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RESEARCH ARTICLE

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Pb and Cd Accumulation of *Avicennia marina* Leaves and Roots in the Angke Kapuk Mangrove Protected Forest, Jakarta, Indonesia

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ABSTRACT

The Angke Kapuk Mangrove Protection Forest (AKMPF) in Jakarta is an urban mangrove area affected by ongoing human-caused pollution. There is little information on how much Pb and Cd accumulate in *Avicennia marina* tissue, the dominant species there. This study measures Pb and Cd concentrations in the leaves and roots of *Avicennia marina* and examines whether distance from the shoreline affects metal accumulation. Sampling was conducted from June to August 2022 using three transect plots (20 × 140 m) in two distance zones: within 100 meters of the shoreline and beyond 100 meters of the shoreline. A total of 12 plant samples (six leaves and six roots) were collected, digested using wet-acid digestion, and analyzed by Atomic Absorption Spectrophotometry (AAS). Data were evaluated using descriptive statistics, Shapiro–Wilk and Levene's tests, paired and Welch's t-tests, correlation analysis, and translocation factor (TF). Pb was found at a higher concentration than Cd in both leaves and roots. Pb levels were significantly higher in leaves compared to roots ($p < 0.05$), but Cd levels were similar in both organs. There were no significant differences between shoreline-distance zones, which suggests that metal exposure was fairly uniform. Translocation factor values above 1 indicate that *Avicennia marina* can move metals to its above-ground parts. Overall, the results suggest that *Avicennia marina* is a tolerant bioindicator that helps take up, store, and move heavy metals in urban mangrove ecosystems.

Introduction

Mangrove forests inhabit extensive regions of tropical, subtropical, and temperate intertidal coastlines worldwide, in part because they can withstand significant fluctuations in salinity, temperature, inundation, and anoxia [1,2]. This ecosystem plays important roles beyond shoreline stabilization and carbon sequestration, including nutrient cycling, habitat provision, and regulating contaminants entering coastal waters. Mangrove forests in Indonesia covered an area of 3,455,628 hectares in 2025 [3], and approximately 35% of that was degraded [4], and one threat to mangrove existence from anthropogenic activities that can lead to pollution [5–7]. Mangroves possess remarkable physiological adaptations that enable them to accumulate various pollutants, including heavy metals, through filtration, adsorption, and root and sediment accumulation [8–10]. Mangroves remediate heavy metal contamination in coastal environments by accumulating, sequestering, and excreting these metals through root intercellular spaces, salt glands, and trichomes [11]. Among heavy metals, lead (Pb) and cadmium (Cd) are particularly concerning because they are persistent, toxic even at relatively low concentrations, non-biodegradable, and capable of bioaccumulating throughout food webs [12–14].

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Mangrove trees, particularly *Avicennia marina*, are known for their high tolerance and ability to accumulate heavy metals [9,10,15]. *Avicennia marina* roots absorb both metals through diffusion or ion exchange [16] and then translocate to the upper parts of the plant, such as stems and leaves, depending on the specific ability of the mangrove species to regulate metal accumulation and excretion mechanisms [17]. Because of these physiological characteristics, *Avicennia marina* has attracted more attention as a bioindicator of coastal pollution and as a species that could help clean up polluted areas. *Avicennia marina* is the dominant mangrove species in the Angke Kapuk Mangrove Protected Forest (AKMPF) [18], where it helps trap pollutants and protect the coast. The AKMPF is one of the urban mangrove forests along the Jakarta coast that faces strong environmental pressures from human activities, including pollution, changes in water quality, and the buildup of domestic waste [19]. The AKMPF ecosystem is exposed to ongoing pollution from crowded neighborhoods, factories, river runoff, and coastal infrastructure, which makes it especially vulnerable to heavy metal contamination [8,20,21].

Previous studies conducted in Indonesian urban mangrove ecosystems have documented elevated concentrations of Pb and Cd in sediments, water, and mangrove tissues, such as studies by Supriyantini and Soenardjo [22] and Yulianto et al. [23] in Semarang. However, these studies have primarily focused on quantifying heavy metal contamination levels, whereas information on spatial variations associated with shoreline distance remains limited. Based on the study by Rashidifard et al. [24] in the Oman Sea, variations in shoreline distance can influence heavy metal accumulation in mangrove sediments. Variations in shoreline distances may reflect variations in anthropogenic influence and tidal exposure [20,25–28]. Therefore, we hypothesized that the distance from the shoreline of *Avicennia marina* would exhibit distinct patterns of heavy metal accumulation due to variations in tidal influence and anthropogenic exposure. Information about the AKMPF is still lacking despite its ecological importance and exposure to multiple pollution sources. This study aimed to (1) quantify Pb and Cd concentrations in the roots and leaves of *Avicennia marina* and (2) evaluate whether shoreline distance influences heavy metal accumulation patterns. The findings of this study are expected to go beyond previous research by integrating spatial shoreline gradients, tissue-specific accumulation, translocation factor analysis, and environmental variables to provide a more comprehensive ecological interpretation of heavy metal accumulation in urban mangrove ecosystems. This study establishes baseline ecological evidence to inform future biomonitoring and enhance management strategies for urban mangrove conservation in Jakarta, especially in the AKMPF and other rapidly urbanizing tropical coastal areas.

Materials and Methods

Study Sites

This research was conducted from June to August 2022 in the Angke Kapuk Protected Forest, Penjaringan District, North Jakarta, Indonesia, located approximately at 106°20’00’’ East Longitude and 06°10’00’’ South Latitude. The Angke Kapuk Protected Forest is a conservation area managed by the DKI Jakarta Provincial Forestry Service, and its vegetation is dominated by *Avicennia marina. Avicennia marina*’s organ sampling was carried out in the tidal area of the Angke Kapuk Protected Forest (Figure 1) and then analyzed at the Forest Influence Laboratory, Department of Silviculture, Faculty of Forestry and Environment, and Dairy Animal Nutrition Laboratory, Department of Nutrition Science and Feed Technology, Faculty of Animal Husbandry, IPB University.

Procedures

Setting Up and Selecting the Research Location

Before starting the study, all necessary materials and equipment were prepared, and a site survey was conducted. Necessary permits were obtained for both the analytical laboratory and research site to ensure compliance with regulatory requirements. Secondary data were collected through a review of the relevant literature. Purposive sampling was applied to determine the research locations based on the distance of the *Avicennia marina* sample trees from the shoreline. The shoreline distance associated with heavy metal accumulation reflects the integration of several ecological processes, including tidal inundation frequency, sediment deposition, hydrological connectivity, and pollutant transport. The sites were classified into two groups: Group 1 (≤ 100 m from the shoreline) and Group 2 (> 100–140 m from the shoreline). The reason for setting a 100 m threshold is that the zone where direct anthropogenic activities are most likely to affect mangrove ecosystem conditions is within 100 m of the shoreline, and that heavy metal exposure may differ within urban mangrove ecosystems.

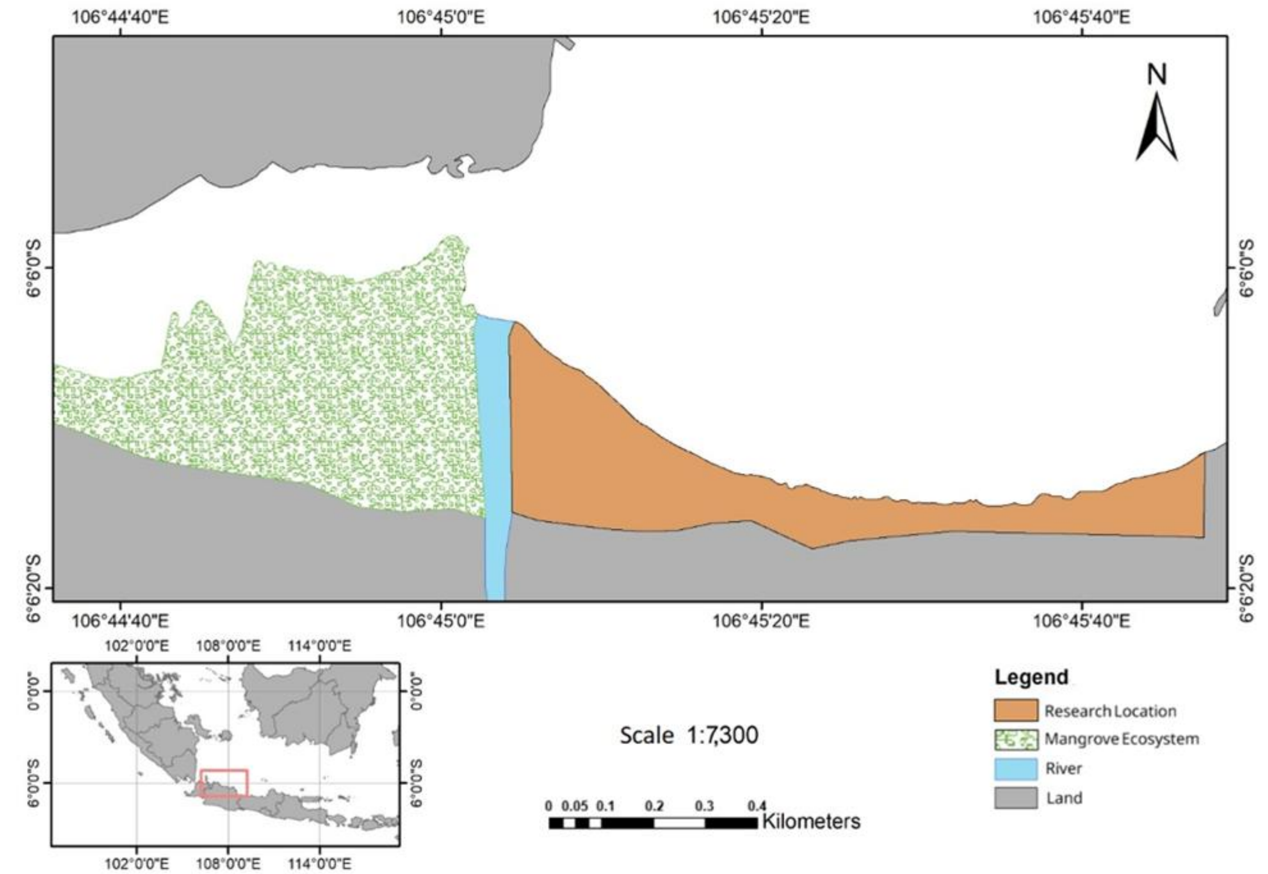

Figure 1. Map of the research location in Angke Kapuk Mangrove Protected Forest, Jakarta. The research area showed by orange polygon and the green polygon is mangrove area outside research location.

Collecting Information on Environmental Conditions for Soil, Water, and Air

Environmental condition data were collected directly within each sampling transect, including water salinity, soil pH, soil temperature, light intensity, air temperature, and air humidity. These parameters were selected because previous studies have shown that heavy metal mobility in mangrove ecosystems is strongly influenced by sediment conditions, such as sediment acidity and salinity, redox-related temperature variation, and microclimatic conditions that affect plant physiology and transpiration, including light intensity, air temperature, and air humidity. Each environmental parameter was measured three times at three locations along the transects. In the following analyses, the values were the average of all measurements obtained within each transect.

Tree Inventory and Sample Selection

To assess the distribution of tree and stand diameters at varying distances from the shoreline, three transects measuring 20 × 140 m were established at 20 m intervals, and the layout of the transect is shown in Figure 2. The transects were grouped by distance (Figure 2). All trees with a diameter of at least 10 cm were identified and measured, after which they were grouped into diameter classes, and their densities were calculated. Sample trees of *Avicennia marina* were selected. Since this sampling took place in a protected urban mangrove forest, we kept destructive sampling to a minimum to avoid disturbing the ecosystem. Therefore, six representative sample trees were selected, consisting of three trees within 100 m of the shoreline and three trees beyond 100 m. From each tree, root and leaf samples were collected, resulting in a total of 12 samples to analyze for Pb and Cd concentrations. While this small sample size limits statistical power and generalization, the study serves as an initial ecological assessment to find early patterns that could inform larger studies in the future.

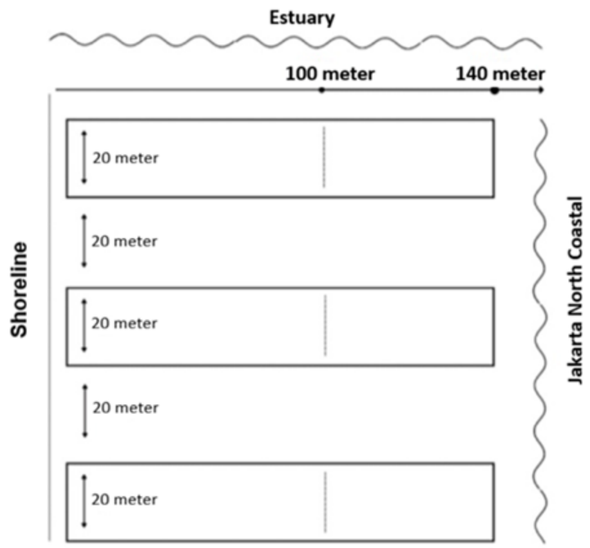

Figure 2. Layout of vegetation transect that used in this research. Three transects were established perpendicular to the shoreline, with observation plots positioned at 100 m and > 100 m from shoreline to represent spatial variation vegetation characteristics.

Root and Leaf Sampling of Avicennia marina

The parts of the sample trees analyzed were divided into two groups: photosynthetic and non-photosynthetic. Roots were chosen because they are non-photosynthetic, whereas leaves represent photosynthetic organs. Root samples were collected from pneumatophore roots near the main stem, either submerged or emerging from the soil surface. The aboveground (pneumatophore) roots were selected because they are directly exposed to tidal water and surface sediments and are therefore appropriate indicators of environmental metal uptake. Additionally, they are easier to sample and cause less disturbance than belowground roots. The samples were then cut, placed in plastic bags, and stored in a cooler box.

Leaf samples were collected from healthy, green leaves on the first branch without damage, following the protocol described by Cornelissen et al. [29]. Leaves were picked along with the nearest twigs from the outermost canopy, which received maximum sunlight, 2–3 hours after sunrise or 3–4 hours before sunset. The samples were then wrapped in damp paper, placed in plastic bags, and stored in a cooler box.

Pb and Cd Metal Content Analysis

Samples of *Avicennia marina* roots and leaves were first dried for 48 hours at 80 °C in an oven, then ground into a powder. To create a sample extraction solution, the powdered samples were subsequently digested using a wet digestion method with concentrated HNO_3 (65%) and $HClO_4$ (60%). An atomic absorption spectrophotometry (AAS) method was then used to determine the amounts of Pb and Cd in this sample solution. All analyses were conducted in a laboratory certified to ISO/IEC 17025. For the quality assurance and quality control (QA/QC) process certified calibration standards were used, reagent blanks were employed in order to check for contamination, and duplicate analyses were carried out to verify precision. The relative percent difference (RPD) for the duplicates remained within an acceptable range (below 10%). The instrument's performance was regularly checked by carrying out repeated calibrations during the analysis.

Data Analysis

Comparison of Pb and Cd Contents

Prior to hypothesis testing, the assumptions of normality and homogeneity of variance were evaluated using the Shapiro–Wilk and Levene's tests, respectively. As all datasets satisfied the assumptions for parametric analysis ($p > 0.05$), heavy metal concentration comparisons were performed using parametric statistical tests. A paired-samples t-test was used to compare the heavy metal concentrations between the roots and leaves of the same individual tree. Differences in heavy metal concentrations between the shoreline distance groups (≤ 100 m and > 100 m from the shoreline) were evaluated using an independent-samples Welch's t-test, which is appropriate for comparisons involving small sample sizes and provides robust estimates when group variances may differ. Cohen's d was used to assess the magnitude of differences between shoreline-distance groups, with α = 0.05. Effect sizes were classified as negligible (d < 0.20), small (0.20–0.49), moderate (0.50–0.79), or large (≥ 0.80) [30]. In addition, an independent-samples t-test was used to assess differences in heavy metal concentrations between the shoreline distance groups, using a p-value of α = 0.05. All statistical analyses were performed in R using RStudio.

The Indonesian seawater quality standards for marine biota (Minister of Environment Decree No. 51/2004) were used only as contextual references because no national guideline values are currently available for heavy metal concentrations in mangrove tissues. Although seawater and plant tissues represent different environmental matrices, mangroves are integral to coastal ecosystems. Consequently, seawater quality standards offer the most relevant benchmark for assessing contamination levels in the study area.

The Translocation Factor (TF) Analysis

The plant's ability to transport metals that it has accumulated in its roots to its leaves was assessed by calculating the translocation factor (TF) as follows: this value was derived by comparing the concentrations of heavy metals in leaves and roots using a standard TF formula. A TF below 1 shows that the plants are under metal stress. A TF greater than 1 indicates that the plants are hyperaccumulators [31,32]. In addition, based on Ali et al. [33], the common phytoremediation criteria are as follows: TF < 1 indicates limited translocation, TF between 1 and 2 indicates moderate translocation, and TF > 2 indicates strong translocation efficiency. The standard TF formula used is based on Mellem et al. [34] as follows Equation 1:

$$\textit{Translocation factor}\ (\mathrm{TF}) = \frac{\text{Metal concentration in leaves}}{\text{Metal concentration in roots}} \tag{1}$$

Correlation Analysis

A pearson correlation test was conducted to identify the factors affecting heavy metal accumulation in *Avicennia marina* organs. The analysis examined the relationships between Pb and Cd concentrations and the environmental parameters measured at the study site. The Pearson correlation method was applied to determine the strength and direction of linear associations between the variables. The statistical analyses were conducted using RStudio. The results were presented using the ‘corrplot’ package [35]. Since the correlation analysis was based on 12 observations, the results should be treated with caution and are therefore exploratory.

Results and Discussion

Results

Environmental Characteristics

The actual environmental conditions at the research location are evident from the measurement results for several parameters (Table 1). The area of Group 1 exhibited slightly higher air temperature (30.20 ± 0.20 °C), soil temperature (30.70 ± 0.10 °C), and salinity (30.50 ± 0.50 ppt) than the area of Group 2, where air temperature, soil temperature, and salinity averaged 29.50 ± 0.30 °C, 29.80 ± 0.20 °C, and 28.70 ± 0.60 ppt, respectively. In contrast, the relative air humidity and soil pH in Group 2 were slightly higher than those in Group 1. Overall, the measured environmental variables indicated relatively similar environmental conditions between the two shoreline distance groups, although slight spatial variations were observed in temperature, salinity, and soil pH.

Table 1. The average environmental parameter measurements in both distance groups. Group 1 is vegetation located at a distance of ≤ 100 m from the shoreline, and Group 2 is vegetation located at a distance of > 100 m.

No	Environmental parameters	Group 1	Group 2
1.	Air temperature (°C)	30.22 ± 0.71	29.14 ± 1.08
2.	Relative humidity/RH (%)	75.33 ± 3.48	73.00 ± 2.73
3.	Light intensity (lux)	11,360.00 ± 1,072.34	8,992.22 ± 75.01
4.	Soil pH	4.50 ± 0.44	5.00 ± 0.44
5.	Soil temperature (°C)	28.22 ± 0.38	28.11 ± 0.42
6.	Water salinity (ppt)	5.00 ± 0.00	4.06 ± 1.11

Vegetation Characteristics

The vegetation conditions at the two research locations differed (Table 2). Vegetation composition varied with distance from the shoreline. The area of Group 1 consisted of *Avicennia marina, Terminalia catappa,* and *Rhizophora mucronata*, whereas only *Avicennia marina* was found in the area of Group 2. However, although the number of species at the Group 1 location was more diverse, the tree density was lower than that at the Group 2 location, which had homogeneous vegetation. Furthermore, when looking at the distribution of *Avicennia marina* diameter classes, which is the dominant species there, at locations close to the shoreline, *Avicennia marina* trees with a diameter of 10–30 cm were dominant, although *Avicennia marina* trees with a diameter of 41–50 cm were still found, albeit in small numbers. In contrast, at the Group 2 location, more than 50% of the *Avicennia marina* trees had a diameter of 21–30 cm, and no *Avicennia marina* trees with a diameter exceeding 40 cm were found (Figure 3).

Table 2. Tree density in both distance groups was similar. Group 1 is vegetation located at a distance of ≤ 100 m from the shoreline, and Group 2 is vegetation located at a distance of > 100 m.

No	Species	Density (Tree ha^{-1})	
		Group 1	Group 2
1.	*Avicennia marina*	70	142
2.	*Terminalia catappa*	15	0
3.	*Rhizophora mucronata*	10	0

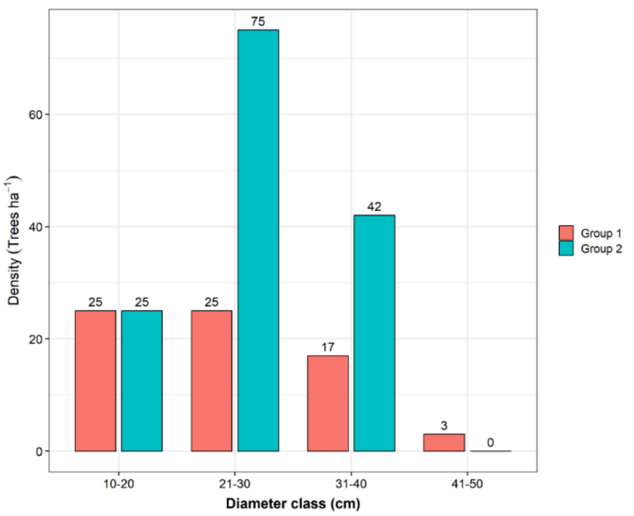

Figure 3. Diameter class distribution of *A. marina* in both distance groups. Group 1 is vegetation located at a distance of ≤ 100 m from the shoreline, and Group 2 is vegetation located at a distance of > 100 m.

Heavy Metals (Pb and Cd) Concentration in Leaves and Roots of Avicennia marina

The *concentrations* of lead (Pb) and cadmium (Cd) in *Avicennia marina* leaves and roots in the two shoreline distance groups are presented in Table 3. In general, the Pb and Cd contents were higher in the leaves than in the roots. In th*e* leaves, the Pb content ranged from 3.996 to 4.070 ppt, and Cd ranged from 0.145 to 0.190 ppt. In the roots, the Pb content ranged from 1.409 to 2.001 ppt, and the Cd content ranged from 0.066 to 0.081 ppt. Prior to hypothesis testing, the assumptions of parametric analysis were evaluated using the Shapiro–Wilk and Levene's tests. Based on the results of both tests, the Pb and Cd concentrations in both leaves and roots were normally distributed (all $p > 0.05$) and showed no significant heterogeneity of variances between the shoreline distance groups or between plant organs (all $p > 0.05$).

The results of the paired-samples t-test for comparing Cd and Pb concentrations between leaves and roots, as well as Welch's independent-samples t-test for assessing differences in metal concentrations between shoreline distance groups, are shown in Table 4. The paired-samples t-test showed no significant differences in Cd concentrations between leaves and roots at either shoreline distance ($t = 2.24$, $df = 5$, $p = 0.075$; 95% CI = −0.01–0.16 ppt). In contrast, the Pb concentrations were significantly higher in the leaves than in the roots ($t = 3.46$, $df = 5$, $p = 0.018$; 95% CI = 0.60–4.06 ppt). Welch's independent-samples t-test showed no significant difference in either Cd ($t = -0.10$, $df = 9.37$, $p = 0.922$) or Pb ($t = -0.31$, $df = 10.00$, $p = 0.761$) over both shoreline distance groups. And the effect sizes were negligible for both Cd (Cohen's d = −0.06) and Pb (Cohen's d = −0.18). This suggests that shoreline distance exerted minimal influence on heavy metal accumulation in the sampled *Avicennia marina* trees. However, given the small sample size (n = 6 trees), these results should be interpreted with caution.

Table 3. The average lead (Pb) and cadmium (Cd) content in the leaves and roots of *Avicennia marina* in both distance groups. Group 1 is vegetation at a distance of ≤ 100 m and Group 2 is vegetation at a distance of > 100 m.

Heavy metal	Distance group	Concentration (ppt)		Environmental reference (ppt)*)
		Leaves	Roots	
Cadmium (Cd)	Group 1	0.145 ± 0.061	0.081 ± 0.002	0.001
	Group 2	0.190 ± 0.087	0.066 ± 0.022	
Lead (Pb)	Group 1	4.070 ± 2.243	2.001 ± 0.283	0.008
	Group 2	3.996 ± 1.807	1.409 ± 0.609	

*) Seawater quality criteria for marine biota according to the Ministerial Decree No. 51 of 2004. These values are presented as environmental reference values for the study area and are not directly comparable to the heavy metal concentrations measured in plant tissues.

Table 4. Statistical comparisons of lead (Pb) and cadmium (Cd) concentrations in leaves and roots of *Avicennia marina*. Comparison of metal concentrations in both *Avicennia marina*'s organ in two difference shoreline-distance groups also assessed using Welch's t-test.

Comparison	Statistical test	t-test	df	*p*-value	95% Confidence interval (CI)	Cohen's *d*
Cd (Leaves vs. Roots)	Paired t-test	2.24	5	0.075	−0.01 to 0.16	-
Pb (Leaves vs. Roots)	Paired t-test	2.46	5	0.018*)	0.60 to 4.06	-
Cd (Group 1/≤100 m vs. Group 2/>100 m)	Welch's t-test	−0.10	9.37	0.922	−0.093 to 0.085	−0.06
Pb (Group 1/≤100 m vs. Group 2/>100 m)	Welch's t-test	−0.31	10.00	0.761	−2.70 to 2.04	−0.18

*) significant differences using a p-value of α = 0.05

Correlation analysis (Figure 4) revealed links between environmental factors and metal levels in *Avicennia marina* tissues. Pb and Cd levels in leaves were lower when soil temperature was higher, whereas root metal levels increased with increased light. The Pb content in leaves also decreased as the soil pH increased. These findings suggest that there may be a connection between environmental conditions and metal buildup. However, because the dataset was small, these results are preliminary and should be viewed with caution.

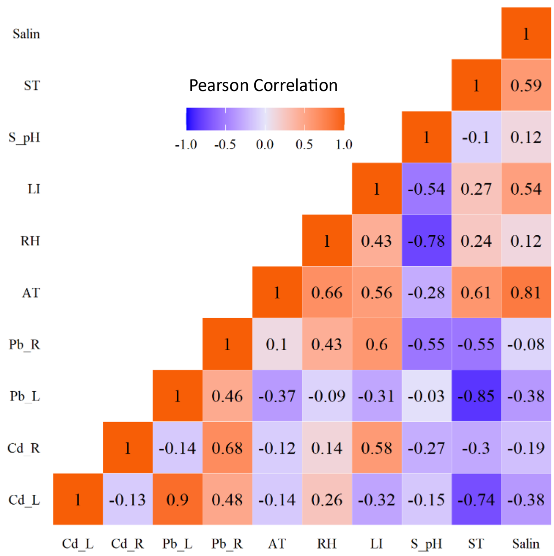

Figure 4. Pearson's correlation of heavy metal (Pb and Cd) concentrations in each *Avicennia marina* organ (leaves and roots) with environmental conditions at the research location. Salin: water salinity, ST: soil temperature, S_pH: soil pH, LI: light intensity, RH: air relative humidity, AT: air temperature, Pb_R: root's Pb concentration, Pb_L: leaves's Pb concentration, Cd_R: root's Cd concentration, Cd_L: leaves's Cd concentration.

Translocation Factor (TF)

The TF values of Pb and Cd heavy metals in *Avicennia marina* organs are presented in Table 5. In both shoreline distance groups, TF values were greater than 1, indicating that heavy metals moved from roots to leaves. The average TF values ranged from 1.79 to 2.61, and Group 2 usually had slightly higher values. The lowest TF value was for Cd in Group 1 (1.79), which fell into the moderate translocation category. In comparison, Cd in Group 2 and Pb in both groups had TF values > 2, indicating a strong translocation category. This result suggests that *Avicennia marina* can move absorbed Pb and Cd from its roots to its leaves. Although TF values were usually higher in Group 2 than in Group 1, no statistical tests were performed for comparison. Therefore, the pattern should be considered as a first observation, not as proof of a clear spatial trend in metal translocation.

Yet these results alone are not enough to qualify a species as a hyperaccumulator or to assess its phytoremediation efficiency. To fully evaluate its phytoremediation potential, it is necessary to consider additional parameters, such as the bioconcentration factor (BCF), bioaccumulation factor (BAF), and the concentration of the metal in environmental matrices such as sediment and water. Consequently, the present findings indicate that *Avicennia marina* serves as an effective metal translocator in the study area, even though its status as a hyperaccumulator cannot be established solely on the basis of TF values.

Table 5. Translocation factor (TF) of lead (Pb) and cadmium (Cd) in leaves and roots of *Avicennia marina* across two distance groups. The TF values are classified according to the degree of metal translocation between roots and leaves.

Heavy metal	Distance group	Translocation factor (TF)	Category
Cadmium (Cd)	Group 1	1.79 ± 1.11	Moderate translocation
	Group 2	2.49 ± 1.21	Strong translocation
Lead (Pb)	Group 1	2.07 ±1.23	Strong translocation
	Group 2	2.61 ± 0.94	Strong translocation

Discussion

The results of this study indicate that environmental and vegetation characteristics were generally comparable between the two shoreline distance groups. The dominance of *Avicennia marina* across the study area suggests that this species is well adapted to the environmental conditions of the AKMPF, including exposure to urban-derived pollutants such as heavy metals. In addition to *Avicennia marina, Terminalia catappa* and *Rhizophora mucronata* were also found near the shoreline. The presence of these species reflects the characteristic heterogeneous vegetation structure of urban mangrove ecosystems. This is because the water conditions in urban areas are less saline [18,34]. The observed diameter class of *Avicennia marina* shows that it has a tree diameter of 20–40 cm, particularly the trees found in Group 2. *Avicennia marina* is a pioneer species that can live in a wide range of environments and has physiological adaptations that enable it to survive environmental stress, such as heavy metal contamination [16,36–38]. This species also has a complex root system consisting of pencil-like respiratory roots that facilitate gas exchange, as well as underground roots. These roots help absorb and translocate heavy metals to other organs of *Avicennia marina*. In addition, *A. marina* leaves also contribute to the phytoaccumulation of heavy metals, where absorbed heavy metals are then accumulated in glandular trichomes and salt glands on the leaves [39,40].

An analysis of the heavy metal concentrations showed that the concentrations of Pb were always greater than those of Cd in both the roots and leaves of *A. marina.* Alzahrani et al. [41] have also reported similar patterns, since Pb is generally more abundant than Cd due to its widespread presence in urban runoff, port operations, atmospheric deposition, and other human-caused sources. The fact that Pb is more predominant than Cd in this study is in agreement with the results obtained from mangrove ecosystems in Indonesia and from other tropical coastal areas [9,22,23,28]. The higher Pb concentration in the *A. marina* organs than Cd is mainly due to high sediment contamination, greater bioconcentration, and the presence of pollution sources [26,42]. Moreover, environmental factors, such as pH and salinity, increase the Pb accumulation [42].

Although Pb and Cd concentrations tended to be higher in leaves than in roots, statistical analyses detected few significant differences between plant organs and shoreline distance groups. Based on a paired t-test analysis of heavy metals (Pb and Cd) in leaves and roots, Pb concentrations were more readily translocated from belowground tissues to aerial organs than Cd under the environmental conditions observed in this study. The physiological characteristics of *Avicennia marina* influence the higher Pb accumulation in the leaves. Following root uptake, Pb is transported through the xylem and subsequently accumulated in the leaf tissues [38]. In contrast, Cd is often retained in root tissues. Cd that is taken up by the root is adsorbed to root cell walls, sequestrated in vacuoles, or complexed with phytochelatins and metallothioneins in root tissues [43,44]. These mechanisms can reduce Cd translocation to aboveground organs, particularly the leaves [12,20]. Consequently, the absence of a statistically significant difference in Cd concentrations between leaves and roots may indicate a more conservative internal Cd transport mechanism than Pb.

Contrary to the initial hypothesis regarding the effect of shoreline distance on heavy metal accumulation in *Avicennia marina* tissue, the results of Welch's t-tests indicate that shoreline distance is unlikely to be a determinant of heavy metal accumulation in the AKMPF. Heavy metal distribution may instead be affected by hydrological processes characteristic of urban mangrove systems, such as in the AKMPF. The regular tidal inundation, river discharge, and anthropogenic runoff, hydrological processes that take place in urban mangrove ecosystems, can cause dissolved and particulate contaminants to spread throughout the mangrove forest, thus reducing the spatial gradients in environmental exposure [8]. However, these results should be interpreted with caution, as the sample included only six representative trees and did not quantify Pb and Cd concentrations in the sediments or surface water.

The fact that higher concentrations were found in the leaves than in the roots is in agreement with the idea that metals absorbed by the plant are transported from belowground parts to the aboveground organs. This trend was additionally confirmed by TF values exceeding 1 for both Pb and Cd. Previous studies on *A. marina* and other mangrove species have reported a similar pattern of translocation, indicating that these plants can transport metals absorbed through their tissues [10,12–14,17,20]. Nevertheless, TF values alone are insufficient to classify *A. marina* as a hyperaccumulator. To classify hyperaccumulator species, we need to consider additional parameters, such as the BCF and the BAF [12,20,21,33]. Consequently, the findings of this study indicate that *A. marina* can translocate Pb and Cd from roots to leaves; however, its effectiveness as a hyperaccumulator or phytoremediation species cannot be confirmed solely from TF values.

The correlation analysis showed that several environmental variables were associated with heavy metal concentrations in *A. marina* tissues. For the leaves, Pb and Cd concentrations showed a negative association with soil temperature. While for the roots, the metal concentrations were positively related to light intensity. In addition, the Pb concentrations in leaves were negatively correlated with soil pH. It seems that environmental conditions could affect how metals accumulate in plant tissues. Factors such as pH, salinity, sediment properties, and microclimatic conditions influence metal mobility, bioavailability, and the process by which plants take up these metals in mangrove ecosystems [5,15,25,36,39]. However, because the analysis was based on a limited number of observations and did not involve experimental manipulation of environmental variables, the detected relationships should not be interpreted as evidence of the causal mechanisms. They should rather be seen as preliminary indications of potential ecological interactions that deserve further investigation. Studies in the future using larger sample sizes and multivariate analytical approaches will help clarify the relative influence of environmental factors on the accumulation of heavy metals in mangrove vegetation.

It is necessary to recognize several limitations when interpreting the results of this study. Firstly, the small sample size and the use of purposive sampling reduce both the statistical power and generalizability of the findings. Secondly, since no data are available on metal concentrations in sediment and water, it is not possible to fully assess the various pathways of environmental exposure and the efficiency of metal bioaccumulation. Thirdly, even though quality assurance and quality control measures were carried out regarding calibration verification, recovery rates, and detection limits, this would increase confidence in the analytical results. Hence, the findings presented here should be seen as preliminary evidence regarding the patterns of heavy metal accumulation in *Avicennia marina* within the AKMPF.

Even though there are these limitations, the study shows the ecological significance of *A. marina* in urban mangrove ecosystems which are affected by anthropogenic contamination. The fact that Pb and Cd have accumulated in both the leaves and roots shows that this species can act as a useful bioindicator of the presence of heavy metals in mangrove areas [1,10,20,26,40,45]. The fact that the metals have been found to move from roots to the leaves also shows that *A. marina* is able to redistribute the contaminants it has absorbed internally [10,14,20]. Nevertheless, further environmental and physiological measurements are needed to fully evaluate the species' phytoremediation efficiency [20,21,33,40]. From a management point of view, preserving healthy *A. marina* stands could help to support long-term environmental monitoring programs and enhance our understanding of contaminant dynamics in urban coastal ecosystems. Future studies that integrate the analyses of plants, sediments, and water over wider spatial scales will lead to a more complete evaluation of the behaviour of heavy metals and the ecological risks in mangrove environments.

Conclusions

The study showed that *Avicennia marina* was able to accumulate both Pb and Cd in the leaves and roots within the AKMPF, with Pb levels being consistently higher than those of Cd. Pb concentrations were found to be considerably greater in leaves than in the roots, which shows that there was an effective translocation of Pb within the plant, while there was no significant difference in Cd concentration between the various plant organs. In contrast, shoreline distance (≤ 100 m and > 100 m from the shoreline) had no significant effect on Pb or Cd accumulation, and the negligible effect sizes suggest that shoreline proximity alone is not a major determinant of heavy metal accumulation in this urban mangrove ecosystem. Furthermore, a TF value greater than 1 indicates the ability of *Avicennia marina* to transport heavy metals internally.

The observed accumulation patterns should still be treated with caution, given the limited sample size and the absence of sediment and water metal concentration data in the study. Although the results indicate that *Avicennia marina* can take up and transport Pb and Cd into its tissues, the TF values alone are insufficient to establish the species' capacity for hyperaccumulation or its efficiency in phytoremediation. That said, the fact that these metals are found in the tissues of *Avicennia marina* does suggest that it has the potential to act as a bioindicator of heavy metal contamination in urban mangrove ecosystems. Future research is required, involving the analysis of plant organs, sediment, and water samples, to better understand heavy metal dynamics and assess the ecological role of *Avicennia marina* in contaminated mangrove environments.

Author Contributions

CK: Conceptualization, Methodology, Writing - Review, Supervision; **ALR**: Software, Writing - Review & Editing, Formal Analysis; Data Interpretation; **FR**: Conceptualization, Methodology, Investigation, Data Curation; and **I**: Writing – Review, Supervision.

AI Writing Statement

During the preparation of this work, the authors used ChatGPT to assist with language editing, grammar correction, and clarity in scientific writing. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

Conflicts of interest

There are no conflicts to declare.

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