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Absorption and Translocation Capacity of Cadmium in Papaya (*Carica papaya* L.) Plants With Addition of Organic Matter

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Abstract

Cadmium (Cd) is a toxic element that can be easily absorbed by crops, and can enter through the frequent use of fertilizers in crop areas. The objective of this study was to evaluate the bioaccumulation percentage (BAP) and translocation factor (TF) of Cd in papaya plants exposed to contaminated soils at 50, 100 and 150 mg L^{-1} and at two concentrations of organic matter: 2% and 10%-MO. Growth variables, chlorophyll and metal concentration were measured after 10 months of cultivation. The results indicated that the greatest growth occurred in soil at 10%-OM in relation to those grown at 2%-OM. Cd bioaccumulation was leaves < stem < root ($9 < 22 < 68\%$) at 50 mg L^{-1}, ($7 < 29 < 65\%$) at 100 mg L^{-1} and ($4 < 34 < 63\%$) at 150 mg L^{-1}, observing the greatest accumulation in the root. The findings showed that organic matter in soil decreases the availability of metal uptake in the roots. The translocation results were < 1, indicating that the root has the ability to restrict metal transport to the aerial part in plants grown in 10%-OM soil, however, in 2%-OM soil it tends to increase this metal accumulation, suggesting that the application of organic amendments is an alternative to reduce the risk of Cd absorption in agricultural soils.

Keywords: absorption, bioaccumulation, plant stress, translocation

1. Introduction

The presence of heavy metals in soil has become an environmental concern, due to the long-term persistence of these elements and the harmful effects they can cause to living organisms. There are no effective controls to regulate the impact of anthropogenic activities on the environment and on agricultural soils, where metals can be absorbed during crop development, and concentrate to toxic levels to plants with the risk of entering the food chain (Kumar et al., 2015; Wei et al., 2020). Cadmium is considered a highly toxic metal, as it is not part of biological function in organisms; its high solubility in water makes it readily available for absorption, and it manages to bioaccumulate to toxic levels (De Paiva Magalhães et al., 2015; Kumar et al., 2017).

In plants, Cd can be readily taken up by the roots and thus can be translocated to the aerial part in ionic form through the xylem and phloem; Cd toxicity can cause adverse effects such as stunting, chlorosis and in some cases plant death (Dong et al., 2019; Varma & Jangra, 2021). The entry of Cd into the plant occurs through nutrient uptake mechanisms in the root, this is because they do not have a selective process to uptake essential elements from the soil (Järup & Åkesson, 2009). Thus, the root absorbs Cd found as free ions in the soil, where it accumulates in the apoplast and is subsequently transported to the aerial part of the plant (Bali et al., 2020; Uraguchi & Fujiwara, 2012; Cosio et al., 2005; Lux et al., 2011). In the cell, Cd will preferentially bind to nitrogen (N) and sulfur (S) donors of functional groups of macromolecules and low molecular weight ligands; it mainly binds to sulfhydryl groups of cysteine, which represents the most important interaction of this metal with biochemical constituents, and can readily bind to the hydroxyl part of phospholipids (Prieto et al., 2009; (Gramlich et al., 2017; Choppala et al., 2014). Cd can interfere with the uptake and transport of essential elements such as Ca, and Fe, leading to major changes in plant development, causing stomatal closure, decreased transpiration rate and inhibition of photosynthesis, significantly affecting a reduction in growth and nutrient imbalance (Zafar-ul-hye et al., 2020; Nazar et al., 2012; Balen et al., 2011).

The entry of Cd into agricultural soil can occur from different sources, such as the use of chemical fertilizers, which can introduce concentrations of some heavy metals, either as an active ingredient or in the form of impurities (Niño-Savala et al., 2019; Kooner, Mahajan, & Dhillon, 2014; Yadav, 2010). Some studies have reported that phosphate fertilizers can contribute concentrations of approximately 10.97 mg kg^{-1} Pb and 10.43 mg kg^{-1} Cd and nitrogen fertilizers of 4.65 mg kg^{-1} Pb and 2.03 mg kg^{-1} Cd (Martí, Burba, & Cavagnaro, 2002). It has also been reported that fertilizers such as diammonium phosphate and triple superphosphate can contribute levels of 3.7 and 8.7 mg kg^{-1} Cd, respectively (Rodríguez Ortiz et al., 2014). The continued use of fertilizers can increase the concentration of metals and make them available for absorption by crops; however, uptake will depend on some soil characteristics such as organic matter content, pH, clay content, and cation exchange capacity (Abedi & Mojiri, 2020; Realpe et al., 2014).

The application of organic amendments in the soil have been implemented as techniques to immobilize Cd, reducing the availability of uptake by plants through the formation of complexes that occur in the soil by absorption or precipitation processes (Wang et al., 2019; Park et al., 2011; Jiang et al., 2012). Organic wastes such as manure, compost, biosolids, household waste, straw and others can be used as amendments to reduce the availability of Cd in soil (Xiu-Zhen et al., 2012). Studies have reported that the application of 5% and 10% biochar to soil can reduce Cd, Zn, and Pb concentrations after 56 days of application (He et al., 2015). The use of manure and clay mineral amendments decrease Cd translocation from root to the wheat shoot (Hamid et al., 2019); while the addition of animal-derived organic matter can reduce Cd uptake by up to 38% in spinach crop (Sato et al., 2010); furthermore in amaranth shoots, it is possible to inhibit cadmium accumulation with the use of a combination of organic amendments (Dong et al., 2021). Hence the interest in finding the most viable strategies for agricultural producers, since heavy metals in soil can cause in addition to plant stress, alterations in growth and a reduction in crop yield (Nagajyoti et al., 2010).

In Mexico, many agricultural crops operate under intensive fertilization systems, as is the case of papaya (*Carica papaya* L.). Papaya is a tropical fruit belonging to the genus *Carica*, which includes 22 species; it is valued for its nutritional and digestive properties (Madrigal, Duniesky, & Boza, 2013). It is the most economically important fruit for Mexico and Central America, it is also considered a fast-growing crop with early and continuous production that requires high amounts of nutrients for its development, its fruit is a commercially important product at national and international levels (García et al., 2003; García & Escobar, 2010). During the crop cycle, excessive applications of nitrogen and phosphate fertilizers are made with the risk of increasing the concentrations of heavy metals in soil and their absorption by the crop plants. This study evaluated the bioaccumulation and translocation capacity of Cd in papaya (*Carica papaya* L.) plants, which are generally grown under uncontrolled fertilization conditions, and analyzed the effect of the addition of organic matter to the soil on the restriction of metal uptake. Thus, some growth response variables in papaya plants, caused by Cd toxicity, were also evaluated. The results of this study allow proposing that the application of a high percentage of organic amendments in the soil can reduce the immobilization of cadmium with a lower risk of uptake in papaya plants.

2. Materials and Methods

2.1 Cultivation and Plant Treatments

The study was conducted at the experimental facilities of the Instituto Tecnológico de Boca del Río, in Veracruz, Mexico; which is characterized by a warm sub-humid climate with temperature of 25-32 °C, and a mean annual rainfall of 1500-2000 mm.

The crop was grown under outdoor conditions in the central zone of the state with a mean temperature of 32ºC and 80% relative humidity. Certified seeds of papaya maradol (*Carica papaya* L.) from Semillas del Caribe® were used. To promote germination, the seeds were immersed in distilled water for 48 h, with water changes every 8 h. The seeds were then placed between two moist, sterile cloths and left to rest in a warm place (32 °C). Germination was achieved within 7 to 10 days with the emergence of 1-2 cm radicles.

For the experiments, sandy loam soil (77% sand, 17% silt, 4% clay and 2% fine gravel) was used, plus adding commercial organic matter (58.71%, pH 3.98, 4.18% nitrogen, 0.70% total phosphorus and 11.15% potassium). The Cd concentration in the initial soil was measured, indicating a value of less than 0.001 mg kg^{-1}. Two soils were prepared, one with a high organic matter content at 10%-OM, and the other with a low organic matter content at 2%-OM. Each soil was homogenized and tested for organic matter content using the ignition method of Schulte and Hopkins (Schulte et al., 1996).

Seeds were sown at 3 cm depth in 250 g plastic bags (15 × 15 cm) and kept protected from direct sunlight using shading screens. After 45 days, the plants were transplanted into 15 kg (30 L) containers, placing one plant per container. Nutrients such as nitrogen, phosphate and potassium were added monthly in a ratio of 16:31:19; these were then placed in an outdoor environment.

A completely randomized design was carried out in soil at 2 and 10%-OM, in treatments with Cd addition at 0, 50, 100 and 150 mg L^{-1}; five plants were used per treatment with three replications. Two weeks after transplanting, the addition of the Cd solution (10 ml kg^{-1}) started, which was applied weekly to the soil through irrigation water (Iannacone & Alvariño, 2009) using cadmium chloride ($CdCl_2$) as the contaminating agent.

2.2 Growth Variables

The experiment was conducted for 10 months after transplanting, for this particular case the number of flowers was not considered. The growth variables were plant height, stem thickness and number of leaves; these were measured every 30 days for 10 months from the addition of the metal. Height was taken from the soil surface to the terminal apex, stem thickness was measured at 5 cm from the ground using a Vernier and true leaf count was performed. Chlorophyll content was determined by nondestructive testing with a portable SPAD-502 meter (Minolta Co., Japan). The SPAD-502 meter uses two light-emitting diodes (650 and 940 nm) and a detector photodiode to measure the transmission of red and infrared light through the leaves, so that the values obtained were proportional to the chlorophyll content (Chang & Robison, 2003). For the measurement, three mature leaves were selected from the central part and three readings per leaf were taken, resulting in nine measurements and the mean per plant for each treatment was obtained (Azia & Stewart, 2001).

2.3 Evaluation of Cd Concentration

Cd concentration was analyzed at the end of the test by atomic absorption spectrophotometry according to the specifications of NOM-117-SSA1-1994 (Diario Oficial, 1994). The structural parts of the plant (leaves, stem and root) were separated, washed with distilled water and oven-dried at 65 °C; they were then sieved to obtain the finest particles. 0.5 g of the sieved sample was weighed and 10 ml of 70% reagent grade (suprapure) J.T. Baker® nitric acid (HNO_3) was added. They were placed in Teflon cups and put into a CEM Mars 5 microwave oven (CEM, Corporation Mathews, NC, USA). After digestion, the samples were filtered using a Nalgene bottle with a 0.45 µm Millipore HAWP04700 filter and a vacuum pump. The filtrate was transferred to a 25 ml volumetric flask and volumetrically filled with deionized distilled water (1 µmho cm^{-1} at 25 °C). The samples were transferred to pre-labelled amber glass vials and kept refrigerated until analysis. At the same time a control sample was taken with 45 ml of double distilled water and 5 ml of HNO_3. Cd quantification was performed in a Thermo Scientific iCE 3500 AAS spectrometer (Thermo Scientific®, China). For the calibration curve, certified High Purity Standards® (Charleston, SC) was used at a concentration of 1000 µg/mL in 2% HNO_3; with a range adjusted from low to high, close to the analyte to obtain a correlation coefficient greater than 0.95. A Praxair® graphite furnace and argon gas (5.0 ultra high purity) at a wavelength of 228.8 nm were used in the analysis of the Cd readings.

The bioaccumulation percentage (BAP) of Cd, obtained from the ratio between the concentration of the metal in root, stem and leaves in relation to the total concentration in the plant, was calculated.

2.4 Translocation Factor (TF)

The translocation factor was evaluated in each of the treatments, the TF is the measure of the internal transport of a metal, it indicates the relationship between the accumulated concentration in the aerial part and in the root of a plant (Mattina et al., 2003). It is calculated by dividing the concentration of the metal in the aerial part by the concentration in the root of the plant according to Zhang et al. (2002), and Olivares and Pena (2009).

2.5 Statistical Analysis

One-way and two-way analysis of variance and Tukey's mean comparison ($p < 0.05$) were performed to determine significant differences in physiological results, Cd accumulation and the translocation factor. Pearson correlation between 10%-OM and 2%-OM experiments was performed using Statistic 7.0 (StatSoft, Inc. Tulsa, USA).

3. Results

3.1 Variation of Growth by Cadmium Addition

At the end of the experiment, higher growth was observed for plants grown in 10%-OM soil compared to those grown in 2%-OM (Table 1). Percent growth inhibition (GI) was calculated relative to the control group in soil-OM, where the values indicated that the greatest growth inhibition occurred in plants grown in 2%-OM soil compared to those grown in 10%-OM soil. This indicated that the growth of plants at 10%-OM, was reduced by -4, 1, 12% in the 50, 100, 150 mg L^{-1} treatments, respectively; the negative value indicates that plants in the treatment at 50 mg L^{-1} grew more than those in the control group. Inhibition of 19, 7, 19% in stem thickness, 5, 17, 15% in leaf number and 11, 4, 24% in chlorophyll was observed in the treatments at 50, 100, 150 mg L^{-1}, respectively. Significant differences ($p < 0.05$) were observed in plant height in soil at 10%-OM of the treatment at 150 mg L^{-1} compared to the rest of the treatments, the same behavior was observed in the variables of stem thickness, number of leaves and chlorophyll.

Plants grown in soil at 2%-OM showed growth inhibition of 8, 18 and 22% in height, 14, 14, 23% in stem thickness, 4, 20, 16% in number of leaves and 29, 27, 41% in chlorophyll in the 50, 100 and 150 mg L^{-1} treatments, respectively. Significant differences were found in plant height in the control and 50 mg L^{-1} treatments compared to the higher concentration treatments (100 and 150 mg L^{-1}), where the latter showed the greatest growth inhibition. A similar case was observed for leaf number, where significant differences occurred between the low concentrations (0 and 50 mg L^{-1}) compared to the highest Cd concentrations used (100 and 150 mg L^{-1}). Stem thickness growth showed significant differences between treatments, where the highest inhibition was observed in the treatment with 150 mg L^{-1}.

The results of the study reported that there were positive correlations in both soil types (2% and 10%-OM), between the stem thickness and the plant height ($r = 0.727$, $p < 0.01$), with chlorophyll content ($r = 0.667$, $p < 0.01$) and in the number of leaves ($r = 0.630$, $p < 0.01$), and in the increase in stem thickness in both treatments ($r = 0.782$, $p < 0.01$). Chlorophyll content in both treatments had a statistically significant correlation ($r = 0.758$, $p < 0.01$) and correlated directly with plant growth ($r = 0.681$, $p < 0.05$) and stem thickness ($r = 0.611$, $p < 0.01$). Increased leaf number was positively related to plant height ($r = 0.681$, $p < 0.01$), stem thickness ($r = 0.729$, $p < 0.01$) and chlorophyll content ($r = 0.645$, $p < 0.01$).

Table 1. Effect of soil types and Cd concentrations on growth traits (mean values ± SD). Different letters indicate statistical differences according to ANOVA test ($p < 0.05$). Inhibition of growth in height, stem thickness and number of leaves; decrease in chlorophyll content (%)

Treatment	OM (%)	Plant height (cm)		Stem thickness (cm)		Leaf number		Chlorophyll (SPAD units)	
			GI (%)		GI (%)		GI (%)		GI (%)
Control	10%	73.80±1.09a	-	31.22±1.48a	-	16.20±0.84a	-	61.04±4.26a	-
	2%	69.50±1.01a	-	27.40±1.62a	-	15.20±0.84a	-	57.84±5.41a	-
50 mg L^{-1}	10%	76.40±4.13a	-4	29.62±2.00ab	19	15.40±1.14a	5	54.22±5.74a	11
	2%	64.00±3.95b	8	23.62±0.98b	14	14.60±0.89a	4	41.76±5.90a	29
100 mg L^{-1}	10%	73.11±3.82a	1	28.34±1.10bc	7	15.00±1.00ab	17	58.48±2.52a	4
	2%	56.90±2.11c	18	23.62±0.56b	14	12.20±0.84b	20	42.7±5.54a	27
150 mg L^{-1}	10%	64.62±5.82b	12	26.01±0.38c	9	13.00±1.14b	15	46.46±7.20b	24
	2%	54.04±3.07c	22	21.22±1.23c	23	12.80±0.84b	16	34.46±5.77b	41

Note. OM: Organic matter; GI: Growth inhibition

However, plants grown in 10%-OM soil showed a significant behavior between plant height and stem thickness ($r = 0.447$, $p < 0.05$), as well as a positive correlation between stem thickness with chlorophyll content ($r = 0.588$, $p > 0.01$) and number of leaves ($r = 0.829$, $p > 0.01$). In the 2%-OM trial, positive correlations were observed between plant height and stem thickness ($r = 0.778$, $p > 0.01$), with chlorophyll ($r = 0.679$, $p > 0.01$) and number of leaves ($r = 0.675$, $p > 0.01$); likewise, positive correlations were seen between stem thickness with chlorophyll content ($r = 0.754$, $p > 0.01$) and with number of leaves ($r = 0.548$, $p > 0.05$); chlorophyll was positively correlated with number of leaves ($r = 0.452$, $p > 0.05$).

Table 2. Correlation matrix of the variables of height, stem thickness, number of leaves and chlorophyll in the treatment of 0, 50, 100 and 150 mg L^{-1} of Cd added to soil with high and low organic matter content

		10%-OM				2%-OM			
		Height	Stem THK	Chlorophyll	Leaves	Height	Stem THK	Chlorophyll	Leaves
10%-OM	Height	1							
	Stem THK	0.447*	1						
	Chlorophyll	0.408	0.588**	1					
	Leaves	0.331	0.829**	0.505*	1				
2%-OM	Height	0.425	0.727**	0.471*	0.681**	1			
	Stem THK	0.338	0.782**	0.611**	0.729**	0.778**	1		
	Chlorophyll	0.409	0.667**	0.758**	0.645**	0.679**	0.754**	1	
	Leaves	0.337	0.630**	0.230	0.375	0.675**	0.548*	0.452*	1

Note. * Correlation is significant at the 0.05 level; ** Correlation is significant at the 0.01 level.

On the other hand, the interaction between two factors was evaluated: soil type (2% and 10%-OM) and treatments (0, 50, 100 and 150 mg L^{-1}) with respect to the variables analyzed; however, significant differences ($p > 0.05$) were only observed in plant height, and no positive correlation was observed in measures of stem thickness, number of leaves, or chlorophyll.

3.2 Bioconcentration and Translocation of Cadmium

Cd accumulation in papaya plants was higher in the root and decreased to the aerial part of the plant (root > stem > leaves) for both crops in 2% and 10%-OM soils.

Plants grown in10%-OM soil, registered a bioaccumulation percentage (BAP) of 9, 7, 4% in leaves, 22, 29, 34% in stem and 68, 65, 63% in root, in the treatments of 50, 100, 150 mg L^{-1} respectively (Table 3). The accumulation of Cd in root and stem showed significant differences among all treatments; however, in leaves, differences were observed between the treatment at 150 mg L^{-1} with respect to the rest of the trials. In the case of plants grown in soil with 2%-OM, the same trend was observed in root and stem, where there were significant differences among all treatments (50, 100 and 150 mg L^{-1}); accumulation in leaves showed significant differences between the control, and the 50 and 100 mg L^{-1} treatments, and in comparison, with the highest concentration of Cd used (150 mg L^{-1}). For this case, accumulation values of 15, 6, 5% in leaves, 34, 40, 35% in stem and 51, 54, 61% in root were recorded in the 50, 100, 150 mg L^{-1} treatments, respectively.

The results of this study indicated that plants grown in soil at 2%-OM accumulated higher levels of Cd in the aerial part compared to plants grown in soil at 10%-OM, where the highest concentration was in the root. In this sense, in plants grown at 10%-OM, it was observed that leaves were positively correlated with the stem ($r = 0.787$, $p < 0.01$) and with the root ($r = 0.794$, $p < 0.01$). There was also a strong correlation between stem and root concentration ($r = 0.991$, $p < 0.01$) (Table 4). The same behavior was observed in plants in 2%-OM soil, where a significant correlation was observed between the concentration in leaves compared to the stem ($r = 0.763$, $p < 0.01$) and root ($r = 0.810$, $p < 0.01$). On the other hand, root and stem were observed to be positively correlated with $r = 0.787$ ($p < 0.01$).

Translocation (TF) results indicated that plants grown in 10%-OM soil increased proportionally with metal exposure, registering a factor of 0.47, 0.55 and 0.60, in the 50, 100 and 150 mg L^{-1} treatments, respectively. The highest translocation was recorded in the treatments with higher Cd addition concentration (100 and 150 mg L^{-1}) with values close to 1, indicating a higher transport rate from the root to the aerial part. In this sense, no significant differences were observed among the treatments with Cd addition. In the 2%-OM plants, the TF values recorded were 0.97, 0.85, 0.65 in the 50, 100 and 150 mg L^{-1} treatments, respectively. A higher transfer rate was observed in all treatments, and significant differences were observed between the treatments with the highest concentrations added (150 mg L^{-1}) compared to the rest of the treatments.

Table 3. Results of Cd concentration in the structural part of the plant by treatment and by soil type at the end of the experiment (mean values±SD) (mg kg^{-1}). Different letters indicate statistical differences according to Tukey's test ($p < 0.05$). Percentage of cadmium accumulation in root, stem and leaves

Treatment	OM	Leaves		Stem		Root		TF
			BAP (%)		BAP (%)		BAP (%)	
Control	10%-OM	0.020±0.003a	-	0.022±0.005a	-	0.046±0.014a	-	0.98±0.44a
	2%-OM	0.022±0.003a	-	0.029±0.003a	-	0.038±0.002a	-	1.32±0.11a
50 mg L^{-1}	10%-OM	0.035±0.009a	9.2	0.085±0.009b	22.4	0.260±0.026b	68.4	0.47±0.07b
	2%-OM	0.049±0.007b	15.2	0.109±0.012b	34.0	0.164±0.010b	50.8	0.97±0.11b
100 mg L^{-1}	10%-OM	0.051±0.009a	6.5	0.225±0.012c	28.9	0.502±0.042c	64.5	0.55±0.05b
	2%-OM	0.043±0.006b	5.7	0.301±0.046c	40.2	0.406±0.014c	54.1	0.85±0.12b
150 mg L^{-1}	10%-OM	0.053±0.006b	4.0	0.451±0.043d	33.5	0.841±0.045d	62.5	0.60±0.05ab
	2%-OM	0.065±0.007c	4.9	0.462±0.007d	34.6	0.806±0.028d	60.5	0.65±0.02c

Note. HPOM: High organic matter content; LPOM: Low organic matter content; BAP: Bioaccumulation percentage.

Table 4. Correlation matrix of Cd uptake in root, stem and leaves, in treatments of 0, 50, 100 and 150 mg L^{-1} of Cd added in soil with high and low organic matter content

		10%-OM			2%-OM		
		Leaves	Stem	Root	Leaves	Stem	Root
10%-OM	Leaves	1					
	Stem	0.787**	1				
	Root	0.794**	0.991**	1			
2%-OM	Leaves	0.755**	0.827**	0.820**	1		
	Stem	0.766**	0.967**	0.982**	0.763**	1	
	Root	0.792**	0.989**	0.996**	0.810**	0.977**	1

Note. ** Correlation is significant at the 0.01 level.

4. Discussion

Cd is a hazardous and highly toxic pollutant, which cannot be degraded and metabolized by plants, so it can bioaccumulate over time, when there is prolonged exposure (Abollino, 2002). It has been observed that this metal has a high transfer rate from soil to plant, showing signs of stress at low concentrations (Mancera-Rodriguez & Alvarez-Leon, 2006).

However, Cd uptake in plants will depend on some physical characteristics of the soil such as pH, organic matter content and clays (Sauvé et al., 2000). Organic matter in soil with heavy metals present allows a greater exchange of ions between the metal and the organic compounds in the soil, thus reducing metal uptake.

This study demonstrated the effectiveness of the use of organic matter in papaya cultivation to reduce the risk of Cd absorption and translocation from the soil to the plant, based on common practices in agricultural fields with the use of organic amendments. The results of the growth response variables of papaya plants showed that those grown in soil with 10%-OM organic amendment application had a higher growth than plants grown in soil in 2%-OM soil. It was found that there was a growth inhibition (GI) proportional to the increase in treatment doses; however, it was evident that plants grown in 10%-OM soil had less inhibition in height, stem thickness, number of leaves, and chlorophyll (Table 1).

In contrast, plants in soil with 2%-OM, showed growth inhibition that was gradual as the treatment dose increased compared to plants with no addition of the metal (control). Stem height and thickness, number of leaves and chlorophyll were observed to be lower as the dose increased. This growth inhibition was probably induced by the presence of Cd, as cell wall suppression occurs due to the toxicity of the metal (Adrees et al., 2015; Aidid & Okamoto, 1993). Similar studies have reported that Cd has caused growth inhibition in tobacco (*Nicotiana tabacum* L.) plants (Lu et al., 2018); in alfalfa (*Medicago sativa* L.) (Yang et al., 2019); in tomato (*Solanum lycopersicum* L.) (Brouquisse et al., 2010), in soybean (*Glycine max* L.) (Chen et al., 2003), in maize (*Zea mays* L.) (Rizwan et al., 2016) and in lettuce (*Lactuca sativa* L.) (Yazdi et al., 2019). Despite this, organic amendments applications were able to alleviate Cd stress as observed in plants grown in soil with 10% OM; as reported by Yen et al. (2021) in previous studies with lettuce, where amendment applications reduced Cd stress growth inhibition by 30-50%.

It was observed that the presence of Cd in the crop caused the appearance of chlorosis in both treatments (2% and 10%-OM) due to a decrease in chlorophyll, which was more evident as the metal concentration increased in the crop treatments. Chlorosis represents a sign of metallic toxicity due to interference in the absorption of essential elements in the photosynthetic process; since Cd can compete in the absorption and transport through essential elements such as Ca, Mg or Fe, causing stomata closure and resulting in an inhibition of photosynthesis, thus plant growth is considerably affected by nutrient imbalance (Nazar et al., 2012; Furcal-Beriguete & Torres-Morales, 2020; Rodríguez, 2007). It has also been reported that Cd is related to the reduction and transport of Mn, which acts as an energy catalyst in the photosynthetic process and interferes with the entry and transport of Ca, P and K, causing a delay in plant growth and inhibition of photosynthetic processes (Seregin & Kozhevnikova, 2008; Benavides, 2011; Huang et al., 2018).

Similarly, prolonged metal exposure, strongly limited flower production in both treatments in relation to the control group. In the case of plants exposed to 50 mg L^{-1}, it caused abortion of all flowers at the immature flower bud stage due to long-term exposure to the metal. Therefore, these data were discarded for the present study.

On the other hand, the results of Cd bioaccumulation in papaya plant showed a sequence in decreasing order from root > stem > leaves in both crops (2% and 10%-OM); correlations between root, stem and leaves showed that the uptake was similar between treatments and this decreased from root to leaves. It was observed that there was a restriction in metal transport from the root to the aerial part of the plant, suggesting that Cd transport to the xylem was restricted (Song et al., 2017). However, the results revealed that the 2%-OM and 10%-OM treatments were positively correlated, indicating that they had the same metal uptake behavior in roots, stems, and leaves throughout the exposure time.

The results indicated that the plants in 10%-OM soil accumulated a higher percentage of Cd concentration in the root than in the aerial part of the plant: leaf < stem < root (9 < 22 < 68%) at 50 mg L^{-1}, (7 < 29 < 65%) at 100 mg L^{-1} and (4 < 34 < 63%) at 150 mg L^{-1} than those grown in soil at 2%-OM, which concentrated in leaf < stem < root of 15 < 34 < 51% at 50 mg L^{-1}, 6 < 40 < 54% at 100 mg L^{-1} and 5 < 35 < 61% at 150 mg L^{-1} (Table 3).

Despite the above, papaya plants had the same behavior in both treatments of accumulating the highest concentration of Cd in the root; however, plants in soil at 10%-OM reduced the transport of the metal to the aerial part, while plants in soil at 2%-OM showed a greater transport to the aerial part.

The application of organic amendments in soil contributes positively to Cd immobilization, as their porous structure, high pH and high cation exchange capacity can immobilize metals in soil (Huaraca-Fernández et al., 2020). This is due to the presence of various functional groups capable of forming stable compounds through adsorption, complexation, ion exchange, precipitation, reduction and volatilization of some metals, reducing Cd uptake in the root (Hakeem, 2015).

Although the addition of organic matter to the soil showed a lower absorption of the metal in the roots in both treatments, it could be observed that during the exposure to 150 mg L^{-1}, the organic matter content was not sufficient for a prolonged exposure time to which the papaya plants were exposed. For this reason, it will be necessary to make frequent applications of organic amendments during the crop cycle in order to alleviate the symptoms of metal stress.

Furthermore, the translocation factor (TF) results showed values of 0.47, 0.55, 0.06 (50, 100 and 150 mg L^{-1} respectively) in plants grown in 10%-OM soil, while the values in 2%-OM soil were 0.97, 0.85, 0.65 (50, 100 and 150 mg L^{-1} respectively) (Table 3). The TF values show the function of the plant root to carry out metal transport to the aerial part (Liu et al., 2020). The translocation factor (TF) is estimated to know the ability of plants to exclude or extract metals from roots (Al-Jobori & Kadhim, 2019). Thus, when TF is greater than 1 (TF > 1), the plant is said to have the capacity to accumulate high concentrations of metals in the aerial part, while when TF is less than 1 (TF < 1), it indicates that the plant has the ability to exclude metal from the root to the aerial part of the plant (Sidhu et al., 2017). Based on our study, the TF values in 10%-OM soil showed TF values < 0.6, revealing the plant tolerance towards Cd-contaminated soils, showing the ability of the root to restrict metal translocation to the aerial part. Similarly, the TF value in plants in soil at 10%-OM increased gradually with respect to the added dose of Cd. In particular, plants at 2%-OM showed TF values close to 1, indicating an ability to translocate to the aerial part. Pancorbo and Ruíz (2020) indicated that when TF is less than 0.5 it indicates that the plant is tolerant to the presence of metals, but when the TF value is less than 1, it is considered to have accumulating capacity and when TF > 1 it is considered hyperaccumulating; this occurs when a metal contaminant is taken up by the plant and is not rapidly degraded, resulting in an accumulation in the plant. However, the TF values in soil at 2%-OM, with respect to the doses of Cd addition in each treatment, showed an inverse behavior and this is probably because there was an increase in the concentration in the plant stem and it was higher than the dose present in the soil.

It is evident that many plants resort to physiological strategies to counteract metal toxicity by restricting the transport of metal ions from the root to the aerial part of the plant (Hasan et al., 2009). This is due to the fact that uptake from the plasma membrane of root cells is regulated by the electrochemical potential difference between Cd^{2+} activity in the cytosol and that of the root apoplasts (Uraguchi & Fujiwara, 2012; Clemens, 2006). Similarly, translocation will depend on the rate of absorption and mobility within the root and different barriers such as the endodermis, loading in the xylem, and mobility into the xylem (Eludoyin et al., 2017; Liu et al., 2020). However, studies with longer exposure times should continue to show the behavior of these crops in contaminated soils.

It was evidenced in our study that the application of organic amendments to the soil plays an important role in the immobilization of the metal in the soil, as it favors the increase of the pH in the soil and the formation of stable complexes with the toxic metals present that achieve a decrease in plant uptake (Porter et al., 2004; Li et al., 2008; Mahmood, 2010). The interaction of toxic metals in the soil with the functional groups of organic matter (carboxyl, hydroxyl and phenoxyl) prevents metals from reaching the plant (Mohamed et al., 2010). It was shown that increased application of organic matter in the soil can effectively reduce the absorption of Cd, making papaya plants more effective in tolerating the metal and thus reducing its translocation to the aerial part (Shahid et al., 2012).

Previous studies have observed that papaya plants have reached TF > 1 value for metals such as Cd, Pb and Zn, indicating that they have bioaccumulation capacity (Akintan et al., 2019). It has also been reported that papaya plant has been considered as an indicator of heavy metal contamination based on tree bark samples (Chukwuka & Uka, 2013), where it has been found that they can absorb elements such as Cd, Pb, Cu, Ni and Zn with the ability to translocate to aerial organs (Assayomo et al., 2021; Eludoyin & Gafar, 2020). Meng et al. (2019) have reported that papaya fruit can accumulate heavy metal concentrations above the maximum permissible limits set by WHO with a potential health risk.

5. Conclusions

The addition of organic matter at 10%-OM allowed greater growth of papaya plants by reducing the availability of metal uptake compared to plants with a lower organic matter content at 2%-OM. Root capacity achieved a restriction of metal transport to the aerial part of the plant, giving a better response in the soil at 10%-OM, however, at 2%-OM, a reduction in the restriction of metal transport was evidenced, achieving an increase in metal accumulation. The results of this work can serve as a basis to broaden the knowledge of the response of papaya plants exposed to cadmium-contaminated soils, and strategies can be established for frequent application of organic amendments to reduce the availability of the metal and thus, the plant can have a better capacity to restrict the absorption and translocation of cadmium.

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