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In situ PHYTOREMEDIATION IN MEXICO: A REVIEW

FITORREMEDIACIÓN *in situ* EN MÉXICO: UNA REVISIÓN

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SUMMARY

In Mexico, contamination by potentially toxic elements in soil and water represents important ecological and health problems. Plants capable of growing on anthropogenically-modified soils reflect their ability to adapt to diverse environmental conditions. Most of the phytoremediation studies are carried out under laboratory conditions, and only a few studies evaluate the phytoextraction capacity *in situ.* This review summarizes the information obtained from scientific sources on *in situ* phytoremediation studies carried out in Mexico. Eighty-five percent of the studies corresponded to sites contaminated with trace metals by mining activities. Plants with potential to be used as accumulators or hyperaccumulators of potentially toxic elements are described, such as *Hydrocotyle ranunculoides, Parietaria pensylvanica* and *Commelina diffusa* for Zn; *Rorippa nasturtium-aquaticum* and *Simsia amplexicaulis* for Cu; *Nicotina glauca, Flaveria angustifolia* and *Flaveria trinervia* for As, and *Buddleja scordioides* for phytoremediation of soils contaminated by Pb. Native plant species should be studied to establish mechanisms of metal extraction and the water-soil-microorganisms interaction to improve the efficiency of *in situ* phytoremediation. The information described here can be useful for planning the remediation of sites contaminated by potentially toxic elements in Mexico and other parts of the world.

Index words: Mining, phytoremediation, pollution, potentially toxic metals.

RESUMEN

En México, la contaminación por elementos potencialmente tóxicos en el suelo y el agua representa importantes problemas ecológicos y de salud. Las plantas capaces de crecer en terrenos antropogénicamente modificados reflejan su capacidad de adaptación a diversas condiciones ambientales. La mayoría de los estudios de fitorremediación se lleva a cabo en condiciones de laboratorio, y sólo unos pocos estudios evalúan la capacidad de fitoextracción *in situ.* Esta revisión resume la información obtenida de fuentes científicas sobre los estudios de fitorremediación *in situ* realizados en México. El 85% de los estudios reportados corresponde a sitios contaminados con metales traza por actividades mineras. Se describen plantas con potencial para ser utilizadas como acumuladoras o hiperacumuladoras de elementos potencialmente tóxicos, como *Hydrocotyle ranunculoides, Parietaria pensylvanica* y *Commelina diffusa* para Zn; *Rorippa nasturtium-aquaticum y Simsia amplexicaulis* para Cu; *Nicotina glauca, Flaveria angustifolia* y *Flaveria trinervia* para As y *Buddleja scordioides* para la fitoremediación de suelos contaminados por Pb. Las especies de plantas nativas deben estudiarse para establecer mecanismos de fitoextracción de metales y la interacción agua-suelo-microorganismos para mejorar la eficiencia de la fitorremediación *in situ.* La información aquí descrita tiene utilidad para planificar la remediación de sitios contaminados por elementos potencialmente tóxicos en México y para diferentes sitios del mundo.

Palabras clave: Contaminación, fitorremediación, elementos potencialmente tóxicos, plantas.

INTRODUCTION

Soil and water pollution are major environmental issues in the world. Metals are not biodegradable, they generally have little mobility and the ability to persist in natural ecosystems for a long time, even if they are in small amounts in the environment (Chițimus *et al*., 2016; Nithiyanantham *et al*., 2018; Strungaru *et al*., 2015).

Mining and smelting are important economic activities in Mexico (INEGI, 2010). The disposal of mining by-products, including metals and metalloids, produce considerable adverse environmental effects (Machado-Estrada *et al*., 2013). Each year, approximately 100 million tons of mining waste is generated in Mexico (SEMARNAT, 2010). Mining industries that extract Ag, Pb and Zn pour their residues into water bodies, which are employed for crop farming (Armienta *et al*., 2020); therefore, these contaminants might be incorporated into the food chain and pose serious risks for human health (Hazrat *et al*., 2013). In addition, the presence of these potentially toxic elements (PTE) could reduce land productivity (Prieto-Garcia *et al*., 2005). Mine tailings in Mexico also represent an important ecological problem due to the dispersion of pollutants (Cortés-Jiménez *et al*., 2013). The PTE in Mexico are Hg, As, Pb, Cd, Zn and Cr. The states from central Mexico have been disturbed by the pollution of soils and water with PTE

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(Covarrubias and Peña, 2017; González-Dávila *et al*., 2012; Hernández-Silva *et al.,* 2012). In addition, intoxication by Hg in humans has been reported (Martínez-Trinidad *et al.,* 2013).

In situ phytoremediation is based on the extraction of organic and inorganic pollutants from the environment, where plants grow in natural conditions and are exposed to different PTE (Figueroa *et al*., 2008). This strategy is non-disruptive, environmentally-friendly and cost-effective in the long-term. This process considers the level of contamination in the polluted site and the output of contaminants (van der Ent *et al*., 2013). The physicochemical parameters that influence the efficacy of *in situ* phytoremediation include pH, dissolved oxygen, sediment type, pollutant concentration, temperature, salinity, organic matter, weather, redox conditions, cation exchange capacity, hydrological cycle and mobilization of these contaminants in soil/water (Anawar, 2015; O'Connor *et al.,* 2019).

A plant considered to be used for phytoremediation must have the following features: high accumulation capacity of contaminants, high biomass production, quick adaptation to prevailing environmental and climatic conditions, capacity for nitrogen fixation, fast growth, deep root system and high pollution translocation from roots to shoots (Hazrat *et al*., 2013; Maiti and Jaiswal, 2008).

In situ phytoremediation involves the study of several polluting elements, evaluates chemical interactions among ions in the water/soil, and assesses the ability of plants throughout their cycle to survive in contaminated environments (González-Chávez *et al*., 2017); therefore, these studies can be useful for planning remediation of sites that have been contaminated with PTE. This review summarizes the information available from *in situ* phytoremediation studies carried out in Mexico.

METHODS

Literature search was performed to analyze studies carried out in Mexico with plants used for *in situ* extraction of PTE and trace metals from soil and water. The information was taken from Scopus, Web of Science, Scielo, and Pubmed. Scientific reports were searched through the following keywords: plant "or" hyperaccumulator, phytoremediation "and" *in situ*, phytoextraction, and Mexico. Scientific documents written in Spanish were also included in this review. Publications involved in this paper dated from the last three decades.

USE OF NATIVE PLANTS FOR *in situ* PHYTOREMEDIATION

Native plants represent a good strategy for *in situ* phytoremediation studies (Santos-Jallath *et al*., 2012). Usually, native plants present better rates of survival, growth, adaptation and reproduction under environmental stress conditions, compared to introduced plants (Fernández *et al*., 2010; Machado-Estrada *et al*., 2013; Yoon *et al*., 2006). In spite of their high ability to accumulate heavy metals, many plants are unable to adapt to different climates or different environmental conditions including drought and salinity. In addition, the introduction of new plant species might affect the dynamics of some ecosystems because some plants are considered invasive (Yoon *et al*., 2006).

The identification and use of native plants with high tolerance and capability to accumulate or stabilize PTE can decrease the spreading of contaminants and help to regenerate vegetation toward remediation of those sites (Carrillo and González-Chávez, 2006; Cortés-Jiménez *et al*., 2013; Salas-Luevano, 2009; Sánchez-López *et al*., 2015). Furthermore, native plants could be used as biomonitors, since they provide evidence on the existence of contaminants and as bioremediators of areas that are contaminated with PTE (Jeddi and Chaieb 2018; Khalid *et al.,* 2019; Ngayila *et al.,* 2007; Tzvetkova and Petkova, 2015). Native plants can be considered as models for studying mechanisms of tolerance and accumulation (Carranza-Álvarez *et al*., 2008).

In situ ACCUMULATION OF TRACE METALS BY PLANTS IN MEXICO

There are many sites in Mexico contaminated with PTE, most of them exceed the levels of trace metals in water/soil considered toxic (Mireles *et al*., 2004; Puga *et al*., 2006). Forty-six plant species were found with potential use on *in situ* phytoremediation studies in Mexico (Table 1). Most of the reports correspond to areas of North Central Mexico polluted with trace metals due to mining activities. This region is characterized by arid and semi-arid climates where small trees grow. The information indicates that members of the Asteraceae family and *Flaveria* genus are the most cited plant species for *in situ* phytoremediation in Mexico. This might indicate that they have developed mechanisms to tolerate, accumulate, or to avoid heavy metals.

The order of accumulation of heavy metals among the studied plants is as follows: Fe > Zn > Mn > Pb > As > Cr > Cu > Cd > Se > Hg. Studies with native vegetation growing on PTE polluted areas in México are scarce compared to other regions of the world (Carrillo and González-Chávez, 2006). Only 25 studies have been carried out in Southern Mexico (Avelar *et al.* 2013), where most areas are covered by rainforest.

Some reports have considered physicochemical characteristics of soil/water and the accumulation of PTE in plants (Carranza-Álvarez *et al*., 2008; Levresse *et al*., 2012; Mireles *et al*., 2004; Santos-Jallath *et al*., 2012). These characteristics are helpful to evaluate bioavailability of trace elements and their subsequent accumulation, sequestration or immobilization in plant tissues. Accumulation of PTE in plants depends on the chemical species of the PTE in soil/water, pH, age of the plant, mechanisms of mobilization at the sediment-water interface, and especially, the metabolism efficiency of plant ecotypes (Carranza-Álvarez *et al.* 2008; Levresse *et al.* 2012).

The highest accumulation of trace metals in roots is a common pattern in many phytoremediation studies in Mexico (Carrión *et al.,* 2012; Martínez-Trinidad *et al*., 2013, Mauricio *et al*., 2010; Mireles *et al*., 2004). The distribution of PTE in roots or aerial parts is affected by variation in the organization of root tissues, the size of the metal influences its movement within plants, and the mobility rate in the transport of PTE from the root to aerial parts (Skorbiłowicz *et al*., 2016; Vaculík *et al*., 2012; Yabanli *et al*., 2014). In some cases, roots can act as a barrier for metal translocation to provide protection against heavvy metal toxicity (Liu *et al*., 2009). Furthermore, the transportation of PTE from roots to shoots could take months; nevertheless, Puga *et al.* (2006) found out that most of the trace metals they evaluated (As and Zn) lied in aerial parts of the plants. It is known that athmospheric deposition might be another factor associated to the high accumulation of toxic elements in aerial parts (De Temmerman *et al.,* 2015).

Variations in accumulation patterns of PTE were observed in different plant species gathered from different sites of collection (Carmona-Chit *et al*., 2016; Franco-Hernández *et al*., 2010; Levresse *et al*. 2012; Salas-Luevano *et al.,* 2009); this might be attributed to the varied accumulation/tolerance mechanisms developed by each plant species against PTE toxicity, as well as variations among plant populations (Wan *et al.,* 2013).

HYPERACCUMULATOR PLANTS UNDER FIELD CONDITIONS IN MEXICO

According to van der Ent *et al*. (2013), plants capable of hyper-accumulating trace metals must meet these criteria: bioaccumulation factor (BF) higher than 1000 μg metal g^{-1} dry weight and translocation factor (TF) higher than 1. In México, a few metal-tolerant, accumulator, and hyperaccumulator plants have been reported (Table 1). Some of these plant species are cited in this review; for instance, *Hydrocotyle ranunculoides*, *Parietaria pensylvanica* and *Commelina diffusa* could be considered as hyperaccumulators of Zn (Carmona-Chit *et al*., 2016; Zarazúa-Ortega *et al.,* 2013), whereas *Polygonium aviculare* accumulated 9230 mg Zn kg^{-1}, which is close to the treshold (10,000 mg kg^{-1}) considered for hyperaccumulator plants (Carrillo and González-Chávez, 2006). *Rorippa nasturtium-aquaticum* (synonym *Nasturtium officinale* W.T. Aiton) and *Simsia amplexicaulis* could be considered as strong accumulators of Cu (Franco-Hernández *et al*., 2010). *Nicotina glauca*, *Flaveria angustifolia* and *Flaveria trinervia* can be considered accumulators of As, rather than hyperaccumulators (Franco-Hernández *et al*., 2010; Santos-Jallath *et al*., 2012). *Flaveria trinervia* easily adapts to grow on different environments, which is a highly desirable criterion in phytoremediation studies. *Buddleja scordioides* is a good candidate to be used in phytoremediation of Pb-contaminated soils (Salas-Luevano *et al.,* 2009); however, special attention is needed with *Buddleja scordioides* and *Simsia amplexicaulis* since they are also used in traditional medicine in Mexico (Cortés *et al*., 2006; Sotero-García *et al*., 2016). Thus, contaminants such as Pb and Cu could be ingested by humans and cause health problems. Puga *et al.,* (2006) studied *Baccharis glutinosa* for the accumulation of As and Zn. *Cynodon dactylon* is a potential accumulator of Zn and Mn (Hernández-Acosta *et al*., 2009; Puga *et al*., 2006). Juárez-Santillán *et al*., (2010) studied plants in a mining area of Mn in Hidalgo, Mexico and identified *Cnidoscolus multilobus*, *Platanus mexicana*, *Solanum diversifolium*, *Asclepius curassavica* and *Pluchea sympitifolia* as accumulator species.

It is interesting to note that plants cited in this review such as *Parietaria pensylvanica, Buddleja scordioides, Flaveria angustifolia* and *Flaveria trinervia* are being reported for the first time for their ability to accumulate metals. This indicates that more studies should be carried out with flora from Mexico to evaluate their use in phytoremediation. From accumulator plant species, *Hydrocotyle ranunculoides* and *Rorippa nasturtium-aquaticum* are dispersed worldwide while *Parietaria pensylvanica* and *Commelina diffusa* are native to America.

PERSPECTIVES AND FUTURE NEEDS

Many phytoremediation reports are conducted using controlled conditions; however, the ability of plants for accumulating PTE under field conditions remains to be studied in Mexico. This review provides information about the potential plant species to accumulate As, Cd, Cr, Cu, Fe, Hg, Mn, Se, Pb and Zn (Table 1).

Table 1. ***In situ* phytoremediation studies in Mexico.**

State	Site of study	Potential plant species	PTE (maximum accumulation reported in mg kg^{-1})										Reference
			As	Cd	Cr	Cu	Fe	Hg	Mn	Se	Pb	Zn	
Chihuahua	San Francisco del Oro	*Baccharis glutinosa* Pers. (Asteraceae)	88.23	-	-	-	-	-	-	-	-	361.46	Puga *et al.* (2006)
		Cynodon dactylon (L.) Pers (Poaceae)	-	-	-	-	-	-	-	-	-	302.18	
	Parral, Santa Barbara, Naica	*Eleocharis* sp. (Cyperaceae)	301 ± 0.72	-	-	-	-	-	-	-	-	-	Flores-Tavizón *et al.* (2003)
Ciudad de México	Xochimilco	*Eichhornia crassipes* (Mart.) Solms (Pontederiaceae)	-	0.7 ± 9	58.1 ± 7	27.3 ± 12	**1660.4** ± 18	-	587.3 ±10	-	7.7 ± 6	135.5 ±17	Carrión *et al.* (2012)
Estado de México	Lerma River	*Hydrocotyle ranunculoides* L. f. (Araliaceae)	-	-	15.76	30.37	**20268**	-	4324	-	7.7	172	Zarazúa *et al.* (2013)
Guanajuato	San German, León	*Scirpus americanus* Pers. (Cyperaceae)	58	65	971	-	-	-	-	90	-	-	Mauricio *et al.* (2010)
	Silver and gold mining	*Ricinus communis* L. (Euphorbiaceae)	-	0.123 ± 0.008	-	2.6 ±0.07	-	-	-	-	2.74 ± 0.06	-	Figueroa *et al.* (2008)
Guerrero	La Concha, Taxco	*Gnaphalium chartaceum* Greenm (Asteraceae)	-	-	-	121	-	-	744	-	2901	4906	Cortés-Jiménez *et al.* (2013)
		Wigandia urens (Ruiz & Pav.) Kunth (Boraginaceae)	-	-	-	-	-	-	-	-	-	1027	
		Senecio salignus DC (Asteraceae)	-	-	-	-	-	-	-	-	-	2477	
	Zimapán	*Zea mays* L. (Poaceae)	4.26 ± 0.96	1.50 ± 0.88	-	-	**1322 ± 284**	-	-	-	91.7 ± 16.5	335 ± 24	Armienta *et al.* (2020)
		Rorippa nasturtium-aquaticum (L.) Hayek (Brassicaceae)	-	-	-	350	-	-	-	-	-	-	
Hidalgo	Zimapán	*Parietaria pensylvanica* Muhl. ex Willd. (Urticaceae)	-	-	-	-	-	-	-	-	-	7630	Carmona-Chit *et al.* (2016)
		Commelina difusa Burm. f. (Commelinaceae)	-	-	-	-	-	-	-	-	-	5086	
	San Francisco and Santa Ana, Zimapán	*Viguiera dentata* (Cav.) Spreng. (Asteraceae)	-	21 ±3	-	-	-	-	189 ± 57	-	-	2231 ± 29	Sánchez-López *et al.* (2015)
		Gnaphalium sp. (Asteraceae)	-	-	-	-	-	-	338 ± 36	-	-	-	
		Cuphea lanceolata W.T. Aiton (Lythraceae)	-	-	-	352 ± 25	-	-	-	-	-	-	

Table 1. Continues.

State	Site of study	Potential plant species	PTE (maximum accumulation reported in mg kg^{-1})										Reference
			As	Cd	Cr	Cu	Fe	Hg	Mn	Se	Pb	Zn	
	Nonoalco	*Ambrosia psilostachya* DC. (Asteraceae)	-	-	-	-	-	-	89.8 ± 27.07	-	-	-	Rivera-Becerril *et al.* (2013)
	Zimapán	*Ricinus communis* L (Euphorbiaceae)	-	8	-	48	-	-	180	-	170	590	Ruiz *et al.* (2013)
	Molango	*Platanus mexicana* Moric. (Platanaceae)	-	-	-	-	-	-	410.86 ± 5.11	-	-	-	Juárez-Santillán *et al.* (2010)
		Asclepias curassavica L. (Apocynaceae)	-	-	-	-	-	-	1507.69 ± 9.78	-	-	-	
		Solanum diversifolium Dunal (Solanaceae)	-	-	-	-	-	-	562.57 ± 49.92	-	-	-	
		Pluchea symphytifolia (Mill.) Gillis (Asteraceae)	-	-	-	-	-	-	1062.58 ± 7.0	-	-	-	
		Cnidoscolus multilobus (Pax) I.M. Johnst. (Euphorbiaceae)	-	-	-	-	-	-	1055.80 ± 22.27	-	-	-	
	Dos Carlos, Pachuca	*Solanum corymbosum* Jacq. (Solanaceae)	-	-	-	6	-	-	-	-	-	-	Hernández-Acosta *et al.* (2009)
		Brickellia veronicaefolia (Kunth) A. Gray (Asteraceae)	-	-	-	-	-	-	-	-	5	20	
		Atriplex suberecta I. Verd. (Amaranthaceae)	-	1	-	-	-	-	-	-	-	-	
		Cynodon dactylon (L.) Pers. (Poaceae)	-	-	-	-	-	-	69	-	-	-	
	Zimapán	*Prosopis laevigata* (Humb. & Bonpl. ex Willd.) M.C. Johnst. (Fabaceae)	1400	-	-	-	-	-	-	-	-	-	Armienta *et al.* (2008)
		Acacia farnesiana (L.) Willd. (Fabaceae)	225	-	-	-	-	-	-	-	-	-	

Table 1. Continues.

State	Site of study	Potential plant species	PTE (maximum accumulation reported in mg kg^{-1})										Reference
			As	Cd	Cr	Cu	Fe	Hg	Mn	Se	Pb	Zn	
	San Joaquín	*Zea mays* L. (Poaaceae)	-	-	-	-	-	0.04 - 8.2	-	-	-	-	Martínez-Trinidad *et al.* (2013)
	San Joaquín	*Zea mays* L. (Poaaceae)	-	-	-	-	-	0.04 -8.7	-	-	-	-	Hernández-Silva *et al.* (2012)
Querétaro		*Nicotiana glauca* Graham (Solanaceae)	91.94	106.07	-	95.17	-	-	-	-	-	1984.48	
	La Negra Mine	*Flaveria pubescens* Rydb. (Asteraceae)	-	-	-	102.46	-	-	-	-	222.89	755.82	Santos-Jallath *et al.* (2012)
		Tecoma stans (L.) Juss. ex Kunth (Bignoniaceae)	-	-	-	-	-	-	-	-	-	942.8	
		Euphorbia prostrata Aiton (Euphorbiaceae)	165	-	-	88	-	-	-	-	66	300	
	Villa de la Paz	*Parthenium incanum* Kunth (Asteraceae)	130	-	-	76	-	-	-	-	34	350	Machado-Estrada *et al.* (2013)
		Zinnia acerosa (DC.) A. Gray (Asteraceae)	93	-	-	70	-	-	-	-	49	340	
	Real de Catorce	*Nicotiana tabacum* L. (Solanaceae)	-	-	-	10.33	-	-	5.15	-	-	6.93	Levresse *et al.* (2012)
San Luis Potosí		*Ambrosia artemisiifolia* L. (Asteraceae),	-	-	-	-	-	-	-	-	-	405.7	
		Simsia amplexicaulis (Cav.) Pers. (Asteraceae),	-	-	-	75.8	-	-	-	-	-	-	Franco-Hernández *et al.* (2010)
	Villa de la Paz	*Flaveria angustifolia* (Cav.) Pers. (Asteraceae),	198.5	-	-	-	-	-	-	-	-	-	
		Flaveria trinervia (Spreng.) C. Mohr (Asteraceae)	179.4	-	-	-	-	-	-	-	-	-	
	Artificial lagoon	*Typha latifolia* L. (Typhaceae)	-	4.6 ± 0.08	-	-	-	-	-	-	-	-	Carranza-Álvarez *et al.* (2008)
		Scirpus americanus Pers. (Cyperaceae)	-	-	344.6 ± 15.4	-	1229.9 ± 20	-	3330.2 ± 125	-	26.5 ± 3.5	-	
Yucatán	Yum Balam Reserve	*Thalassia testudinum* Banks & Sol. ex K.D. Koenig (Hydrocharitaceae)	-	0.2-5	0.5-1.1	-	141.4 - 504.3	-	-	-	-	-	Avelar *et al.* (2013)
	Zacatecas	*Asphodelus fistulosus* L. (Asphodelaceae)	-	-	-	-	-	-	-	-	917 ± 1	1946 ± 2	Flores *et al.* (2018)

Table 1. Continues.

State	Site of study	Potential plant species	PTE (maximum accumulation reported in mg kg^{-1})										Reference
			As	Cd	Cr	Cu	Fe	Hg	Mn	Se	Pb	Zn	
Zacatecas	Fresnillo	*Dalea bicolor* Humb. & Bonpl. ex Willd. (Fabaceae)	-	-	-	-	-	-	-	-	970 ± 2	1296 ± 1	Salas-Luévano *et al*. (2017)
		Acacia schaffneri (S. Watson) F.J. Herm. (Fabaceae)	3838	**17**	-	-	-	-	-	-	534	-	
		Amaranthus hybridus L. (Amaranthaceae)	2218	17	-	-	-	-	-	-	842	-	
		Arundo donax L. (Poaceae)	1078	7.9	-	-	-	-	-	-	272	-	
		Asphodelus fistulosus L. (Asphodelaceae)	4387	13	-	-	-	-	-	-	512	-	
		Buddleja cordata Kunth (Scrophulariaceae)	3454	24	-	-	-	-	-	-	1282	-	
		Plantago lanceolata L. (Plantaginaceae)	4150	17	-	-	-	-	-	-	556	-	
	Guadalupe	*Zea mays* L. (Poaaceae)	98.15	-	-	213.63	-	-	629.71	-	293.24	849.74	González-Dávila *et al.* (2012)
	Francisco I. Madero	*Amaranthus hybridus* L. (Amaranthaceae)	-	-	-	-	-	-	-	-	2208 ± 136	-	Salas-Luevano *et al*. (2009)
		Buddleja ser. Scordioides E.M. Norman (Scrophulariaceae)	-	-	-	-	-	-	-	-	1378 ± 153	-	
		Cerdia congestiflora Hemsl. (Caryophyllaceae)	-	-	-	-	-	-	-	-	1175 ± 126	-	
	El Bote, San Martín, Fresnillo and Noria de los Ángeles	*Polygonum aviculare* L. (Polygonaceae)	-	-	-	-	-	-	-	-	-	9236	Carrillo and González-Chávez (2006)
		Jatropha dioica Sessé ex Cerv. (Euphorbiaceae)	-	-	-	-	-	-	-	-	-	6249	

PTE: potentially toxic elements. Concentrations of heavy metals obtained in hyperaccumulators plants are shown in bold type.

As far as we know, the mechanism of metal accumulation by plants cited in this review remains to be studied; thus, it is essential to generate scientific evidence to understand how these plant species accumulate or hyperaccumulate trace elements at the molecular level. Several plants that grow for years under heavy metal-induced stress have used physiological strategies for their adaption and growth under these conditions. Some of these mechanisms include the enhance of xylem loading capacity for PTE, as well as the excretion of phytochelatins, metallothioneins and low molecular weight organic acids (Koźmińska *et al.*, 2018). The efficacy of *in situ* phytoremediation will rely on understanding these molecular mechanisms.

Some microorganisms such as *Streptomyces tendae*, *Funneliformis mosseae, Bacillus thuringiensis, Microbacterium saperdae, Pseudomonas monteilii, Enterobacter cancerogenes, Serratia marcescens* and *Rhodotorula mucilaginosa* (Babu *et al*., 2013; Dimkpa *et al*., 2009; Hassan *et al*., 2013; Ji *et al*., 2012; Whiting *et al*., 2001) can enhance phytoremediation through several pathways: i) accelerating plant growth, ii) increasing bioavailability of PTE, iii) facilitating metal translocation from the soil to the roots, and iv) inducing the translocation from the roots to shoots (Ma *et al.,* 2001; Rajkumar *et al.,* 2012). Mycorrhizal status of PTE-accumulating plants growing in contaminated sites should also be studied. The interactions among Mexican native plants and microorganisms is an interesting topic to study in the framework of *in situ* phytoremediation. It is important to use herbarium techniques for taxonomic identification of plant species to be incorporated in phytoremediation studies under controlled and field conditions.

Before carrying out a phytoremediation study, the speciation of metals in soil and water should also be considered to evaluate their bioavailability, mobilization processes of these elements in soil-plant or water-plant systems, and their possible interactions with soil particles (Guo *et al.,* 2019; Pan *et al.,* 2019).

CONCLUSIONS

Native plants should be considered as a good strategy for remediation and reclamation of soil and water contaminated with PTE. This review clearly demonstrates that more studies are needed with flora from Mexico to evaluate their use in phytoremediation. There are several crop species (*i.e. Amaranthus hybridus* and *Zea mays)* that present tolerance to heavy metal contamination. Some of these plants could be metal excluders. In addition, the molecular mechanisms by which plants hyperaccumulate toxic elements remain to be explored.

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