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ORIGINAL ARTICLE

Effect of plant growth on Pb and Zn geoaccumulation in 300-year-old mine tailings of Zacatecas, México

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Abstract
Concentrations of Pb and Zn, plant uptake of these metals, the influence of the plants' growth on the physicochemical properties and metal concentrations in the tailings of an abandoned 300-year-old mine tailing dam in Zacatecas, Mexico were investigated. Tailings were found to be heavily contaminated, with average levels of 2621 ± 53 and 3827 ± 83 mg/kg for Pb and Zn, respectively (maximum concentrations of 8466 ± 116 and 12,475 ± 324 mg/kg, respectively), exceeding international standards. Though physico-chemical conditions (pH, conductivity, redox potential, moisture, organic matter, nitrate, nitrite, ammonium nitrogen, total nitrogen, phosphorus and sulfates) do not favor the development of vegetation, some plants have adapted to these adverse conditions. Moreover, there was a significant reduction of Pb and Zn concentration in the rhizosphere (between 10–78% for Pb and 18–62% for Zn, depending on plant species). *Sporobolus airoides* showed average biomass concentrations of 173 ± 2 and 313 ± 6 mg/kg, for Pb and Zn, respectively; which implies a risk for mobility and possible incorporation into the food chain. *Barcleyanthus salicifolius, Asclepsias linaria* and *Cortaderia selloana* on the other hand, showed average biomass concentrations of 28 ± 3 and 121 ± 5 mg/kg of Pb and Zn, respectively, thus representing a lower biomagnification risk. The effect of these plants to reduce metal concentrations in the rhizosphere, improve physico-chemical conditions in metal polluted substrates, but with limited metal accumulation in biomass, suggests that they can be evaluated for use in stabilizing metal polluted tailings.

Keywords Contamination · Metals · Bioaccumulation · Translocation · Rhizosphere

Introduction

Mining for high economic value ore mineral deposits often results in a simultaneous release of toxic elements into the environment (Álvarez-Ayuso et al. 2012; András et al. 2012). These waste materials when poorly managed, are usually associated with the pollution of surrounding areas thus representing a serious threat to environmental quality and human health (Álvarez-Ayuso et al. 2012; Rashed 2010; Kim et al. 2010; Otones et al. 2011). Mine tailings generally contain high concentrations of heavy metals, which through phenomena such as surface run-off, leaching and windborne transport, may eventually affect various components of the natural environment (Al-Rashdi and Sulaiman 2013; Ding et al. 2011). Though soils have a limited capacity to stabilize high concentrations of metals, these metals tend to accumulate in the system (soil–rhizosphere–plant) (Adamo et al. 2003). Untreated metal pollution is considered nondegradable (Li et al. 2014; Tüzen 2003).

Zacatecas, Mexico has historically been a mining state par excellence, and it continues to be an activity upon which the economy greatly depends. Due to minimal attention being given to waste generation, high concentrations of heavy metals have accumulated in urban areas, principally in large tailings dams on the outskirts of towns and cities,

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such as the study area of the present study (Guadlardi et al. 2015; Flores and Albert 2004).

It is well known that the accumulation of metals in soils represents a serious risk to the environment and human health. These elements accumulate in the body tissues of living organisms (bioaccumulation) and their concentrations increase as they pass from lower to higher trophic levels, a phenomenon known as biomagnification (Velásquez and Dussan 2009; Ali et al. 2013). These two phenomena depend on, and vary according to the metal type, under specific chemical, biological, and environmental parameters effectively describing the dynamic process known as bioavailability, consideration of which is paramount when evaluating remediation strategies (Guala Sebastian et al. 2010; Mitchell et al. 2016).

Among the remediation techniques used on soils polluted with toxic elements, phytoremediation has emerged as a potential cost-effective alternative to the physical and chemical techniques, which are usually expensive, environmentally and/or labor intensive (Malandrino et al. 2011; Wang et al. 2001). Due to the economic implications, phytostabilization technologies in particular have proven to be the pragmatic approach in highly contaminated sites. (Otones et al. 2011; Pratas et al. 2013). It is important, however, to consider inherent biological limitations when using plants, as many metals have no known biological function and in most species, uptake and tissue accumulation can produce adverse effects on plant morphology and health (Bini et al. 2012). Nevertheless, some plants have the ability to sequester large amounts of metals via bioaccumulation without observable toxicological effects, and as such found to be ideal for use in the stabilization of metals in contaminated soils (Minkina et al. 2012; Xiong et al. 2013; Roberts et al. 2014).

The aims of this study were to (1) assess the concentration and distribution of Pb and Zn in mine tailings from an abandoned mine in the state of Zacatecas, Mexico (2) identify the principal plants adapted to the site, (3) determine the main physico-chemical factors related to metal mobility and plant growth, (4) determine the effect of the plants on mine tailings, (5) calculate the geoaccumulation index of metals in the affected area, (6) calculate the bioaccumulation factor and translocation factor of heavy metals in plants. The study outcomes will provide data and information for the possible application of phytostabilization techniques in the area.

Materials and methods

The study area is an abandoned mine located 5 km north of downtown Zacatecas city, Mexico, 22°47 × 07″N, 102°36 × 27″W (Fig. 1). Though vegetation cover varies in type and percentage, arid conditions prevail in the area with an average of 472.1 mm/year rainfall and an average annual temperature of 20 °C. It was mined for gold, argentum and zinc from 1520 till the 1950s. The concentrated ore was smelted on site. As per the usual practice at the time, tailings were deposited on the ground. (Servicio Geológico Mexicano 2015). The predominant soil type

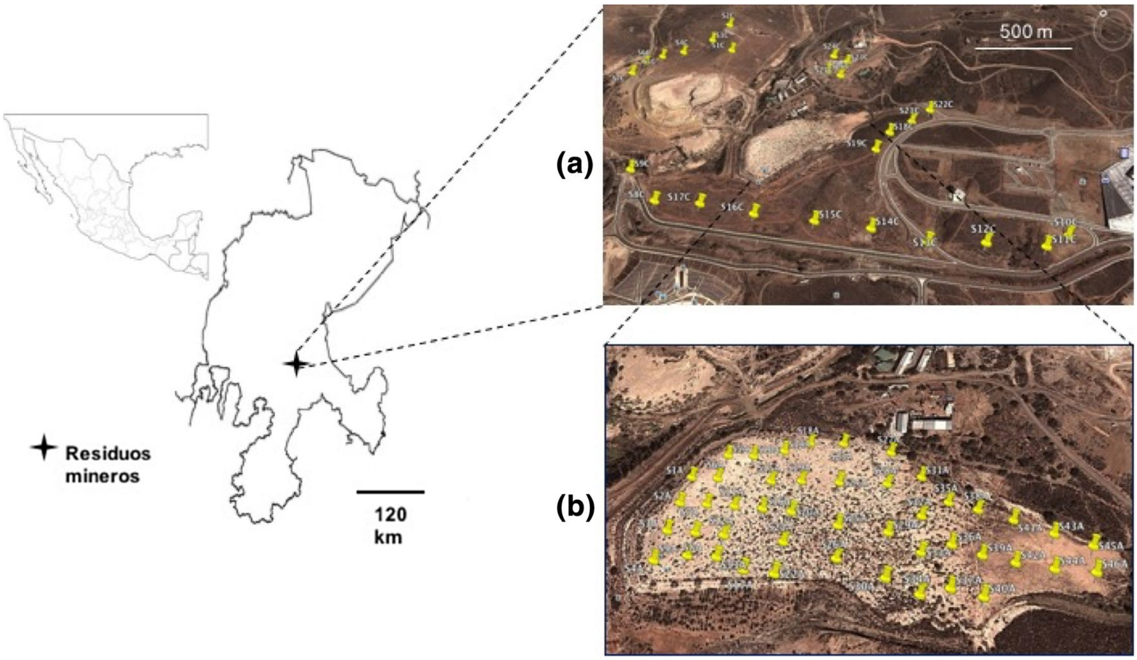

Fig. 1 Localization of the mine tailings, **a** soil control sampling points, **b** sampling sectorization (tailings, rhizosphere and plants)

is silt, with an average particle size of 15–20 µm (USDA 1987). After mining operations ended, the site was abandoned and starting 10 years ago, the surrounding area has been used for the construction of houses, offices and a shopping center.

Equidistant systematic sampling was carried out in a 1470 m^2 abandoned tailings dam. Samples were obtained from all the points indicated in Fig. 1b, from four subsamples, which were subsequently homogenized and an appropriate amount was taken (0.5 kg). Three types of samples were obtained: (1) soil, used as control (Fig. 1a), (2) mine tailings free from plant contact (Fig. 1b) and (3) mine tailings in contact with the root of the plant (the rhizosphere). At each selected point a plant of each type, the rhizosphere and a tailings sample were taken. Samples were taken to a depth of approximately 15–20 cm [USEPA (1992); NOM-147-SEMARNAT/SSA1-2004 (2004); NMX-AA-132-SCFI-2006 (2006)], samples were sieved (<0.5 mm) and dried to 80 °C (Hao and Jiang 2015). The following characteristics were determined in all samples; pH, conductivity and redox potential, using the potentiometric method (USEPA 2002, 2004), organic matter content, using the Walkley–Black metric titration method (Moore 2014). Liquid extracts were obtained after shaking solid samples in deionized water 1:10 m/v for 24 h and used in the determination of total nitrogen, ammonium nitrogen, nitrate, nitrite, sulfate, sulfide, phosphorus and cyanide using the nitraver, ammoniaver, sulfaver, phosphover and cyanidever (HACH registered trademark) methods respectively (Robledo-Santoyo and Maldonado-Torres 1997).

Roots and the aerial parts of the characteristic woody and herbaceous plant species growing in this site were collected from the previously sectored sample sites. Abundance was calculated based on plant count per sector. Plants samples were separated into above-ground tissues and roots. Above-ground tissues were also separated into stems and leaves. The different plant sections were washed with tap water and finally rinsed with distilled water. Afterwards, these plant samples were dried at 70 °C for 48–72 h then milled and sieved (<0.5 mm) for analysis. Plants were systematically identified by leaf, flower and stem characterization (Stuessy 2009).

Psuedo-total concentrations (representing the maximum potentially soluble or mobile metals) of Pb and Zn in soil, rhizosphere and tailings samples were determined according the EPA method 3050B, including digestion using an acid mixture HCl:HNO_3. Total concentrations of Pb and Zn was also determined in plants samples using the same method (USEPA 1996; Relic et al. 2011; Álvarez Ayuso et al. 2013). Quantification was done by flame atomic absorption spectrophotometry (Perkin Elmer Mod PinAAcle 900 H). The accuracy of the digestion procedure and analytical methods were verified with standard reference materials (NIST SRM-8704, Buffalo river sediment), with analytical errors $<5\%$ (Moore 2014; McLean and Bledsoe 1992; Adamo et al. 2003).

The bioaccumulation factor was calculated for the metal concentration in tailings; determined as the ratio of element concentration in plant biomass (roots and aerial parts) to the element in tailings (Minkina et al. 2012):

$$\mathrm{BF} = \frac{[M]_{\mathrm{plant}}}{[M]_{\mathrm{tailings}}} \tag{1}$$

where: $[M]_{\mathrm{plant}}$ is plant metal concentration and $[M]_{\mathrm{tailings}}$ is tailings metal concentration.

The translocation factor, the ratio of element concentration in plant above-ground tissues to that in roots was also determined (Minkina et al. 2012):

$$\mathrm{TF} = \frac{[M]_{\mathrm{aerial\ parts}}}{[M]_{\mathrm{roots}}} \tag{2}$$

where: $[M]_{\mathrm{aerial\ parts}}$ is metal concentration in aerial parts (leaves or stems) and $[M]_{\mathrm{roots}}$ is metal concentration in roots.

The geoaccumulation index (I_{geo}), introduced by Müller (1969), enables the assessment of environmental contamination by comparing differences between current and preindustrial concentrations. In this study, the I_{geo} was calculated using the logarithmic ratio of tailings metal concentration and control soils metal concentration was calculated with the equation:

$$I_{\mathrm{geo}} = \log_2\left(\frac{C_n}{1.5\ C_{\mathrm{B}}}\right) \tag{3}$$

where: C_n is tailings or rhizosphere metal concentration and C_{B} is control soils metal concentration.

The I_{geo} consists of seven classes (Table 1) (Li et al. 2014).

All samples were processed in duplicate and analyzed in triplicate with results reported as means. Means were compared using the non-parametric Kruskal–Wallis ($p<0.05$).

Table 1 Seven classes comprising the geoaccumulation index (Li et al. 2014)

Class	Value	Soil quality
0	$I_{\mathrm{geo}} < 0$	Practically uncontaminated
1	$0 < I_{\mathrm{geo}} < 1$	Uncontaminated to moderately contaminated
2	$1 < I_{\mathrm{geo}} < 2$	Moderately contaminated
3	$2 < I_{\mathrm{geo}} < 3$	Moderately to heavily contaminated
4	$3 < I_{\mathrm{geo}} < 4$	Heavily contaminated
5	$4 < I_{\mathrm{geo}} < 5$	Heavily to extremely contaminated
6	$5 < I_{\mathrm{geo}}$	Extremely contaminated

Results and discussion

Perennial plants predominated the study area, though with variations in growth conditions and abundance as shown in Table 2. Five species from four plant families were collected from the mine tailings dam. Two species in the *Sporobolus* family, *Sporobolus airoides* and *Cortaderia selloana* presented abundant biomass, 25 and 30%, respectively. The other species *Dalea bicolor, Barkleyanthus salicifolius, Asclepias linaria* and *Asphodelus fistoulosus* presented less biomass than 20%. Though these plant species are the dominant plants in the studied mining waste, a few other species were found in the area, including *Boissiera squarrosa* and *Salix cordata*. As these plants are not traditionally considered toxic, the intake of both the aerial sections and the roots by herbivorous animals and the subsequent entrance of toxic metals into the food chain is possible. According to several authors as cited by Domènec et al. (2006), *Cortaderia selloana* and *Sporobolus airoides* are resistant to extreme environmental conditions thus explaining their prevalence in the studied tailings. Numerous authors have reported their growth under arid conditions and tolerance for a wide range of anthropogenically disturbed sites (Rascon et al. 2015; Flores Moya et al. 1995; Dominguez et al. 2005; Fernandez et al. 2016; Doménec and Vilá 2008; Gelviz Gelvez et al. 2015; Elmore et al. 2000).

Physicochemical characteristics of tailings

According to the data presented in Table 3, the pH of tailing was 8.07, indicating an alkaline nature (SSSA 2007), values that are consistent with other studies in mining wastes (András et al. 2012 and Zagury et al. 2004). This contrasts the neutral pH values (between 7.27 and 7.51)

Table 2 Predominant plants found in the site studied

Binomial classification	Abundance in the site (percentage)[a]
Asclepias linaria Cav	4
Asphodelus fistulosus (Huds.) Hook	6
Barkleyanthus salicifolius (Kunth) H. Rob. & Bretell	5
Cortaderia selloana (Schult. and Schult. f.) Asch. & Graebn	25
Dalea bicolor (Humb. And Bonpl) Ex. Willd	20
Sporobolus airoides (Torr.) Torr	30

The abundance was calculated from the total count of each plant species, out of a total of al reported plant species 1597

[a] The missing percentage in the abundance of the plants corresponds to another type of plants found in the site in smaller proportion

Table 3 Physicochemical characteristics of tailings and rhizosphere

Parameter	Unit	Tailings	Rhizosphere					
			D. bicolor	*B. salicifolius*	*S. airoide*	*A. fistulosus*	*A. linaria*	*C. selloana*
pH_{water}	NA	8.07 ± 0.1	7.4 ± 0.1	7.51 ± 0.1	7.39 ± 0.1	7.27 ± 0.1	7.31 ± 0.1	7.38 ± 0.2
Organic matter	%	0.03 ± 0.01	0.07 ± 0.01	0.09 ± 0.01	0.07 ± 0.01	0.08 ± 0.01	0.07 ± 0.01	0.04 ± 0.01
Soluble N	mg/kg	19.2 ± 0.5	15 ± 0.7	5 ± 0.8	5 ± 0.6	5 ± 0.5	5 ± 0.6	6 ± 0.2
Soluble NO_2	mg/kg	0.12 ± 0.02	0.08 ± 0.01	0.08 ± 0.01	0.08 ± 0.01	1.14 ± 0.14	0.24 ± 0.01	0.08 ± 0.01
Soluble NO_3	mg/kg	9.3 ± 0.5	12.5 ± 0.1	1.6 ± 0.2	1.3 ± 0.2	1.3 ± 0.2	0.8 ± 0.1	1.8 ± 0.01
Soluble $N–NH_3$	mg/kg	1.18 ± 0.02	1.06 ± 0.08	0.03 ± 0.01	2.78 ± 0.01	0.23 ± 0.01	0	0.21 ± 0.03
Soluble P	mg/kg	3.2 ± 0.2	2.3 ± 1.1	1.5 ± 0.1	2.15 ± 0.1	1.5 ± 0.1	3.1 ± 0.1	2.45 ± 0.1
Soluble SO_4	mg/kg	66.7 ± 2.8	15 ± 0.1	80 ± 2.4	45 ± 0.7	115 ± 7.3	50 ± 1.4	50 ± 2.9
Soluble S^-	ug/kg	416 ± 8	112 ± 9	213 ± 6	128 ± 2	259 ± 8	135 ± 7	129 ± 6
Soluble CN	mg/kg	1.2 ± 0.1	0.5 ± 0.05	0.4 ± 0.03	0.4 ± 0.04	0.4 ± 0.02	0.5 ± 0.04	0.6 ± 0.02
Moisture	%	2.62 ± 0.8	3.93 ± 0.21	0.31 ± 0.10	0.61 ± 0.01	0.22 ± 0.01	1.01 ± 0.01	0.33 ± 0.01
RedOx	mV	219 ± 7	225 ± 1	224 ± 8	218 ± 3	230 ± 6	205 ± 1	266 ± 5
Conductivity	uS/cm	70.6 ± 2.3	63.7 ± 0.6	71.7 ± 6.7	61.5 ± 0.5	83.7 ± 5.2	66.4 ± 2.4	108.8 ± 6.6

Rhizosphere (tailings obtained from the root of plants)

Tailings $n = 30$, rhizosphere $n = 5$

of the rhizosphere (SSSA 2007); conditions that tend to reduce the metal mobility and facilitate plants' growth (Houben et al. 2013; Laghmouchi et al. 2017). Organic matter content in tailings was classified as very low with a value of 0.03% (SSSA 2007). In the rhizosphere, though organic matter content was higher at 0.07%, it was also classified as very low. These values are well below those reported by Canadian Society of Soil Sciences (CSSS 1993), indicating that these tailing and rhizosphere present high biological and chemical instability. According to the classification used by the SSSA (2007), total nitrogen and nitrogen in all its forms (NO_2^-, NO_3^-, NH_4^+) were very low in tailings and rhizosphere samples indicating a primarily inorganic nature, except for the rhizosphere *Sporobolus airoides*, with values of ammonium nitrogen of 2.78 mg/L, that probably comes from nitrogen-fixing microorganisms (Franche et al. 2009). The P content was also classified as very low (SSSA 2007) for tailings and rhizosphere samples analyzed, between 1.5 and 3.2 mg/L, concentrations that have been shown to limit plant growth (Hao and Jiang 2015). Sulfates, sulfides and cyanides content was classified as moderate (CSSS 1993), conditions that also results in limited plant development (Hao and Jiang 2015). Moisture content was low (2.62%) in tailings (CSSS 1993), and even lower in rhizosphere samples (0.22–1.01%), except *D. bicolor* (3.93%). In general, physicochemical characteristics and nutrients availability in tailings were adverse for plant growth. The rhizosphere had slightly improved pH conditions and slightly increased organic matter content. On the other hand, it had depleted moisture levels and some nutrients (N, P and S^-).

Moderately reduced conditions were found in both tailings and rhizospheres with redox potential values between + 205 and + 266 mV, suggesting conditions that favor metal mobility (USEPA 2002). All samples were classified as slightly saline with conductivity values between 61 and 108 uS/cm (USEPA 2002) with the rhizosphere of *Cortaderia selloana* presenting the highest values. It is important to note that these saline conditions may also enhance mobility due to the availability of ions which can form complexes with free metals (USEPA 2002).

Pb and Zn content in tailings and rhizosphere

Pb concentrations in the rhizosphere (Fig. 2), with the exception of *A. linaria*, showed significantly lower levels than in tailings (followed the order: *D. bicolor* > *C. selloana* > *A. fistulosus* > *B. salicifolius* > *S. airoide*). Zn concentrations in the rhizosphere, with the exception of *D. bicolor* and *A. fistulosus*, were also significantly lower than in tailings (followed the order: *A. linaria* > *C. selloana* > *B. salicifolius* > *S. airoide*). Nevertheless, the concentrations of Pb and Zn in both tailings and rhizosphere exceed current national (Pb 400 mg/kg) and international (Pb 91.3 mg/kg, Zn 315.0 mg/kg) regulations in soils for agricultural, residential or commercial use [NOM-147-SEMARNAT/SSA 1-2004 (2004); CCME (2015); USEPA (2002)].

According to Table 4, tailings were classified as heavily contaminated with an I_{geo} value of 3.7 for both Pb and Zn, and rhizospheres were classified as moderately contaminated, suggesting a beneficial effect of plants on the tailings. The geoaccumulation index in rhizospheres, followed

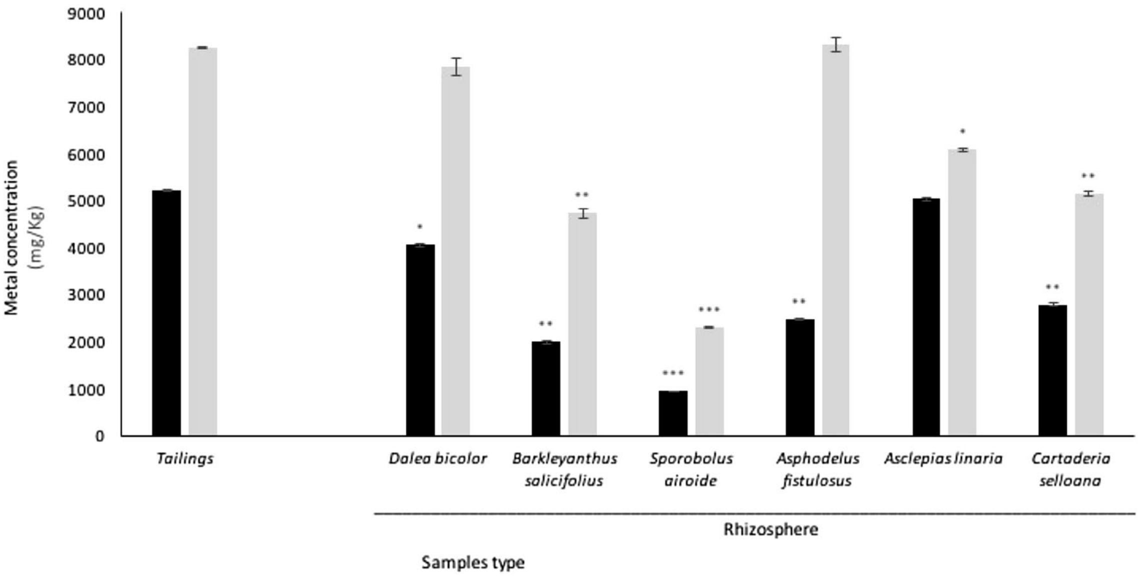

Fig. 2 Pb (filled bars) and Zn (unfilled bars) concentrations (dry weight, mean ± SE, $n=5$) in tailings ($n=30$) and rhizosphere ($n=5$) (tailings obtained from the root of plants). *Significant differences between tailings and rhizosphere ($p<0.05$)

Table 4 I_{geo} values for Pb and Zn (< 1 uncontaminated, > 2 moderately contaminated, ≥ 3 Heavily contaminated) Eq. (3) (Li et al. 2014)

Metal	I_{geo}						
	Tailing	Rhizosphere					
		D. bicolor	*B. salicifolius*	*S. airoide*	*A. fistulosus*	*A. linaria*	*C. selloana*
Pb	3.7	3.0	1.9	0.9	2.3	3.3	2.4
Zn	3.7	3.0	2.3	1.3	3.1	2.7	2.4

Rhizosphere (tailings obtained from the root of plants)

the order of *S. airoide* < *B. salicifolius* < *A. fistulosus* < *C. selloana* < *D. bicolor* < *A. linaria* for Pb and *S. airoide* < *B. salicifolius* < *C. selloana* < *A. linaria* < *D. bicolor* < *A. fistulosus* for Zn.

Pb and Zn content in plants

Metal concentrations in the predominant plant species are shown in Table 5, where root concentrations of Pb and Zn in *D. bicolor* and *B. salicifolius* do not differ significantly. A similar trend was observed with *S. airoide* and *A. linaria*. For *A. fistulosus* higher concentrations of (Pb and Zn) accumulated in the root, corresponding to 48% of Pb and 24% of Zn found in the rhizosphere, though low bioaccumulation and translocation to stems and leaves were observed. *B. salicifolius* incorporated 19% of the Pb and 18.7% of the Zn present in the study tailing with bioaccumulation and translocation factors ranging between 0.01 and 0.2. *D. bicolor* incorporated similar amounts of Pb (17.6%). However, it incorporated significantly more Zn at 66.8%, with a translocation factor greater than unity, suggesting high bioaccumulation in plant leaves. In the case of *A. linaria*,

Table 5 Pb and Zn concentrations (dry weight) in plants growing in the tailings dam

	Pb			Zn		
	(mg/kg)	BF	TF	(mg/kg)	BF	TF
Dalea bicolor						
Roots	704 ± 1	0.173		1003 ± 1	0.127	
Stems	316 ± 2	0.077	0.448	444 ± 2	0.056	0.442
Leaves	970 ± 2	0.239	1.310	1296 ± 1	0.165	1.292
Barcleyanthus salicifolius						
Roots	706 ± 1	0.354		917 ± 2	0.189	
Stems	14 ± 1	0.006	0.019	97 ± 5	0.020	0.105
Leaves	23 ± 2	0.011	0.032	257 ± 1	0.054	0.280
Flower	21 ± 3	0.010	0.029	90 ± 1	0.018	0.098
Sporobolus airoides						
Roots	151 ± 1	0.158		223 ± 2	0.096	
Stems	141 ± 2	0.147	0.933	189 ± 1	0.081	0.847
Leaves	229 ± 3	0.240	1.516	527 ± 2	0.228	2.363
Asphodelus fistulosus						
Roots	917 ± 1	0.370		1946 ± 2	0.011	
Stems	89 ± 3	0.035	0.097	524 ± 1	0.038	0.269
Leaves	419 ± 2	0.165	0.456	502 ± 2	0.031	0.257
Asclepia linaria						
Roots	167 ± 1	0.033		194 ± 1	0.031	
Stems	221 ± 2	0.043	1.323	237 ± 2	0.038	1.221
Leaves	46 ± 4	0.009	0.275	67 ± 1	0.011	0.345
Cortaderia selloana						
Roots	24 ± 3	0.008		176 ± 1	0.034	
Leaves	17 ± 3	0.006	0.708	40 ± 2	0.007	0.227
Flower	45 ±2	0.016	1.875	81 ± 2	0.015	0.460

The ratio between biomass/tailing metal concentrations (bioaccumulation factor, BF) and aerial part/root metal concentrations (translocation factor, TF) are also shown ($n = 5$, for each plant section) incorporation of Pb and Zn in roots varied by 3% with a bioaccumulation factor less than 0.04, but a translocation factor greater than unity, suggesting high bioaccumulation in the stem of the plant. *C. selloana* incorporated the least amount of metal, 0.8 and 3.5% of Pb and Zn, respectively, in the root, with a negligible translocation factor, indicating a potential reduction in ecotoxicology due to its inability to enter the food chain (Alvarez Ayuso et al. 2012). *S. airoide*, a species of the same family incorporated 15.1% of the Pb and 8.9% of the Zn in tailings, with elevated bioaccumulation and translocation factor of 2.

Results of bioaccumulation and translocation factors (Table 5) indicate that the plants with the lowest bioaccumulation factors in roots for Pb such as *A. fistulosus* and *S. airoide* have the highest translocation factors in leaves for both Pb and Zn. The bioaccumulation factor for plants reflects the metal accumulation capacity for different plant sections (roots, stems, leaves), with the leaves of *S. airoide* having the highest potential for bioaccumulation with values of 0.24. All other plants have bioaccumulation factor values below 0.24 in all sections.

In this study, plants cited in Table 5 were classified as non-hyperaccumulators, also called excluder plants according to the plant-tailings relationship and do not accumulate metals at concentrations superior to 1000 mg/kg (Bech et al. 2016). *C. selloana* showed less Pb and Zn bioaccumulation capacity (0.006–0.016), with this capacity increasing in the following order for Pb leaves < roots < flowers, the latter being the section of the plant with the highest affinity for the metal to be translocated (translocation factor 1.875). For Zn, the bioaccumulation factor ranged from 0.007 to 0.034 and it varied in the following order, leaves < flower < roots, showing a smaller translocation factor when compared to Pb, with a value of 0.460. *C. selloana* and *A. linaria* both showed similar bioaccumulation factor values for Pb and Zn. All other species studied had varying bioaccumulation factor values. According to Domenéc and Vila (2008), *C. selloana*, is considered invasive, primarily due to its worldwide ubiquity and its reported tolerance to a wide range of environmental conditions.

According to the United States Department of Agriculture (2000), research has demonstrated that plants are effective in cleaning up contaminated tailing. Plants have been used to stabilize or remove metals from soils. The three mechanisms used are phytoextraction, rhizoremediation and phyto-stabilization, provided they comply with characteristics: tolerance or hyperaccumulation (Chen et al. 2014; United States Department of Agriculture 2000; Vanessa and Esposito 2010). Among the studied plants, *D. bicolor, B. salicifolius* and *A. fistulosus* accumulated the highest concentrations of metals, however, if they are to be used in remediation strategies, steps must be taken to prevent exposure to herbivores and the potential incorporation of toxic metals into the food chain. *C. selloana* and *S. airoide*, though considered invasive species, accumulated the least concentrations of metals and as such represent the least risk in terms of toxic metals entering the food chain (Domènec and Vila 2008; Plante et al. 2011). Thus, its use in phytostabilization techniques should also be carefully monitored.

Conclusion

The ancient mine tailings the "El Bote Mine", Zacatecas, Mexico represent a risk to the environment due to the high concentrations of Pb and Zn, and the current physicochemical properties (pH, redox potential, conductivity and organic matter) that favor metal mobility and potential bioavailability. Notwithstanding the severe environmental conditions, scarcity of nutrients and moisture, and hostile physico-chemical characteristics of tailings, few plant species (with low abundance) have adapted. Results showed that plant growth had a beneficial impact on tailings, significantly reducing the levels of these metals and ameliorating pH conditions in the rhizosphere (reducing the metal mobility and facilitating plants' growth), and slightly increasing the organic matter content. On the other hand, depleted moisture levels and some nutrients (N, P and S^{-}) were observed. Regarding Pb and Zn uptake, none of these plant species were classified as hyperaccumulators. *C. selloana* however, showed the lowest Pb and Zn uptake values and a significant reduction of the concentration of these metals in the rhizosphere, thus decreasing the risk of metals being incorporated into the food chain. Despite high biomass production, resistance to adverse conditions and a low capacity to incorporate metals into its biomass, this plant species represents a potential risk for invasive environmental proliferation. Thus its eventual use in phytoremediation must take this risk into account.

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