HEAVY METAL PHYTOREMEDIATION POTENTIAL OF PLANT SPECIES IN A MANGROVE ECOSYSTEM IN PATTANI BAY, THAILAND

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Abstract. In a mangrove forest in Pattani Bay, Thailand, rhizosphere soil and leaf, stem and root tissue from various plant species were tested for concentrations of Cd, Cr, Cu, Mn, Ni, Pb and Zn. Of these metals, Pb concentrations in the mangrove sediment were somewhat elevated. Mn occurred in highest concentrations in tissue of all mangrove species whereas Cd contents were lowest. Both sediment physicochemical properties (e.g., pH, EC, redox potential) and plant species characteristics have likely influenced metal concentrations in plant tissue. Several mangrove species fit the criteria for excluder plants as they accumulated metals mainly in roots, with a resultant translocation factor (TF) < 1 and a bioconcentration factor (BCF) > 1. These include *Cyperus involucratus* for Cu, *Ipomoea pes-caprae* for Zn, *Typha angustifolia* for Mn, and *Phragmites karka* for Pb. Furthermore, some species have accumulator potential, as metals accumulated in aboveground biomass (leaves and stem), and have TF > 1 and BCF > 1; however, these species (e.g., *Thespesia populnea* for Ni and *C. involucratus* for Cr) did not accumulate metals to the extent that they fit the criteria for hyperaccumulators. Continued investigation of metals in sediment and plant organs must be carried out to determine additional species suitable for phytoremediation, and to ensure healthy food chains in coastal ecosystems.
Keywords: *phytoremediation, mangrove, Pattani Bay, heavy metals*

Introduction

Mangrove forests are among the most biologically productive ecosystems worldwide, and comprise an important component of both coastal and marine ecosystems (Sandiyan and Kathiresan, 2012; Sandiyan and Thiyagesan, 2010). Mangroves are located primarily in tropical and sub-tropical zones (Peters et al., 1997; Moreira et al., 2013). These unique forests serve as nurseries for myriad aquatic fauna; they are critical habitats for a wide spectrum of biota including fish, crustaceans and other macro- and microfauna comprising the food web.

The root systems of mangrove trees reduce soil erosion and help stabilize adjacent coastal landforms (Harty, 1997). Moreover, it has been documented that mangrove sediments act as a sink for immobilization of metals from anthropogenic sources which enter local ecosystems (Peters et al., 1997; Tam and Wong, 1997). Metals occurring in mangrove ecosystems are adsorbed to surfaces of clay and fine silt, entrapped within the lattice structure of silicate clays, adsorbed to Fe and Mn oxides (Harbison, 1986), and

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precipitate as sulphides. In addition, metals can become immobilized within the biomass of rhizosphere microorganisms.

For decades phytoremediation technology has proven successful in treating a range of soil contaminants (Ghosh and Singh, 2005). Certain plants have the ability to uptake and accumulate metallic contaminants via the root system and store them in various plant compartments (Tangahu et al., 2011). According to Baker (1981), plants considered for phytoremediation embrace three key groups based on physiological mechanism: excluders (as employed in phytostabilization), accumulators (for phytoextraction), and indicators. Excluders are those plants that restrict contaminant uptake and accumulation, while accumulators translocate contaminants from roots to aboveground biomass. Indicator plants control the movement of contaminants from roots to shoots; therefore, the concentration of metal in the parent soil is reflected by a proportional concentration in the shoots.

Recent studies have documented the incidence and severity of sediment contamination by heavy metals in mangrove ecosystems (Anouti, 2014; Ratheesh Kumar et al., 2010). Contaminants are released via industrial activities and ultimately enter aquatic ecosystems (Ratheesh Kumar et al., 2010). The primary contaminant metals are Cu, Mn, Ni, Zn, Pb, Cd, and As, which have been detected in significant concentrations in coastal and inshore waters (Kapi et al., 2011; Machado et al., 2002).

Pattani Bay is located along the coast of the Gulf of Thailand, Pattani Province. The bay provides critical habitat for many macroalgal and seagrass species (Hajisamae et al., 2006; Ruangchuay et al., 2007). Some species cultivated in the bay, such as *Gracilaria fisheri* and *G. tenuistipitata*, are important local foods as well as products for overseas export (Ruangchuay et al., 2007). The coastal zone also contains large expanses of sandy and muddy sediments important for clam farming and local fisheries (Swennen et al., 2001).

Several local industries including mining, cement manufacture, ship construction, and food processing have, in recent decades, released a suite of heavy metals into Pattani Bay (Cheewasedtham et al., 2003). As a result, mangrove sediments may contain elevated concentrations of metallic contaminants. Recent reports indicate that the Pattani Bay region contains high concentrations of Pb and As and exceeds the soil quality standards of the United States Environmental Protection Agency for residential areas (> 400 and 4 mg kg^{-1} for Pb and As, respectively) (Sowana et al., 2011). Industrial activities and domestic wastes are believed to be the main causes of heavy metal contamination in seawater of the bay, which adversely affects aquatic organisms, for example the blood clam (*Anadara granosa*), an important cultured benthic organism in this area, via accumulation of metals (Suwanjarat et al., 2009).

A number of innovative technologies are available for the removal or immobilization of heavy metals from soil and sediments including soil flushing, electrokinetic remediation, chemical oxidation/reduction, and vitrification. Many of these technologies, however, are energy-intensive, have substantial start-up and operational costs, require specialized training, and require the use of hazardous chemicals (Pichtel, 2007).

Phytoremediation is a relatively low-cost and environmentally benign technology which can minimize concentrations of contaminant heavy metals that persist in soil and sediment. Specifically, phytoextraction (i.e., metal uptake and removal) and phytostabilization (metal immobilization in or near the rhizosphere) are applicable technologies for use in mangrove forests (Gohre and Paszkowski, 2006; Paz-Alberto and Sigua, 2013). Some researchers have indicated that phytostabilization is, to some

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extent, more reliable for remediation of metal contamination as it prevents the release of secondary contaminants that may occur during planting (Singh and Tripathi, 2007). *Rhizophora mucronata* is considered one of the most effective excluder mangrove trees – it has been documented to have stabilized Cu, Cd, Cr, Fe, Mg, Ni, Pb and Zn, primarily in the root (Panfili et al., 2005; Pahalawattaarachchi et al., 2009). However, there are no reports on the use of mangroves for phytoremediation in Thailand.

The identification of effective phytoremediation species in Thailand's mangrove forests is especially urgent, as there are concerns of significant losses of mangrove communities due to anthropogenic activities such as human settlement, water transportation, and agricultural and aquaculture activities (Aksornkoae, 1993; Plathong and Sitthirach, 1998). It is estimated that mangrove forests along Thailand's east coast have been reduced by at least 10% over the past five decades (Thampanya et al., 2006).

The current report describes the first investigation of the potential of mangrove plants for phytoremediation in Thailand. Different parts of the mangrove plant were assessed for heavy metal uptake and accumulation; these data were compared with corresponding concentrations in sediments. Plant parts were subsequently classified for their potential for phytoremediation of heavy metals in contaminated mangrove ecosystems.

Materials and Methods

Site Description

Pattani Bay is located on the eastern Gulf of southern Thailand (*Fig. 1*). This semi-enclosed estuarine bay, measuring approximately 74 km^2, receives input from two major rivers, the Pattani and the Yaring (Hajisamae et al., 2006; Suwanjarat et al., 2009; Swennen et al., 2001). The water regime of the bay is a complex system which receives significant influences from tidal inputs and the tropical monsoon climate as well as surface runoff and drainage from the two rivers. Water depth in the bay ranges from 0.2 to 1.5 m with a maximum 5 m depth at the mouth of the bay. Cumulative annual rainfall and average annual temperature at Pattani Bay in 2014 were 2008.5 mm and 27.5 °C, respectively.

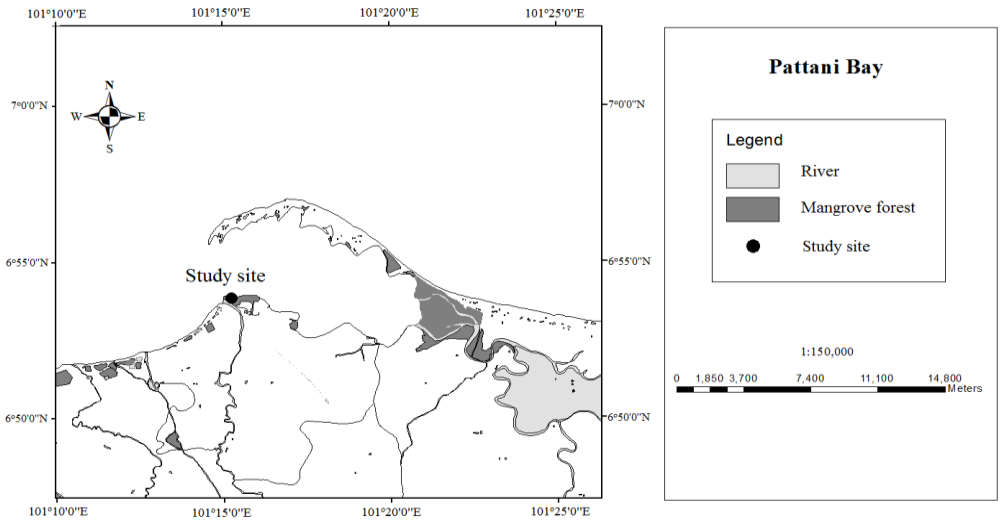

Figure 1. *Map of study site, Pattani Bay, Thailand*

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Plant sampling

The sampling site, considered representative of a mangrove ecosystem, measures approximately 40 ha and is located near the mouth of the bay (*Fig. 1*).

In the study area, dominant mangrove plants were identified and used for tissue analysis and for collection of rhizosphere soil. Three plants from each species were collected. Plant tissue was returned to the laboratory and stored in a plant press. Tentative identification of species was via Aksornkoae et al. (1992) and later confirmed by the Department of Forestry, Thailand.

Physicochemical properties of soil material

Fifteen samples of surface sediments (0-15 cm depth) were collected near the rhizosphere of each mangrove plant. Samples were mixed in the field to create a composite sample. Samples were returned to the laboratory, oven-dried at 80 °C, ground using an agate mortar and pestle, and sieved through a 2-mm mesh nylon sieve. Samples were stored in plastic bags until analysis.

Sediment pH was analyzed in a 1:5 suspension of soil to deionized (DI) water using a pH meter (Accumet® AP115 pH meter). Electrical conductivity (EC) was analyzed in sediment extracts (1:5) using an EC meter (Hanna instruments; HI 993310). Sediment organic matter content was determined by the Walkley-Black titration method (Walkley and Black, 1934). Cation exchange capacity (CEC) was measured by leaching with 1 N ammonium acetate buffered to pH 7.0 (Sparks, 1996). Salinity was determined by a salinometer. Texture was determined by the hydrometer method (Allen et al., 1974). Total N was determined by the Kjedahal method (Black, 1965), extractable P using Mehlich-3 (Bray and Kurtz, 1945), and extractable K by ICP-OES after extraction with NH_4OAc (pH 7.0) (Sparks, 1996).

Total metal (Cd, Cr, Cu, Mn, Ni, Pb, Zn) concentrations were determined by either FAAS or GF-AAS (APHA/AWWA/WEF, 2005), depending on metal concentration in the samples, after acid digestion in a microwave digestion system (ETHOS One; Milestone Inc., Shelton, CT, USA). Extractable metals were recovered using 0.5 *M* diethylene triamine pentaacetic acid (DTPA), then determined by flame atomic absorption spectrophotometry (FAAS) or graphite furnace atomic absorption spectrophotometry (GF-AAS) (APHA/AWWA/WEF, 2005). An appropriate sediment and plant tissue standard reference material (NIST SRM® 2710a Montana soil, and NIST SRM® 1515 apple leaves, respectively) and a reagent blank (Merck®; trace metal grade) were used to check the quality and metrological traceability of the samples and to validate analytical methods.

Plant sampling and heavy metals analyses

Leaves, stems and roots were cut from selected locations on each plant using stainless steel scissors. All plant parts were thoroughly washed with tap water and phosphate-free soap in a plastic container, then rinsed several times to remove any attached soil and soap. Finally, plant tissue was rinsed twice with DI water. Leaf, stem and root tissue was oven-dried at 80 °C for 2-3 days. Tissue was subsequently ground to a fine powder and sieved through a 2-mm mesh nylon sieve. One-half g of plant tissue was placed in each vessel tube with conc. 70% HNO_3 and 37% HCl for microwave digestion (ETHOS One; Milestones Inc.). The digested samples were tested for concentration of Cd, Cr, Cu, Mn, Ni, Pb and Zn by either FAAS or GF-AAS.

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Data analyses

The translocation factor (TF) for each plant was calculated by dividing metal concentration in the shoot by metal concentration in the root. A TF value >1 indicates the plant's potential to translocate metal effectively from root to shoot (Rezvani and Zaefarian, 2011). The equation was as follows:

$$TF_{leaf} = C_{leaf}/C_{root}$$

$$TF_{stem} = C_{stem}/C_{root}$$

where C_{leaf}, C_{stem} and C_{root} are the metal concentrations in leaf, stem and root, respectively.

The bioconcentration factor (BCF) is defined as the ratio of metal concentration in the shoot to the extractable metal concentration in the rhizosphere soil (Rezvani and Zaefarian, 2011). This value reflects the progressive accumulation of metal in the plant (Branquinho et al., 2007). The bioconcentration factor for metals was calculated as follows:

$$BCF_{leaf} = C_{leaf}/C_{sediment\ (extractable\ metal)}$$

$$BCF_{stem} = C_{stem}/C_{sediment\ (extractable\ metal)}$$

$$BCF_{root} = C_{root}/C_{sediment\ (extractable\ metal)}$$

where C_{leaf}, C_{stem} and C_{root} are the metal concentrations in leaf, stem and root, respectively, and $C_{sediment}$ is the metal concentration in the sediment.

Data were expressed as mean±standard deviation (SD). Analysis of variance (One way ANOVA; SPSS version 18.0) was used to assess differences in plant metal uptake characteristics.

Results and Discussion

Sediment characteristics in mangrove forest

The pH of the mangrove sediments was slightly alkaline (pH 7.3) (*Table 1*). Sediment EC was relatively high (5.5 mS cm^{-1}), which reflects the influence of seawater. Concentrations of total N and extractable P and K were relatively low; however, values were still within the ranges found for mangrove sediments in other studies (Sowana et al., 2011). Soil OM content was 2.3%. High concentrations of soil OM have been measured in mangrove forests of Pattani Bay, with maximum values reaching 4.5% (Sowana et al., 2011). The relatively high organic matter content in the mangrove sediment arises from decomposition of plant material and other detritus of both terrestrial and marine origin (Marchand et al., 2011). Soil texture was loam; however, other mangrove sediments worldwide are known to contain high clay and silt content (Stokes and Harris, 2015; Zhang et al., 2013).

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Table 1. *Selected physicochemical properties of the mangrove sediment*

Parameter	Sediment
pH	7.3±0.2
EC (mS cm^{-1})	5.5±2.9
CEC (cmol(+) kg^{-1})	11.6±2.5
OM (%)	2.3±0.6
Total N (%)	0.1±0.0
Ext P (mg kg^{-1})	880.0±100.1
Ext K (mg kg^{-1})	886.0±105.8
Salinity (ppt)	16.4±5.9
Soil texture	Loam

EC=electrical conductivity, CEC=cation exchange capacity, OM=organic matter, Ext = extractable

Sediment metal concentrations (*Table 2*) were similar to or lower than those recorded in studies of metal-contaminated sediments from other locations worldwide (Xu et al., 2015; Banerjee et al., 2012; Chakraborty et al., 2012). Concentrations of Cd, Cr, Cu, Mn, Ni and Zn were within world average concentrations for sediments as proposed by Turekian and Wedepohl (1961). However, sediment Pb concentration was 47 mg kg^{-1}, which is slightly elevated and believed to arise from industrial activities located nearby.

Table 2. *Total and extractable forms of metals in mangrove sediments of selected coastal zones*

Metal	Pattani Bay (Present study)	Shenzhen City (Xu et al., 2015)	Ganges (Banerjee et al., 2012)	Godavari (Chakraborty et al., 2012)
Cd (mg kg^{-1})	0.2±0.1	BDL[1]	2.0	24.8
Cr (mg kg^{-1})	58.3±7.5	33.8±16.4	40.1	71.2
Cu (mg kg^{-1})	22.1±1.7	52.9±29.1	21.6	103.4
Mn (mg kg^{-1})	101.4±18.3	331.0±133.0	502.4	-
Ni (mg kg^{-1})	16.9±8.7	21.8±8.0	34.0	63.8
Pb (mg kg^{-1})	47.3±7.1	48.3±17.8	23.5	424.0
Zn (mg kg^{-1})	26.6±3.9	182.0±94.1	53.4	3876.7
Ext Cd (mg kg^{-1})	BDL	-[2]	-	-
Ext Cr (mg kg^{-1})	0.7± 0.2	-	-	-
Ext Cu (mg kg^{-1})	6.5±1.1	-	-	-
Ext Mn (mg kg^{-1})	22.9±9.4	-	-	-
Ext Ni (mg kg^{-1})	2.9±0.9	-	-	-
Ext Pb (mg kg^{-1})	7.5±2.3	-	-	-
Ext Zn (mg kg^{-1})	2.3±0.2	-	-	-

[1] = BDL = below detectable limits.
[2] = Data not available.

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Plant survey in the study site

Based on field observations the predominant mangrove and mangrove associated species show a remarkable diversity in the study area at Pattani Bay. A total of 18 species were identified and grouped based on plant habits as follows: groundcover (*Wedelia biflora*, *Sesuvium portulacastrum*, *Ipomoea pes-caprae*, *Phyla nodiflora*); climbing plants (*Derris trifoliata*, *Passiflora foetida*); grass plants (*Dichanthium caricosum*, *Phragmites karka*), shrub (*Avicennia marina*, *Acanthus ebracteatus*, *A. alba*, *Pluchea indica*,); trees (*Thespesia populnea*, *Rhizophora mucronata*); aquatic plants (*Typha angustifolia*, *Eleocharis dulcis*, *Cyperus involucratus*), and pteridophyte plants (*Acrostichum aureum*). Only *Avicennia* spp. and *R. mucronata* were classified as mangrove species, while others were mangrove-associated species. The mangrove shrubs are the primary ecotone species in mangrove ecosystems and serve as habitat for both terrestrial and marine organisms. *Wedelia biflora* and *S. portulacastrum* were the predominant groundcover species, while *A. marina* and *P. indica* were the dominant shrub species. *Avicennia marina* was reported to grow abundantly in several mangrove forests in Pattani province (Plathong and Sitthirach, 1998), while Hajisamae and Yeesin (2014) found that *Rhizophora* spp. was the dominant mangrove tree species occurring in coastal zones of Pattani Bay. However, many mangrove species such as *Rhizophora mucronata*, *R. apiculata*, *Sonneratia alba*, *A. alba*, *A. officinalis*, *Bruguiera gymnorhiza*, *B. cylindrical*, *Xylocarpus moluccensis*, *Acanthus ilicifolius*, *Excoecaria agallocha* and *Nypa fruticans* were found to be dominant nearby (Hajisamae et al., 2006).

Heavy metal content and phytoremediation potential of mangrove species

Each mangrove species accumulated metals at different rates ($p < 0.05$), depending on both species and plant organ (Madejón et al., 2003; Marschner, 1986) (*Table 3*).

Table 3. *Metal concentrations in mangrove plant parts. (n=3)*

Plant	Tissue	Metal concentration (mg kg^{-1})						
		Cu	Zn	Ni	Mn	Cr	Cd	Pb
W. biflora	Stem	8.1±0.6^{b}	20.0±0.8^{b}	17.0±2.9^{a}	11.3±1.8^{a}	1.8±0.1^{a}	0.4±0.0^{b}	15.8±0.3^{b}
	Leaf	8.6±0.3^{b}	14.0±2.0^{a}	14.0±4.4^{a}	26.0±4.0^{c}	1.1±0.1^{a}	0.4±0.0^{c}	4.1±0.3^{a}
	Root	16.2±0.0^{b}	19.0±1.5^{ab}	11.0±0.4^{a}	25.7±3.0^{b}	1.0±0.0^{a}	0.3±0.0^{b}	7.9±0.3^{a}
S. portulacastrum	Stem	17.3±2.1^{d}	21.7±0.3^{b}	40.2±1.2^{c}	9.4±0.0^{a}	0.6±0.1^{a}	0.2±0.1^{b}	6.9±0.5^{a}
	Leaf	8.3±0.3^{b}	19.0±3.3^{b}	32.8±8.2^{c}	12.8±1.7^{b}	0.6±0.0^{a}	0.3±0.0^{b}	3.6±0.2^{a}
	Root	8.3±0.7^{a}	17.1±0.6^{a}	30.6±2.3^{c}	19.5±1.7^{a}	0.6±0.0^{a}	0.3±0.1^{b}	17.0±3.6^{b}
I. pes-caprae	Stem	3.8±0.1^{a}	8.6±0.4^{a}	22.9±1.1^{b}	22.9±1.1^{b}	31.4±5.7^{c}	0.6±0.1^{c}	17.7±1.2^{b}
	Leaf	5.0±0.5^{a}	14.4±5.3^{a}	25.1±0.7^{b}	38.5±5.1^{d}	37.6±1.4^{c}	0.6±0.0^{d}	25.9±1.9^{c}
	Root	20.8±0.7^{c}	78.1±1.3^{c}	52.9±7.4^{d}	236.2±21.4^{c}	107.1±4.0^{c}	0.5±0.1^{c}	4.4±0.6^{a}
P. nodiflora	Stem	12.8±0.6^{c}	22.2±0.1^{b}	23.6±3.8^{b}	10.7±0.5^{a}	13.0±1.5^{b}	0.1±0.0^{a}	BDL[1]
	Leaf	7.8±0.6^{b}	17.2±0.1^{a}	18.6±3.8^{ab}	5.7±0.5^{a}	8.0±1.5^{b}	0.1±0.0^{a}	3.1±0.1^{a}
	Root	22.5±1.8^{d}	20.7±0.1^{b}	23.1±2.3^{b}	23.1±2.3^{a}	26.6±1.0^{b}	0.2±0.0^{a}	BDL
D. trifoliata	Stem	13.3±1.4^{a}	17.5±3.0^{a}	26.2±1.0^{a}	82.4±7.0^{b}	38.5±6.0^{a}	BDL	40.8±2.1^{b}
	Leaf	8.3±1.4^{a}	12.5±3.1^{a}	21.2±1.0^{b}	77.4±7.0^{b}	33.5±6.0^{b}	BDL	45.8±2.1^{b}
	Root	15.1±0.2^{a}	14.0±1.3^{a}	22.5±0.5^{a}	8.9±0.2^{a}	16.8±1.5^{a}	0.1±0.0^{a}	5.2±0.1^{a}
P. foetida	Stem	14.3±0.5^{c}	28.2±0.7^{b}	20.9±0.5^{a}	20.3±1.4^{a}	20.4±1.1^{b}	0.1±0.0	27.8±0.8^{a}
	Leaf	9.4±0.4^{b}	23.3±0.7^{b}	16.0±0.6^{a}	15.4±1.5^{a}	15.5±1.0^{a}	0.1±0.0	22.9±1.0^{a}
	Root	20.3±0.9^{b}	26.9±3.1^{b}	22.6±1.3^{a}	11.3±1.9^{b}	21.8±2.3^{b}	0.1±0.0^{a}	32.0±2.0^{b}
D. caricosum	Stem	6.9±0.3^{a}	10.1±0.6^{a}	21.8±0.6^{b}	94.1±1.7^{b}	22.3±0.7^{a}	0.2±0.0^{a}	11.9±1.5^{b}
	Leaf	-[2]	-	-	-	-	-	-
	Root	21.8±0.2^{b}	14.6±0.4^{a}	23.3±3.7^{b}	234.1±3.2^{b}	52.5±3.2^{b}	0.2±0.1^{a}	51.8±5.2^{a}
P. karka	Stem	10.5±3.6^{b}	23.1±1.2^{b}	18.0±1.4^{a}	8.6±0.4^{a}	20.1±4.6^{a}	0.3±0.1^{b}	9.0±0.4^{a}
	Leaf	6.2±0.5	29.8±1.3	19.9±0.8	26.1±1.3	48.3±1.8	0.1±0.0	15.9±0.7
	Root	15.5±0.8^{a}	22.0±1.0^{b}	21.5±0.9^{a}	87.0±13.3^{a}	33.1±1.0^{a}	0.4± 0.1^{b}	71.2±1.2^{a}
A. marina	Stem	8.0±0.4^{b}	12.9± 1.2^{b}	18.7± 4.4^{a}	37.3±4.7^{b}	0.8± 0.0^{a}	0.3±0.1^{a}	61.7±1.4^{c}
	Leaf	10.8±0.9^{b}	11.1± 0.6^{b}	38.3±7.4^{c}	224.0±20.2^{c}	0.4±0.1^{a}	0.4±0.0^{a}	30.3± 0.3^{b}
	Root	9.7±2.0^{b}	19.1±1.5^{b}	24.6±1.3^{b}	129.0±7.5^{b}	1.1± 0.1^{b}	0.4±0.0^{ab}	75.7±0.5^{c}
A. ebracteatus	Stem	9.9±0.9^{b}	18.9±1.5^{a}	20.0±0.8^{a}	47.2±3.0^{b}	16.0±0.8^{b}	0.5±0.0^{b}	47.3±1.0^{b}

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	Leaf	-	-	-	-	-	-	-
	Root	19.5±0.6^{c}	14.5±0.5^{a}	18.7±2.7^{a}	110.7±82.3^{b}	21.8±1.7^{c}	0.5±0.0^{b}	25.2±1.7^{b}
A. alba	Stem	3.0±0.6^{a}	13.4±1.1^{b}	18.9±0.4^{a}	61.8±5.5^{c}	0.6±0.0^{a}	0.3±0.0^{a}	3.6±0.2^{a}
	Leaf	2.5±0.6^{a}	8.4±1.1^{b} 13.0±1.9^{a}	14.0±0.5^{a}	56.9±5.8^{b}	6.5±0.4^{b}	0.4±0.0^{a}	BDL
	Root	1.1±0.1^{a}		19.0±0.5^{a}	113.2±12.9^{b}	0.3±0.1^{a}	0.2±0.0^{a}	BDL
P. indica	Stem	15.3±2.3^{c}	16.3±0.5^{c}	15.6±7.1^{a}	6.2±0.2^{a}	0.6±0.0^{a}	0.3±0.0^{a}	4.0±0.3^{a}
	Leaf	22.6±3.8^{c}	32.6± 3.1^{e}	22.8±1.5^{b}	40.3± 2.1^{a}	0.5±0.0^{ab}	0.6±0.0^{b}	2.6±0.3^{a}
	Root	17.6±1.0^{d}	13.0±0.7^{a}	19.6±0.7^{ab}	16.9±1.0^{a}	0.4±0.0^{a}	0.3±0.0^{b}	9.4±0.4^{a}
T. populnea	Stem	19.8±0.6^{b}	22.4±0.8^{b}	45.8± 1.3^{b}	7.6±1.7^{a}	0.6± 0.0^{a}	0.2±0.0^{b}	11.4±1.2^{b}
	Leaf	5.6±1.3^{a}	23.6±1.0^{b}	60.2±4.7^{b}	21.9±4.7^{a}	1.3±0.1^{a}	0.2±0.0^{b}	6.7±0.2^{a}
	Root	4.5±0.4^{a}	13.8±0.5^{a}	42.5±5.8^{b}	11.4±1.7^{a}	0.5± 0.1^{a}	0.2±0.0^{b}	21.5±0.9^{b}
R. mucronata	Stem	4.9±0.2^{a}	7.7±0.9^{a}	20.5±0.4^{a}	257.8±6.8^{b}	14.3±0.5^{b}	0.1±0.0^{a}	5.8±0.6^{a}
	Leaf	3.9±0.1^{a}	2.8±0.9^{a}	15.8±0.5^{a}	255.4±7.6^{b}	15.2±0.5^{b}	0.1±0.0^{a}	6.8±0.6^{a}
	Root	16.8±0.6^{b}	15.5±1.8^{b}	19.7±2.7^{a}	230.6±6.0^{b}	12.1±2.0^{b}	0.1±0.0^{a}	4.3±0.5^{a}
T. angustifolia	Stem	1.9±0.4^{a}	16.7±0.3^{a}	28.7±2.2^{b}	212.6±11.6^{c}	2.8±0.1^{a}	0.3±0.0^{b}	5.5±0.9^{a}
	Leaf	-	-	-	-	-	-	-
	Root	5.6±0.3^{a}	28.8±3.7^{b}	48.5±3.7^{b}	322.5±0.6^{b}	1.4±0.0^{a}	0.5±0.0^{b}	34.4±0.4^{b}
E. dulcis	Stem	8.1±1.5^{b}	16.2±1.1^{a}	20.1±1.3^{a}	43.9±7.0^{a}	20.0±3.9^{b}	0.3±0.0^{b}	13.1±2.3^{b}
	Leaf	-	-	-	-	-	-	-
	Root	23.4±1.5^{b}	25.0±0.6^{a}	22.1±1.6^{a}	65.5±7.6^{a}	25.7±5.0^{c}	0.2±0.1^{a}	19.0±0.5^{a}
C. involucratus	Stem	19.1±2.9^{c}	23.5±2.4^{b}	20.8±0.8^{a}	81.3±2.3^{b}	64.7±3.0^{c}	0.1±0.0^{a}	13.1±0.9^{b}
	Leaf	-	-	-	-	-	-	-
	Root	30.0±0.7^{c}	21.0±3.5^{a}	20.1±4.3^{a}	61.8±7.6^{a}	19.1±3.5^{b}	0.1±0.0^{a}	70.8±1.3^{c}
A. aureum	Stem	23.4±0.3	25.1±0.9	21.6±1.6	3.7±0.1	19.1±1.6	0.0±0.0	6.3±0.3
	Leaf	-	-	-	-	-	-	-
	Root	41.5±1.3	28.4±3.2	24.3±2.8	23.5±1.7	29.3±4.3	0.1±0.0	22.1±1.2

[1]BDL = below detectable limits.

[2] = Data not available.

Values followed by the same letter are not significantly different at $p < 0.05$. Small letters indicate the difference of metal contents when compared between each plant organ among different plant types (ground cover, climbing plant, grass, shrub, tree, aquatic and pteridophyte species, respectively) (LSD: $p < 0.05$).

Copper in tissue ranged from 1.1 (*A. alba* root) to 23.4 mg kg^{-1} (*E. dulcis* root); Zn from 2.8 (*R. muconata* leaf) to 78 mg kg^{-1} (*I. pes-caprae* root); Ni from 11.0 (*W. biflora* root) to 60.2 mg kg^{-1} (*T. populnea* leaf); Mn from 5.7 (*P. noniflora* leaf) to 257 mg kg^{-1} (*R. muconata* stem); Cr from 0.4 (*P. indica* root) to 107 (*I. pes-caprae* root); Cd from BDL (various species and parts) to 0.6 mg kg^{-1}; and Pb from BDL (various) to 75.7 mg kg^{-1} (*A. marina* root) (*Table 3*).

The low availability of several metals (e.g., Cu, Ni, Zn) to plants in the mangrove ecosystem may be explained by: (1) the organic content of the detritus-rich bottom sediments form complex refractory organics, which are believed to be a major cause of reduced metal bioavailability (MacFarlane et al., 2003); (2) high levels of salinity result in the formation of metal-chloride complexes of low availability for plant uptake and accumulation (Greger, 2004); (3) the nature of metals trapped by mangrove sediments -- metals are adsorbed to sediments/or clay minerals either at permanent charge sites (ion exchanges sites of fine silts/clays) or at surface-hydroxyl (amphoteric) sites (Cowan et al., 1992; Harbison, 1986), resulting in low plant availability (Lacerda, 1997); (4) metals react with sulphides to form metal sulphides in the anoxic layer of the sediment. Metal sulphides tend to be highly insoluble; however, they may be partially taken up by roots and transported via the xylem (Youssef and Saenger, 1996). In mangrove surface soils, low sulphide concentrations were found (< 1 mM) along with correspondingly high redox values (+ 250 mV to -150 mV), whereas low redox potentials were determined in sediments below 30 cm depth with correspondingly higher sulphide concentrations (~ 2 mM) (Lyimo et al., 2002) (5) The relatively high pH (7.4, *Table 1*)

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will result in precipitation of many metals as oxides, carbonates, etc. (Meeinkuirt et al., 2012, 2013; Pichtel, 2007; Usman et al., 2013).

Manganese was the only element that plant organs accumulated in high quantities, followed by Cr. Cadmium and Pb were accumulated minimally by all plant organs. These phenomena are consistent with reports on metal behavior in mangrove sediments elsewhere (Chowdhury et al., 2015; Kim et al., 2010).

Translocation values between roots and aboveground parts (leaves and stems) ranged from 0.2-4.4 for Cu, 0.1-2.5 for Zn, 0.4-1.6 for Ni, 0.1-9.3 for Mn, 0.2-4.4 for Cr, 0.1-2.1 for Cd, and 0.1-7.9 for Pb (*Table 4*). Of 217 tissue samples, 128 had TF values < 1 and 89 had TF values > 1. TF values < 1 indicate low metal translocation to shoots. These data are consistent with results for terrestrial plants grown in other metal-contaminated soils (Meeinkuirt et al., 2012; Phaenark et al., 2009). Different plant types have markedly different physiology, which results in different translocation potential for metals (Chen et al., 2005)

High metal concentrations in roots combined with TF values < 1 indicate the potential of the plant for well-balanced metal accumulation and translocation (Haque et al., 2008). In order for a plant growing on contaminated soil to avoid metal toxicity, sequestering the metal in the root serves as an appropriate metal exclusion strategy (Marques et al., 2009). There is evidence of plant mechanisms which allow roots to accumulate high levels of trace metals as compared with other plant parts (MacFarlane et al., 2003; Naidoo et al., 2014). This phenomenon was detected in mangrove species such as *Avicennia marina*, *Rhizophora* spp., and *Kandelia* spp. (Peters et al., 1997) and is consistent with data for the present study (except for Mn). Several reports have shown that fine roots of mangrove plants accumulate high trace metal concentrations; however, the extent of accumulation depends upon plant mechanisms and sediment chemistry (Chaudhuri et al., 2014).

Aerial roots of mangrove plants diffuse oxygen into the substrate such that oxidation occurs in the rhizosphere, resulting in metal accumulation in fine roots (Chaudhuri et al., 2014; Machado et al., 2005; Marchand et al., 2011). The large surface area and high density of the root system may encourage metal uptake, along with adsorption of metals subsequent to oxidation of metal sulphides (Lacerda et al., 1992, 1993; Marchand et al., 2011; Otero et al., 2006). Highest TF values were found in stems of *D. trifoliata* (9.3 and 7.9 for Mn and Pb, respectively). Plants with TF values > 1 have a high efficiency of translocation of metals from roots to aboveground parts (Murray et al., 2009).

Among 334 plant tissue samples, high capacities for metal absorption from sediments to plant tissue (i.e., BCF values > 1) were expressed in 285 plant organs, while low BCF values were found in 49 plant organs (*Table 5*). In this study, BCF values of leaves ranged from 0.4-9.0 for Cu, 1.6-16.0 for Zn, 3.9-28.3 for Ni, 0.2-8.3 for Mn, 0.7-65.1 for Cr, 0.2-24.0 for Cd, and 0.2-22.7 for Pb, respectively. BCF values for stems ranged from 0.5-12.2 for Cu, 3.4-19.3 for Zn, 4.8-22.4 for Ni, 0.3-16.4 for Mn, 0.7-52.0 for Cr, 0.4-23.7 for Cd, and 0.1-26.7 for Pb, respectively, and BCF values for roots ranged from 0.2-36.9 for Cu, 5.7-30.9 for Zn, 3.1-29.5 for Ni, 0.4-24.8 for Mn, 0.7-115.2 for Cr, 0.6-21.8 for Cd, and 0.2-30.2 for Pb, respectively. High BCF values were noted for many metals in roots; in particular, highest BCF values for Cu, Zn, Ni and Cr were in roots of *I. pes-caprae*, while highest BCF values for Mn and Pb were in *T. angustifolia*. The highest BCF value for Cd was in leaves of *I. pes-caprae*.

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Table 4. *Translocation factor for mangrove plant parts. (n=3)*

Plant	Tissue	TF						
		Cu	Zn	Ni	Mn	Cr	Cd	Pb
W. biflora	Stem	0.5±0.0	1.1±0.1	1.6±0.3	0.4±0.0	1.8±0.1	1.2±0.1	2.0±0.1
	Leaf	0.5±0.0	0.7±0.1	1.3±0.4	1.0±0.0	1.1±0.1	1.3±0.1	0.5±0.1
S. portulacastrum	Stem	2.1±0.2	1.3±0.1	1.3±0.1	0.5±0.0	1.0±0.2	0.9±0.4	0.4±0.1
	Leaf	1.0±0.1	1.1±0.2	1.1±0.3	0.7±0.1	1.0±0.1	1.3±0.6	0.2±0.0
I. pes-caprae	Stem	0.2±0.0	0.1±0.0	0.4±0.0	0.1±0.0	2.9±0.3	1.1±0.2	4.1±0.6
	Leaf	0.2±0.0	0.2±0.1	0.5±0.1	0.2±0.0	3.5±0.0	1.1±0.1	5.9±1.2
P. nodiflora	Stem	0.6±0.0	1.1±0.0	1.0±0.2	0.5±0.0	0.5±0.1	0.5±0.1	1.2±0.1
	Leaf	0.3±0.0	0.8±0.0	0.8±0.2	0.3±0.0	0.3±0.1	0.4±0.1	-[1]
D. trifoliata	Stem	0.9±0.1	1.3±0.2	1.2±0.1	9.3±0.6	2.3±0.6	0.5±0.1	7.9±0.2
	Leaf	0.5±0.1	0.9±0.2	0.9±0.1	8.7±0.6	2.0±0.5	0.4±0.1	8.9±0.2
P. foetida	Stem	0.7±0.0	1.1±0.2	0.9±0.0	1.8±0.2	0.9±0.1	0.6±0.1	0.9±0.1
	Leaf	0.5±0.0	0.9±0.1	0.7±0.0	1.4±0.1	0.7±0.1	0.5±0.1	0.7±0.1
D. caricosum	Stem	0.3±0.0	0.7±0.0	0.9±0.0	0.4±0.0	0.4±0.0	1.2±0.4	0.2±0.0
	Leaf	-	-	-	-	-	-	-
P. karka	Stem	0.7±0.2	1.1±0.1	0.8±0.1	0.1±0.0	0.6±0.1	0.8±0.1	0.1±0.0
	Leaf	0.4±0.1	1.4±0.1	0.9±0.0	0.3±0.0	1.5±0.1	0.2±0.0	0.2±0.0
A. marina	Stem	0.9±0.2	0.7±0.1	0.8±0.2	0.3±0.0	0.8±0.1	0.8±0.2	0.8±0.0
	Leaf	1.1±0.2	0.6±0.1	1.5±0.3	1.8±0.2	0.4±0.1	1.1±0.1	0.4±0.0
A. ebracteatus	Stem	0.5±0.0	1.3±0.1	1.1±0.1	1.2±1.5	0.7±0.0	1.1±0.1	1.9±0.1
	Leaf	-	-	-	-	-	-	-
A. alba	Stem	2.7±0.4	1.1±0.2	1.0±0.0	0.5±0.0	1.9±0.4	1.6±0.3	0.2±0.1
	Leaf	2.2±0.4	0.7±0.2	0.7±0.0	0.5±0.0	2.0±0.4	2.1±0.4	0.4±0.1
P. indica	Stem	0.9±0.2	1.3±0.0	0.8±0.4	0.4±0.0	1.5±0.1	0.9±0.2	-
	Leaf	1.3±0.3	2.5±.02	1.2±0.1	2.4±0.2	1.3±0.1	1.9±0.1	0.3±0.0
T. populnea	Stem	4.4±0.5	1.6±0.0	1.1±0.2	0.7±0.0	1.2±0.3	0.8±0.1	0.5±0.0
	Leaf	1.2±0.4	1.7±0.1	1.4±0.1	1.9±0.3	2.6±0.4	0.7±0.0	0.3±0.0
R. mucronata	Stem	0.3±0.0	0.5±0.1	1.1±0.2	1.1±0.0	1.2±0.2	0.9±0.0	1.4±0.2
	Leaf	0.2±0.0	0.2±0.1	0.8±0.1	1.1±0.0	1.3±0.2	0.8±0.0	1.6±0.3
T. angustifolia	Stem	0.3±0.1	0.6±0.1	0.6±0.1	0.7±0.0	2.0±0.1	0.7±0.0	0.2±0.0
	Leaf	-	-	-	-	-	-	-
E. dulcis	Stem	0.3±0.1	0.6±0.0	0.9±0.1	0.7±0.1	0.8±0.2	1.1±0.2	0.7±0.1
	Leaf	-	-	-	-	-	-	-
C. involucratus	Stem	0.6±0.1	1.1±0.2	1.1±0.2	0.5±0.0	3.5±0.6	1.3±0.6	0.2±0.0
	Leaf	-	-	-	-	-	-	-
A. aureum	Stem	0.6±0.0	0.9±0.1	0.9±0.1	0.2±0.0	0.7±0.1	0.6±0.1	0.3±0.0
	Leaf	-	-	-	-	-	-	-

[1] = Data not available.

Several mangrove species may be categorized as accumulators as they have TF and BCF values > 1 (e.g., *T. populnea* for Ni and *C. involucratus* for Cr). Many species in this study are classified as excluder plants for metals as they have TF < 1 and BCF > 1 (*C. involucratus* for Cu, *I. pes-caprae* for Zn, *T. angustifolia* for Mn, and *P. karka* for Pb).

The root systems of mangrove species reduce soil erosion and may stabilize metals within coastal sediments. In this investigation, *T. angustifolia*, a monocot present in mangrove areas in Thailand, possess an extensive root distribution in both vertical and horizontal planes (Yen and Saibeh, 2013). It also has excluder potential for Cu. Thus, this grass species can reduce soil erosion and stabilize metals simultaneously.

For successful phytoextraction, plant biomass production must be considered. In some cases, mangrove plants may have high potential for phytoremediation even if tissue metal levels are relatively modest; a high biomass producer still has potential for significant metal removal from soil.

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Table 5. *Bioconcentration factor for mangrove plant parts. (n=3)*

Plant	Tissue	BCF						
		Cu	Zn	Ni	Mn	Cr	Cd	Pb
W. biflora	Stem	1.2±0.1	8.5±0.3	5.9±1.0	0.5±0.1	2.6±0.1	10.5±0.7	2.1±0.0
	Leaf	1.3±0.0	6.0±0.8	4.8±1.5	1.1±0.2	1.6±0.1	11.5±0.5	0.5±0.0
	Root	2.5±0.0	8.1±0.6	3.8±0.1	1.1±0.1	1.5±0.0	9.0±0.5	1.0±0.0
S. portulacastrum	Stem	2.6±0.3	9.2±0.1	13.9±0.4	0.4±0.0	0.9±0.2	6.1±1.6	0.9±0.1
	Leaf	1.3±0.0	8.1±1.4	11.3±2.8	0.6±0.1	0.9±0.1	9.4±0.2	0.5±0.0
	Root	1.3±0.1	7.3±0.2	10.6±0.8	0.9±0.1	0.9±0.0	7.8±3.1	2.3±0.5
I. pes-caprae	Stem	0.6±0.0	3.7±0.2	7.9±0.4	1.0±0.0	43.9±5.8	15.3±2.6	2.4±0.2
	Leaf	0.8±0.1	6.1±2.3	8.7±0.2	1.7±0.2	53.4±1.9	15.5±0.8	3.5±0.3
	Root	3.2±0.1	3.3±0.6	18.2±2.6	10.3±0.9	15.2±0.6	14.1±1.7	0.6±0.1
P. nodiflora	Stem	2.0±0.1	9.5±0.0	8.1±1.3	0.5±0.0	18.5±2.1	2.0±0.6	0.3±0.0
	Leaf	1.2±0.1	7.3±0.0	6.4±1.3	0.2±0.0	11.4±2.1	1.7±0.6	0.4±0.0
	Root	3.4±0.3	8.8±0.0	8.3±0.8	1.0±0.1	37.7±1.4	4.3±0.3	-[1]
D. trifoliata	Stem	2.0±0.2	7.5±1.3	9.0±0.3	3.6±0.3	54.6±8.5	0.9±0.1	5.4±0.3
	Leaf	1.3±0.2	5.3±1.3	7.3±0.3	3.4±0.3	47.6±8.5	0.8±0.1	6.1±0.3
	Root	2.3±0.0	6.0±0.6	7.8±0.2	0.4±0.0	23.9±2.2	2.0±0.5	0.7±0.0
P. foetida	Stem	2.2±0.1	12.0±0.3	7.2±0.2	0.9±0.1	29.0±1.5	1.8±0.2	3.7±0.1
	Leaf	1.4±0.1	9.9±0.3	5.5±0.2	0.7±0.1	22.0±1.5	1.6±0.2	3.1±0.1
	Root	3.1±0.1	11.5±1.3	7.8±0.4	0.5±0.1	31.0±3.3	3.1±0.4	4.3±0.3
D. caricosum	Stem	1.1±0.0	4.3±0.3	7.5±0.2	4.1±0.1	31.6±1.0	5.0±0.3	1.6±0.2
	Leaf	-	-	-	-	-	-	-
	Root	3.3±0.0	6.2±0.2	8.8±0.1	10.2±0.1	74.5±4.5	4.7±1.7	6.9±0.7
P. karka	Stem	1.6±0.5	9.9±0.5	6.2±0.5	0.4±0.0	28.6±6.5	8.8±2.0	1.2±0.0
	Leaf	1.0±0.1	12.7±0.6	6.9±0.3	1.1±0.1	68.5±2.5	2.1±0.4	2.1±0.1
	Root	2.4±0.1	9.4±0.4	7.4±0.3	3.8±0.6	46.9±1.4	10.5±1.5	9.5±0.2
A. marina	Stem	1.2±0.1	5.5±0.5	6.5±1.5	1.6±0.2	11.9±0.1	7.9±1.7	8.2±0.2
	Leaf	1.7±0.1	4.7±0.3	12.6±2.1	9.8±0.9	6.0±1.5	12.2±1.2	4.1±0.1
	Root	1.5±0.3	8.1±0.6	8.5±0.5	5.6±0.2	15.8±1.8	10.6±0.7	10.1±0.1
A. ebracteatus	Stem	1.5±0.1	8.1±0.7	6.9±0.3	2.1±0.1	22.7±1.1	14.7±1.2	6.3±0.1
	Leaf	-	-	-	-	-	-	-
	Root	3.0±0.1	6.2±0.2	6.5±0.9	4.8±3.6	30.9±2.3	13.7±0.7	3.4±0.2
A. alba	Stem	0.5±0.1	5.7±0.4	6.5±0.1	2.7±0.2	8.5±0.5	9.2±0.3	0.1±0.0
	Leaf	0.4±0.1	3.6±0.5	4.8±0.2	2.5±0.3	9.2±0.5	12.0±0.3	0.2±0.0
	Root	0.2±0.0	5.5±0.5	6.6±0.2	4.9±0.6	4.7±0.8	6.0±1.2	-
P. indica	Stem	2.3±0.4	6.9±0.2	5.4±2.4	0.3±0.0	8.8±0.3	6.8±1.1	0.5±0.0
	Leaf	3.5±0.6	13.9±1.3	7.9±0.5	1.8±0.1	7.5±0.4	15.5±0.3	0.4±0.0
	Root	2.7±0.2	5.5±0.3	6.8±0.2	0.7±0.0	5.7±0.1	8.0±0.2	1.3±0.1
T. populnea	Stem	3.0±0.1	9.6±0.3	15.8±0.4	0.3±0.1	8.5±0.6	4.9±0.6	1.5±0.2
	Leaf	0.9±0.2	10.1±0.4	20.8±1.6	1.0±0.1	18.4±1.0	4.3±0.2	0.9±0.0
	Root	0.7±0.1	5.9±0.2	14.7±2.0	0.5±0.1	7.2±1.3	5.9±0.2	2.9±0.1
R. mucronata	Stem	0.7±0.0	3.3±0.4	7.1±0.1	11.3±0.3	20.3±0.7	2.2±0.2	0.8±0.1
	Leaf	0.6±0.0	1.2±0.4	5.4±0.2	11.2±0.3	21.8±0.7	1.9±0.2	0.9±0.1
	Root	2.6±0.1	6.6±0.7	6.8±0.9	10.1±0.3	17.2±2.8	2.4±0.2	0.6±0.1
T. angustifolia	Stem	0.3±0.1	7.1±0.1	10.1±0.6	9.3±0.5	39.4±0.9	8.8±0.6	0.7±0.1
	Leaf	-	-	-	-	-	-	-
	Root	0.9±0.0	12.3±1.6	16.9±1.0	14.1±0.0	19.5±0.5	13.0±0.0	4.6±0.1
E. dulcis	Stem	1.2±0.2	6.9±0.5	6.9±0.5	1.9±0.3	28.4±5.5	7.3±0.8	1.7±0.3
	Leaf	-	-	-	-	-	-	-
	Root	3.6±0.2	10.7±0.3	7.6±0.5	2.9±0.3	36.5±7.1	6.5±1.5	2.5±0.1
C. involucratus	Stem	2.9±0.4	10.0±1.0	7.2±0.3	3.5±0.1	91.8±4.2	3.6±1.1	1.8±0.1
	Leaf	-	-	-	-	-	-	-
	Root	4.6±0.1	9.0±1.5	6.9±1.5	7.1±0.3	27.1±4.9	2.9±0.7	9.4±0.2
A. aureum	Stem	3.6±0.1	10.7±0.4	7.5±0.5	0.2±0.0	27.1±2.3	1.0±0.1	0.8±0.0
	Leaf	-	-	-	-	-	-	-
	Root	6.4±0.2	12.1±1.4	8.4±1.0	1.0±0.1	41.5±6.1	1.8±0.2	2.9±0.2

[1] = Data not available.

Conclusions

Mangrove plant species in Pattani Bay, Thailand were assessed as a biological tool for remediation and reduction of metal mobility in sediments. Pattani Bay is an important region for aquaculture and as a nursery for numerous marine organisms; however, this area has received large quantities of anthropogenic contaminants, particularly metals from domestic and industrial sources. Investigation of metal

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behavior in mangrove sediments and plants is important for clarifying the ability of mangroves to treat soil contamination. In the current study, mangrove plant species generally accumulated low concentrations of metals. However, some species demonstrated the potential for metal phytostabilization or phytoextraction. Given that mangrove shrub species have a long life span, produce high biomass and possess an extensive root system, we suggest that these species be used for stabilization of metals in mangrove ecosystems.

Phytoremediation may be an optimal remediation option in metal-contaminated coastal sediments; this is an effective solar-driven and low-cost technology which uses native plants for metal immobilization or extraction. Furthermore, this technology does not require addition of fertilizer (which increases treatment costs), and does not produce secondary wastes that require further treatment (Cunningham et al., 1995; Prasad, 2003); it is therefore an environmentally benign technology which does not alter local soil properties.

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