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Bioaccumulation of Heavy Metals by *Acanthus ilicifolius* in Polluted Mangrove Ecosystems

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Abstract

Mangrove forests in Sicanang Belawan, North Sumatra, covering 1,510 hectares, are essential for coastal ecosystem services, such as silvofishery and polyculture ponds. Despite their potential, heavy metal pollution has emerged due to anthropogenic activities upstream. Therefore, this study aims to determine the bioaccumulation and translocation capacities of *Acanthus ilicifolius* for copper (Cu), lead (Pb), and zinc (Zn). Samples were collected from 4 sites, representing varying pollution levels, namely Station 1 (mangrove ecotourism area), Station 2 (control site), Station 3 (industrial area with power plant activities), and Station 4 (industrial site near manufacturing facilities). Atomic absorption spectroscopy (AAS) was then used to measure metal concentrations in sediments and plant tissues (roots, stems, and leaves). The results showed that there were significant site-specific differences in Cu and Pb levels, while Zn concentrations had no significant variation. *A. ilicifolius* exhibited the highest bioconcentration factor for Cu at Station 1 (2.43±0.76 ppm), while extreme translocation of Pb to leaves was observed at the same location (9.21 ppm). Despite moderate Pb toxicity at Station 1, overall sediment contamination was considered low. This is the first study reporting heavy metal contamination in Sicanang mangrove, identifying *A. ilicifolius* as an effective phytoremediator for Cu, Pb, and Zn, aiding pollution mitigation in mangrove ecosystems.

Keywords:

Acanthus ilicifolius L.;
Anthropogenic Activities;
Hyperaccumulator;
Mangrove; Sicanang.
North Sumatra.

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1- Introduction

Mangrove forests serve as a critical buffer between terrestrial and aquatic environments, effectively adapting to tidal areas in tropical and subtropical regions [1]. Although less than 1% of global tropical forests contain mangroves, these valuable ecosystems provide numerous essential goods and services, contributing to the livelihoods and security of coastal communities [2]. Several studies have shown that pollution is one of the major threats to coastal areas, increasingly driven by industrial infrastructure [3]. In addition, industrialization and extensive agricultural activities contribute to elevated heavy metal levels in water bodies [4]. Excessive exploitation of natural land, urban waste disposal, and the widespread use of metal-enriched pesticides and fertilizers further introduce toxic metals into coastal areas, including mangrove forests, which are globally threatened by these pollutants [5].

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Indonesia is home to 243 identified mangrove species, with 157 found in Sumatra. Sicanang Belawan, a coastal area in North Sumatra, has a mangrove forest area covering 1,510 hectares (ha). A portion of this area is inhabited, with the primary activities centered around port operations for the mass transportation of goods and people [6]. The Sei Belawan River and its tributaries flow through the mangrove forests, carrying pollutants from upstream anthropogenic activities in urban regions before reaching the estuary or the Malacca Strait. The close proximity of the Sicanang Belawan mangrove forests to residential areas and industrial zones increases the risk of contamination from domestic waste and industrial activities, rendering the waters particularly susceptible to heavy metals pollution [7]. Despite this condition, the area still holds significant potential for community-based mangrove conservation and management due to its rich biodiversity, which is also prospective for the ecotourism business [8, 9]. Ecosystem services currently utilized in Sicanang by the local community include mangrove-based silvofishery and polyculture ponds, with tiger shrimp (*Penaeus monodon*), tilapia (*Oreochromis niloticus*), and mud crab (*Scylla serrata*) as the primary cultivated species [10, 11]. Over the years, mangrove waters and adjacent industrial waters in Sicanang have shown a significant accumulation of heavy metals, including lead (Pb), cadmium (Cd), and mercury (Hg). This accumulation reflects ongoing environmental contamination, likely due to persistent anthropogenic activities [12].

Mangrove forests are natural absorbers, which can accumulate heavy metals, helping to reduce pollutant concentrations in aquatic environments [13]. Mangrove species, such as *Avicennia marina* (Forssk.) Vierh., have been shown to accumulate various heavy metals, including copper (Cu), cadmium (Cd), lead (Pb), and zinc (Zn) [14]. *Acanthus ilicifolius* L. has also been used as a phytoremediation agent to reduce Cu pollutants in the Jagir River estuary, Wonorejo Village, Surabaya, Indonesia, and has demonstrated potential for phytoremediation of chromium (Cr) [15]. In addition, the species shows the ability to accumulate arsenic (As), Cu, Cr, Pb, and Zn [4]. In a previous study, *A. ilicifolius* was identified as a dominant mangrove species on Sicanang Island based on initial surveys, suggesting that it may play a significant role in the accumulation and translocation of heavy metals within the Sicanang Belawan mangrove forests [16]. The widespread presence of *A. ilicifolius* on Sicanang Island indicates that the species may be particularly efficient as a phytoaccumulator, especially in areas near industrial and human activities where heavy metals can be leached into the aquatic ecosystems. Therefore, this study aims to determine the concentrations of Pb, Cu, and Zn in sediments and *A. ilicifolius* (roots, stems, and leaves), as well as to assess the species' capacity as tolerant or accumulator plants in Sicanang Mangrove, North Sumatra, Indonesia. The methodology section describes the sampling and analytical procedures used. The results section presents the findings on heavy metal concentrations in sediments and *A. ilicifolius* tissues, followed by a detailed discussion comparing the results with previous studies (Figure 1). Finally, the conclusion shows the implications of these findings for mangrove conservation and pollution mitigation.

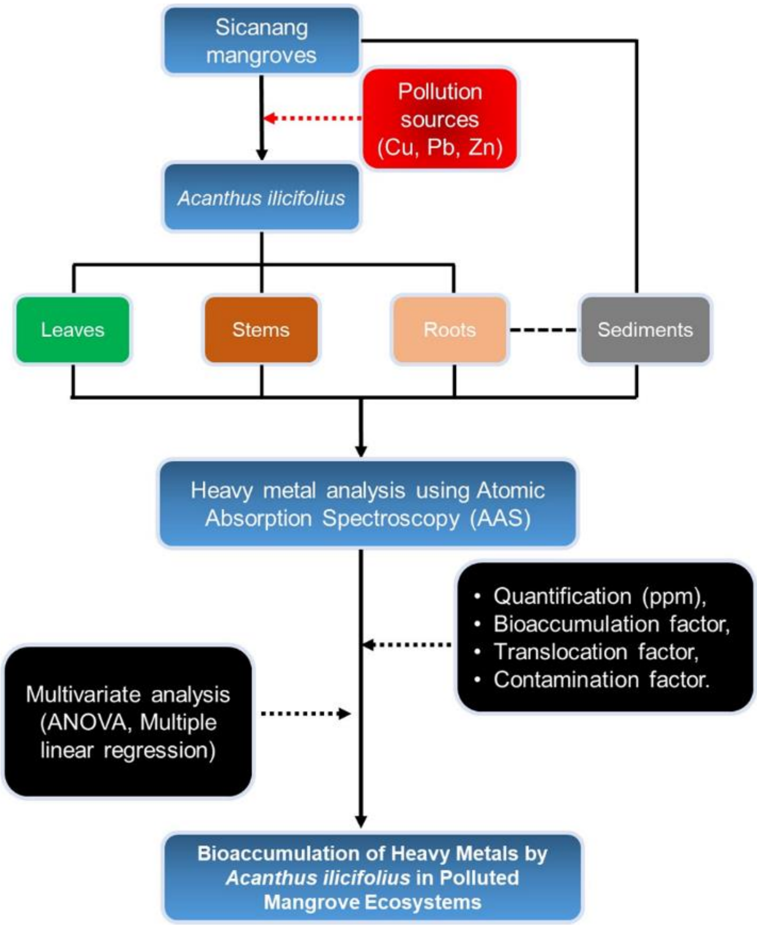

Figure 1. **Flowchart illustrating the methodology for analyzing the bioaccumulation of heavy metals (Cu, Pb, Zn) in *Acanthus ilicifolius* within the polluted mangrove ecosystem of Sicanang**

2- Material and Methods

2-1- Study Area

This study was conducted from June to September 2024. The observation stations were divided into 4, namely Station 1, a mangrove ecotourism area of Sicanang, at 3°45'31.6" north (N), 98°39'06.0" east (E). Station 2, located at 3°45'56.3"N, 98°38'41.3"E, serving as the designated control site, is strategically positioned far from settlements and industrial activities. This location was situated near the Sei Deli River and was intended to represent baseline environmental conditions, minimally influenced by pollution sources. Station 3 was an industrial site settled by Belawan Combined Cycle Electric Power Plant (Gas-Steam) and Berkat Bima Sentana Company at 3°46'21.3"N, 98°40'01.8"E, and Station 4 was an industrial site settled by Canang Indah Company at 3°46'03.4"N, 98°40'13.6"E (Figure 2).

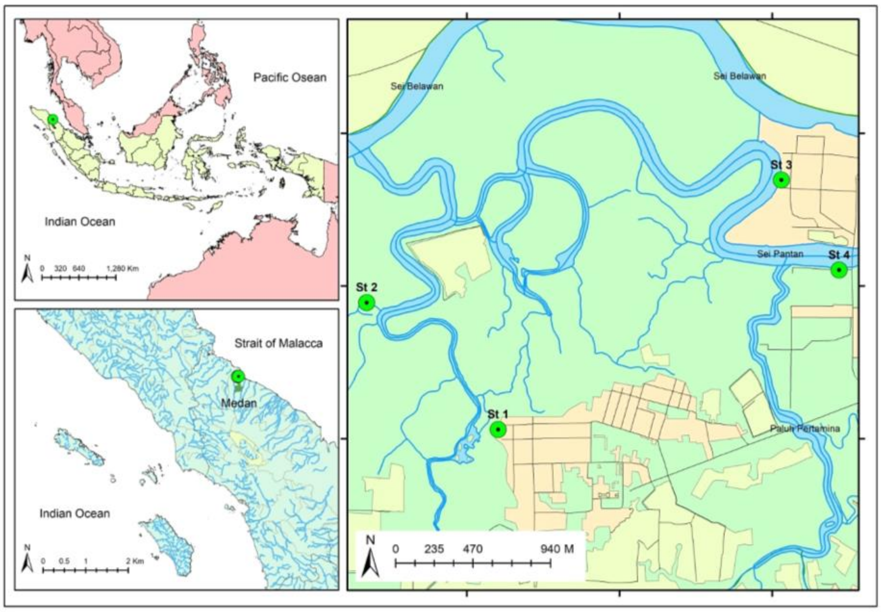

Figure 2. Geographical location of the study area in Sicanang mangrove, North Sumatra, Indonesia

2-2- Specimen Collection of Acanthus ilicifolius

Sediment samples were collected at a depth of about 30 cm, with 500 grams obtained from each station in triplicate and placed in labeled sample bags. Indicator species, *A. ilicifolius*, including roots, stems or branches, and leaves, were manually collected by hand-picking for leaves and using a pre-cleaned steel knife for roots and stems. Each plant sample (root, stem, leaf) was obtained in 250-gram portions in triplicate from all stations, totaling 36 plant samples. Collected plant samples were washed with clean water and transferred to the laboratory for further analysis.

2-3- Heavy Metal Analysis

Sediment samples were prepared by removing foreign objects such as plastic pieces, leaves, or other non-sample materials, then air-dried at 40 to 45 degrees Celsius (°C) for 4 hours (h). Subsequently, approximately 10 grams (g) of the sample were placed in a 250 milliliters (mL) beaker, mixed with 30 mL of concentrated hydrochloric acid (HCl, 37% w/w, Merck, Germany) and 10 mL of concentrated nitric acid (HNO_3, 65% w/w, Merck, Germany).

The mixture was heated on a hot plate until the volume reduced to 20 mL, then cooled afterward, and was transferred to a 100 mL volumetric flask, rinsed with distilled water to remove any residue, filled to the mark, homogenized, filtered using Whatman 42 paper, and placed in test tubes. Furthermore, the plant samples (roots, stems, and leaves) were cut into small pieces, washed with distilled water, oven-dried at 40°C for 48 hours, and then ground using a blender. A total of 5 grams of the finely ground plant sample were placed in a 100 mL beaker, mixed with 5 mL of concentrated HNO_3 , homogenized, covered with a watch glass, and slowly boiled on a hot plate at 95 °C. When the volume was reduced to 15 to 20 mL, the beaker was removed from the hot plate and cooled. Subsequently, 10 mL of concentrated HNO_3 and 10 mL of concentrated perchloric acid ($HClO_4$, 70% w/w, Merck, Germany) were added, homogenized, and reheated on a hot plate until $HClO_4$ vapor disappeared. The solution was cooled, 50 mL of distilled water was added, filtered, and rinsed with distilled water until a filtrate volume of 100 mL was obtained, and the solution was homogenized. In this study, heavy metal concentrations (Cu, Pb, Zn) in sediment and plant samples were analyzed using an Atomic Absorption Spectrophotometer (AAS Shimadzu AA7000, Japan). The wavelengths for heavy metals were Pb = 283.3 nanometers (nm), Cu = 324.8 nm, and Zn = nm, and the calculation of Cu, Pb, and Zn levels was determined as [17].

$$\text{Heavy metal content (mg/kg)} = \frac{C \times P \times V}{G} \tag{1}$$

where *C* is Concentration of heavy metal in the sample, *P* is Dilution factor, *V* is Volume of solvent, *G* is Weight or volume of the sample.

2-4- Data Analysis

Bioaccumulation Factor (BAF) referred to the ratio of heavy metal concentration in specific plant tissues (roots, stems, and leaves) to the concentration in the surrounding environment. The Translocation Factor (TF) was the plant's ability to absorb and distribute metals throughout its body, estimated by calculating the following translocation factor [18]:

$$\text{BAF} = \frac{\text{Concentration of metal in plant tissue (mg/kg)}}{\text{Concentration of metal in sediment (mg/kg)}} \quad (2)$$

BAF for pollutants was divided into 3 categories, namely BAF>1 = Accumulator; BAF=1 = Indicator; and BAF<1 = Excluder. The BAF parameter indicated the level of heavy metal accumulation from sediment to plants. According to Baker [19], a BAF<1 revealed that the plant effectively prevented heavy metal from entering the upper parts of the plant, though metal concentration in the roots remained high. TF indicated whether a species was a phytoextractor (TF > 1) or a phytostabilizer (TF < 1). The parameter reflected the ability of the plant to transport contaminants from roots to shoots, which was calculated as follows [20]:

$$\text{TF} = \frac{\text{Concentration of metal in leaves or stems (mg/kg)}}{\text{Concentration of metal in roots (mg/kg)}} \quad (3)$$

The contamination factor (C_f^i) referred to the ratio between the concentration of heavy metals in the sediment and the concentration of heavy metals in nature (background value), and could be calculated as follows [21]:

$$\mathrm{C_f^i} = \frac{\mathrm{C_m^i}}{\mathrm{B_m^i}} \quad (4)$$

where C_m^i is Concentration of an element in the sediment, B_m^i is Average concentration of heavy metals in nature (Background value). Background values served as reference standards to determine the increase in heavy metal concentrations in an environment [22]. The background values for heavy metals used in this study referred to Turekian & Wedepohl [23] with concentrations of Pb = 20 mg/kg, Cd = 0.03 mg/g, and Zn = 95 mg/kg. Furthermore, the contamination factor values in sediment could be classified into 4 categories, such as Low (C_f^i<1), Moderate (1≤C_f^i≤3), High (3≤C_f^i≤6), and Very high (C_f^i≥6) [21]. Numerical data were statistically analyzed using Analysis of Variance (ANOVA), followed by Tukey's Honestly Significant Difference (HSD) post-hoc test for multiple comparisons of means across different stations, performed in Minitab version 19.0. The graphical representations and multivariate linear regression analyses were conducted using GraphPad Prism version 8.0.

3- Results and Discussions

Industrialization and urbanization had increased the anthropogenic release of heavy metals into the biosphere, with varying degrees of impact depending on the source and the environmental capacity to mitigate the harmful levels. These impacts could potentially be alleviated by mangrove trees in mangrove ecosystems, which have a natural ability to absorb and reduce heavy metal contamination [24]. In this study, the dominant mangrove species, *Acanthus ilicifolius*, were collected from 4 sites within the Sicanang Belawan mangrove ecosystems, each exhibiting distinct environmental characteristics and varying levels of human activity as surveyed (Figure 3). Maximum concentrations of Cu, Pb, and Zn were obtained across all sediments, with variations observed among the sites. Furthermore, the mangrove ecosystems accumulated heavy metals in both sediments and plant tissues, with sediments typically containing higher concentrations, as reported in previous studies [25–27]. Mangrove vegetation could enhance heavy metal accumulation in sediments while potentially reducing their bioavailability and mobility [26]. This also acted as the primary reservoir for metals, holding more than 90% of the total metal content within the ecosystems [28], and effectively retained metals in the upper layers through several mechanisms, including flooding and associated redox changes. Subsequently, it enhanced metal immobilization by clay minerals, organic matter, iron oxides, and sulfides [29, 30]. As a result, these sediments interacted with dominant mangrove vegetation to facilitate the mobilization of metals within the ecosystems. Statistically significant differences in heavy metal concentrations between the sites were demonstrated for Cu (F = 0.22; P = 0.024) and Pb (F = 4.32; P = 0.043), but not for Zn (F = 0.22; P = 0.880).

The concentration of Cu in *A. ilicifolius* ranged from 0.006 to 7.83 ppm, showing significant variation depending on the sampling site (ANOVA, F = 5.66; P = 0.003). No considerable differences were observed in the accumulation of Cu across the vegetative organs of *A. ilicifolius* (ANOVA, F = 2.15; P = 0.132). Meanwhile, Pb concentrations in *A. ilicifolius* ranged from 0.003 to 9.79 ppm. Unlike Cu, there were no significant differences in Pb detection among the vegetative organs of *A. ilicifolius* (F = 0.57; P = 0.568) and among the sampling sites (F = 2.69; P = 0.063). The uptake of Zn in *A. ilicifolius* ranged from 1.29 to 13.3 ppm and did not show significant differences either among the organs (F = 0.57; P = 0.568) or across the sampling sites (F = 2.69; P = 0.063) in the mangrove area. Based on heavy metal concentrations, Site-2, which served as the control site, displayed lower concentrations of copper (Cu) and lead (Pb) compared to the other sites, though this trend was not observed for zinc (Zn). This showed that Cu and Pb contamination at the industrial sites was significant, likely originating from industrial activities or nearby pollution sources. Pb contamination was observed to exhibit the highest concentration in the ecotourism area (33.41 ppm), significantly exceeding concentrations at other sites. This level was much higher compared to studies of sediments at other ecotourism areas, the Bee Jay Bakau Resort, East Java, Indonesia, where *Avicennia alba* and *Rhizophora mucronata* sediments showed concentrations of 10.43 ppm and 10.76 ppm, respectively [31]. Currently, there were no specific regulations addressing Pb and other heavy metal contamination in mangrove sediments in Indonesia. According to the Interim Sediment Quality Guidelines (ISQG) by the Canadian Council of Ministers for the Environment (CCME), the acceptable limit for Pb concentration in sediment was 30.2 to 112 ppm, indicating heavy contamination at the *A. ilicifolius* site (Site-1). While the exact sources of Pb contamination at this site remained unclear, previous studies in other ecotourism areas had suggested that Pb levels exceeding 30 ppm could result from activities such as the use of fossil fuel-operated motorboats for transport and reliance on rechargeable batteries due to electricity shortages, especially in an area with heavy ecotourism traffic [32].

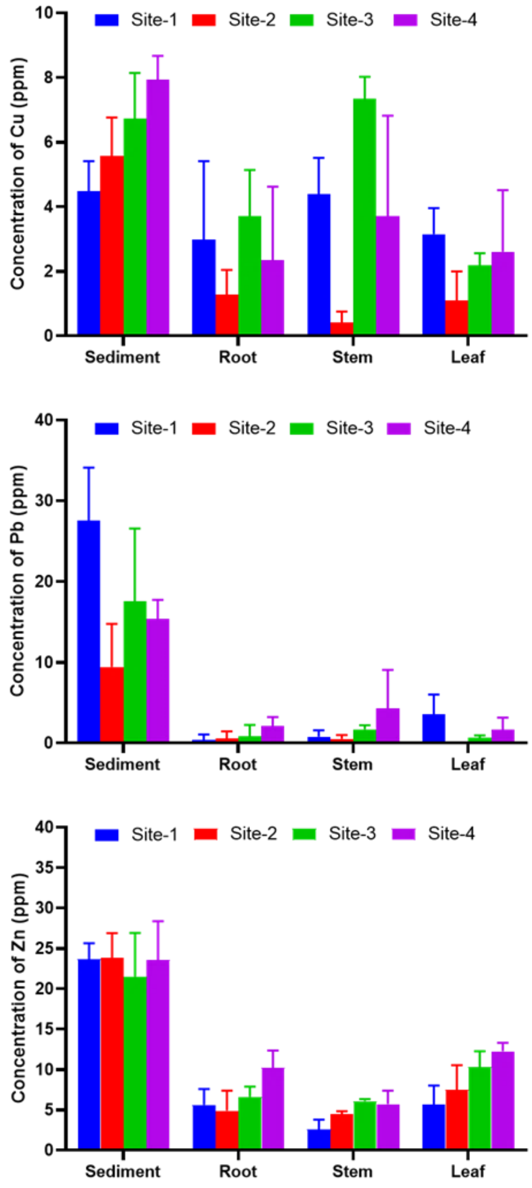

Figure 3. **Heavy metal concentrations (Cu, Pb, Zn) in *Acanthus ilicifolius* across sampling sites**

Heavy metals were commonly found in both roots and leaves [33]. Furthermore, the bioaccumulation pattern of *A. ilicifolius* was influenced by its uptake capacity, environmental conditions that supported its growth and development, and adaptability traits specific to the phenotype of a haplotype in a given region. In Bangladesh, populations of *A. ilicifolius* were observed to accumulate heavy metals in the following order, namely Zn (105.71 ppm) >Pb (27.85 ppm) > Cu (16.12 ppm), with the highest concentrations found in the leaves compared to the roots [4]. Reports from mangrove ecosystems in different localities showed considerable variation in metal bioaccumulation. In India, the order of accumulation was Zn (18.34 ppm) > Cu (14.37 ppm) > Pb (2.22 ppm) [34], in South China, Zn (74 ppm) > Cu (61.75 ppm) > Pb (9.95 ppm) [24], in China, Zn (126.5 ppm) > Cu (20.51 ppm) > Pb (1.03 ppm) [35], and in Southeast Sulawesi, Indonesia, Cu (25.14 ppm) > Zn (18.93 ppm) > Pb (0.37 ppm) [36]. This variation implied that spatiotemporal differences in heavy metal uptake were evident across species and locations, including the present study. The process of heavy metal binding in plants occurred through mechanisms of accumulation and tolerance [37].

A multiple linear regression model was a statistical technique to generate multiple predictors from the relationships between 1 dependent variable and 2 or more independent variables. The multivariate linear regression model results (Figure 4) indicated that the concentration of metals in the sediments of *A. ilicifolius* did not display a statistically significant relationship with the concentration of metals in all plant parts ($P > 0.05$). However, high and positive relationships were found between the concentration of Pb in the sediment and the leaves ($R^2 = 0.85$), and a moderate-to-low correlation between the concentration of Zn in the sediment and the stems and leaves ($R^2 = 0.35$; 0.13, respectively). Arumugam et al. [14] also applied multivariate linear regression analysis to model the relationship between heavy metal concentrations in sediment and plant tissues of *Avicennia marina* in India, reporting that a strong correlation was observed between the bark and roots ($R^2 = 0.94$), as well as between the leaves and stems ($R^2 = 0.74$). Hossain et al. [38] also reported a high correlation value ($R^2 > 0.6$) of heavy metals when modeling the interactions between sediments and plant parts (roots, leaves) of 3 mangrove species, namely *Avicennia officinalis*, *Excoecaria agallocha,* and *Sonneratia apetala* in Bangladesh. The lack of statistical significance and strong correlation in this study suggested that sediment metal levels could not reliably predict metal concentrations in plant tissues, possibly due to the limited sample size or the differing immobilization mechanisms of several heavy metal ions across plant species and environments [39].

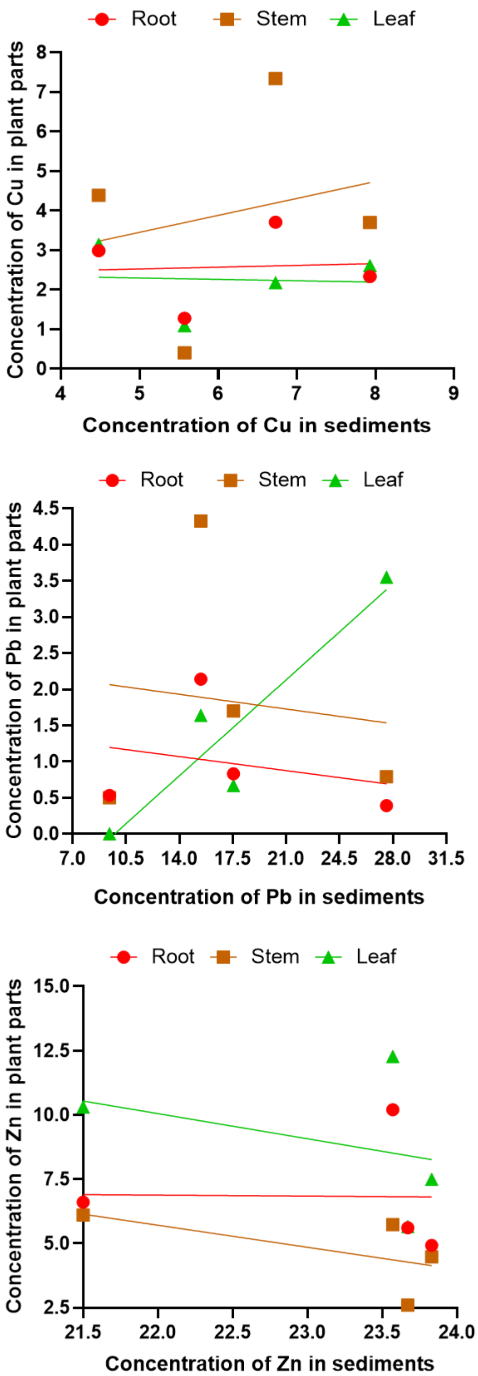

Figure 4. Multivariate linear regression between heavy metal concentrations (Cu, Pb, Zn) in sediments and different tissues of *Acanthus ilicifolius*. Regression models described the relationships using the adjusted determination coefficient (R^2) and significance level (P).

The term 'contamination factor' (C^i_f) was used to account for the relative toxicity of a particular metal in the environment, comparing the pollution severity at a specific site to a reference value from the industrial period. Based on this parameter, the overall toxicity was considered low, with only Pb showing moderate toxicity at Site-1 (Figure 4). A similar trend was also observed in the sediments of Mongla and Karamjal, Bangladesh which showed low contamination in the area with only Cu indicating C^i_f >1.0 [38]. Heavy metals, unlike organic pollutants, were highly soluble in water and resisted degradation into less toxic forms [40]. Upon entering aquatic ecosystems, it could disperse within the water column, be taken up by organisms, or settle and accumulate in mangrove sediments [41]. Due to processes like remobilization and desorption, sediments served as a continuous source of contamination in the food web. The relatively low contamination factor (C^i_f) values found in the Sicanang mangrove ecosystems suggested that the risk to organisms at various trophic levels was minimal. However, this assumption required further investigation to thoroughly evaluate the potential ecological risks. The bioconcentration or bioaccumulation factor (BAF) parameter indicated the potential of *A. ilicifolius*, naturally growing at several sampling sites, to accumulate heavy metals in their vascular systems (Figure 5). *A. ilicifolius* was accumulated Cu with the highest BAF value at Site-1 (2.43±0.76), followed by Site-3 (2.01±0.33) and Site-4 (1.15±0.88). The BAF values for Zn also exceeded the threshold (BAF > 1.0) for *A. ilicifolius* collected from Site-3 (1.10±0.21) and Site-4 (1.24±0.40). However, high BAF values were not obtained for Pb in this study.

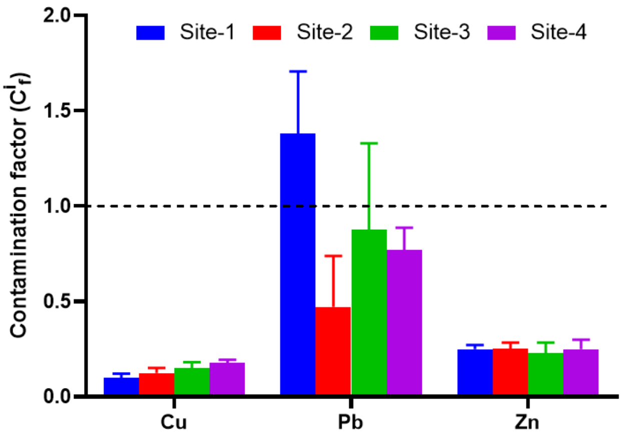

Figure 5. Contamination factor (C^i_f) of mangrove sediments near *A. ilicifolius* across sampling sites with a limit (Dashed line - - -) of particular toxicity level of heavy metals (Cu, Pb, Zn)

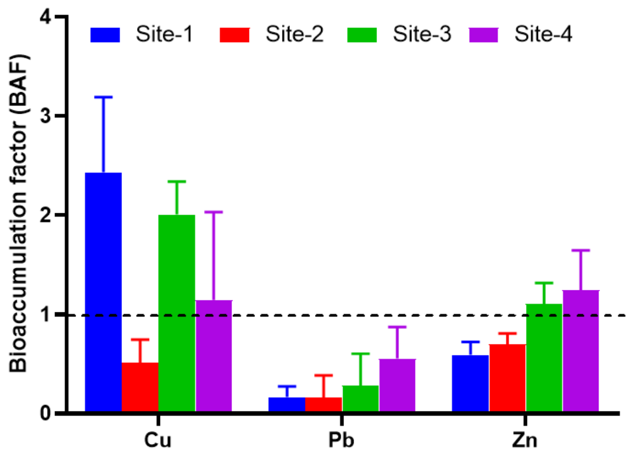

Figure 6. Bioaccumulation factors (BAF) of toxic heavy metals (Cu, Pb, Zn) at different sampling sites. The dashed line (- - -) showed the value of 1 of the BAF values limit

The Translocation Factor (TF) in plants measures how effectively elements, especially metals, were moved from the roots to other parts of the plant, such as the shoots or leaves. This factor was frequently used in environmental toxicology to evaluate the efficiency of metal transport and distribution within the plant. The TF in *A. ilicifolius* inhabiting several sampling sites exhibited variable values as shown in Table 1. Based on the presented results, the extreme translocation capacity of Pb was observed in the leaf portion at Site-1 (9.21), while the lowest extreme translocation was also obtained for Pb at Site-2 (0.01). This variability in translocation suggested that, depending on spatial characteristics, there was a tendency to translocate from roots to leaves rather than from roots to stems. Plants with bioconcentration and translocation factors > 1 could serve as bioaccumulators. In this study, bioconcentration values > 2 were considered high. Plants were used as phytostabilizers when bioconcentration factors > 1 were exhibited and translocation factors < 1, and as phytoextractors when bioconcentration factors < 1 and translocation factors > 1 were shown. However, determining these functional criteria in *A. ilicifolius*, particularly those living in the area of study, was challenging given the dynamic nature of environmental characteristics in this study.

Table 1. Translocation factors (TF) of heavy metals (Cu, Pb, Zn) in *A. ilicifolius* vascular systems

Station(s)	Cu		Pb		Zn	
	Stem	Leaf	Stem	Leaf	Stem	Leaf
Site-1	1.47	1.05	2.04	9.21	0.46	1.01
Site-2	0.32	0.85	0.94	0.01	0.91	1.52
Site-3	1.98	0.59	2.04	0.81	0.92	1.56
Site-4	0.36	0.26	0.42	0.16	0.56	1.20

Translocation factors for heavy metals in plants need to exceed 1 to be considered bioaccumulators. Hyperaccumulator plants could accumulate high concentrations of heavy metals on their tissue surfaces, particularly above ground, when found in their natural habitats [42]. Translocation of essential metals (Cu and Zn) from roots to leaves was lower compared to non-essential metals (Pb). The low translocation factors of essential metals suggested that mangroves used these metals for metabolic activities and growth, while non-essential metals exhibited higher mobility from roots to leaves. Pb toxicity in leaves could impact plant functions such as photosynthesis, chlorophyll synthesis, and antioxidant enzyme production [43]. Roots could prevent the transport of non-essential metals, leading to their accumulation in roots [44]. Translocation values exceeding 1 for root-leaf and root-stem indicated higher metal concentrations in leaves or stems compared to roots, suggesting roots had a greater absorption capacity than accumulation ability for the studied heavy metals. Material translocation in plants occurred through the vascular system, specifically the xylem tissue, primarily responsible for water transport, though heavy metals could potentially be transported from roots to leaves [33]. The rate of heavy metal translocation was influenced by capillary action systems in plants [45]. *A. ilicifolius* used several mechanisms to mitigate metal toxicity, including the activation of antioxidant systems, anatomical adaptations, and alterations in elemental distribution patterns [46, 47]. For instance, the enhanced tolerance to elevated levels of toxic metal ions in *A. ilicifolius* tissues was supported by its altered anatomical characteristics. The higher accumulation of Zn near the central vascular tissues of the root indicated the complexity of Zn^{2+} within the xylem vessels [46]. Furthermore, the existence of mangroves was also vital, as habitats for fisheries were provided. Further investigation was focused on the response of aquatic biota to the accumulation of various heavy metals, particularly in areas surrounding *A. ilicifolius* and waterbodies [48]. Mangrove ecosystems' service to bioaccumulate heavy metals from sediments could enhance environmental quality. Moreover, mangrove trees remediated nearby ponds affected by heavy metal pollution and mitigated negative impacts on human health and sediment-dwelling organisms [49]. This strategy was consistent with the United Nations Sustainable Development Goal 6 (Clean Water and Sanitation) and addressed the urgent need to remediate environmental pollution [50]. Mangrove plants played a critical role in mitigating metal contamination in sediments, with many species exhibiting phytoextraction or phytostabilization capabilities.

In the context of this study, understanding the metal accumulation patterns of *A. ilicifolius* could help identify its potential as a native candidate for remediating heavy metal-contaminated mangrove ecosystems. Such findings had practical implications for environmental managers and policymakers, enabling the strategic use of local mangrove species to restore polluted areas and preserve ecosystems health. To further support these efforts, long-term monitoring and expanded studies on the phytoremediation potential of other native mangrove species were essential, particularly those producing fruits that could be consumed by coastal communities of Sicanang. Those studies were critical for identifying potential risks of heavy metal accumulation in the human food chain. This information was vital for developing a comprehensive understanding and ensuring the effective management and conservation of mangrove ecosystems.

4- Conclusion

In conclusion, industrialization and urbanization had significantly increased the anthropogenic release of heavy metals into the environment, leading to severe ecological impacts. This study investigated the capacity of *Acanthus ilicifolius* to accumulate heavy metals, specifically copper (Cu), lead (Pb), and zinc (Zn), from sediments in different environmental settings. The analysis revealed that sediments contained the highest concentrations of Cu, Pb, and Zn, with significant variations among the sites. While the overall metal concentrations in the plant parts did not reveal a statistically significant correlation with sediment concentrations, positive relationships were identified for Pb between the sediment and leaves, and for Zn between the sediment and both stems and leaves. Furthermore, these findings indicated that certain metals could be more readily translocated to specific plant parts under varying environmental conditions. The Translocation Factor (TF) of *A. ilicifolius* exhibited variability across the sampling sites. Notably, the highest translocation capacity of Pb was observed in the leaf tissues at Site-1, while the lowest was also for Pb at Site-2. The significant variability suggested that spatial characteristics influenced the plant's tendency to translocate metals from roots to leaves more effectively than from roots to stems, identifying the critical role of site-specific factors in bioaccumulation processes. In the Sicanang mangrove area of North Sumatra, *A. ilicifolius* demonstrated its effectiveness as both an indicator and accumulator species for Cu, Pb, and Zn, making it a valuable asset for mitigating heavy metal contamination in mangrove ecosystems. Despite the presence of other mangrove species, *A. ilicifolius* was distinct due to its vegetative dominance and significant role in heavy metal uptake. The bioaccumulation capacity of *A. ilicifolius* at representative sites within the Sicanang mangrove forests, along with biomagnification from exposure to polluted sites, emphasized the urgency for outreach to nearby coastal communities. Furthermore, the local community, which actively participated in preserving the Sicanang mangrove ecotourism forests, also possessed traditional knowledge in using the forests' resources, including processing *A. ilicifolius* fruit into various food products. This information was crucial when the distribution of heavy metals posed a potential threat to polyculture cultivations of mud crabs (*S. serrata*), tiger shrimp (*P. monodon*), and tilapia (*Oreochromis niloticus*), particularly when these metals penetrated the human food chain or impacted economic trade. Further investigation was needed to cover the toxicological aspects concerning aquatic fauna cultivated in the vicinity of *A. ilicifolius*.

5- Declarations

5-1- Author Contributions

Conceptualization, E.S.S., M.B., and E.J.; methodology, E.S.S., E.J., M.T., and A.S.; formal analysis, E.S.S., E.J., A.S., and C.K.; investigation, M.T. and A.S.; writing—original draft preparation, E.S.S. and A.H.; writing—review and editing, C.K. and R.R.; visualization, E.J. and A.H.; supervision, M.B.; project administration, E.S.S.; funding acquisition, E.S.S. and M.B. All authors have read and agreed to the published version of the manuscript.

5-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5-3- Funding

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5-4- Institutional Review Board Statement

Not applicable.

5-5- Informed Consent Statement

Not applicable.

5-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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