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Mangrove species selection for phytoremediation of heavy metals from the Sundarbans, Northeast coast of India

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In the Sundarbans mangrove forest, heavy metals like Zn, Cu, Ni, Co, Pb, and Cr were assessed in soil, leaf, stem and root tissue of various mangrove species. Except for Zn and Cu, the levels of other metals in plant organs were lower than the metal concentration in sediments. Cu and Cr accumulations were to some extent higher in tissues of all mangrove species in comparison to the permissible limit in plants. Physicochemical properties of sediments might greatly influence the availability of metals to mangroves. The mangroves, *Nypa fruiticans*, *Ceriops decandra* and *Phoenix paludosa* are classified as excluders of Cu with more accumulation of metals mainly occurring in roots, with a resultant Translocation Factor (TF) < 1 and a Bioconcentration Factor (BCF) > 1. Both *Heritiera fomes* and *Aegialitis rotundifolia* are classified as accumulators, extractors and translocators of Cu and extractors and translocators of Zn. Accumulators could be considered as tolerant as well as indicator plants for controlling the movement of metals from root to shoot that becomes proportional to the metals in the sediment. All of these characteristics of mangrove species in terms of heavy metal accumulation could be considered as phytoremediation potentiality of mangrove plants and associates. More investigation in these aspects needs to be carried out not only to identify other species suitable for phytoremediation but also to ensure safe food chains in the coastal ecosystems.

[**Keywords**: Heavy metals, Mangrove species, Selection, Sundarbans]

Introduction

Mangroves are known as forest ecosystems, which occur in the tidal zones of subtropical and tropical coastlines[1]. These are the most productive and biologically important ecosystems of the world that play a definite role in providing unique ecosystem goods and services to humankind[2]. It serves as nursery and breeding grounds for several commercially important species of marine fauna; protects coastlines from erosion, cyclonic storms, tidal surges, natural calamities; and helps to regulate climate[3]. People residing in coastal areas find their livelihood through exploitation of terrestrial as well as marine mangrove resources in the form of food, raw materials, medicinal resources, tourism, recreation and education[4,5]. All these services are contributed by mangroves communities growing in harsh environmental conditions at the boundary between sea and land. Salinity stress is overcome by developing salt accumulation, salt exclusion and salt excretion mechanisms[6,7]. In addition, the stress from anthropogenic sources associated with population explosion, unplanned urbanization, deforestation, industrial developments and profit-oriented capitalism have elevated pressure by introducing large amounts of toxic heavy metals on mangroves through sewage disposal, industrial discharge, transportation, dredging, shipping and aquaculture[8,9].

Heavy Metals (HMs) are found naturally in the earth's crust and may be essential (such as Fe, Co, Ni, Cu, Zn, etc.) with definite chemical and biological roles or non-essential (toxic) like Pb, Cd, Hg, As, Al, etc. having no biochemical role to play[8,10]. Heavy metals are biologically non-degradable and are transferred and concentrated in plant tissues via sediments, posing long-term damaging effects not only in the plants but also when entering the food chain show harmful effects to higher trophic level consumers. Thus, HMs have been recognized as one of the most serious pollutants in mangrove environments due to their toxicity, persistence, bioaccumulation and long residence times within the food chains[11,12]. In order to tackle the problems from HMs, mangroves play important roles in the biogeochemistry of these contaminants in coastal areas depending on variations in space, species and time[10]. As a result, numerous studies have used mangrove species as reliable bio-indicators for heavy metal pollution and contamination[13-15]. The increasing concentrations of heavy metals in mangroves have adverse effects on various metabolic processes and are directly proportional to the concentration of metals in the surrounding environment[16]. It is generally considered that different mangrove species have different metal accumulation abilities and can tolerate heavy metal pollution at relatively high rates[17,18]. Hence, some mangrove species may be bio-indicators, accumulators, extractors or excluders and can be efficiently used in phytoremediation of incredibly toxic metals[19].

In light of the above, the purpose of the present study is to highlight the categorization of mangrove species of the Sundarbans in India in terms of (1) preferences of HMs as accumulators (such as Cu, Zn, Co, Ni, Pb and Cr), (2) the degree of Bioconcentrator Factors (BCF) of various HMs, (3) the extent of heavy metal translocation in different parts of mangrove plants, and finally, (4) phytoremediation potentiality of the mangrove species which could be used for conservation and sustainable management of the Sundarban areas.

Materials and Methods

Study sites

The Sundarbans is located (latitude 21°32′ – 22°40′ N, and longitude 88°05′ – 89°00′ E) in the south of the state West Bengal in India at the apex of the Bay of Bengal. The Bangladesh border is to the east, and the Hooghly River (Ganga) is to the west of the Sundarbans. The Dampier Hodges Line stretches above it through the north-eastern side. It is a natural forest of true mangrove species and associates situated intertidally and influenced greatly by the tides as a part of the Ganga estuary. The total area of the Sundarbans is 9063 km^2, with 4264 km^2 as intertidal habitat. This is a unique bio-climate zone for the biodiversity of flora and fauna in land and water and is the largest delta in the world. The mangrove forest area has been included in the list of World Heritage Sites by UNESCO and as a Biosphere Reserve by India. There are 102 islands, and of these, only 48 islands are inhabited. The present study was conducted in one of the islands in the reserved forest of Sudhanyakhali (latitude 22°06′06″ N, longitude 88°48′0″ E), which is easily accessible and situated upstream of the estuarine zone of the river Matla. The area is very close to the island of the Sajnekhali Tiger reserve forest. Tourists frequently visit the watch tower and the area is protected by fences all around. In this part of the island, various mangroves are found; most of these are natural, and only a few are planted by the people looking after the place.

Sample collection and preservation

Samplings were done from this protected area only during the winter season. Fresh plant organs such as roots, stems, and leaves were randomly collected from some mangroves of more than 1 m tall with the help of a thin stainless-steel knife. Sediment samples were also collected by hand-operated auger within a 10 cm depth from this area. Plant samples were thoroughly washed with seawater initially and with distilled water in the laboratory to remove any foreign materials. The roots were carefully collected after removing the sediments. All the samples were kept in plastic containers, labelled and stored in a cool box with ice at 4 °C and were transported to the laboratory. These were then turned into pieces and oven-dried at 105 °C in air oven. Sediment samples were also dried, and the foreign debris was removed. The completely dried samples of plants and soil were then ground, homogenized and kept in clean sealed plastic zip pouches for further analyses. Sediment samples were sieved by 80 mm mesh.

Analysis procedures

Analysis of sediments was performed in duplicate for pH (1:2.5 soil:water, w/v) by pH meter (WTW, Model Multi 340); conductivity (1:5 soil:water, w/v) by conductivity meter (Systronic model); grain size analysis by pipette method[20], Cation Exchange Capacity (CEC)[20] using ammonium acetate at pH 7; and organic carbon by standard methods[21]. Sediments were digested according to USEPA (1996)[22] and heavy metals were estimated by Atomic Absorption Spectrophotometer (AAS, model: Agilent Technology 200 Series AA).

The ground plant samples were digested in duplicate with concentrated HNO_3 and H_2O_2[ref. 11] at 110 °C for 12 h in an electrical oven. After cooling, H_2O_2 was added and was again digested at 110 °C for 30 min. The residual HNO_3 was destroyed by heating. The samples were centrifuged and then diluted using deionized water and stored at 4 °C until analysis. The trace elements were determined by AAS, and the concentrations were expressed in ppm (μg/g). A reagent blank was prepared to remove any matrix interference, and the elements were analyzed against the blank with the help of a standard curve. The precision and accuracy of the analytical method was checked by standard procedure. The recoveries of trace elements were between 92 % and 102 %. Analytical grade of all chemicals and standards were followed, and the solutions were prepared in double distilled water.

Bio-concentration Factor (BCF) and Translocation Factors (TF)

To compare the degree of bioaccumulation of the metals, BCF was calculated as concentration of metals in tissue over the concentration of metals in the sediment. BCF is usually an indicator of the phytoremediation capability of the concerned plant species. The BCF was calculated for every metal in the system as follows:

BCF = *C* root / *C* sediment (extractable metal)

The Translocation Factor (TF) was calculated as a ratio of trace metal in plant shoot to that in the plant root[23].

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

Statistical analysis

Data subjected to descriptive statistical analysis expressed as minimum, maximum, mean, Standard Deviation (SD), and Coefficient of Variation (CV). The comparison method of *t*–test was used to assess differences in plant metal uptake characteristics. Samples were considered significantly different at $P < 0.05$. All statistical operations were carried out by using the SPSS-11 statistical package for Windows.

Results and Discussion

Sediment properties

Mangrove sediments (Table 1) were with pH ranging from 7.3 to 8.1, indicating poor buffering capacity of the sediment. Organic Carbon (OC) content varied from 0.61 to 1.21 % with an average of 0.82 % sediment dry weight. The content of OC was similar in values to previous studies of the coastal areas[24-26]. Grain size analysis indicated sand, silt and clay contents in the range 18.2 – 30.0 %, 35.5 – 44.2 % and 32.5 – 42.3 %, respectively. Cation Exchange Capacity (CEC), a measure of fertility and nutrient retention ability, ranged from 18.2 to 32.5 meq.100 g^{-1} with a mean of 25.3 meq.100 g^{-1} and was almost similar to the previous studies as recorded in the downstream part of this estuarine system. The mean level of the studied heavy metals (Fig. 1) followed the order Zn > Pb > Cr > Cu > Ni > Co. These were however lower than the level of metals present in either continental crust[27] or soil during pre-industrial period[28], and this fact might support the occurrence of lower levels of these metals in this mangrove island.

Metal concentration in mangrove plants

The extent of heavy metal accumulation (Fig. 2) depends on the chemical nature of heavy metals, the physiological characteristics of mangrove species[29] as well as the physico-chemical properties of mangrove sediments[30,31]. The metals Zn, Cu, Cr and Ni are essential micronutrients and showed maximum accumulation in various parts of the species following the order: Zn > Cu > Cr > Ni > Pb > Co. The higher bio-accumulation level of Zn and Cu in plants could be due to increasing demand for biochemical activities such as enzyme systems, protein synthesis, growth hormones and carbohydrate metabolism. Zn levels in plants were lower than the sediments. The metals Ni, Co and Pb showed very limited uptake, probably due to lower requirements for bio-chemical activities (for Ni) or having no significant biochemical role. Evidently, this phenomenon could

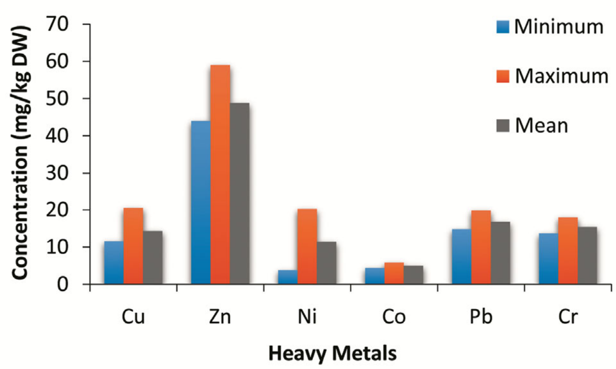

Fig. 1 — Distribution of heavy metals in mangrove sediments

Table 1 — Physico-chemical characteristics in mangrove sediments of the study site

Components	Minimum	Maximum	Mean (±SD)	Coefficient of variation (%)
Sand %	18.20	30.0	20.80±12.10	28.9
Silt %	35.50	44.20	42.0±8.90	26.8
Clay %	32.50	42.30	38.0±15.50	49.6
pH	7.30	8.10	7.62±0.75	9.8
Electrical conductivity (mS)	4.0	8.0	7.22±2.50	34.6
Cation exchange Capacity (meq/100 gm)	18.20	32.50	25.30±8.50	33.6
Organic carbon (%)	0.62	1.25	0.82±0.20	24.4

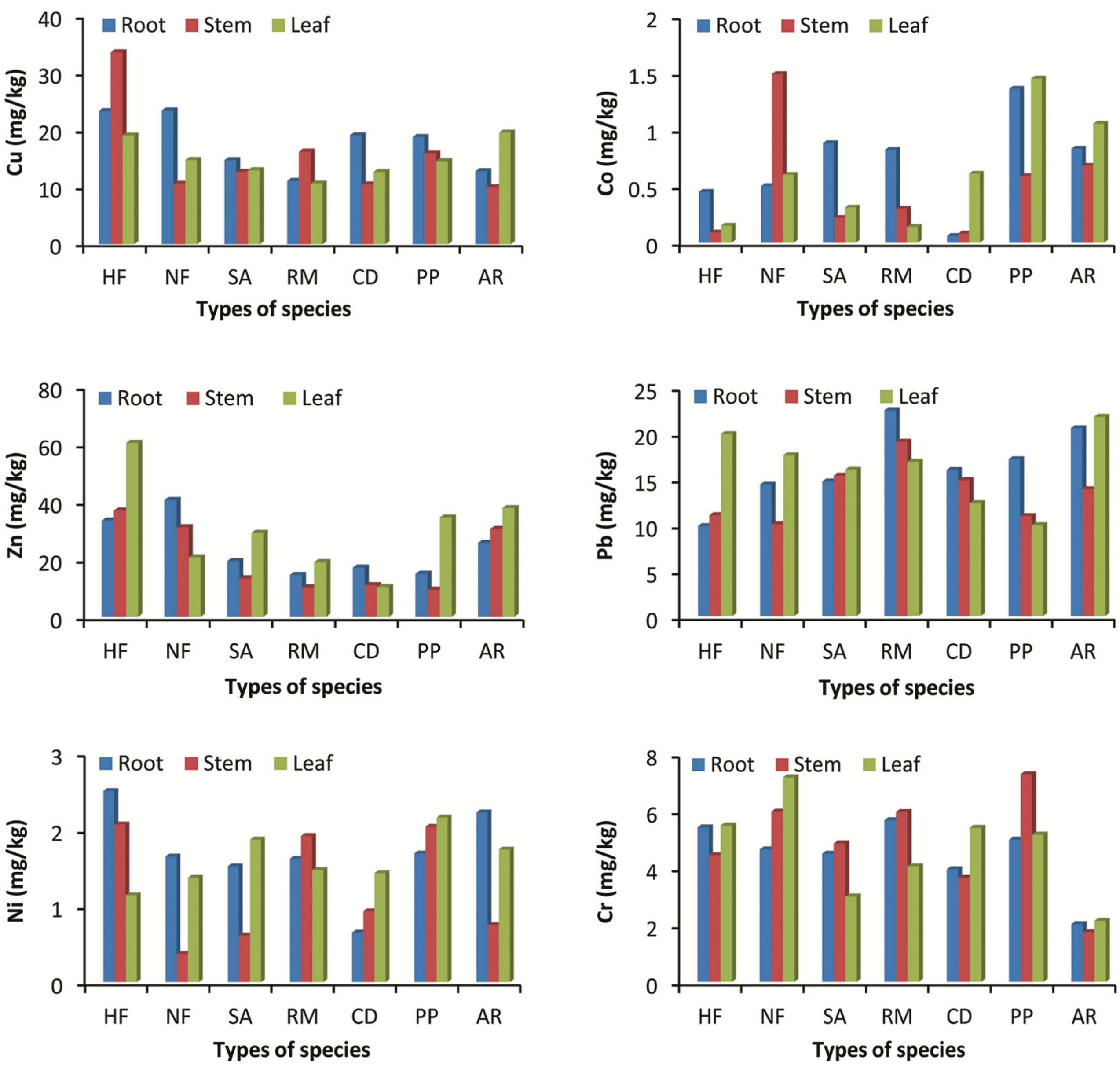

Fig. 2 — Bio-accumulation of heavy metals in mangrove species: *Heritiera fomes* (HF), *Nypa fruiticans* (NF), *Sonneratia apetala* (SA), *Rhizophora mucronata* (RM), *Ceriops decandra* (CD), *Phoenix paludosa* (PP), *Aegialitisro tundifolia* (AR)

support the existence of strong exclusion mechanisms of metals in these plants. Further, soluble Pb can react with sulfates, phosphates, hydroxides, carbonates, clays and organic matter, that might result in reducing pore water solubility and its availability to plant roots[23]. In addition, Fe in anoxic conditions in mangrove sediments undergoes precipitation with sulphide complexes, which may also act as major sinks for metals[16]. Similar observations were reported by many previous studies from the islands of downstream areas[15,16,32]. However, Cu and Cr levels in tissues were relatively higher than the permissible limit[12], suggesting that mangroves have the ability to bioaccumulate and tolerate these metals. Accumulation of non-essential metals in tissues suggests a possible function of sequestration[18] in the plants by extracting the available form from the sediment. These mechanisms include: (1) the sub-cellular compartmentalization of the metal in vacuoles; (2) the sequestration of the metal by producing phytochelatins; and (3) concentrating metals in the plant roots[34]. Furthermore, there were significant differences

Table 2 — Variation of Bio-concentration Factor (BCF) and Translocation Factor (TF) in mangrove species

Metals →	Cu		Zn		Ni		Co		Pb		Cr	
Species ↓	BCF	TF	BCF	TF	BCF	TF	BCF	TF	BCF	TF	BCF	TF
HF	1.72	1.22	0.76	1.80	0.66	0.45	0.08	0.40	0.06	2.13	0.39	1.01
NF	1.15	0.68	0.88	0.51	0.08	0.83	0.09	1.50	0.09	1.22	0.27	1.54
SA	1.05	0.91	0.44	1.50	0.40	1.23	0.15	0.35	0.08	1.08	0.33	0.66
RM	0.82	0.96	0.33	1.23	0.43	0.91	0.12	0.25	0.03	0.75	0.41	0.72
CD	1.65	0.56	0.28	0.60	0.05	2.20	0.01	1.01	0.08	0.78	0.24	1.36
PP	1.23	0.72	0.30	2.44	0.12	1.27	0.23	1.06	0.09	0.56	0.33	1.06
AR	1.07	1.52	0.45	1.47	0.11	0.76	0.13	1.26	0.01	0.96	0.11	1.05

Heritiera fomes (HF), *Nypa fruiticans* (NF), *Sonneratia apetala* (SA), *Rhizophora mucronata* (RM), *Ceriops decandra* (CD), *Phoenix paludosa* (PP), and *Aegialitis rotundifolia* (AR)

Table 3 — Selection of mangrove species in terms of heavy metal accumulation using BCF and TF

Metals	Hyper/ Accumulator (Both BCF and TF > 1)	Metal excluder (BCF > 1, TF < 1)	Indicator/ Extractor (L/Sed > 1)	Translocator (L/R > 1)
Cu	HF and AR	NF, CD and PP	HF and AR	HF and AR
Zn	--	--	HF	HF, SA, RM, PP and AR
Ni	--	--	--	SA, CD and PP
Co	--	--	--	NF and AR
Pb	--	--	--	HF and NF
Cr	--	--	--	NF and CD

Heritiera fomes (HF), *Nypa fruiticans* (NF), *Sonneratia apetala* (SA), *Rhizophora mucronata* (RM), *Ceriops decandra* (CD), *Phoenix paludosa* (PP), and *Aegialitis rotundifolia* (AR)

($P < 0.05$) in metal accumulation within tissue organs and between different species.

Bio-concentration Factor (BCF) and Translocation Factor (TF)

The ability of plants to accumulate metals from sediment is assessed by BCF, the ratio of metal content in tissue to that in sediment[23]. From the results (Table 2), the BCF values in root were: 0.82 – 1.72 for Cu, 0.28 – 0.76 for Zn, 0.05 – 0.66 for Ni, 0.01 – 0.23 for Co, 0.06 – 0.13 for Pb, and 0.11 – 0.41 for Cr. Comparatively high BCF values of Cu and Zn in these mangrove species indicated that these metals were highly accumulated, probably due to higher affinity, mobility and availability in sediments than the other metals. The low BCF values of toxic metals like Pb and Co could be due to avoiding toxic metals or due to their low availability in the sediments. On the other hand, the ability of translocation of metals from the roots to leaves of the mangrove plants is expressed by TF, which is the ratio of the metal level in leaves to the roots[23]. Different plant types have markedly different physiology, which results in different translocation potential for metals[7]. TF values in the present study varied from 0.56 to 1.72 for Cu, 0.60 to 2.44 for Zn, 0.45 to 2.20 for Ni, 0.25 to 1.50 for Co, 0.57 to 1.36 for Pb, and 0.66 to 1.54 for Cr. Relatively, higher TF values were encountered for Cu in *Heritiera fomes* (1.22) and *Aegialitis rotundifolia* (1.52); Zn in *Heritiera fomes* (1.80), *Sonneratia apetala* (1.50), *Rhizophora mucronata* (1.23), *Phoenix paludosa* (2.44), and *Aegialitis rotundifolia* (1.47); Ni in *Sonneratia apetala* (1.23), *Ceriops decandra* (2.20), and *Phoenix paludosa* (1.27); Co in *Nypa fruiticans* (1.50) and *Aegialitis rotundifolia* (1.26); Pb in *Heritiera fomes* (2.13) and *Nypa fruiticans* (1.22); and Cr in *Nypa fruiticans* (1.54) and *Ceriops decandra* (1.36). Almost all these mangrove species are classified as highly efficient for metal translocation from the roots to above-ground plant parts. Similar levels of BCF and TF of these groups of metals were reported from other parts of this mangrove area[15,16].

Categorization of mangrove species

To reduce metal toxicity, avoidance of metal uptake at the root of the mangrove species is an appropriate metal exclusion strategy that depends on plant physiology and sediment chemistry[16]. The mangrove species in the present study could be categorized by considering the bio-accumulation level of heavy metal with the help of BCF and TF or by both (Table 3). Mangrove species could be categorized as - (1) excluders (high metal concentrations in roots, (BCF > 1 combined with TF values < 1); (2) accumulators (both BCF and TF > 1; (3) translocators – (TF > 1); and (4) extractors or indicators (ratio of metal concentration in leaves to sediment > 1). Excluders restrict contaminant uptake and accumulation while accumulators translocate contaminants from roots to above-ground biomass. Indicator plants control the movement of contaminants from roots to shoots, therefore the concentrations of metals in the parent sediment is reflected by a proportional concentration in the shoots[34,35].

Mangrove species such as *Nypa fruiticans*, *Ceriops decandra* and *Phoenix paludosa* are classified here as excluders for the metal Cu. The existence of plant mechanisms to accumulate high levels of heavy metals in roots as compared to other plant organs has been recorded by many studies[16,35]. The species of *Heritiera fomes* and *Aegialitis rotundifolia* are apparently accumulators, extractors or translocators of Cu and extractors and translocators of Zn. All mangroves plants have the capability to translocate one or more heavy metals from root to leaves. Accumulators are not only tolerant but also show high BCF and TF (both > 1). Indicator plants can control the movement of the contaminants from roots to shoot; thus, metal concentration in sediment becomes proportional to the metal in the shoot. All of these above characteristics of mangrove species in terms of heavy metal accumulation could be considered as reflecting the phytoremediation potentiality of mangrove plants and associates.

Conclusion

Heavy metals like Zn, Cu, Ni, Co, Pb and Cr were measured in sediments, leaf, stem and root tissue of various mangrove species in the Sundarbans forest in India. Except for Zn and Cu, metal concentrations in plant organs were lower than the metal concentrations in sediments. Cu and Cr exhibited slightly higher concentrations in mangrove trees than the permissible limit of the WHO. High TF for Zn and Cu may be due to high physiological requirements, as both elements are essential in photosynthesis. Sediment properties might greatly influence the availability of metals to the plant species. Pb and Co were characterized by low BCF with medium TF due to their lower bioavailability in sediment and the limited physiological roles of those elements.

The mangrove species of *Nypa fruiticans*, *Ceriops decandra* and *Phoenix paludosa* might be classified as Cu excluders with a TF < 1 and a BCF > 1. *Heritiera fomes* and *Aegialitis rotundifolia* may be classified as Cu accumulators, extractors and/or translocators. Accumulator indicator plant species are tolerant due to metal content that may be proportional to the level in the sediments. All these characteristics are essential to be considered as phytoremediation potentiality of mangrove plants. Mangroves also act as sinks when metals are stored in different plant organs.

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Conflicts of Interest

No conflicts of interest have been declared.

Ethical Statement

This is to certify that the reported work in the paper entitled “Mangrove species selection for phytoremediation of heavy metals from the Sundarbans, Northeast coast of India” submitted for publication is an original one and has not been submitted for publication elsewhere. We further certify that proper citations to the previously reported work have been given and no data/table/figure has been quoted verbatim from other publications without giving due acknowledgement and without the permission of the author(s). The consent of all the authors of this paper has been obtained for submitting the paper to the “Indian Journal of Geo-Marine Sciences”.

Author Contributions

PM: Conceptualization, formal analysis, funding acquisition and supervision; PKD: Investigation, resources, and software; and PG: Writing - review and editing.

References

1 Chaudhuri A B & Choudhury A, *Mangroves of the Sundarbans*: Vol 1: India, edited by Hussain Z & Acharya G, (IUCN Publication, The World Conservation Union, Bangkok), 1994, pp. 247. ISBN: 978-2-8317-0209-4

2 Kathiresan K, Why are mangroves degrading, *Curr Sci*, 83 (10) (2002) 1246-1249.

3 Ramanathan A L, Sing G, Majumdar J, Samal A C, Chauhan R, *et al*., A study of microbial diversity and its interaction with nutrients in the sediments of Sundarbans mangroves, *Indian J Geo-Mar Sci*, 37 (2) (2008) 159-165.

4 Hoque M A, Sarkar M S, Khan A K U, Moral M A H & Khurram A K M, Present status of salinity rise in Sundarbans area and its effect on Sundari (*Heritiera fomes*) species, *Res J Agric Biol Sci*, 2 (3) (2006) 115-121.

5 Lee S Y, Mangrove out welling: a review, *Hydrobiologia*, 295 (1995) 203-212.

6 Alongi D M, The dynamics of benthic nutrient pools and fluxes in tropical mangrove forests, *J Mar Res*, 54 (1996) 123-148.

7 Boto K G & Wellington J T, Soil characteristics and nutrient status in the northern Australian mangrove forest, *Estuaries*, 7 (1984) 61-69. https://doi.org/10.2307/1351957

8 De T K, De M, Das M, Ray R & Ghosh P B, Level of heavy metals in some edible marine fishes of mangrove dominated tropical estuarine areas of Hooghly River, North-east coast of Bay of Bengal, India, *Bull Environ Contam Toxicol*, 85 (4) (2010) 385-390. https://doi.org/10.1007/s00128-010-0102-1

9 Ghosh P B & Chaudhury A, Cu, Zn and Pb in sediments of Hooghly estuary, *Environ Ecol*, 7 (2) (1989) 427-430.

10 Jaishankar M, Tseten T, Anbalagan N, Mathew B B & Beeregowda K N, Toxicity mechanism and health effects of some heavy metals, *Interdiscip Toxicol*, 7 (2) (2014) 60-72. https://doi.org/10.2478/intox-2014-0009

11 Macfarlane G, Pulkownik A & Burchett M, Accumulation and distribution of heavy metals in the grey mangrove, Avicennia marina (Forsk) Vierh: biological indication potential, *Environ Pollut*, 123 (1) (2003) 139-151. https://doi.org/10.1016/s0269-7491(02)00342-1

12 Kannan N, Thirunavukkarasu N, Suresh A & Rajgopal K, Analysis of heavy metal accumulation in mangroves and associated mangrove species of Ennore mangrove ecosystem, East Coast India, *Indian J Sci Technol*, 9 (46) (2016) 1-12. https://doi.org/10.17485/ijst/2016/v9i46/101551

13 Chatterjee M, Massolo S, Sarkar S K, Bhatterjaya A K, Bhatterjyaya B D, *et al*., An assessment of trace element contamination in intertidal sediment cores of Sundarban mangrove wetland, India, *Environ Monit Assess*, 150 (2009) 307-322. https://doi.org/10.1007/s10661-008-0232-7

14 Ghosh S, Bakshi M, Kumar A, Ramanathan A L, Biswas J K, *et al*., Assessing the potential ecological risk of Co, Cr, Cu, Fe and Zn in the sediments of Hooghly–Matla estuarine system, India, *Environ Geochem Health*, 41 (2019) 53–70.

15 Ray R, Mandal S K, González A G, Pokrovsky O S & Jana T K, Storage and recycling of major and trace element in mangroves, *Sci Total Environ*, 780 (2021) p. 146379.

16 Choudhury R, Favas P J C, Pratas J, Jonathan M P, Sankar Ganesh P, *et al*., Accumulation of trace metals by mangrove plants in Indian Sundarban Wetland: Prospects for phytoremediation, *Int J Phytoremediation*, 17 (9) (2015) 885–894. https://doi.org/10.1080/15226514.2014.981244

17 Tam N F Y & Wong Y S, Spatial variation of heavy metals in surface sediments of Hong Kong mangrove swamps, *Environ Pollut*, 110 (2) (2000) 195–205. https://doi.org/10.1016/S0269-7491(99)00310-3

18 Yadav S K, Heavy metals toxicity in plants: An overview on the role of glutathione and phytochelatins in heavy metal stress tolerance of plants, *S Afr J Bot*, 76 (2) (2010) 167–179. https://doi.org/10.1016/j.sajb.2009.10.007

19 Nedjimil B, Phytoremediation: a sustainable environmental technology for heavy metals decontamination, *SN Appl Sci*, 3 (2021) 286. https://doi.org/10.1007/s42452-021-04301-4

20 Jackson M L, *Soil Chemical Analysis*, (Prentice Hall of India Pvt Ltd, New Delhi), 1967, pp. 498.

21 Walkley A & Black T A, An examination of the Degradation method for determining soil organic matter: proposed modification of the chromic acid titration, *Soil Sci*, 37 (1934) 29-35.

22 US EPA, *Method 3050B: Acid digestion of sediments, sludges and soils*, (US Environmental Protection agency, USA), 1996, pp. 12.

23 Usman A R A, Lee S S, Awad Y M, Lim K J, Yang J E, *et al*., Soil pollution assessment and identification of hyper accumulating plants in chromated copper arsenate (CCA) contaminated sites, Korea, *Chemosphere*, 87 (8) (2012) 872–878. https://doi.org/10.1016/j.chemosphere.2012.01.028

24 Ghosh P B, Chakraborty C, Saha A, Singh B N & Chaudhury A, Mangrove litter production in a tidal creek of Lothian island of Sundarbans, India, *Indian J Geo-Mar Sci*, 19 (1990) 292-293.

25 Ghosh P B, Chakraborty C, Saha A, Singh B N & Chaudhury A, Productivity of grass *Porteresia coarctata* in mangrove forest of Sundarbans, *Indian J Geo-Mar Sci*, 20 (1991) 280-282.

26 Mukherjee D P, Mukherjee A & Kumar B, Chemical fractionation of metals in freshly deposited marine estuarine sediments of Sundarbans ecosystem, India, *Environ Geol*, 58 (2009) 1757-1767. https://doi.org/10.1007/s00254-008-1675-4

27 Wedepohl K H, The composition of the continental crust, *Geochim Cosmochim Acta*, 59 (7) (1995) 1217-1232. https://doi.org/10.1016/0016-7037(95)00038-2

28 Hakanson L, Ecological risk index for aquatic pollution control, a sedimentological approach, *Water Res*, 14 (8) (1980) 975-1001. https://doi.org/10.1016/0043-1354(80)90143-8

29 Agoramoorthy G, Chen F A & Hsu M J, Threat of heavy metal pollution in halophytic and mangrove plants of Tamil Nadu, India, *Environ Pollut*, 155 (2) (2008) 320-326. https://doi.org/10.1016/j.envpol.2007.11.011

30 Mukherjee S, Ghosh P B, Sarkar S & Saha T, Environmental variability of some edaphic components from virgin areas of tropical mangrove forest of sundarbans, India, *Indian J Geo-Mar Sci*, 44 (11) (2015) 1815-1824.

31 Sundaray S K, Nayak B B, Lin S & Bhatta D, Geochemical speciation and risk assessment of heavy metals in the river estuarine sediments - a case study: Mahanadi basin, India, *J Hazard Mater*, 186 (2-3) (2011) 1837–1846. https://doi.org/10.1016/j.jhazmat.2010.12.081

32 Kumar S, Karmoker J, Pal B K, Luo C & Zhao M, Trace metals contamination in different compartments of the Sundarbans mangrove: A review, *Mar Pollut Bull*, 148 (2019) 47–60. https://doi.org/10.1016/j.marpolbul.2019.07.063

33 Ross S M & Kaye K J, The meaning of metal toxicity in soil-plant system, In: *Toxic Metals in Soil-Plant System*, edited by Ross S M, (John Wiley & Sons, New York), 1994, pp. 27-61.

34 Murray H, Thompson K A & Macfie S M, Site and species-specific patterns of metal bioavailability in edible plants, *Botany*, 87 (7) (2009) 702-711.

35 Naidoo G, Hiralal T & Naidoo Y, Ecophysiological response of the mangrove *Avicennia marina* to trace metal contamination, *Flora-Morphol Distrib Funct Ecol Plants*, 209 (1) (2014) 63-72. https://doi.org/10.1016/j.flora.2013.10.003