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Phytoabsorption of heavy metals from leachates using the species *Cyperus laxus* and *Chrysopogon zizanioides*

Fitoabsorción de metales pesados provenientes de lixiviados empleando las especies *Cyperus laxus* y *Chrysopogon zizanioides*

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Abstract

This study aimed to evaluate and compare the phytoremediation potential of *Cyperus laxus* and *Chrysopogon zizanioides*, exposed to a mixture of leachates containing heavy metals. *C. laxus* is a native species from Mexico and *C. zizanioides* is an introduced species. Exposure to the leachate was performed using concentration kinetics concerning exposure times (TE) (Control 1, Control 40, 1,7, 15, 30, and 40 days). For this purpose, a completely randomized two-factor design with a 2x7 arrangement in triplicate was performed. The data were analyzed by ANOVA followed by an LSD multiple range test. For the quantification of metals in leachate and plants, inductively coupled plasma atomic emission spectroscopy (ICP-OES) was used. Ten chemical elements (Al, As, Ba, Cr, Hg, Ni, Pb, Se, Tl, and Zn) were identified in leachate and plants. It was observed that *C. laxus* absorbed mostly Al, Ba, Cr, Cr, Hg, and Ni, while *C. zizanioides* absorbed As, Pb, Se, Tl, and Zn. In translocation factor (TF) calculations *C. laxus* translocated only As, whereas *C. zizanioides* translocated As>Tl>Ba>Cr>Ni, respectively.

Keywords: phytoremediation, native plant, introduced plant, translocation factor, sanitary landfill.

Resumen

El objetivo de este estudio fue evaluar y comparar el potencial fitorremediador de *Cyperus laxus* y *Chrysopogon zizanioides*, expuestas a una mezcla de lixiviados con metales pesados. *C. laxus* es una especie nativa de México y *C. zizanioides* es una planta introducida. La exposición al lixiviado se realizó por medio de una cinética de concentración con respecto a tiempos de exposición (TE) (Control 1, Control 40, 1 ,7, 15, 30 y 40 días). Para ello se realizó un diseño completamente aleatorizado de dos factores con un arreglo de 2x7 por triplicado. Los datos fueron analizados mediante un ANOVA seguido de una prueba de contraste múltiple de rangos LSD. Para la cuantificación de metales en lixiviado y plantas, se empleó la técnica espectroscopía de emisión atómica de plasma acoplado inductivamente (ICP-OES). Se identificaron 10 elementos químicos (Al, As, Ba, Cr, Hg, Ni, Pb, Se, Tl y Zn) en lixiviado y plantas. Se observó que *C. laxus* absorbió más de Al, Ba, Cr, Hg y Ni, mientras que *C. zizanioides* absorbió más de As, Pb, Se, Tl y Zn. En los cálculos del factor de translocación (TF) *C. laxus* translocó solo el As, mientras que *C. zizanioides* translocó el As>Tl>Ba>Cr>Ni, respectivamente.

Palabras clave: fitorremediación, planta nativa, planta introducida, Factor de translocación, relleno sanitario.

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1 Introduction

The generation and management of solid waste require the commitment of society to minimize the adverse effects on the environment and health, mainly those that are disposed in landfills (Valderrama *et al*., 2018). In order to contain the generation of waste, a variety of methods have been proposed for its final disposal. For example, until a few years ago, solid urban waste was deposited in open-air dumps that caused water, soil, and air pollution. To reduce environmental impact, these sites became what we now know as landfills (Vallero and Blight, 2019). It should be noted that in the first landfills, liquid emissions (leachates) were not controlled and these drained to surface water sources or infiltrated the lower soil layers and in many cases contaminated aquifers (Méndez *et al*., 2004). Due to the toxicity of its components, some studies have considered leachates as the major pollutant of a landfill (Méndez *et al*., 2002).

Because of the complexity of leachates, various studies have been carried out comparing different remediation technologies; in which bioremediation is contemplated (Giraldo, 2001). There are different bioremediation technologies capable of reducing the concentration of various compounds through biochemical *in situ* or *ex situ* processes carried out by plants and microorganisms associated with them; one of these is phytoremediation (Delgadillo *et al*., 2011). This technique has positioned itself as an economic alternative due to its low cost, since it takes advantage of biological processes and plant mechanisms to remove, degrade, metabolize, or volatilize different pollutants such as metals (macronutrients, trace metals, and radioactive isotopes), petroleum hydrocarbons, HPA, PCBs, industrial solvents, pesticides, VOCs, BTEX, explosives among others (Dickinson, 2017; Wei *et al*., 2021). Petenello and Feldman (2012) suggest using native plants for the phytoremediation of a contaminated site, because they are easily adapted to the particular environmental conditions of the region.

Cyperus laxus is a native plant from the southeastern region of Mexico and other South American countries such as Venezuela and Peru. Its common name is “Pelo de Chino", but in some states of the country like Veracruz, it is known as “Zacate Chontul" (López, 2013). It taxonomically belongs to the Tracheophytes division of the class Angiospermae and sub-classes Monocotyledonous, it is in the Family Cyperaceae, and belongs to the genus: *Cyperus*, species: *Cyperus laxus* lamouroux (López *et al*., 2008).

Chrysopogon zizanioides (L) Roberty, also known as vetiver, is an introduced plant in Mexico, native to the Indian subcontinent. It can be found in floodplains and riverbanks, also in tropical and subtropical regions of Africa, Asia, America, Australia, and Southern Europe (Maffei, 2002). It belongs to the family Poaceae, subfamily; Panicoideae, tribe: Andropogonae, and subtribe: Sorghina, and the genus includes ten species (Bertea and Camusso, 2002).

To date, studies and assessments related to *C. laxus* remain scarce, but there are other successful cases in which the *Cyperus* genus has been used (Escalante *et al*., 2005; López *et al*., 2008).

On the other hand, *C. zizanioides* has morphological and physiological characteristics that make it suitable to be used in the field of environmental protection (Roongtanakiat *et al*., 2007). It has also been widely studied since the twentieth century and nowadays it is internationally recognized for soil conservation (Veldkamp, 1999), erosion control (Dalton *et al*., 1996), tolerance to extreme conditions in soil and heavy metals (Roongtanakiat and Chairoj, 2001), absorption of heavy metals in soil (Wong, 2003), and the capacity to phytoremediate hydrocarbon contaminated soils (Brand *et al*., 2006), leachates (Roongtanakiat *et al*., 2007) and sewage sludge (Torres, 2010). As well for biological nutrient removal from wastewater (Wang *et al*., 2009), landfill rehabilitation and restoration (Ghosh *et al*., 2015), use in artificial wetlands (Ramirez, 2018), and hydroponic phytoremediation (Davamani, 2021). As it is an introduced species, some projects consider the use of native species with phytoremediation potential in the region, where *C. laxus* figures out as a pollutant removal agent.

For those reasons, this research aimed to identify and evaluate the efficiency of heavy metals removal from the leachates of a municipal solid waste (MSW) landfill using the native plant *C. laxus* and the introduced plant *C. zizanioides*.

2 Materials and methods

2.1 Sampling of plants, soil, and leachate

The plants were obtained from a nursery garden within the landfill facilities. It is located on a hillside far away from any contamination, and the site must be controlled under its regulations. The landfill is located at the Villahermosa - Teapa highway Km. 25 in Villahermosa, Tabasco, Mexico, with coordinates 17°48’32.20 "N, 92°59’33.23 "W. Both plant species were randomly collected. Twenty-one complete modules were extracted from mother plants of each species.

On the other hand, 15 L of leachate from the artificial leachate lagoon near the MSW cell was sampled based on NMX-AA-003-1980 (SECOFI, 1980) in high-density polyethylene (HDPE) containers and preserved at 4 ºC for the determination of heavy metals. The soil was obtained from the landfill nursery based on standard method (NMX-AA-132-SCFI-2006, SECOFI, 2006) from 0 - 30 cm depth and placed in black polyethylene bags. A preliminary study was conducted to identify that the soil was free of pollutants.

All samples were transported to the Soil Science Laboratory of the Academic Division of Biological Sciences

(DACBiol) for pretreatment where the plants were carefully washed to remove any adhering soil and then acclimatized. The soil was dried in an oven at 100 °C, grounded, and sieved with a 2 mm mesh (#10). On the other hand, the leachate was filtered through Whatman #40 paper to remove particles that could interfere with the analyses for characterization.

2.2 *Experimental design*

The design consists of the elaboration of a metal concentration vs time kinetic to determine the metals taken up by the plants *C. laxus* and *C. zizanioides*. For that purpose, seven exposure times were established: 1, 7, 15, 30, and 40 days, besides the control samples on day 1 and day 40, for each species in triplicate for a total of 42 experimental units.

One kilogram of soil was placed in each pot. One plant module per pot was incorporated to obtain statistical independence between plants. The plants were previously washed, planted on the homogenized soil, and acclimatized for one month. At the end of this process, the plants were prepared to be exposed to the leachate, for which a fixed volume of 250 mL of crude leachate (100 % concentration) was added per pot to prevent other variables from affecting the results. In the case of the controls, they were irrigated with drinking water every 3 days.

2.3 *Sample pretreatment*

After the exposure time established for each pot, the plants were harvested completely and washed thoroughly with potable water, taking care not to leave soil adhered to the roots and leaves. They were dried in the shadow at room temperature. Once dried, the plants were separated into two parts (leaf and root) and ground to powder.

2.4 *Acid digestion of plants, soil, and leachate*

For each solid sample of root and lead for both species, 0.25 g was weighed and a volume of 10 mL of the leachate (liquid sample) was extracted. The samples were placed in 50 mL Teflon tubes. To the solid samples, 10 mL of concentrated HNO_3 (Nitric Acid) and 2 mL of H_2O_2 (Hydrogen Peroxide) were added and for the liquid sample, 5 mL of HNO_3 were poured. Subsequently, the samples were placed in a microwave oven for 15 minutes and when finished, they were allowed to cool at room temperature. Finally, they were gauged to 50 mL with deionized water and filtered with Whatman #40 paper due to the sample turbidity (Ramos *et al*., 2019).

2.5 *Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)*

After the acid digestion treatment, the metal content in the leaves and roots was analyzed using an inductively coupled plasma optical emission spectroscope (ICP-OES), IRIS Advantage from Thermo Jarrel Ash Corporation, by using a calibration curve with a Sigma-Aldrich 51844 standard solution.

2.6 *Determination of the translocation factor*

The Translocation Factor (TF) allows to know the efficiency of a plant to mobilize an element accumulated in the roots to the aerial part of the plant (stem, leaves, flowers, seeds, or fruits), this factor is calculated through the following expression Eq. (1) (Ramos *et al*., 2019).

$$\text{Translocation factor (TF)} = \frac{\text{Metal concentration} \in \text{the aerial part}}{\text{Metal concentration} \in \text{roots}} \tag{1}$$

2.7 *Statistic analysis*

A completely randomized two-factor design with a 2×7 arrangement was used. Factor A was the two plant species consisting of two levels: *C. laxus* and *C. zizanioides*. Factor B was the exposure time to the leachate with 7 levels: Control Day 1, Control Day 40, Day 1, Day 7, Day 15, Day 30, and Day 40. To determine the effects of the species and the different times, a multifactorial analysis of variance (ANOVA) followed by an LSD rank test was performed using the statistical package Stat graphics Centurion© XVI. Metal characterization in the leachate was performed in triplicate. A significance level of 0.05 ($\alpha = 0.05$) was used for all cases.

3 Results

3.1 *Metal concentration in leachate*

Table 1 shows the concentrations of the 10 chemical elements identified in the leachate: Al, As, Ba, Cr, Hg, Ni, Pb, Se, Tl, and Zn. The concentrations obtained were contrasted with the ranges reported by El-Fadel *et al*. (1997), who made a compendium of other studies where they report the normal concentration ranges for each metal in landfills and with the values reported by Gajski *et al*. (2012) who evaluated leachate samples for metal concentrations.

The elements Al, As, Ba, Cr, Hg, Ni, Pb, Se y Zn were found within the ranges presented by El-Fadel *et al*. (1997) except Tl which exceeded the range 0-0.32 mg kg^{-1} with a value of 25.42±0.04 mg kg^{-1}.

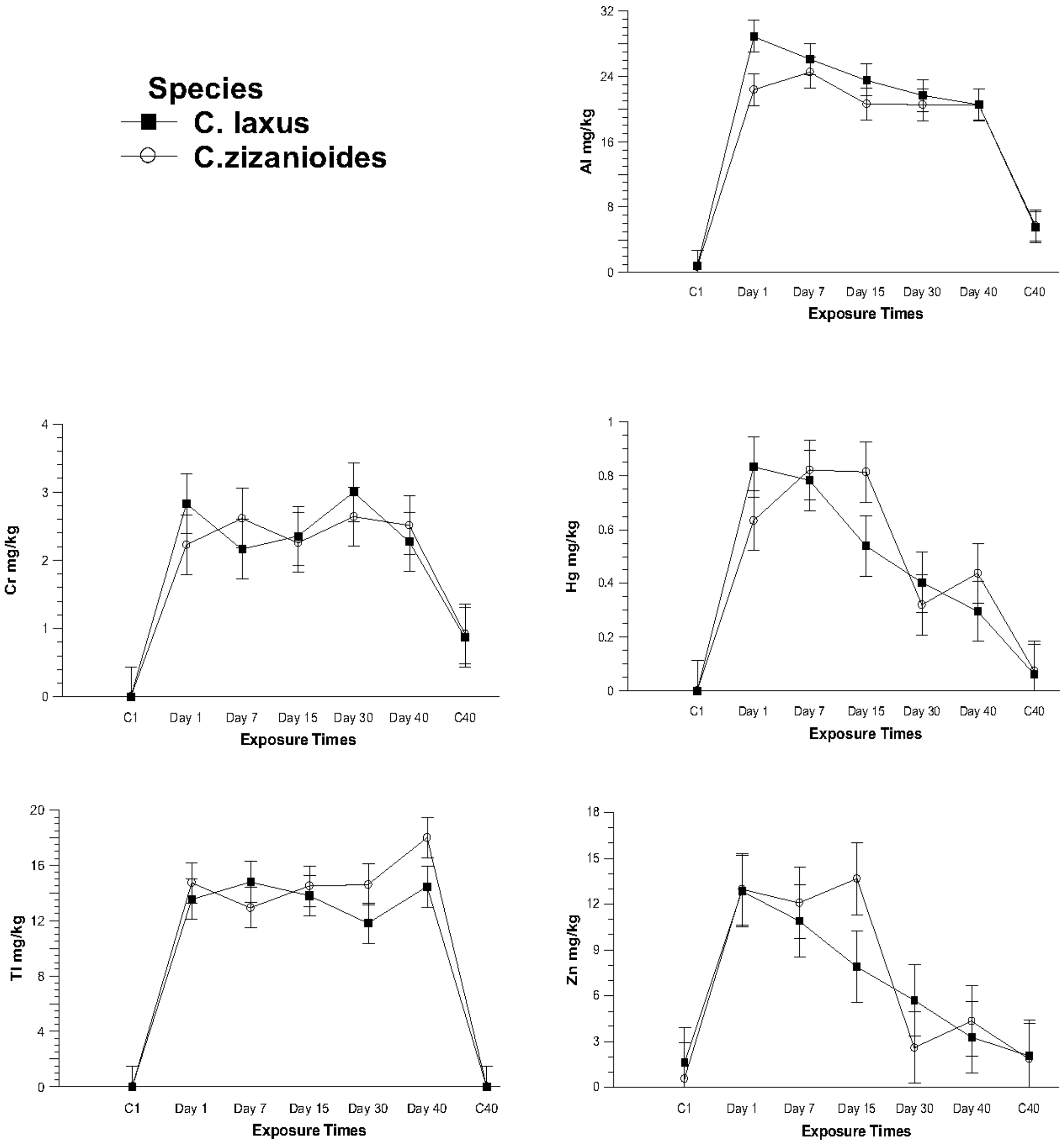

Figure 1. kinetics of the phytoabsortion of Al, Cr, Hg, Tl and Zn of both species (whole plant). Values are represented by the mean (± LSD). C1 = control day 1 and C40 = control day 40.

On the other hand, the values reported by Gajski *et al.* (2012) observed that As, Cr, Hg, Ni, Pb, Se, and Zn, exceed the values by far. There was no comparison point for Al, Ba, and Tl elements.

3.2 Metal concentration in plants

Figures 1 and 2 show the kinetics of the concentration of each metal obtained for both species. This phytoremediation mechanism has been reported as phytoabsorption or phytoextraction and is generally characterized as being effective in heavy metal removal (Peralta and Volke 2020). In this case, the entire plant will be lost, and the concentrations obtained in roots and leaves will be unified. Each rate has two controls: day one control (C1) and day 40 control (C40). Furthermore, according to the absorption trends, phytoabsorptions were divided into two groups.

Figure 1 is constituted by the phytoabsorption of Al, Cr, Hg, Tl, and Zn. This group is characterized because both species showed high phytoabsorption since the first day, proving to be higher than the concentrations obtained in the samples of the initial controls.

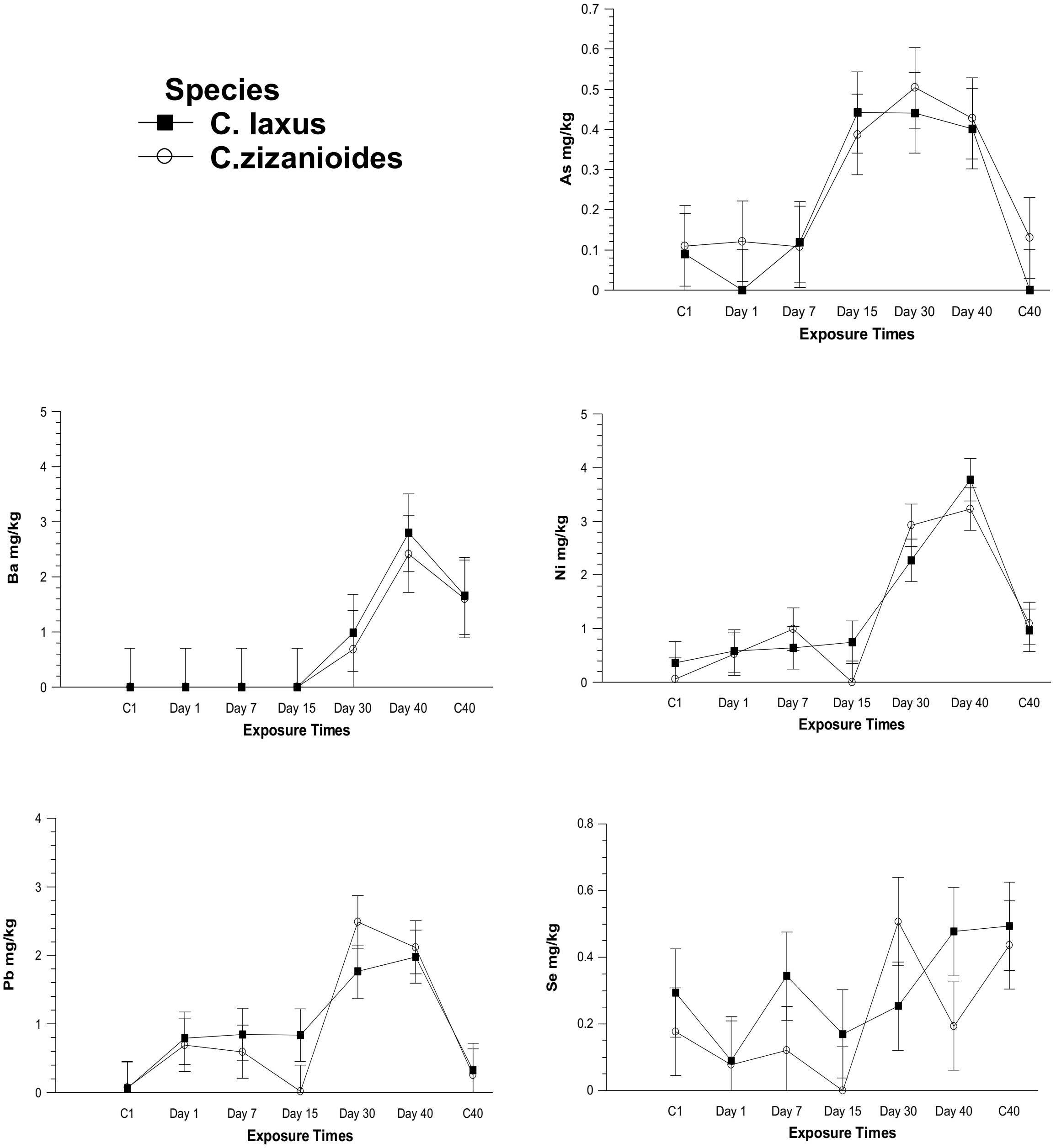

Figure 2. kinetics of the phytoextraction of As, Ba, Ni, Pb and Se of both species (whole plant). Values are represented by the mean (± LSD). C1 = control day 1 and C40 = control day 40.

Their phytoabsorption trends after day one decreased until day 40, but these concentrations were still higher than those of the final controls.

Figure 2 is formed by the phytoabsorption of As, Ba, Ni and Pb, and Se. This group is characterized because both species presented low phytoabsorptions on the first day, but the phytoabsorption tendency gradually increased with the passing of the days.

3.3 Translocation factor

Figures 3 and 4 show the TF values for both species. These values are based on the maximum phytoabsorptions obtained in the kinetics for each metal and are represented by the mean ± Standard Deviation. Ramos *et al.*, (2019) mention that plants with a TF> 1 % are considered as accumulators or hyperaccumulators, so they can accumulate large amounts

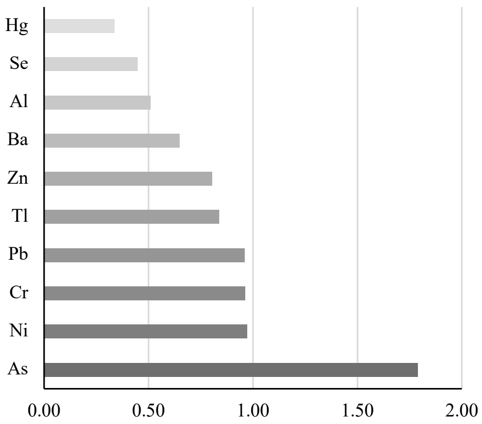

Figure 3. Translocation factor of *C. laxus*. n=3.

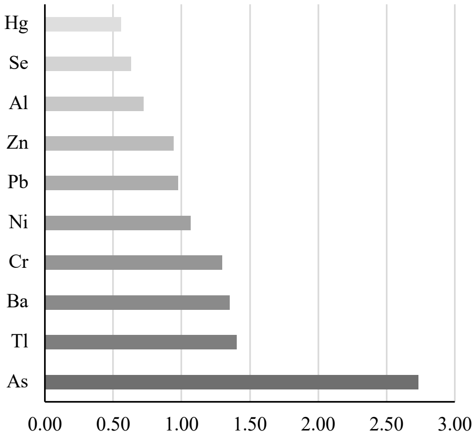

Figure 4. Translocation factor of *C. zizanioides*. n=3.

Table 1. Concentration of metals in leachate from the landfill compared to the ranges of El-Fadel *et al*. (1997) and concentrations from Gajski *et al*. (2012).

Metals	Concentrations obtained*	Concentration ranges El-Fadel *et al*. (1997)	Gajski *et al*. (2012)
Al	31.15±1.22	0.5-85	-
As	0.96±0.06	0-70.2	0.043
Ba	3.01±0.08	0-12.5	-
Cr	3.23±0.28	0-22.5	0.040
Hg	1.12±0.12	0-3	0.029
Ni	4.25±0.32	0-7.5	0.125
Pb	2.86±0.01	0-14.2	0.025
Se	0.44±0.01	0-1.85	0.01
Tl	25.42±0.04	0-0.32	-
Zn	18.00±0.01	0-1000	0.334

*The values are represented by mean ± standard deviation. n=3. All values are expressed in mg kg^{-1}.

of metals. Those with values between 0.1 and 1 % are considered as tolerant and those with values <0.1 % are considered exclusion plants.

4 Discussion

4.1 *Metal concentration in leachate*

In Table 1, the presence of heavy metals in the samples analyzed, which may be related to the fact that in open dumps and landfills, there are mixtures of various wastes, mainly used oils, batteries, and electronic devices, as well as glass, various metals, pesticides, fertilizers, and paints. It has been reported that these residues are altered by direct contact with liquids that come from various sources (rainfall, groundwater table, floods, among others), generating runoff through them (known as percolation), this set of liquids it is known as leachate. This mixture of liquids is generally a function of the components in the site since these are made up of a wide range of organic and inorganic polluting compounds (Kjeldsen *et al*., 2002; Wiszniowski *et al*., 2006; Aziz *et al*., 2010; San *et al*., 2021). Table 2 presents the main sources of the heavy metals identified.

One of the greatest risks posed by the heavy metals present in the leachate is migration out of the landfill, either due to a leak or a failure of the sanitary landfill lining (Hussein *et al*., 2020). For this reason, this implies a serious threat to public health and aquatic and terrestrial ecosystems, since heavy metals are very challenging to remedy due to their persistence, non-biodegradability, toxicity, and bioaccumulation (Alloway, 2012). Also, these results, are according to the ones reported by Cameron (1992), except for Al and Ba, As, Cr, Hg, Ni, Pb, Se, Tl and Zn, which are included in the list of priority organic pollutants. Additonally, there are some elements that present the greatest risk to humans and ecosystems like: Pb, Hg, Ni, and Zn. Those elements can be found, due to the frequency of use in different domestic, agroindustrial, and industrial activities (Cameron, 1992).

However, other reports mention that certain metals do not represent risks at certain concentrations depending on the matrix where they are found (rivers, sea, estuaries, etc.).

Tabla 2. Main sources of heavy metals identified in the leachate.

Metal	Sources	References
Al	Cans, doors, linnings, car body parts, food packaging, candy, cigarrette wrappers, dross, salt cake, black dross, White dross.	Calder and Stark (2010)
As	Enamels, pigments, alloys, ceramics, lubricant oils, Wood preservatives, Fireworks, glass, printing, tanning process, semiconductors, photoconductors.	Cameron (1992)
Ba	Paints, bricks, tiles, glass, rubber, making ceramics, insect and rat poisons, oil and fuel additives, paper making and sugar refining, refining vegtables and animal oils.	ATSDR (2007)
Cr	Steel and other metal alloys, Chrome plating, electroplating, varnishes, dye fixatives, corrosion inhibitors, photographic emulsions, production of other chromium derivates.	Cameron (1992)
Hg	Batteries, paints, plastics, fungicides, pharmaceutical products, paper production, electrical appliance manufacturing, catalytic process products.	Cameron (1992)
Ni	Batteries, paints, cosmetics, pigments, electroplating solutions, lacquers, cellulose derivatives, steels and alloys, spark plugs, gasoline.	Cameron (1992)
Pb	Lead-acid batteries and electronic devices, lead-based solder which is used for attaching components to printed circuit boards, and cathode ray tubes (leaded glass for X-ray protection) in monitors or television production.	Jang and Townsend (2003)
Se	Paints, pigments, and electrical industry products, bleaching and manufacture of colored glass, production of calcium sulfide selenium pigments.	Cameron (1992)
Tl	Iron, cadmium, and zinc refining by-products, use in metal alloys, costume jewelry, optical lenses, artistic pigments, semiconductor ceramics, X-ray detection devices, and green fireworks.	Gad and Pham (2014)
Zn	Galvanization of iron and steel and brass manufacturing. Galvanized objects such as wire, nails, and plates, among others, are used in several activities such as automotive, construction, office equipment, and kitchen utensils.	Rubio *et al*. (2007)

For example, Al is stable in the environment without interacting with biological processes, its concentration in the soil varies between 10,000 and 300,000 ppm depending on the pH of the soil, but in acidic soils pH <5, it is transformed into its toxic form Al^{+3} (Gupta *et al*., 2013). In the case of As, the concentrations in soil are between 1 and 60 ppm and in water for human consumption, values of 50 μg/L have been reported (Cameron, 1992; Irgolic, 1992). Normal Ba concentrations reported for soil are between 15 and 3,500 ppm, while values of <5 to 15,000 μg/L have been reported in water (ATSDR, 2007).

Likewise, for Cr concentrations of 80 - 200 μg/g have been reported in soil, while in water the concentrations are less than 1 ng/ml (Miller, 1992). In the case of Hg, concentrations of 0.1 to 0.3 ppm have been reported in soil, while in water the values are between 0.04 and 500 ng/Kg (Cameron, 1992; Drabæk and Iverfeldt, 1992). For Ni, the concentrations in soil are between 3 to 300 ppm, in the case of water their values are <60 ppm. For Pb, the concentrations in soil can contain up to 10 ppm of total lead (Cameron, 1992).

On the other hand, the concentrations of Se in soil are between 0.079 - 78 ppm, while in water they are between 0.000016 to 0.041 ppm (Ihnat, 1992). Tl is ubiquitous in the environment, but in very low concentrations, its average abundance in the crust is 0.8 ppm (Voegelin, 2015), on the other hand, the Cameron, 1992 mentions that the Tl concentration ranges in German soils are from 0.17 to 0.53 ppm. Finally, Zn concentrations in soils are from 100 to 300 ppm and in bodies of water from 0.6 to 5 ppb (Cameron, 1992; Jones *et al*., 2014).

4.2 Metal concentration in plants

The identified metals could be divided into two categories according to their role in plants: essential metals (nutrients required by the plant for its development): Al, As, Cr, Ni, Se, and Zn (Prieto *et al*., 2009; Marin *et al*., 2010; Toneatti and Rivera 2006) and non-essential metals (nutrients that do not have a biological function): Ba, Hg, Pb, and Tl (Prieto *et al*., 2009; Lamb *et al*., 2013).

Overall, the ANOVA test reports that there is no effect on the interactions of the kinetics of all metals (Figures 1 and 2) ($p>0.05$). This indicates that the phytoabsorption for each kinetics was not different in both species type and phytoabsorption times, therefore, both species can phytoabsorb metals equally. Table 3 shows the statistically significant differences between species for each metal. Particularly in the mean of Al, there is a significant effect between species ($p<0.05$), where *C. laxus* with a value of 18.15 ± 10.49b was able to phytoabsorb more Al than *C. zizanioides* with a value of 16.42 ± 8.89a. There are no significant differences between species for the rest of the metals ($p>0.05$).

Table 3. Metal concentration means for each species.

Species	Metals									
	Al	As	Ba	Cr	Hg	Ni	Pb	Se	Tl	Zn
C. laxus	18.15 ± 10.49^b	0.21±0.21^a	0.77 ± 1.33^a	1.92 ± 1.17^a	0.41 ± 0.33^a	1.33 ± 1.26^a	0.94 ± 0.81^a	0.30 ± 0.22^a	9.77 ± 6.51^a	6.33 ± 4.96^a
C. zizanioides	16.42 ± 8.89^a	0.25±0.20^a	0.67±1.08^a	1.88 ± 0.99^a	0.44 ± 0.32^a	1.26 ± 1.29^a	0.89 ± 0.98^a	0.21 ± 0.19^a	10.68 ± 7.26^a	6.87 ± 5.81^a

The values are represented by the mean ± standard deviation (SD) and in mg kg^{-1}. n=21.Numbers with different letters in the same column indicate a significant difference $p<0.05$ according to the ANOVA test.

The kinetics in Figure 1 indicate that the metals are being absorbed as they get in contact with the leachate since they are bioavailable for the plant. However, it is also quite likely that the plant might have passed the non-essential metals as essential metals. For this reason, the plant absorbs them quickly as they are required for growth.

In the kinetics of Al, the species *C. laxus* and *C. zizanioides* presented their maximum phytoabsorptions on days 1 and 7 with concentrations reaching 28.9 mg kg^{-1} and 24.5 mg kg^{-1} respectively. Schachtschneider *et al.* (2017) and Banerjee (2016), reported concentrations values of Al in *Cyperus marginatus* and *C. zizanioides* at 2097 mg kg^{-1} and 214.02 mg kg^{-1} respectively. According to the authors, these values do not mean that *C. laxus* absorbs less amount of the metal, but the concentrations may vary due to the variables of each study. Schachtschneider *et al.* (2017) reported that *C. marginatus* was used together with other plant species to enhance higher water quality in a river as riparian vegetation, whereas Banerjee (2016) used *C. zizanioides ex situ* as an alternative method for an iron mine rehabilitation. Some authors have reported that Al is not essential for most plants, despite its ubiquity and its presence during the life cycle of plants (Poschenrieder *et al.*, 2008). Under acidic conditions with pH values below 4.3, Al^{+3} is the most abundant and toxic form for plants (Nogueirol *et al.*, 2015). Frech and Cedergren (1992) mentioned that normal Al rates range from 0.9-1000 mg kg^{-1} in different types of plants.

The kinetics of Cr in the species *C. laxus* and *C. zizanioides* were both obtained at day 30, with maximum phytoabsorptions of 2.99 mg kg^{-1} and 2.639 mg kg^{-1}, respectively. De Moya (2016) and Banerjee (2016) reported Cr values in *Cyperus odoratus* and *C. zizanioides* of 36.8 mg kg^{-1} and 13.22 mg kg^{-1}, respectively. De Moya (2016) employed *C. odoratus* to evaluate Cr and Zn accumulation in the species. Cr is a non-essential metal for most plants but might be essential for some of them. Cameron (1992) mentions normal ranges of Cr in plants at 0.1-0.5 mg kg^{-1} and toxic ranges of 5-30 mg kg^{-1}.

In the Hg kinetics, the species *C. laxus* and *C. zizanioides* presented maximum phytoabsorptions on days 1 and 7, with values of 0.83 mg kg^{-1} and 0.82 mg kg^{-1}, respectively. Perez *et al.* (2016) and Troung *et al.* (2010), reported Hg levels in *C. laxus* and *C. zizanioides* of 5.47 mg kg^{-1} and 0.41 mg kg^{-1}, respectively. The study by Perez *et al.* (2016) was focused on the isolation and identification of Hg-resistant bacteria in symbiosis with *C. laxus* to remediate soils from a mine in Colombia, in contrast, Troung *et al.* (2010) showed the uptake of Hg from a heavy metal-contaminated soil. Hg is a non-essential metal for the plant that is toxic at low concentrations. Drabæk and Iverfeldt (1992) reported that normal ranges of Hg in plants lie between 0.1 and 9.5 mg kg^{-1} and 18.02 mg kg^{-1} for *C. zizanioides*.

Talium is the most important metal, with the higher toxicity and concentration in leachate showing the kinetics of maximum phytoabsorptions at days 7 and 40 reaching values of 14.8 mg kg^{-1} for *C. laxus* and 18.02 mg kg^{-1} for *C. zizanioides*. Alvarez *et al.* (2013) and De la Cruz *et al.* (2018), reported Tl concentrations of 0.26 mg kg^{-1} and 5.55 mg kg^{-1} respectively in *Cyperus longus* and *C. zizanioides*. The study by Alvarez *et al.* (2013) evaluated the environmental impact caused by the meteorization of mining waste containing sphalerite. In addition, De la Cruz *et al.* (2018) evaluated the phytoremediation potential of leachate for heavy metals. The elevated accumulation of this metal in plants seems to be a function of its concentration in the soil mobile fraction. The process of Tl assimilation by plants is relatively easy as it is generally present as an analog of K. Its transfer from the soil to the plants depends on the properties of each plant species, as well as the soil properties such as texture and humic content, cation exchange capacity, pH, and other properties (Madejón, 2012). Tl is a nonessential metal, and it is highly toxic to plants, as well as for animals and humans. Normal Tl levels in plants range from 0.008 - 0.126 mg kg^{-1} (Cameron, 1992).

Phytoabsorption of Zn, obtained peaks on days 1 and 15, reaching concentrations of 12.86 mg kg^{-1} and 13.65 mg kg^{-1}, in *C. laxus* and *C. zizanioides*, respectively. Alvarez *et al.* (2013) and Truong *et al.* (2010), reported Zn contents of 591 mg kg^{-1} and 975 mg kg^{-1}, in C. longus and *C. zizanioides*, respectively. Zn is an essential element for the plant and in elevated concentrations, it might be detrimental. According to Cameron (1992), Zn normal ranges in plants are 27-150 mg kg^{-1}.

The kinetics in Figure 2 indicate that these metals were poorly bioavailable for the plants on the first days, mainly influenced by factors such as temperature, pH, growth conditions, and even the leachate nature.

The As kinetics of the species *C. laxus* and *C. zizanioides* exhibited maximum phytoabsorption on days 15 and 30, with As concentrations of 0.44 mg kg^{-1} and 0.50 mg kg^{-1}, respectively. Raab *et al.* (2007) and Troung *et al.* (2010) reported As concentrations of 8.6 mg kg^{-1} and 130.5 mg kg^{-1} in *Cyperus papyrus* and *C. zizanioides*, respectively. The Raab *et al.* (2007) study consisted of the selection of a variety of similar species, to find out the behavior of metal uptake in those species. As a result of the low availability of As, its concentration in plants is low and fluctuating. Huang *et al*. (2006) mentioned that the normal As content in plants can vary from less than 0.01 to 5 μg g^{-1}, while the Cameron (1992) mentions that normal ranges are <0.5 mg kg^{-1} and that the toxic ranges are within 5-20 mg kg^{-1}.

The kinetics of Ba in *C. laxus* and *C. zizanioides* obtained maximum phytoabsorptions of 2.8 mg kg^{-1} and 2.41 mg kg^{-1} respectively, both recorded at day 40. In this case, Li *et al*. (2011) and Ramos *et al*. (2019) obtained Ba concentrations of 159.3 mg kg^{-1} and 76 mg kg^{-1} in *Cyperus iria* and *C. zizanioides*, respectively. Li *et al*. (2011) used *C. iria* to evaluate whether it had the potential for remediating soils contaminated with uranium waste from a factory in southern China. Conversely, Ramos *et al*. (2019) focused on the identification of metals in a heterogeneous leachate mixture. Ba is non-essential metal for the plant and only a few research on its toxic effect is available. Chaudhry *et al*. (1977) reported normal non-toxic concentrations of 4-50 mg kg^{-1} in plants.

The Ni kinetics for the species *C. laxus* and *C. zizanioides* showed phytoabsorptions of 3.77 mg kg^{-1} and 3.22 mg kg^{-1} respectively, both obtained at day 40. Li *et al*. (2011) and Melato *et al*. (2016) reported Ni concentrations of 28.05 mg kg^{-1} and 126 mg kg^{-1} respectively for *C. iria* and *C. zizanioides* species. The study by Melato *et al*. (2016) consisted of researching *C. zizanioides* po-tential for the rehabilitation of the tailings of a gold mine in South Africa. Ni is an essential mineral for some plants but is highly toxic. According to Cameron (1992), the normal ranges are from 0.1 to 5 mg kg^{-1}, and toxic ranges in plants are from 10-100 mg kg^{-1}.

Pb kinetics, presented maximum concentrations for *C. laxus* and C. zizaniodes to be 1.98 mg kg^{-1} and 2.48 mg kg^{-1}, at days 40 and 30, respectively. Li *et al*. (2011) and Banerjee (2016) reported values of 89.5 mg kg^{-1} in *C. iria* and 2.53 mg kg^{-1} for *C. zizanioides*. Lead is a non-essential toxic metal. Reeves and Baker (2000) stated that normal ranges of Pb are between 0.1-5 mg kg^{-1}.

Finally, the Se kinetics of *C. laxus* and *C. zizanioides* species were obtained at days 40 and 30 with values of 0.47 mg kg^{-1} and 0.50 mg kg^{-1}, respectively. Although studies to compare Se accumulation in Cyperus sp are scarce, authors such as Brieger *et al*. (1992) and Cherry and Guthrie (1979) reported concentrations of 1.9 mg kg^{-1} and 3.5 mg kg^{-1}, in *Cyperus odoratus* and *Cyperus retrofractus* species, respectively. For *C. zizanioides* Ramos *et al*. (2019) obtained a concentration of 0.80 mg kg^{-1}. The study by Brieger *et al.* (1992) focussed on the identification of plants to analyze the concentration of metals, while Cherry and Guthrie (1979) investigated the bioaccumulation of metals from a drainage. It is an essential metal, and it is toxic for plants at high concentrations. According to Cameron (1992) normal Se ranges from 0.01-2 mg kg^{-1} and toxic levels range from 5-30 mg kg^{-1}.

4.3 Translocation factor

In Figure 3 *C. laxus* translocated only As to its aerial part, with a TF value of 1.79±0.21 %, this value of TF> 1 % indicates that the specie is a hyperaccumulator of this metal; on the other hand, it could be observed that *C. laxus* obtained TFs near 1 % being Ni, Cr and Pb, having values of 0.97±0.03 %, 0.96±0.39 % and 0.96±0.50 %, respectively, which demonstrates that the specie is tolerant to these metals.

Moreover, in Figure 4 the species *C. zizanioides* translocated to its aerial part five metals that were As>Tl>Ba>Cr>Ni at values of 2.73±3.93 %, 1.40±0.16 %, 1.35±2.09 %. 1.30±0.76 % and 1.06±0.19 %, respectively. It also obtained TF close to 1%, being Pb and Zn with values of 0.98±0.11 % and 0.94±0.71 %, respectively, indicating that the plant showed tolerance to these metals.

The results reveal that both species were not excluders of any metal since the translocation factors were greater than 0.1 % according to Ramos *et al*. (2019). The species *C. laxus* despite not being as pioneer as *C. zizanioides*, possesses the ability to compete in the translocation of heavy metals of great importance. Due to the limited number of studies, it was not possible to establish a comparison point in the translocation factors for both species, so this work would be one of the first to provide comparison results for future research.

Conclusions

This study demonstrated the high potential for the removal of heavy metals that the native species *C. laxus* possesses and that it also can compete with the species *C. zizanioides*, known for being a pioneer in phytoremediation. For these reasons, phytoremediation as an alternative to metal removal using native plants may be key to mitigating environmental problems related to leachate management in landfills. On the other hand, TF studies of the *C. laxus* species are very scarce, so the data reported in this study are one of the first contributions. The data obtained from TF showed that it can be considered a hyperaccumulator species, since it obtained TF values greater than one, indicating that it could accumulate large amounts of heavy metals in the aerial parts. Finally, this study confirms that the use of native plants is ideal to avoid the introduction of species that may be invasive to the region.

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