

Research Paper

ECOLOGICAL ROLES OF MERCURY ACCUMULATION IN MANGROVE FORESTS OF SEKOTONG, WEST NUSA TENGGARA, INDONESIA

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ARTICLE HIGHLIGHTS

- Examines mercury accumulation in leaves and roots of nine mangrove species near gold mines
- Shows mangroves can stabilize, extract, and accumulate mercury
- Evaluates translocation, bioaccumulation, and phytoremediation potential
- Identifies mangroves as indicators of mercury contamination
- Supports selecting suitable mangrove species for reforestation of contaminated coasts

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ABSTRACT

This study aimed at assessing mercury accumulation in mangrove organs (leaves and roots) and sediments in potentially polluted coastal mangrove ecosystem of Sekotong, West Lombok Regency, West Nusa Tenggara, Indonesia. The research was conducted in mangrove stands adjacent to conventional gold-processing areas. Mercury concentrations were analyzed in leaves, roots, and underlying sediments of nine mangrove species: *Avicennia marina*, *Bruguiera cylindrica*, *Clerodendrom inerme*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Rhizophora stylosa*, *Scyphiphora hydrophyllaceae*, *Bruguiera gymnorrhiza*, and *Lumnitzera racemosa*. Mercury levels were quantified using Atomic Absorption Spectrophotometer (AAS). The mean mercury concentration in sediment was 0.30 ± 0.122 ppm, which was lower than the mean concentrations in leaves (0.48 ± 0.716 ppm) and roots (0.33 ± 0.204 ppm). Four mangrove species showed phytostabilization potential, with translocator factor (TSF) values < 1 (*Bruguiera gymnorrhiza*, *Clerodendrom inerme*, *Lumnitzera racemosa*, and *Scyphiphora hydrophyllaceae*), while five other species functioned as phytoextractors with TSF values > 1 (*Avicennia marina*, *Bruguiera cylindrica*, *Rhizophora mucronata*, *Rhizophora apiculata*, and *Rhizophora stylosa*). Leaf bioconcentration factor (BAF) values ranged from 0.02 to 15.73, with a mean of 2.65 ± 4.961 , while root BAF values ranged from 0.04 to 4.33, with a mean of 1.45 ± 1.280 . The translocation distribution factor (FTD) values for leaves ranged from -0.48 to 8.12, with a mean of 1.10 ± 2.275 , whereas root FTD values ranged from -5.55 to 3.87, with a mean of -0.10 ± 2.449 . The negative mean root FTD indicates that mercury distribution tended to be higher in aboveground part of the plants, particularly leaves.

Keywords: accumulation, heavy metals, mangroves, mercury, substrates

INTRODUCTION

Heavy metal pollution is a significant global challenge due to its adverse effects on organisms and ecosystems (Briffa *et al.* 2020; Singh *et al.* 2023; Piwowska *et al.* 2024). Anthropogenic activities such as mining, metal smelting, industrial processes (e.g., coal, oil, chemical, fertilizer, and pesticide industries), and port operations, are major sources of heavy metals in coastal environments (Shah 2021; Zhang *et al.* 2022; Daripa *et al.* 2023).

Illegal gold mining that does not comply with environmentally sound principles poses serious risks to human health and causes environmental pollution (Essah 2022; Achina-Obeng & Aram 2022; Meutia *et al.* 2023; Haroon & Hayyat 2025). In Indonesia, one such activity occurs in Sekotong, West Lombok Regency, West Nusa Tenggara Province, Indonesia, where illegal mining and conventional gold processing are widespread. During gold ore separation, local mining

communities continue to use mercury as the primary agent in conventional processing methods (Wongsasuluk *et al.* 2021; Donkor *et al.* 2024).

Evidence on mercury contamination is further supported by Ahyadi *et al.* (2022), who reported 721 gold mining sites and 2,645 processing units, with estimated mercury and cyanide usage of 1,001.6 kg/month and 2,368.8 kg/month, respectively. Numerous studies have demonstrated the capacity of mangroves to accumulate mercury (Hg). Ismail *et al.* (2020) and Kahula *et al.* (2024) reported significant mercury uptake in the roots and leaves of *Rhizophora mucronata*, whereas Jafar and Pertiwi (2021) detected mercury accumulation in mangrove roots and the gastropod *Telescopium telescopium* in North Halmahera. Similar findings were also reported by Ichwani *et al.* (2025) in Semarang and Setiawan (2013) in South Sulawesi, indicating widespread heavy metal bioconcentration in mangrove ecosystems across Indonesian coastal regions. This situation is particularly concerning because mercury is often regarded as a common material and its waste is frequently discharged into coastal areas and marine environments (Githiria & Onifade 2020; Diarra & Prasad 2021; Onyena *et al.* 2024).

Coastal and marine environments are highly vulnerable to pollution because contaminants disperse more rapidly in aquatic systems than in terrestrial systems (Bashir *et al.* 2020; Kye *et al.* 2023). This risk is amplified when mercury accumulates in marine organisms, including fish (Yang *et al.* 2021), molluscs (Pan & Han 2023), shellfish (Lee *et al.* 2022), crabs (Saadati *et al.* 2020). Conventional gold mining and processing activities in the Sekotong area, West Lombok Regency, Indonesia further degrade environmental quality because processing waste is directly discharged into surrounding areas adjacent to coastal and marine ecosystems. These waters are also critical to the livelihood of local fishing communities.

This situation is compounded by the limited availability of recent studies addressing mercury accumulation in biota from Sekotong, West Lombok, particularly in areas close to conventional gold-processing waste disposal site. Specifically, information on mercury accumulation among different mangrove species remains scarce.

Mangrove species have great adaptability in coastal areas. As an aquatic plant, mangroves are often referred to as aquatic bioindicators because of their ability to accumulate pollutants, including heavy metals, in polluted aquatic environments (Wang *et al.* 2020; Aljahdali & Alhassan 2020; Rajaram *et al.* 2020; Chowdhury *et al.* 2021; Martínez-Colón *et al.* 2021; Hossain *et al.* 2022; Huang *et al.* 2024). Mangrove species can accumulate mercury and store them in mangrove organs and sediments through processes such as rhizodegradation (Hao *et al.* 2012; Hunt *et al.* 2014; Maylani *et al.* 2020; Nedjimi 2021), phytostabilization (Luthansa *et al.* 2021; Uddin & Huang 2023; Chakraborty 2024), and phytoextraction (Khan *et al.* 2020; Rahman *et al.* 2021; Wu *et al.* 2022).

Several research on conventional gold-processing in Sekotong still focused on the topic of blue carbon mangrove ecosystems (Candri *et al.* 2020), spatial analysis of mangrove ecosystems (Sukuryadi *et al.* 2025), and mangrove ecotourism (Hadiprayitno *et al.* 2023). On the other hand, topic on mercury accumulation in mangrove vegetation in coastal areas is limited.

Each mangrove species has different abilities in accumulating mercury, therefore, it is very important to assess the ability of each mangrove species that grows adjacent to gold-processing areas. Information generated from such assessment may be used to develop recommendations for future mangrove restoration that have ecological advantages (Wang *et al.* 2021; Zhou *et al.* 2021; Mahdavian 2023). This study aimed at assessing mercury accumulation in the organs (leaves and roots) and sediments of several mangrove species located in potentially polluted areas in Sekotong, West Lombok Regency, West Nusa Tenggara, Indonesia.

MATERIALS AND METHODS

Research Time and Location

Geographically, the Sekotong mangrove ecosystem is located in West Lombok Regency, West Nusa Tenggara Province, Indonesia (Fig. 1). The research was carried out in May – July 2025 in an area of ± 36 ha mangrove ecosystem located in the Central Sekotong ecotourism area, namely

the Tanjung Batu and Bagek Kembar mangrove ecosystems, adjacent to conventional gold ore mining and processing.

Study Design

This study used a global positioning system (GPS), pH meter, hand refractometer, analytical balance, oven, sample bottles, digital thermometer, and spectrophotometer (Perkin Elmer Spectrophotometer). The materials used included mangrove leaves, mangrove roots, water, substrate, HClO₄, and HNO₃. The research began with the identification of mangrove species using mangrove identification guide by Noor *et al.* (2006), followed by measurements of physicochemical water parameters, including water temperature, substrate temperature, substrate pH, water salinity, and water pH. Environmental parameter measurements were conducted repeatedly over a three-month period (May – July 2025).

Leaf, root, and substrate samples were collected using a purposive random sampling method. Leaf and root samples were obtained from trees with stem diameters of 5 – 30 cm or stem circumferences of 15 – 95 cm. Sampling was conducted three times for nine mangrove species at different locations and tree stands within the study area. Repeated sampling of each organ and species was performed to improve data robustness and minimize analytical bias. Substrate samples were collected at the base of the same trees from which leaf and root samples were obtained.

Mercury concentrations in leaf, root, and substrate samples were determined using atomic absorption spectrophotometry. Laboratory analyses were conducted at the Agricultural Instrument Standardization Agency, which complies with SNI ISO/IEC 17025:2017 and is accredited by the National Accreditation Committee (certificate number LP-394-IDN) for chemical analysis of soil and plant tissues.

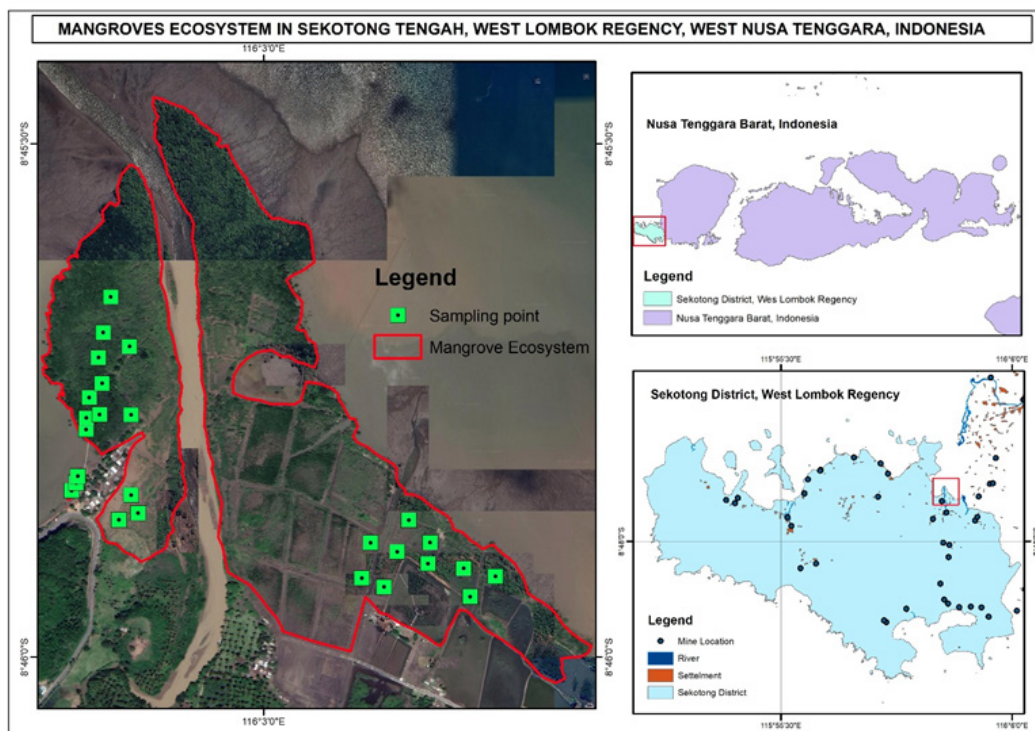


Figure 1 Study location in mangroves ecosystem in Sekotong, West Lombok, West Nusa Tenggara, Indonesia

Sample Extraction and Mercury Analysis

Approximately 2.5 g of plant samples (leaves and roots) and mangrove soil with particles sizes < 0.5 mm were weighed and placed into digestion tubes. Each sample was treated with 5 mL of concentrated HNO₃ and allowed to stand for 24 hours. The samples were then heated at 100 °C for 1 hour 30 minutes, cooled and supplemented with an additional 5 mL of HNO₃ and 1 mL of HClO₄. The mixture was heated to 130 °C for 1 hour, followed by heating at 150 °C for 2 hours and 30 minutes until yellow fumes disappeared; heating time was extended if yellow fumes persisted. Afterwards, the temperature was increased from 113 °C to 170 °C for 1 hour, followed by another temperature increase to 200 °C for 1 hour until white fume appeared. The extraction process was considered complete when a white residue formed or approximately 1 mL of clear solution remained.

After cooling, the extract was diluted with deionized water to a final volume of 25 mL, shaken thoroughly until homogeneous, and allowed to stand overnight (Eviati *et al.* 2009; Horwitz 2010; Lisle *et al.* 1991; USDA 2004). Clear extracts were analyzed for mercury using atomic absorption spectrophotometry equipped with a vapor generation system at a wavelength of 253.7 nm using a mercury standard series for calibration. The carrier gas, SnCl₂ reagent, diluted H₂SO₄ solution, and standards or samples were introduced into the generator through separate inlet lines. Mercury concentrations in the extracts were calculated using the atomic absorption spectrophotometric method according to the following formula:

$$\begin{aligned} \text{Hg heavy metal content (ppm)} &= \text{ppb curve} \times \text{mL extract} / 1,000 \\ &= \text{ppb curve} \times 25 \text{ mL} / 1,000 \times 1,000 \text{ g/sample} / \text{fp} \times \text{fk} \\ &= \text{ppb curve} \times 10 \times \text{fp} \times \text{fk} \end{aligned}$$

where:

- ppb = The sample rate derived from the regression curve represents the connection between the standard series rate and its value after subtracting the blank readings.
- 1,000 = Conversion factor to ppm (mg/kg)
- fp = Dilution factor
- fk = Water content correction factor (100 / (100 - % moisture content))

Data Analysis

Further calculations were performed using data from laboratory analysis on each leaf, root and substrate sample to determine Translocation Factor (TSF), Biological Accumulation Factor (BAF) and Phytoremediation (FTD) values, as indicators to evaluate the capacity of each mangrove species to remediate heavy metals in Sekotong Tengah (Mellem *et al.* 2012; Supriyantini *et al.* 2017; Rachmawati *et al.* 2018; Manikasari & Mahayani 2019), using the following formulas:

(a) Translocation factors (TSF)

$$\text{TSF} = \text{Mercury heavy metal in leaves} / \text{Mercury heavy metal in root} \dots\dots\dots(1)$$

Category:

TSF value < 1: phytostabilization

TSF value > 1: phytoextraction

(b) Bioaccumulation Factors (BAF)

$$\text{Leaf BAF} = \text{Hg heavy metal in leaves} / \text{Hg heavy metal in substrates} \dots\dots\dots(2)$$

$$\text{Root BAF} = \text{Hg heavy metal in root} / \text{Hg heavy metal in substrates} \dots\dots\dots(3)$$

Category:

BAF > 1 : Accumulator

BAF = 1 : Indicator

BAF < 1 : Excluded

(c) Phytoremediation (FTD)

$$\text{Leaf FTD} = \text{BAF of leaf} - \text{TSF}$$

$$\text{Root FTD} = \text{BAF of root} - \text{TSF}$$

RESULTS AND DISCUSSION

Species of Mangroves

Mangrove species diversity show an important ecological role in maintaining the balance of coastal ecosystems. Based on the identification results, nine mangrove species were observed consisting of seven genera from six families. The Rhizophoraceae family is the most dominant with three genera and five species, namely *Bruguiera cylindrica*, *Bruguiera gymnorrhiza*, *Rhizophora apiculata*, *Rhizophora mucronata*, and *Rhizophora stylosa* (Table 1). Species of the genus *Rhizophora* are known to have a strong root support system which function is to resist abrasion and maintain the stability of the coastline (Cahyaningsih *et al.* 2022; Usman *et al.* 2022). *Avicennia marina* of the Acanthaceae family has a special adaptation in the form of pneumatophores, which facilitates gas exchange

on anaerobic substrates (Hao *et al.* 2021). Other species such as *Lumnitzera racemosa* and *Clerodendrum inert* also shows adaptive role in high salinity conditions (Liang *et al.* 2022).

The diversity of mangrove species in Sekotong mangrove ecosystem is lower compared to other polluted areas. For example, the Pattani Bay mangrove ecosystem of Thailand hosts 18 species (Kaewtubtim 2016) and the Lembar Bay ecosystem contains 10 species, despite being affected by basin activities (Rahman *et al.* 2025). Other regions show similarly low diversity, such as the mangrove ecosystem in the Coral Triangle Ecoregion, Southeast Sulawesi, Indonesia has seven species (Analuddin *et al.* 2017), the Segara Anakan Cilacap, Indonesia has five species (Hilmi *et al.* 2023), Sitio Oyon and Sitio Asinan in Masinloc, Zambales, Philippines have three species (Paz-Alberto *et al.* 2014), and the north coast of Puerto Rico also have three species (Maldonado-Román *et al.* 2012).

Analysis of Physicochemical Parameters

Environmental parameters in the Sekotong Tengah mangrove ecosystem show considerable variations in physicochemical conditions across sampling points. Water temperature ranged from 31.70 °C to 33.50 °C, with an average of 32.69 ± 0.79 °C, remaining within the tolerance range for

mangrove organisms. Salinity was relatively stable (31.00 - 31.50 ppt; 31.25 ± 0.29 ppt), reflecting an estuarine environment that supports typical tropical mangrove species. Water pH was alkaline (8.04 - 8.56), while soil pH was more acidic (5.75 - 6.70), a common feature of mangrove substrates resulting from organic matter accumulation and decomposition. Dissolved oxygen (DO) fluctuated widely (4.81 - 8.90 ppm; 6.87 ± 2.30 ppm), reflecting variations in photosynthetic activity and organic matter degradation. Biochemical oxygen demand (BOD) also varied (3.32 - 8.87 ppm), indicating differences in microbial activity and organic matter load among sites.

The physicochemical conditions of the Sekotong mangrove waters are suitable for mangrove growth and development, according to Government Regulation of the Republic of Indonesia Number 22 year 2021 on the Implementation of Environmental Protection and Management with National Water Quality Standard Specifications. Previous studies reported that water physicochemistry can influence mangrove physiology, affecting nutrient absorption and limiting the uptake of heavy metals accumulated in the substrate and water column (Tang *et al.* 2010; Kumar *et al.* 2015; Liu *et al.* 2016).

Table 1 Mangrove species observed in Sekotong mangrove ecosystems

No.	Family	Genus	Species
1.	Acantaceae	Avicennia	<i>Avicennia marina</i>
2.	Rhizophoraceae	Bruggeria	<i>Bruguiera cylindrica</i> <i>Bruguiera gymnorrhiza</i>
3.	Lamiaceae	Cleroderma	<i>Clerodendrum inerme</i>
4.	Cambreta	Lumnitzera	<i>Lumnitzera racemosa</i>
5.	Rhizophoraceae	Rhizophora	<i>Rhizophora apiculata</i> <i>Rhizophora mucronata</i> <i>Rhizophora stylosa</i>
6.	Rubiaceae	Scyphiphora	<i>Scyphiphora hydrophyllacea</i>

Table 2 Environmental parameters observed in Central Sekotong mangrove ecosystems

No.	Parameters	Unit	Sampling point				Average $\pm$ standard deviation	Quality standards*
			1	2	3	4		
1.	Water temperature	°C	33.10	33.50	32.45	31.70	32.69 ± 0.79	28.00 – 31.00 °C
2.	Salinity	ppt	31.00	31.00	31.50	31.50	31.25 ± 0.29	Max: 34 ppt
3.	Water pH	-	8.13	8.56	8.11	8.04	8.21 ± 0.24	7.00 – 8.50
4.	Soil pH	-	5.75	6.35	6.70	6.40	6.30 ± 0.40	7.00 – 8.50
5.	DO	ppm	4.93	4.81	8.82	8.90	6.87 ± 2.30	> 5.00 mg/L
6.	BOD	ppm	3.32	3.32	8.87	8.62	6.03 ± 3.13	Max: 20 mg/L

Notes: Data presented are results obtained in this study; * = Government Regulation of the Republic of Indonesia Number 22 year 2021 on the Implementation of Environmental Protection and Management with National Water Quality Standard Specifications.

Table 3 Mercury accumulation in leaves, roots, and substrates of nine mangrove species

No.	Mangrove species	Mercury concentration (ppm)		Mercury concentration in substrates (ppm)	SNI 7387:2009	Government Regulation of the Republic of Indonesia Number 22 year 2021
		Leaf	Roots			
1.	<i>Avicennia marina</i>	0.37	0.36	0.16	0.50	0.001
2.	<i>Bruguiera cylindrica</i>	2.36	0.31	0.15		
3.	<i>Bruguiera gymnorrhiza</i>	0.01	0.02	0.46		
4.	<i>Clerodendrum inerme</i>	0.36	0.78	0.18		
5.	<i>Lumnitzera racemosa</i>	0.08	0.35	0.43		
6.	<i>Rhizophora apiculata</i>	0.35	0.32	0.43		
7.	<i>Rhizophora mucronata</i>	0.23	0.22	0.28		
8.	<i>Rhizophora stylosa</i>	0.21	0.21	0.25		
9.	<i>Scyphiphora hydrophyllacea</i>	0.38	0.39	0.33		
Average		0.48	0.33	0.30		
Standard deviation		0.716	0.204	0.122		

Note: Data presented are results obtained in this study.

Hg Heavy Metal Content in Mangrove Sediments, Roots, and Leaves

Mercury (Hg) concentrations in the leaves of nine mangrove species varied significantly, ranging from 0.01 to 2.36 ppm, with an average of 0.48 ± 0.716 ppm (Table 3). The highest concentration was observed in *Bruguiera cylindrica* leaves (2.36 ppm), while the lowest was recorded in *Bruguiera gymnorrhiza* leaves (0.01 ppm), both species belonging to the Rhizophoraceae family. This wide range suggests generally low leaf absorption efficiency for mercury. Other species, such as *Scyphiphora hydrophyllacea* (0.38 ppm), *Avicennia marina* (0.37 ppm), and *Clerodendrum inerme* (0.36 ppm) exhibited mercury levels above 0.35 ppm, indicating relatively efficient metal translocation from roots to leaves. In contrast, *Rhizophora mucronata* (0.23 ppm), *Rhizophora stylosa* (0.21 ppm), and *Lumnitzera racemosa* (0.08 ppm) showed lower leaf accumulation, suggesting preferential retention of mercury in the roots.

Mercury accumulation in the roots of nine mangrove species ranged from 0.02 to 0.78 ppm, with an average of 0.33 ± 0.204 ppm. The highest concentration was observed in *Clerodendrom inerma* (0.78 ppm) and lowest in *Bruguiera gymnorrhiza* (0.02 ppm). In five species (*Avicennia marina*, *Bruguiera cylindrica*, *Rhizophora apiculata*, *Rhizophora mucronata*, and *Rhizophora stylosa*), root mercury concentrations were lower than those in the leaves, whereas in four species (*Bruguiera gymnorrhiza*, *Clerodendrom inerma*, *Lumnitzera racemosa*, and

Scyphiphora hydrophyllacea), root accumulation exceeded leaf levels. Higher mercury accumulation in roots indicates the capacity of mangroves to adsorb and retain metals in the root zone, functioning as phytostabilizing agents. Species of the Rhizophoraceae family generally showed lower root accumulation (< 0.35 ppm), suggesting efficient translocation of mercury to aerial tissues. These data provide an important basis for selecting mangrove species for root-based phytoremediation strategies.

Mercury concentrations in the substrate beneath each mangrove stand averaged 0.30 ± 0.122 ppm, lower than the average concentrations in leaves (0.48 ± 0.716 ppm) and roots (0.33 ± 0.204 ppm). However, certain species exhibited higher substrate accumulation than in plant tissues. For example, *Avicennia marina* (0.16 ppm), *Bruguiera cylindrica* (0.15 ppm), *Clerodendrom inerma* (0.18 ppm), and *Scyphiphora hydrophyllacea* (0.33 ppm) accumulated less mercury in substrate than in plant tissues, whereas *Bruguiera gymnorrhiza* (0.46 ppm), *Lumnitzera racemosa* (0.43 ppm), *Rhizophora apiculata* (0.43 ppm), *Rhizophora mucronata* (0.28 ppm), and *Rhizophora stylosa* (0.25 ppm) showed higher substrate accumulation. Variations in substrate mercury concentrations are influenced by particle size and deposition mechanisms (Brady *et al.* 2014; Rezania *et al.* 2016; Baran *et al.* 2019; Harmesa *et al.* 2020), consistent with previous studies in Lembar Bay, West Lombok, where substrate lead concentrations exceeded leaf and root levels (Rahman *et al.* 2025).

Table 4 Translocation factor, Bioaccumulation factor, and phytoremediation of nine mangrove species observed in this study

No.	Mangrove species	TSF	Leaves BAF	Roots BAF	Leaves FTD	Roots FTD
1	<i>A. marina</i>	1.03	2.31	2.25	1.28	1,22
2	<i>B. cylindrica</i>	7.61	15.73	2.07	8.12	-5,55
3	<i>B. gymnorrhiza</i>	0.50	0.02	0.04	-0.48	-0,46
4	<i>C. inerma</i>	0.46	2.00	4.33	1.54	3,87
5	<i>L. racemosa</i>	0.23	0.19	0.81	-0.04	0,59
6	<i>R. apiculata</i>	1.09	0.81	0.74	-0.28	-0,35
7	<i>R. mucronata</i>	1.05	0.82	0.79	-0.22	-0,26
8	<i>R. stylosa</i>	1.00	0.84	0.84	-0.16	-0,16
9	<i>S. hydrophyllacea</i>	0.97	1.15	1.18	0.18	0,21
	Average	1.55	2.65	1.45	1.10	-0.10
	Standard Deviation	2.296	4.961	1.280	2.725	2.449

*Notes: Data presented are results obtained in this study; TSF = Translocation factor; BAF = Bioaccumulator factor; FTD = Phytoremediation

Several species exceeded the SNI 7387:2009 threshold for mercury contamination in plant tissues; *Bruguiera cylindrica* leaves (2.36 ppm) and *Clerodendrom inerma* roots (0.78 ppm), whereas no substrate samples exceeded 0.50 ppm. Compared with the Decree of the Minister of Environment of the Republic of Indonesia No. 51 year 2004 on the Quality of Marine Tourism Health, mercury concentrations in both plant tissues and substrates indicate a polluted condition (> 0.001 ppm).

Translocation factor (TSF) values for mercury in the nine mangrove species ranged from 0.23 to 7.61, with an average of 1.55 ± 2.296 . The highest TSF was observed in *Bruguiera cylindrica* (7.61) and the lowest in *Lumnitzera racemosa* (0.23), reflecting interspecific differences in metal transport from roots to aerial tissues (Analuddin *et al.* 2017; Arumugam *et al.* 2018). Four species (*Bruguiera gymnorrhiza*, *Clerodendrom inerma*, *Lumnitzera racemosa*, *Scyphiphora hydrophyllacea*) had TSF values < 1 , functioning primarily as phytostabilizers, while five species (*Avicennia marina*, *Bruguiera cylindrica*, *Rhizophora mucronata*, *Rhizophora apiculata*, and *Rhizophora stylosa*) exhibited TSF > 1 , indicating phytoextraction capacity (Table 4).

Phytostabilization in roots is mediated by binding of metal ions through root mucilage or cell walls, followed by chelation with phytochelatins or metallothioneins and storage in vacuoles (Abreu & Magalhães 2009; Shackira & Puthur 2019; Hunt *et al.* 2014; Nedjimi 2021). This is supported by higher average mercury concentrations in roots (0.39 ± 0.311 ppm) compared with leaves (0.21 ± 0.190 ppm) in the four phytostabilizing species.

The Rhizophoraceae family, including *Bruguiera cylindrica*, *Rhizophora mucronata*, *Rhizophora apiculata*, and *Rhizophora stylosa*, and the Acanthaceae family (*Avicennia marina*) exhibited ecological capabilities as phytoextractors (TSF > 1), supported by higher mercury accumulation in leaves than in roots. Similarly, Rahman *et al.* (2025) reported that *R. stylosa* in Lembar Bay, West Lombok, functions as phytoextractor, with leaf lead concentrations (4,230 ppm) exceeding root concentrations (2,843 ppm; TSF= 1.488). Other studies also indicate that Rhizophoraceae species predominantly function in phytoextraction (Majid *et al.* 2014; Takarina & Pin 2017; Baharvand *et al.* 2021; Mentari *et al.* 2022).

Bioaccumulation factors (BAF) indicate the capacity of mangroves to absorb and accumulate heavy metals from the environment into plant tissues (Dajam *et al.* 2024). In this study, leaf BAF values ranged from 0.02 to 15.73, with an average of 2.65 ± 4.961 , while root BAF values ranged from 0.04 to 4.33, with an average of 1.45 ± 1.280 . Leaf BAF values were generally higher than root BAF values, indicating preferential translocation of mercury to aboveground tissues. This pattern aligns with observed mercury accumulation in leaves of *Bruguiera gymnorrhiza*, *Clerodendrom inerma*, *Lumnitzera racemosa*, *Scyphiphora hydrophyllacea* and *Avicennia marina*, whereas the other five species showed higher root BAF values. *Bruguiera cylindrica* exhibited the highest leaf BAF (15.73), indicating strong accumulation in aerial tissues, whereas *Bruguiera gymnorrhiza* showed very low BAF values (< 0.05) in both tissues, reflecting minimal mercury accumulation.

Four mangrove species (*Avicennia marina*, *Bruguiera cylindrica*, *Clerodendrom inerma*, and *Scyphiphora hydrophyllacea*) had BAF value > 1 in both leaves and roots, indicating their role as accumulator plants. Accumulators transfer metals from roots to leaves and store them in aboveground tissues (Baker & Walker 1990; Tam *et al.* 1998; Analuddin *et al.* 2017). Physiologically, metal ions are absorbed through roots, transported via xylem, chelated by phytochelatins or metallothioneins, and sequestered in vacuoles of stems or leaves (Cobbett & Goldsbrough 2002; Nair 2022; Sharma *et al.* 2023).

Meanwhile, five mangrove species (*Rhizophora mucronata*, *Rhizophora stylosa*, *Rhizophora apiculata*, *Bruguiera gymnorrhiza*, *Lumnitzera racemosa*) had BAF values < 1 in both organs, functioning as excluders. Excluder plants limit metal accumulation in aboveground biomass, concentrating metals primarily in (Hunt *et al.* 2014; Santana *et al.* 2018). This may also reflect mercury distribution in the substrate, as root uptake and translocation occur through xylem-mediated transport (Ariesabeth 2005; Hao *et al.* 2012).

The Factor of Translocation and Distribution (FTD) reflects the efficiency of heavy metal distribution between roots and leaves. FTD values in leaves ranged from -0.48 to 8.12 (mean 1.10 ± 2.275), while root FTD values ranged from -5.55 to 3.87 (mean -0.10 ± 2.449). Negative mean FTD in roots suggests preferential accumulation in leaves. For example, *Bruguiera cylindrica* exhibited the highest leaf FTD value (8.12), consistent with high BAF and TSF values. In contrast, *Rhizophora mucronata*, *Rhizophora stylosa*, *Rhizophora apiculata*, and *Bruguiera gymnorrhiza* showed negative FTD values in both organs, indicating low accumulation in aboveground tissues and a stronger phytoextraction function.

CONCLUSION

Mangrove diversity in the study area comprised nine mangrove species, including: *Avicennia marina*, *Bruguiera cylindrica*, *Clerodendrom inerme*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Rhizophora stylosa*, *Scyphiphora hydrophyllacea*, *Bruguiera gymnorrhiza*, and *Lumnitzera racemosa*. The physicochemical conditions of the Sekotong mangrove ecosystem were suitable for mangrove growth and development, based on the Decree of the Minister of Environment of the Republic of Indonesia No. 51 year 2004 concerning Quality

Standards for the Health Quality of Marine Biota. Mercury concentrations were generally higher in leaves than in roots and substrates, indicating active metal translocation in several species. Four species function primarily as phytostabilizers, with translocation factor (TSF) values < 1 (*Bruguiera gymnorrhiza*, *Clerodendrom inerma*, *Lumnitzera racemosa*, and *Scyphiphora hydrophyllacea*), while five other species act as phytoextractors (TSF > 1) (*Avicennia marina*, *Bruguiera cylindrica*, *Rhizophora mucronata*, *Rhizophora apiculata*, and *Rhizophora stylosa*). Leaf bioaccumulation factors exceeded root values, indicating preferential mercury allocation to aboveground tissues. Accumulator (BAF > 1) was observed in *Avicennia marina*, *Bruguiera cylindrica*, *Clerodendrom inerma*, and *Scyphiphora hydrophyllacea*, while the remaining five mangrove species acted as excluders (*Rhizophora mucronata*, *Rhizophora stylosa*, *Rhizophora apiculata*, *Bruguiera gymnorrhiza*, and *Lumnitzera racemosa*). Negative mean root FTD values further suggest dominant mercury distribution to leaves. These findings highlight species-specific phytoremediation strategies and support the use of mangroves for mercury management in contaminated coastal ecosystems.

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