

Transport of Heavy Metals in Materials With Diameter Analogous to Xylem Vessels

Oropeza-Garcia, N.^{1*}, Hausler, R.¹, Glaus, M.¹, Vega-Azamar, R.¹, and Romero-Lopez, R.²

¹Station expérimentale des procédés pilotes en environnement, École de technologie supérieure, Université du Québec, Canada, 1100, rue Notre-Dame Ouest, Zip Code H3C 1K3, Montréal, Québec, Canada

²Universidad Veracruzana, Facultad de Ingeniería Civil, Lomas del Estadio s/n Zip Code 91000, Zona Universitaria, Xalapa, Veracruz, México

Received 19 March 2013;

Revised 12 July 2013;

Accepted 17 Aug. 2013

ABSTRACT: In vascular plants, the soil solution is transported from the roots to the leaves through small diameter vessels found in the xylem; this transport not only allows the nutrient uptake but also the accumulation of heavy metals in their shoots. By analogy to this phenomenon, the present study aimed at the evaluation of heavy metals transport (Pb, Cr, As, Cd, Zn, Ni and Al) in pH 4 and pH 8 solutions using a capillary siphon consisting of small pore diameter materials. Determination of the metal concentration in the solutions was performed by means of Inductively Coupled Plasma. The largest transport of metal ions is produced at pH 4, on ascending order, Cr < Pb = Al < As < Ni < Zn < Cd. Results showed that there is capillary transport of aqueous solutions with heavy metals in materials with pore diameter similar to that found in the xylem of plants. Some authors have argued that there is a remarkable similarity between soil and xylem, which makes possible the soil-plant-atmosphere system continuity; in this sense, the performance of the tested materials should be investigated under similar conditions to those present in the interface soil-xylem in a bid to replicate this continuity.

Key words: Capillary transport, Heavy metals, Small pore diameter materials, Soil solution, Hyperaccumulator plants

INTRODUCTION

Soil pollution by toxic metals (Pb, Cr, As, Zn, Ni, Cd, etc.) is a growing preoccupation in the world that strongly affects industrialized countries (Belluck, 2006; Blais, 2010; Dermont *et al.*, 2008; Sun *et al.*, 2007). Given that heavy metals are not biologically degraded, the main problem with this type of elements stems from their mobility and their capacity of bioaccumulation in living organisms, starting with vegetables, which are placed at the beginning of the food chain (Garbisu and Alkorta, 2001; He *et al.*, 2005; Pilon-Smits and Freeman, 2006). The bioavailability of heavy metals is determined by their redistribution between the solid and aqueous phases of the soil. Because vegetable roots take up only the elements in the soil solution, the content of heavy metals in the aqueous phase of soils is essential in the soil-plant transfer (Bourrelrier *et al.*, 1998; Fritioff and Greger, 2003; Girard *et al.*, 2005). A fundamental factor for heavy metal solubilization is pH (Ghorbani, 2008; Ghosh and Singh 2005b; Kabata-Pendias and Pendias, 2001). In soils, the pH range is commonly found

between 3.5 and 9 (USDA, 1998) and, generally, low pHs increase the bioavailability of metals (Alloway and Jackson, 1991; Kashem and Singh, 2001; Rachou and Sauvé, 2008; Sinha *et al.*, 2007). Thus, the transfer of metals towards plants has been described qualitatively as high for Zn, Ni and Cd and medium for Cr, Pb and As, in acidic conditions, while Pb, Cd, Zn and As exhibit low transfer and Cr, Ni and Al very low transfer, in basic conditions (Tremel-Shaub and Feix, 2005).

For the plant, heavy metals bioavailability is closely related to their solubility in the aqueous phase. Usually, soluble compounds are formed at low pH soil solution; as result of this, metal bioavailability increases for plants, and, on the contrary, fewer soluble compounds are formed at high pH soil solution, which reduces the heavy metal uptake by plants (Seregin and Ivanov, 2001). Table 1 exhibits the predominant heavy metals chemical species in soils and some aspects of mobility and bioavailability related to plants.

*Corresponding author E-mail: norma-angelica.oroepza-garcia.1@ens.etsmtl.ca

Table 1. Prevalent chemical species in soils, mobility and phytoavailability (Adapted form Tremel-Schaub and Feix, 2005 and *Vitorello et al., 2005)

Heavy metal	Prevalent chemical species in soils	Mobility and phytoavailability
Pb	Pb(II): Pb^{2+} , $PbHCO_3^+$, $PbOH^+$, PbS, $PbSO_4$, $Pb(OH)_2$, $PbCO_3$, PbO, $Pb(PO_4)_2$, $PbCl^+$.	Low mobility. Pb is poorly absorbed by the roots of plants, where it is normally retained.
Ni	Ni(II): Ni^{2+} , $NiSO_4$, $NiHCO_3^+$, $NiCO_3$.	Medium mobility. Plants easily absorb Ni.
Zn	Zn(II): Zn^{2+} , $ZnSO_4$, $ZnHCO_3$, $ZnCO_3$, $ZnFe_2O_4$, Zn_2SiO_4 , $Zn_3(PO_4)_2$.	High mobility Minimal concentration of Zn in solution is found at pH between 7 and 8, whereas at pH < 6, the concentration of Zn increases considerably. Plants easily absorb Zn.
*Al	Al(III): Al^{3+} , $AlOH^{2+}$, $Al(OH)_3$, $Al(OH)_4^-$.	Low mobility Al is found soluble in soils in acidic pH between 3 and 4.5. Toxic species of Al are Al^{3+} and $AlOH^{2+}$. Al damages the root of the plant where is normally retained; its transport to the leaves is very low.
As	<i>In oxidizing conditions:</i> As(V): $H_2AsO_4^-$ is prevalent in acidic conditions, $HAsO_4^{2-}$ is prevalent in alkaline conditions. <i>In a reducing environment:</i> As(III): $HAsO_2$, AsO_2^-	As(V) species are less soluble and toxic as compared to As(III). As precipitates with Fe and Al hydroxides. As(V) precipitation is more effective than As(III). Acidic pH (< 5) and basic (pH > 8) favour its absorption by plants
Cr	Cr (III) is the most stable and common form as insoluble oxide precipitate Cr(VI): $HCrO_4^-$, CrO_4^{2-} , mainly of anthropogenic pollution	Low mobility. Cr(VI) is considered the most toxic form of Cr. Cr(III) co-precipitate with several metallic hydroxides. Cr(VI) may co-precipitate with Al hydroxide at pH between 7 and 9.4. Phytoavailability of Cr is very low when compared to other heavy metals. Cr(III) usually remains in the roots of plants and Cr(VI) is commonly transported to the tops. Cr in neutral or basic conditions is more phytoavailable than in acidic conditions.
Cd	Cd(II) Cd^{2+} , $CdSO_4$, $CdCl^+$, $CdHCO_3^+$, CdO , CdO_3 , $Cd(PO_4)_2$, CdS, $CdCl_2$	Cd is a very mobile element in soils. Cd co-precipitate with Al hydroxide. pH is the most important factor in the phytoavailability of this element. Cd concentration in the soil increases considerably at pH < 6.

In this regard, plants have developed several strategies to reduce or increase the mobility of components retained in the solid phase of the soil by changing the soil pH, such as chelating biosurfactants secretion, exudates and sugars, among other substances (Barcelo and Poschenrieder, 2003; McGrath *et al.*, 2002; Singh *et al.*, 2007;). From there, the pollutant in the soil reaches the plants roots through mass flow and diffusion phenomena. Once in the rhizosphere, lipophilic pollutants cross through the root by the symplasmic way (inside the cells), and the hydrophilic ones by the apoplasmic way (between the cell membranes) until they reach the xylem (Padmavathiamma and Li, 2007). Xylem consists of sap-conducting vessels composed of cellulose (De Boer, 2003; Wu *et al.*, 1999) which very small diameter (10-200 μm) (Hacke *et al.*, 2006) allows them to transport the soil solution (or the xylem sap) to the aerial parts of vascular plants by means of capillary action and transpiration (Campbell and Recce, 2004; Kvesitadze *et al.*, 2006; Nijsee, 2004). Some authors have pointed out the similarities between the hydraulic conductivity of soils and that of the vascular plants xylem, which make possible the soil-plant-atmosphere continuity (Sperry *et al.*, 2003). This mechanism has also been described as a sort of wick, which communicates the soil with the atmosphere (Harper, 1977). The same phenomenon of capillary transport, but without the intervention of roots, takes place in the transfer of water with dissolved salts from the soil to the walls of buildings, resulting in efflorescence or saltpeter. The phenomenon is also observed in materials such as wood, concrete, mortar and bricks. The water height that can be reached by capillarity, theoretically estimated, is around 10 km for concrete and 122 m for wood (Lstiburek, 2007). In turn, the amount of metal that can be taken up by plants depends on both the environmental conditions and the plant species. The term hyperaccumulation is commonly used to define the capability of plants to accumulate exceptionally high quantities of heavy metals. The qualification of "hyperaccumulator plants" is generally given to species that absorb above 1000 mg of metal/kg in dry weight of plant tissue (Environment Canada, 2003; Gisbert *et al.*, 2008; Shah *et al.*, 2010). Thus, levels of hyperaccumulation for Zn reach more than 10000 mg/kg; for Pb, Ni, As, Al and Cr, they are greater than 1000 mg/kg, while for Cd, they surpass 100 mg/kg (Shah *et al.*, 2010), these kind of plants usually exhibit concentrations of heavy metals in the shoots higher than in their roots and have a high tolerance to toxic metals compared to other species (Wei *et al.*, 2006).

In this context, by analogy to the transport mechanism in vascular plants, this work aimed at assessing the transport of heavy metals from aqueous

solutions at pH 4 and pH 8 using a capillary siphon (Guo and Cao, 2005) as means of transport in order to test the effective transport of heavy metals in wicks composed of a natural and a synthetic fibre. Values of single and total ions transported by the wicks were compared to accumulation values reported for hyperaccumulator plants.

MATERIALS & METHODS

Key issues considered during the experimental design to establish the parameters were,

i) soil solution transport from the roots to the aerial parts through the xylem capillaries and a diameter in the reported range for capillaries (10-200 μm). These features were used to define the type of fibre and the pore diameter (see Table 2) and tested by using a capillary siphon (Fig. 1).

ii) M1 allowed the setting of mobility similarities between M1 to the species reported in the phytoremediation literature, considering that cellulose is the main component of plants. The fibre composition can be seen in Table 2;

iii) heavy metal used in the experimental work are normally found in contaminated soils, because contamination is usually due to a mixture of heavy metals rather than to only one metal. The concentration used (1.5 mg/L) was higher than that reported for uncontaminated soil solutions (1 to 100 $\mu\text{g/L}$) (Kabata-Pendias and Pendias, 2001);

iv) an acidic pH(4), to ensure solubility of the metal in the solution, and a basic pH (8), to compare mobility in both conditions to that reported in the literature (see Table 1), were applied in the experiments;

v) performance in phytoremediation processes takes into account the heavy metal accumulation in the roots and the transport to the tops; this is why both accumulation on the material and transport in the solution were considered; they were tested by using mass balance.

A capillary siphon (Fig. 1) was built with plastic pipes (0.30 m long and 0.008 m diameter) and filled up using two small pore diameter materials (M1 and M2) as capillary means of transport (absorbent wicks). Before filling up the pipes, they were washed with a nitric acid solution (10% HNO_3) for 3 hours and rinsed with distilled water. Both materials were washed with distilled water for 3 hours and set to constant weight. Table 2 shows the weights of materials, their pore diameters and their composition.

Metal content, transferred by capillary action through the materials, was estimated every 24 hours. Tubes 1 and 2 were changed on a daily basis, tube 1 by

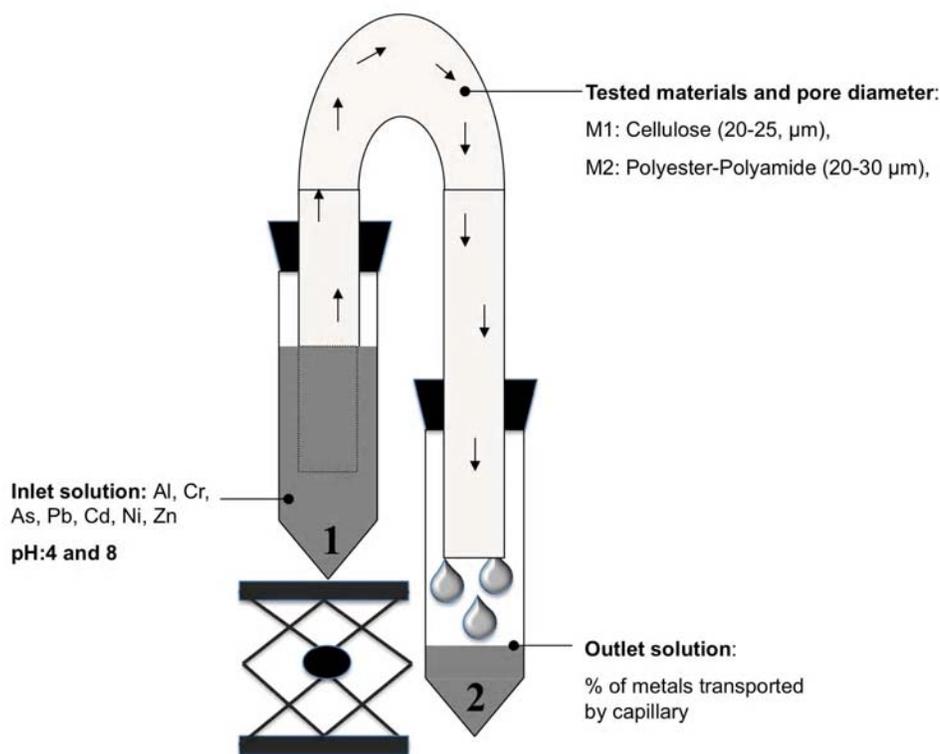


Fig. 1. Capillary siphon

Table 2. Properties of the tested materials for heavy metal capillary transport

Material	Weight (g)	Material pore diameter (μm)	Wick diameter (cm)	Wick material composition
M1	2.4	20-25	0.80	Cellulose 99%
M2	1.2	20-30	0.80	Polyester80% -polyamide 20%

adding 45 mL of multi-element solution (pH 4 or 8) and tube 2 to collect the solution at the outlet (Fig. 1). The volume of solution transported from tube 1 to tube 2 was measured and the metal content in the inlet tube (in the materials) and in the outlet tube was calculated by mass balance. This procedure was repeated eight times running in order to observe whether the metals were effectively transported through the materials. A refill solution at pH 4 and another one at pH 8 were prepared from a multi-element standard solution (1000 μg/L). Heavy metals in the standard solution were As (V), Al (III), Cd (II), Cr (III), Ni (II), Pb (II) and Zn (II) in 5% HNO₃ and 10% HCl (SCP SCIENCE). The pH of the solutions with metals was adjusted to 4 by adding environmental grade water (Fisher) and to 8 by adding NaOH (1 M) prepared from 97% NaOH (Anachemia). The concentration used to refill both solutions was 1.5 mg/L for each metal.

Determination of the heavy metal concentration in the inlet and outlet solutions was made by ICP-OES Varian Vista MPX model. The calibration curve was obtained with a correlation coefficient of 0.99. The wavelengths (λ) used for the metals were, lead, λ=220,353 nm; nickel, λ=231,604 nm; zinc, λ=213,857 nm; arsenic, λ=228,812 nm aluminum, λ=396,152 nm; chrome, λ=267,716 nm and cadmium, λ=226,502 nm. Data obtained in this work were subjected to statistical analysis of variance (ANOVA) with the aid of JMP 8 software (SAS Institute Inc.). Differences were considered significant at P<0.05 using the Student's t test. The Student's t-test is a statistical significance test used for comparing the means of two treatments based on small independent samples (Caprette, 2013). A confidence level of 95% (P<0.05) is generally used in the field of chemical analysis (Efstathiou, 2013).

RESULTS & DISCUSSION

The work's experimental approach involved the transport of solutions with heavy metals, under acidic and basic conditions, by capillary action through the materials M1 and M2. The accumulated volumes of solution for each material are shown in Fig. 2. In this respect, no significant differences were observed on the same material as result of the pH change. As it can be seen in Fig. 2-a, M1 showed practically the same volumes of transported solutions in acidic and in basic conditions, while for M2, the transport velocity was slightly higher for the acidic conditions and, accordingly, the accumulated volume was increased a little (see Fig. 2-b). These slight variations can be attributed to differences in the structure of the porous media. Thereby, although an average pore diameter for the materials is commonly used (see Table 2), usually porous media present variation in pores sizes, which are interconnected, and form a three-dimensional network system specific for each material, which modifies the flow inside these (Chatterjee and Gupta, 2002). Furthermore, densities of materials (different weight in the same volume for the wicks, see Table 2), as well as solutions characteristics, affect the absorption capacity of the materials.

Although the accumulated volumes of solution in the outlet tube exhibited no great differences, the transport of ions did show significant dissimilarities depending on the material used, especially under acidic conditions. In general, higher ion transport rates were observed at pH=4 (Fig. 3-a and 3-c) where metals are more soluble, when compared to the basic solution (pH=8). M1 displayed an important transport of Zn, Ni, Cd and As, and a higher accumulation for certain metals such as Pb, Al and Cr (Fig. 3-a), while M2 showed a greater transport capacity for all ions, as illustrated in Fig. 3-c, and a relatively low metal accumulation potential.

In this regard, the pH value has a preponderant effect on the heavy metal adsorption on materials (Gérente *et al.*, 2000); on one hand, pH affects the metal species that coexist in solution and, on the other, it modifies the surface charge of the adsorbent materials (in this case, M1 and M2) in such a way that the presence and type of the functional groups in the material (hydroxyl, amino, carboxyl, etc.) determines the surface charge. At low pH values, the functional groups on the surface of the materials are protonated facilitating the fixation of negatively charged molecules as a result of the electrostatic attractions which in turn allow the passage of positively charged molecules by the repulsion force (Tobin *et al.*, 1984; Vargas-Nieto *et al.*, 2011).

Owing to the materials composition, M1 has a greater number of active sites when compared to M2 (Figure 4). Thus, at low pH, hydroxyl (-OH) and amino (-NH₂) groups on the surface of the materials are highly protonated and facilitate the pass of cationic molecules (Nikiforova and Kozlov, 2010; Öztürk *et al.*, 2009; Tobin *et al.*, 1984; Vargas-Nieto *et al.*, 2011;), this is the case of Zn, Ni, Cd and As, and, on the other hand metals such as Cr, Pb and Al showed affinity with M1, while M2 did not present high amounts of active sites capable to fix the same metals.

Similar results to those obtained in the present study, concerning the accumulation of metals at low pH values, have been reported for materials with high cellulose content. Low accumulation of Cd, Zn and Ni was exhibited in papaya wood (Gérente *et al.*, 2000; Saeed *et al.*, 2005), while metals such as Pb on sugar beet pulps (Gérente *et al.*, 2000; Reddad, 2002), Cr in maple sawdust (Yu *et al.*, 2003) and compost (Vargas-Nieto *et al.*, 2011) showed important levels of accumulation. In the basic solution, precipitation of hydroxides has prevented the transport of heavy metals through the material; equation 1 shows the general chemical reaction of metal ions in alkaline conditions (Feng *et al.*, 2000).



The transport percentages observed in Figs 3-b and 3-d provide elements to confirm that most of the metal ions were precipitated in the inlet tube. M1 showed a very low percentage of accumulated or transported ions through the material; As was the most abundant ion found in the outlet tube with around 30% (Fig. 3-b). For M2, about 39% of As and 20% of Cd were found in the outlet tube (Fig. 3-d). As and Cd presented a high mobility in both acidic and basic conditions. In this case, the differences in the transport of As by the same material but under different conditions of pH can be attributed to the formation of aluminum hydroxides which co-precipitate with arsenic ions in the basic medium and reduce their transport under these conditions (Tremel-Schaub and Feix, 2005), while, in turn, soluble traces of cadmium can be fixed by the active sites on M1. Values of heavy metal content in plants considered as levels of accumulation and hyperaccumulation are presented in Table 3. These values were compared to those obtained for the tested materials in the present work, considering 1 kg of material. Because most of the hyperaccumulator plants are selective, criteria for defining a hyperaccumulator species are given as a function of single metals. Table 3 allows bringing into comparison the values of each metal transported and the sum of transport (T) and

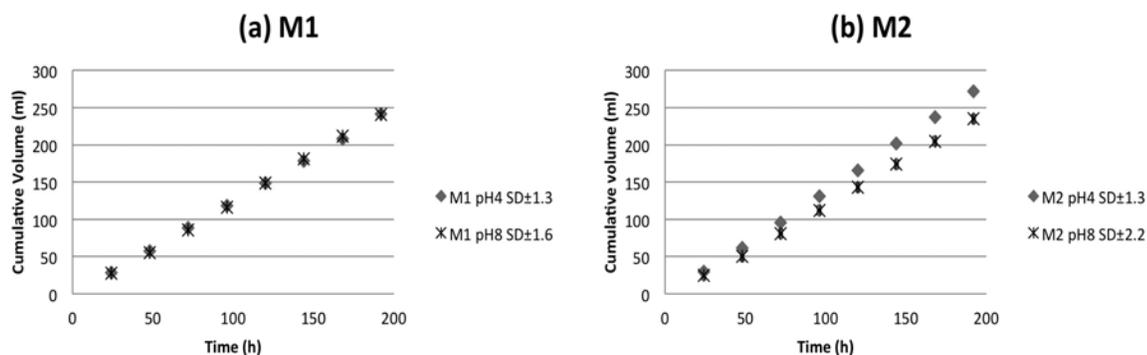


Fig. 2. Cumulative volume of transported solution by the tested materials, M1 and (b) M2 ± standard deviation (SD)

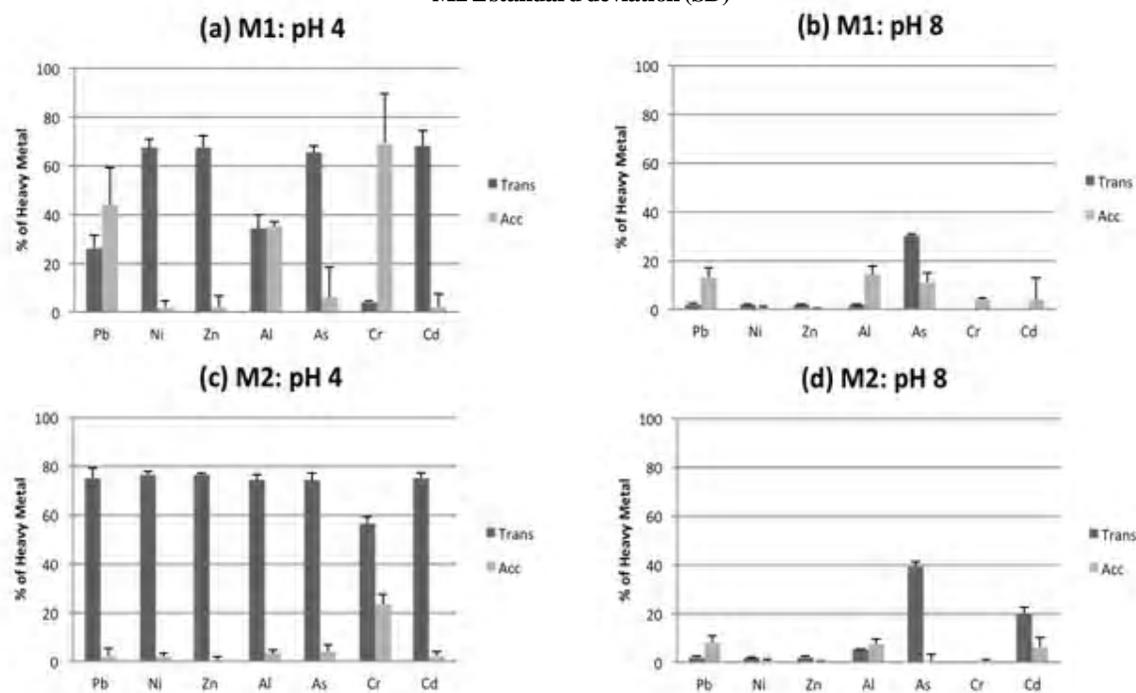


Fig. 3. Percentage of heavy metals transported (Trans) and accumulated (Acc) by the materials, (a) in acidic conditions, (b) M1 in basic conditions, (c) M2 in acidic conditions and (d) M2 in basic conditions, bar errors represent the standard deviation

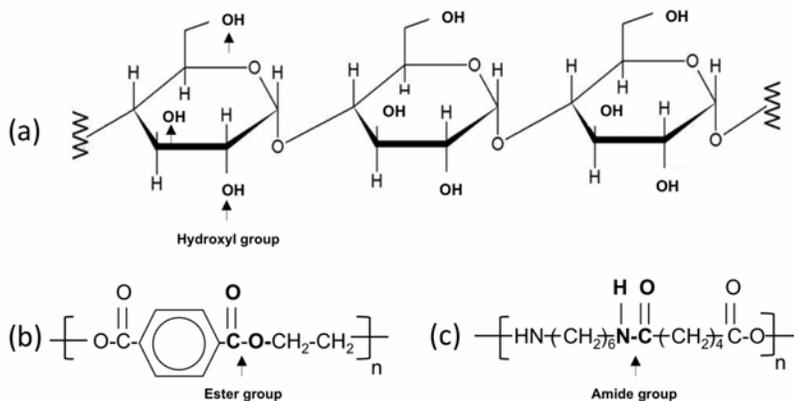


Fig. 4. Chemical structure of (a) cellulose, (b) polyester and (c) polyamide

Table 3. Accumulation and hyperaccumulation levels in plants compared to the estimated levels of transport (T) and to the total sum of transport and accumulation (T+A), in acidic conditions

Heavy metal	*Plant/Families of Heavy Metal Hyperaccumulators	Minimum levels of accumulation found in plants (mg/kg ⁻¹)	Hyperaccumulation levels in plants (mg/kg ⁻¹)	Estimated for 1 kg of M1 (mg/kg ⁻¹)		Estimated for 1 kg of M2 (mg/kg ⁻¹)	
				T	T+A	T	T+A
Pb	Compositae Brassicaceae	200	>1,000	58	154	333	342
Ni	Brassicaceae	100	>1000	150	154	342	350
Zn	Fabaceae/Leguminaceae	500	>10,000	158	162	358	358
	Geraniaceae						
	Crassulaceae						
	Brassicaceae						
Al	Vochysiaceae	100	>1,000	79	162	350	367
As	Brassicaceae	100	>1,000	146	158	333	350
	Ericaceae						
	Labiatae						
	Geraniaceae						
Cr	Asteraceae	100	>1,000	8	175	267	375
	Brassicaceae						
	Convolvulaceae						
	Gerinaceae						
	Leguminosae/Fabaceae						
	Chenopodiaceae						
Cd	Asteraceae	10	>100	158	162	358	367
	Brassicaceae						
Total				757	1,127	2,341	2,509

* From Sheoran *et al.*, 2011 and Miranda *et al.*, 2011

accumulation (A), as well as the total sum values (including all the metals present in the solution). In Table 3's last row, values highlighted in bolds indicate that the tested materials showed similar levels to those reported individually for most metals in hyperaccumulator plants. These results exhibited M2 as more efficient to transport heavy metals and M1 with greater accumulation capacity, with important correspondence to that reported for the translocation of metals in plants.

In this way, metals transported with the greatest difficulty in M1 were Cr, Pb and Al. Comparatively, some authors have reported that Cr and Pb are the least transported by plants to their aerial parts (Adriano, 2001; Kabata-Pendias and Pendias, 2001; Lübben and Sauerbeck, 1991). On the contrary, Ni, Zn and Cd were the most easily transported by M1, similar to plants where Ni is transported with relative ease and Cd and Zn are readily transported (Adriano, 2001; Alkorta *et al.*, 2004; Alloway and Jackson, 1991; Kabata-Pendias and Pendias, 2001).

On the other hand, it must be taken into account that the life cycle of plants allow the introduction of

heavy metals in the food chain or their reintroduction to the soil once the contaminated plant perishes. Because in phytoextraction processes it is not considered if the metal is adsorbed on the cell walls surface or within the cells, desorption and recovery of heavy metals directly from the plants is not guaranteed (Olguin and Sanchez-Galvan, 2012). Thus, when plants are harvested and removed from the site, the accumulation of huge volumes of hazardous biomass becomes a problem. Phytoremediation wastes must be treated and disposed; some alternatives for their treatment are composting and compaction, combustion and gasification, and pyrolysis (Ghosh and Singh, 2005). However, treatment of the formed leachate, CO₂ emission and heavy metals recovery from leachate or from ashes, as results of these processes, must be considered also in the cost-benefit balance.

As a general rule, mobility of heavy metals in soils is strongly related to pH conditions. Usually, acidic pH allows the mobilization of metals, while basic pH reduces the solubility of metals and, in consequence, their mobilization. Using a qualitative scale for the mobility of metals in soils at pH 4, the following

behavior can be stated. Cd has strong mobility, Ni and Zn have medium mobility and Pb, Cr and Al have weak mobility (Kabata-Pendias and Pendias, 2001). Cd is reported as a very mobile metal in soils and readily available for plants, while Pb has low water solubility, which is why this metal turns out to be very immobile in soils (Miclean *et al.*, 2000). In this sense, M1 displayed a great similarity to the described behavior. Some of these elements can be found in soils presenting different oxidation states, such as Cr (III and VI) and As (III and V). In other cases, the metal has only one oxidation state, such as Cd (II), Ni (II), Pb (II), Zn (II), and Al (III) (Tremmel-Schaub and Feix, 2005). However, different chemical species of the same metal can co-exist under the same pH conditions (Feng *et al.*, 2000). Because the present study was focused solely in determining the metal ion transport through the materials, speciation studies were not performed. However, subsequent work may consider the elements speciation and the mobility of each chemical species through the materials.

So far, most of the environmental regulation for soil pollution sets maximum total limits for each metal. These criteria are strongly questioned by some authors that consider that the chemical species must be known in order to establish more safe limits depending on the toxicity of each species (Hsiu-Chuam *et al.*, 2006). Nevertheless, numerous studies suggest that the interaction of many environmental variables can change the mobility of metals in soils (Chojnacka *et al.*, 2005; Ernst, 1996; Violante *et al.*, 2010). In this sense, it could be safer to reduce the total concentration of toxic metals in soils, bringing along a risk minimization for particular elements that can change their oxidation state and become a threat for the environment and public health.

Finally, an important aspect to be studied in future research avenues is the possibility of testing layered double hydroxide-type structures (LDH) in basic pH. These materials are composed of layers with a positive charge, which permit the formation of interlayer anions to balance the load between the layers. Because fibres are layered materials that also exhibit weak positive charges, this must be considered to obtain similar compounds using the methodology followed in this work. Such composites are currently being applied in water treatment for removing organic and inorganic contaminants used by industrial and biomedical sciences to exchange capacity (Zümreoglu-Karan and Nadim, 2012; Dumas, *et al.*, 2012).

CONCLUSION

The tested materials showed to be effective for heavy metals transport by capillary action; these

materials allowed the transport of several metals at the same time. The best performance for ions transport was observed under acidic conditions for M2, while M1 showed important similarities to the reported for heavy metals in soil and plants. It should be remarked, from an environmental point of view, that M1 is composed of cellulose, the most abundant biomolecule on Earth, while M2 is a synthetic non-biodegradable material. In general, nickel, zinc and cadmium were the metals the most easily transported in both materials. Minimal amounts of Cr, Pb and Al were transported by M1 due to their affinity for the material, whereas M2 displayed a higher capacity to transport the same ions. Both materials transported arsenic at pH 4 and at pH 8, and M2 also showed a slight transport of cadmium in basic conditions. The transported quantities of metal ions at pH 4, in ascending order, were,

- M1, Cr < Pb < Al < As < Ni = Zn = Cd
- M2, Cr < Pb = Al = As < Ni = Zn = Cd

Transport of heavy metals from the roots to the aerial parts of plants is a key factor in phytoextraction processes because the pollutant may be removed from the site once the plants are harvested. In this context, the transport of heavy metals through materials with a similar diameter to those found in the plants xylem may be of practical use in the development of new techniques to remove these pollutants based on the capillary properties showed by certain materials, replicating the soil-plant-atmosphere continuity (Sperry *et al.*, 2003). Under these premises, research must be carried out to learn more about the performance of the materials, particularly, in relation to the change of certain environmental variables (concentrations, temperature, pressure, type of contaminants, etc.) and, in turn, applications *in situ* should also be undertaken. Given the wide range of micro and nanomaterials (properties, life spans, costs, etc.) and the changing conditions of the contaminated sites, the emulation of transport of pollutants based on the vascular system of plants may have an interesting potential of development in soil remediation.

ACKNOWLEDGEMENTS

The authors wish to thank Mrs. Mirela Sona for technical assistance in the ICP-OES analysis.

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