S and 48° 26' 32,65" W). At an approximate altitude of 14 m.

According to the Af category of Koppen, the weather in this area is equatorial hot and humid (Kottek *et al.,* 2006).

The temperature and air humidity, during the experiment, were measured using a thermo-hygrometer installed in the greenhouse. The medium temperature values oscillated between 28 and 35°C. The average relative humidity during the experimental period was approximately 70%.

Crop system

Hydroponics were used as crop system; plants were grown in 2 L vases with an inert substrate, and Hoagland and Arnon (1950) formulation 2 was used as nutritive solution. The nutritive solution was composed of 1ml/L NH_4NO_3, 6m/L KNO_3, 4ml/L $Ca(NO_3)_2$, 2ml/L $MgSO_4$, 1ml/L Fe-EDDHA, and 1ml/L micronutrient solution. Vases were illed with pre-washed ground silica, coated with aluminum foil to avoid the incidence of solar radiation, and drilled at the base; a silicone tube was placed in the system to facilitate the recirculation of the nutritive solution. Throughout the experiment, the nutritive solution was oxygenated by draining it at the end of the afternoon, and replacing it at the beginning of the morning (Sampaio *et al.,* 2020).

Production of seedlings

The jambu seeds was obtained from the germplasm bank in the horticultural sector from UFRA, were sown in the second week of February 2020 in 128-cell polystyrene trays filled with coconut fiber. In each cell, 10 to 15 seeds of Yellow Flower jambu, a regional variety, were deposited. After germination, the seedlings were watered with Hoagland and Arnon (1950) nutritive solution in a 25% ionic force (Sampaio *et al*., 2020). Thinning of the smallest plants was performed 10 days after germination, leaving only one seedling per cell.

After 21 days, those seedlings with four expanded leaves and in good phytosanitary conditions were removed from the polystyrene trays, washed with deionized water, and transplanted to vases with inert silica and nutritive solution at 50% of ionic force; to ensure the correct acclimatization of the system, these conditions were kept unchanged for seven days. Both the pH and electrical conductivity of the nutritive solution were monitored daily during the experiment. The pH was maintained within a 5.5 to 6.5 range, and the electric conductivity within a 1.0 - 1.8 µs·cm-1 range.

Experimental design

The experimental design was fully randomized, with five treatments and six repetitions, totaling 30 plants with one plant per vase. Treatments included four different doses of cadmium (1, 3, 6, and 9mg/L cadmium chloride, $CdCl_2$) and the control with nutrient solution only (Hungria *et al.,* 2019). Every seven days, the nutrient solution was renewed, and the same was done with $CdCl_2$ solutions to ensure that the correct Cd concentration was supplied to plants until the end of the experiment. Water that was evapotranspirated during the day was replenished with deionized water.

To measure the Cd effect in nutrient absorption, was performed the harvest of the plants in the end of the growth cycle, 40 days after the transplantation.

Chemical analysis

After drying, the leaves, stems, inflorescences, and roots of jambu plants were milled in a porcelain bowl. Subsequently, 0.25g aliquots of each part of the plant placed in Teflon tubes with 4.0ml HNO_3 (7 mol/L), 2ml H_2O_2 (30%/mm), and 2ml ultrapure water, and left standing for about 1h. Samples were then allocated for complete digestion in a microwave digester. The digestion ramp consisted of three steps: a temperature rise from 0 to 180°C in 10 min at 800 W, left stand at a constant temperature of 180°C for 20 min, and ventilation for 50 min (Pereira and Dantas, 2016). After digestion, the samples were filtered and adjusted to 50ml with deionized water. The Cd content was determined by atomic absorption spectrophotometry using a Varian AA 240 Z graphite oven at the Laboratory of Water Quality of the Amazon of the State University of Pará.

Statistical analysis

The data were subjected to analysis of variance (ANOVA) and the assumptions of data homogeneity, homoscedasticity and independence from errors were met. Means were compared using the Scott-Knot test ($p < 0.05$) using the R software version 3.5.2 (R Core Team, 2018).

Results

The Cd in jambu can be observed in fig. 1. In the leaves, the higher content of K was on dose 6mg/L (40.96 ± 1.88mg/kg) and minor on dose 9mg/L (28.00 ± 1.33mg/kg), however, both doses was statistically high than the control doses (25.62 ± 2.14mg/kg). In the stem, the higher contents were found in doses 1 and 3mg/L (41.72 ± 2.55mg/kg) and (42.12 ± 2.02mg/kg) respectively, without significant differences between itself. The minor content was on dose 9mg/L (10.44 ± 1.87mg/kg), statistically minor than the other doses and control (36.71 ± 2.13mg/kg).

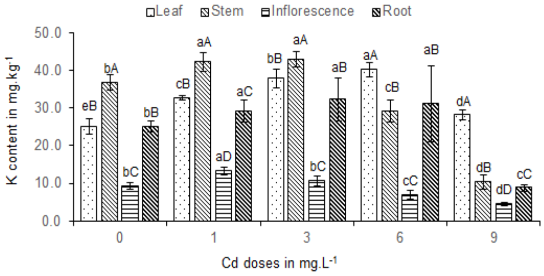

Fig. 1. K distribution in jambu plants subjected to increasing doses of Cd. The lowercase letters points the significant differences between the cadmium doses; the uppercase letters points the significant differences between the plant parts, according to Scott-Knot ($p<0.05$) test. Bars represent the mean ± S.D.

In the inflorescence, the 1mg/L (32.32 ±3.09mg/kg) dose was the one which shows higher content of the nutrient and the 6 and 9mg/L (4.55±0.45mg/kg) and (4.67±0.13mg/kg) respectively were the ones with minor content statistically. In the root, only the dose 9mg/L (8.66±0.95mg/kg) shows statistically minor than the other doses and control. Be noteworthy that the doses of 1 and 3mg/L the K highly concentrates on the stem. With the increasing of Cd doses to 6 and 9mg/L there was an increase in the nutrient content in leaves and decreasing in other parts of the plant (fig. 1).

In general, the Mg uptake have a bigger stimulus in the 1 and 3mg/L dose of Cd in nutritive solution (fig. 2). In leaf, stands out respectively the doses of 3 and 6mg/L (11.10±0.67mg/kg) and (11.76±1.17mg/kg) as the ones with bigger uptake on Mg content, do not shows significant differences between itself, however, were bigger statistically than the other doses and control (8,79±0,55mg/kg). In stem, doesn't have difference in 1 and 3mg/L (4.30±0.49mg/kg) dose and (4.63±0.25 mg/kg -1), nevertheless, these doses highlights from the other ones, stimulating bigger Mg uptake. The 9mg/L dose was the one with minor uptake in relation with control (3.05±0.31mg/kg). This tendency on Mg uptake by jambu was observed also in the inflorescence and root, with the 1mg/L dose promoting bigger content in inflorescence (10.99±0.20mg/kg). In root, the 1 to 6 mg,L^{-1} dose highlights for do not present significant difference, but were significantly bigger than the control and the 9mg/L dose in the nutrient uptake (fig. 2). Another point to note is that as concentrations of Cd increased in the nutrient solution, Mg concentrated more in the leaves than in other parts of the plant.

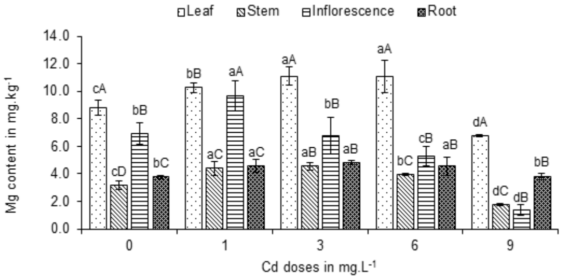

Fig. 2. Mg distribution in jambu plants subjected to increasing doses of Cd. The lowercase letters points the significant differences between the cadmium doses; the uppercase letters points the significant differences between the plant parts, according to Scott-Knot ($p<0.05$) test. Bars represent the mean ± S.D.

The Ca behavior fronts to Cd in leaf shows bigger capacity of uptake in dose 9mg/L (7.52±1.01mg/kg) from the metal, differing from the other doses and control (1.56±0.10mg/kg). In stem and inflorescence, the higher nutrient content was on dose 6mg/L (1.61±0.29mg/kg) and (2.70±0.09mg/kg) respectively, standing out from control and 1 and 9mg/L dose, that didn't differ (fig. 3). The root uptake of Ca shows different behavior of the other parts of the plant with bigger content in dose 1mg/L (3.85±0.32mg/kg), differing from control (1.73±0.54mg/kg) and from other doses, showing a decreasing tendency of Ca content with the Cd dose increasing. Noteworthy that the doses 1 and 3mg/L of Cd, the nutrient highly concentrates on jambu root and posteriorly on leaf. In dose 6 and 9mg/L, the higher concentration of Ca were found in leaves and inflorescence.

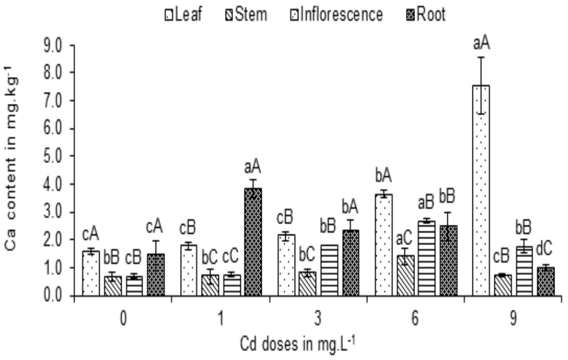

Fig. 3. Ca distribution in jambu plants subjected to increasing doses of Cd. The lowercase letters points the significant differences between the cadmium doses; the uppercase letters points the significant differences between the plant parts, according to Scott-Knot ($p<0.05$) test. Bars represent the mean ± S.D.

The fig. 4 highlights the Fe uptake by jambu in relation of Cd increasing doses. In analysis of Fe in jambu leaves front to Cd doses, it can be observed bigger induction of nutrient uptake in doses 3 and 6mg/L (0.79±0.05mg/kg) and (0.76±0.06mg/kg) respectively, don't differing from control (0.72±0.03mg/kg). However, the Fe content in leaf was statistically minor in doses 1 and 9mg/L of Cd, standing out negative influence in nutrient uptake. In stem, inflorescence and root, the high Fe content was on 9mg/L dose. It can be highlighted that the 1mg/L dose doesn't have a significant difference between leaf, inflorescence and root, only the stem shows minor nutrient content. With 3, 6 and 9mg/L of Cd, the Fe concentrates more in inflorescence, following root, leaf and stem (Fig. 4).

The Zn in leaf obtained more content in 1 and 3mg/L of Cd in solution (0.91±0.03mg/kg) and (0.91±0.06mg/kg) respectively, differing from control (0.80±0.06) and other doses. In stem there was no significant difference between doses, however, in relation to inflorescence and root the dose of 9mg/L of Cd promoted bigger Zn content, with significant difference in relation to control and other doses. Noteworthy that in dose 1 and 3mg/L the ZN concentrates itself in leaf and in dose 6 and 9mg/L the higher concentrations were found in inflorescence (Fig. 5).

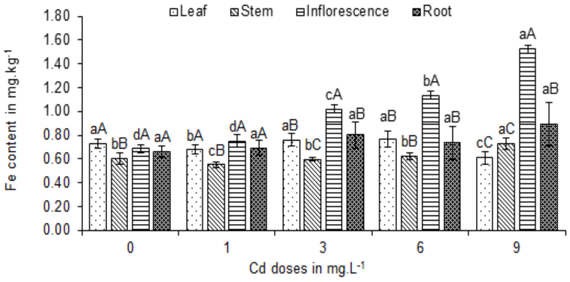

Fig. 4. Fe distribution in jambu plants subjected to increasing doses of Cd. The lowercase letters points the significant differences between the cadmium doses; the uppercase letters points the significant differences between the plant parts, according to Scott-Knot ($p<0.05$) test. Bars represent the mean ± S.D.

The Mn uptake can be observed in fig. 6 and shows that in doses 1 and 3mg/L of Cd promoted bigger content of Mn in leaf, stem, root and inflorescence. Stands out that the higher contents of Mn were found in leaf over other parts of the plant.

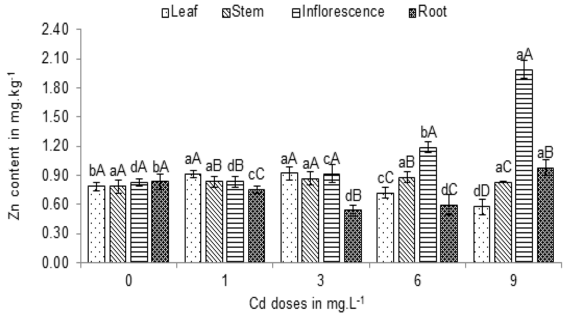

Fig. 5. Zn distribution in jambu plants subjected to increasing doses of Cd. The lowercase letters points the significant differences between the cadmium doses; the uppercase letters points the significant differences between the plant parts, according to Scott-Knot ($p<0.05$) test. Bars represent the mean ± S.D.

Differing from Mn, Cu presents higher content for leaf, stem, inflorescence and root in dose 9mg/L of Cd in relation to control. When the parts of the plants are analyzed in relation of Cu content fronts to Cd, it can be notice that was on inflorescence that have nutrient uptake (Fig. 7).

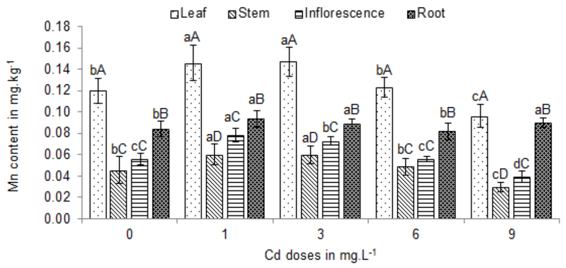

Fig. 6. Mn distribution in jambu plants subjected to increasing doses of Cd. The lowercase letters points the significant differences between the cadmium doses; the uppercase letters points the significant differences between the plant parts, according to Scott-Knot ($p<0.05$) test. Bars represent the mean ± S.D.

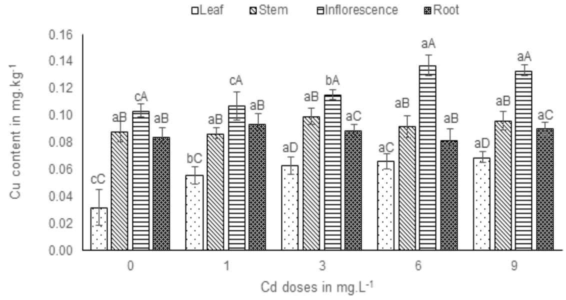

Fig. 7. Cu distribution in jambu plants subjected to increasing doses of Cd. The lowercase letters points the significant differences between the cadmium doses; the uppercase letters points the significant differences between the plant parts, according to Scott-Knot ($p<0.05$) test. Bars represent the mean ± S.D.

The table 1 shows the regression models for each nutrient in relation to Cd doses. As can be observed, the K uptake in leaf, stem and root was in quadratic form, thus, being able to estimate that the Cd concentrations that induce the plant to absorb more nutrient content are the 1.8mg/L for stem, 3.4mg/L for root and 4.7mg/L for leaf. To inflorescence the Cd doesn't shows influence on K uptake (table 1). Important to highlight that at the dose 3mg/L, the metal promotes an uptake of 38% more than the K in relation to control plants, and in dose 9mg/L have a decrease of 46% of the nutrient.

Mg shows a uptake in quadratic form in all parts of the plant, and the Cd dose whose promoted higher stimulus to nutrient uptake was the 4.01mg/L of the metal to leaf and the minor content of Cd was 0.74mg/L to inflorescence (Table 1).

In general, the Cd can induce stimulus in Mg uptake, mainly in 1mg/L dose, with an increase of 27% on the nutrient in relation to control. The dose 9mg/L has a decrease of 39.5% of Mg.

In Ca, the behavior was similar with K and Mg, with Cd influencing a higher uptake with quadratic behavior, however, the plant part that, according with the regression model, presents higher content of the metal to induce maximum uptake of Ca was the inflorescence, with 5.86mg/L of Cd in nutritive solution and the minor content was 1.03mg/L, in leaf. Showing that jambu when exposed to Cd will induce higher uptake of Ca in the reproductive phase of the plant (table 1). In relation to the stimulus of the metal in absorbing this nutrient, it was observed that the dose of 9mg.L $^{-1}$ promoted an increase of 151.9% in relation to the control plants.

The jambu showed quadratic behavior in the uptake of Fe in the leaf and stem, with 3.79mg/L and 2.24mg/Lmg/L of Cd respectively estimated by the regression model (table 1). The inflorescence showed a linear increasing behavior with increasing doses of Cd in the solution, indicating that the Fe contained in the stem and leaf was translocated to the inflorescence. According to regression analysis, the presence of Cd in the root of jambu did not influence the Fe uptake by the plant, and there was no significant difference between the doses of Cd and the content of micronutrient in jambu (Table 1). Based on the total content of Fe uptake by the jambu, it can be seen that there was a growth of 40.3% of the micronutrient when the plant was subjected to a dose of 9mg/L.

The Zn uptake in leaf was according to the quadratic model, with higher content stimulated by 0.40mg/L of Cd according to the regression model. There wasn't Cd influence in Zn uptake by the stem. To inflorescence and root, the jambu behavior was similar with the quadratic regression model, with inflexion point of the curve to inflorescence in 1.35mg/L and 0.87mg/L for root (table 1). In case of Zn behavior in inflorescence and root, the regression models suggest that parting from the inflexion point of the curve, the uptake rate of the micronutrient tends to increase, differing from the Zn behavior on leaf. In relation to the stimulus promoted by Cd in Zn uptake, it can be observed that the 9mg/L dose provided an increase of 35.4% of the micronutrient in relation to control plants.

Table 1. Regression models for nutrient content in leaf, stem, inflorescence and root of jambu exposed to Cd.

Nutrients	Plant parts	Regression Analysis	Adjusted R²	*p-Value*	Maximum effect doses
K	Leaf	$Y=-0.6636D^{2***}+6.2647D^{***}+25.8174$	0.8673	<0.0000	4.720
	Stem	$Y=-0.6178D^{2***}+2.3286D^{***}+38.5353$	0.9380	<0.0000	1.885
	Inflorescence	ns			
	Root	$Y=-0.8103D^{2***}+5.5327D^{***}+25.0795$	0.7304	<0.0000	3.414
Mg	Leaf	$Y=-0.2030D^{2***}+1.6298D^{***}+8.7087$	0.8364	<0.0000	4.014
	Stem	$Y=-0.1045D^{2***}+0.7618D^{***}+3.3029$	0.8970	<0.0000	3.645
	Inflorescence	$Y=-0.0979D^{2**}+0.1455D+7.9335$	0.7378	<0.0000	0.742
	Root	$Y=-0.0567D^{2***}+0.4989D^{***}+3.9215$	0.5635	<0.0000	4.399
Ca	Leaf	$Y=0.0903D^{2***}-0.1860D+1.7242$	0.9553	<0.0000	1.030
	Stem	$Y=-0.0181D^{2**}+0.1794D^{**}+0.6587$	0.2733	<0.0051	4.956
	Inflorescence	$Y=-0.0585D^{2***}+0.6860D^{**}+0.4224$	0.8716	<0.0000	5.863
	Root	$Y=-0.0537D^{2***}+0.3141D+2.4422$	0.4356	<0.0000	1.790
Fe	Leaf	$Y=-0.0064D^{2***}+0.0486D+0.6934$	0.5238	<0.0000	3.797
	Stem	$Y=-0.0027D^{2**}-0.0121D+0.5967$	0.5986	<0.0000	2.241
	Inflorescence	$Y=0.0907D^{2***}+0.6740$	0.9544	<0.0000	0.674
	Root	ns			
Zn	Leaf	$Y=-0.0075D2^{***}+0.0367D^{*}+0.8362$	0.7095	<0.0000	0.409
	Stem	ns			
	Inflorescence	$Y=0.0196D^{2***}-0.0531D^{**}+0.8531$	0.9699	<0.0000	1.354
	Root	$Y=0.0893D^{2***}-0.1565D^{**}+0.8524$	0.8179	<0.0000	0.876
Mn	Leaf	$Y=-0.0013D^{2***}+0.0079D^{**}+0.1305$	0.3468	<0.0000	3.038
	Stem	$Y=-0.0009D^{2***}+0.0059D^{**}+0.0497$	0.5618	<0.0000	3.278
	Inflorescence	$Y=-0.0009D^{2***}+0.0051D^{**}+0.06385$	0.6778	<0.0000	2.833
	Root	ns			
Cu	Leaf	$Y=-0.0007D^{2***}+0.0099D^{**}+0.0383$	0.6394	<0.0000	7.071
	Stem	ns			
	Inflorescence	$Y=0.0038D^{***}+0.1048$	0.7031	<0.0000	
	Root	ns			

*** significant to 1% of probability; ** significant to 5% of probability; ns - not significant; (F test); D=dose; D^2=square dose.

The way that Cd influence in Mn uptake by jambu was through the quadratic model to leaf, stem and inflorescence, for root there was not Cd influence in the Mn uptake (table 1). Having the regression models it was possible to estimated that the concentration of 3.03mg/L will provide maximum uptake of Mn by leaf; for stem the maximum uptake dose was estimated in 3.27mg/L and for inflorescence the concentration of 2.83mg/L of Cd in nutritive solution will provide higher Mn uptake. The greatest stimulation of Mn uptake by Cd occurred at a dose of 1mg/L, an increase of 23.8% of this micronutrient in relation to the control plants.

The Cu uptake in leaf, similar to Mn, was in quadratic form, with estimated content of 7.07mg/L of Cd as the one that could provide high uptake of Cu by jambu. The stem and root showed no influence of Cd on the uptake of Cu. In the inflorescence, on the other hand, the regression model points to a linear increasing behavior of Cu uptake (table 1). In general, Cd promoted an increase of 23.02% in Cu uptake in relation to the control.

Discussion

The data shows that the nutrient uptake by jambu exposed to Cd had a behavior different from the majority of plants. Many studies have been demonstrating the toxic effect of the metal, could be citing the surveys of Solis-Dominguez *et al.* (2007) and Rizwan *et al.* (2017), that demonstrates how the Cd affects the photosynthesis, production, quality and efficiency of biomass due to its high toxicity, further the nutrient substitution as Zn for Cd in metalloenzymes. Kurdizel *et al. (*2004) shows that in some plants, the Cd substitutes the Mg in Rubisco, modifying its structure. Perfus-Barbeoch *et al. (*2002) related in their study with Arabidopsis thaliana L. that the metral can induce the release of Ca from the endoplasmatic reticulum and vacuoles, increasing the citosol level, conducting to minor stomatal opening. As result, it occurs inhibition of growth and translocation of nutrients as Mn and Cu. On the other hand, this study shows that in small doses, Cd produced a stimulating effect on the uptake of nutrients by jambu.

When K uptake is observed, it can be seen that up to a dose of 6mg/L, there was an increase of 38% induced by Cd. This behavior was observed in all parts of the plant, with emphasis on the leaf and stem of jambu. According to Taiz *et al.* (2017), K is required as a cofactor in more than 40 enzymes, being responsible for turgor and maintenance of cell electroneutrality. In jambu, possibly due to a deregulation of osmotic potential, the plant may have absorbed more K to maintain leaf turgor and greater stomatal opening, thus regulating osmotic potential and reestablishing water relations that may have been affected by Cd. According to Nassar *et al.* (2012), the presence of K minimizes oxidative stress because it reduces the production of reactive oxygen species. As for the dose of 9mg/L, the effect of Cd was toxic, with a 46% reduction in uptake of the macronutrient, showing that this is the toxic dose of the metal for K uptake.

Unlike the studies of Khaliq *et al.* (2019) in rice and Dias *et al.* (2013) in lettuce that reported reduction in Mg uptake with increasing Cd concentration, jambu absorbed higher Mg content as the increase in the doses of the metal occurred. Like K, Mg had a synergistic effect with the doses of 1, 3 and 6mg/L of Cd in the nutrient solution, obtaining an increase of 27.4% in the uptake of this macronutrient. As Mg is constituent of the chlorophyll molecule and required by many enzymes involved in the transfer of phosphorus (Taiz *et al.,* 2017), its increase, by the inductive effect of Cd, promoted a greater performance of jambu. Importantly that the increase in magnesium content may be an adaptation of jambu to minimize Cd effects on its photosynthetic apparatus, increasing the photosynthetic activity. According to Nassar *et al.* (2012), the presence of Mg reduced Cd toxicity in rice root. At the dose of 9mg/L, however, there was an antagonistic effect between Mg and Cd, denoting toxicity by the metal.

The content of Ca in the stem, inflorescence and root of jambu, showed a biphasic behavior with increasing uptake of the macronutrient between the doses of 3 and 6mg/L of Cd in the solution. In the leaf, the content of Ca increased with the concentration of Cd. Although Ca and Cd compete for the absorption route, this effect was not demonstrated in jambu, because Cd promoted uptake of 151.9% of Ca than control plants, demonstrating a synergistic effect.

The Fe is a protein constituent as iron-sulfur, is a key nutrient in the transport chain of electrons of mitochondria, acting as cofactor in photosynthesis (Marschner, 2012). In this study the uptake of Fe by jambu suffered an increase of 40.3% in relation to the control plants. In the leaf, stem and root the content of Fe is almost not altered by the presence of the metal, however, the content of Fe in the inflorescence showed a great influence of Cd, with a significant increase of the micronutrient. Plants exposed to Cd present leaf chlorosis due to reduced Fe uptake and thus impairing the biosynthesis of chlorophyll (Haider *et al.,* 2021; Chang *et al.,* 2003), however, the jambu did not present this phenomenon, especially at lower doses of Cd. This behavior suggests that Cd may have been retained in the chloroplast, as reported by Qureshi *et al.* (2010).

Chemically similar to Cd, Zn is considered an element antagonistic, limiting the entry of Cd into plants, however in some hyperaccumulating plants, Cd ends up having a genetic role similar to Zn (Quin *et al.,* 2020). In this study, leaf Zn behaved in a quadratic form, demonstrating a stimulant effect up to 3mg/L of Cd, with effect toxic from 6mg/L of the metal. Reverse effect was observed in inflorescence and root, demonstrating that the jambu was stimulated with high doses of Cd. This behavior can be attributed to chemical similarity between Zn and Cd.

Required in some activities dehydrogenases, carboxylases,oxidases and peroxidases, Mn has a structural role and acts in photosynthesis (Taiz *et al.,* 2017; Epstein and Bloom 2006). In this study it was demonstrated the biphasic behavior in the uptake of Mn by the leaf, stem and inflorescence of jambu, showing synergistic effect until the dose of 3mg/L of Cd, with an increase of 23.8% in the uptake of the micronutrient. However, an antagonistic effect was demonstrated, with a reduction in the uptake of the micronutrient at higher doses of Cd. Zornoza *et al.* (2010) reported a protective role in photosynthetic tissues for Mn in the face of Cd toxicity, with an increase in the antioxidant capacity of the lupin root, along with an increase in Mn at the aerial part of the plant, a similar behavior to the jambu highlighted in this research.

Cd induced an increment of 23.02 % of Cu uptake mainly by the inflorescence and leaf of jambu. According to Quin *et al.* (2020), few studies have reported positive effects in reducing Cd toxicity by Cu. Liu *et al.* (2003), show synergistic relationship between Cd and Cu in leaves and roots of different rice cultivars and corroborate with this research.

Although the exposure of plants to Cd causes adverse effects, especially in the absorption of nutrients, some studies have shown that the metal in small doses has an inductive effect on the growth of some plants. This concept is called Hormesis, and occurs when there is a biphasic behavior in the dose-response curve. At the moment that an organism organism is subjected to increasing doses of a stress agent, for example, a heavy metal, it produces a stimulatory and inhibitory response (Ray, *et al.,* 2014; Pincelli-Souza *et al.,* 2020; Calabrese and Blain, 2009).

Conclusions

Jambu showed synergistic relationship with Cd at low concentrations and of toxicity with increasing levels of the metal in the nutrient solution. The concentration of 6mg/L Cd promoted greater uptake of the K, Ca and Mg in all parts of the jambu, indicating a stimulating effect of the metal. Cd in small concentrations did not reduce the uptake of the micronutrients Fe, Zn, Mn and Cu, showing that there was no competition between the micronutrients and the metal. This does not occur in most plants which release phytochelatins and promote the fixation of Cd in the root. At doses above 6mg/L Cd, jambu showed reduced nutrient uptake, possibly revealing signs of plant toxicity to Cd. In general, jambu showed biphasic behavior, with increased nutrient uptake when exposed to small concentrations of the metal and a reduction in nutrient uptake with increasing exposure. This behavior indicates that the jambu presents a hormetic effect. This effect in jambu may be due to an adjustment of the plant to tolerate Cd toxicity, thus increasing nutrient uptake and reducing the deleterious effects of the metal.

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