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Phytoremediation potential of *Avicennia marina, Rhizophora mucronata,* and *Bruguiera gymnorrhiza* in lead (Pb) contaminated urban coastal areas

Potensi fitoremediasi *Avicennia marina, Rhizophora mucronata,* dan *Bruguiera gymnorrhiza* di kawasan pesisir perkotaan yang terkontaminasi timbal (Pb)

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ABSTRACT

Heavy metal contamination in urban coastal areas poses a serious environmental threat, with lead (Pb) being one of the most persistent and hazardous pollutants. Mangrove forests, which act as natural buffers between land and sea, have the potential to mitigate heavy metal pollution through phytoremediation. This study evaluates the phytoremediation potential of three mangrove species—*Avicennia marina, Rhizophora mucronata,* and *Bruguiera gymnorrhiza*—in lead-contaminated coastal areas of Wonorejo and Gunung Anyar, Surabaya, Indonesia. Sediment, root, and leaf samples were collected using a survey method and purposive random sampling. Physiochemical analysis included soil texture, pH, electrical conductivity (EC), and Pb concentration. Pb levels in Gunung Anyar sediments reached 12.0 ppm, higher than Wonorejo's 4.05 ppm. *A. marina* exhibited the highest Pb accumulation, with a bioconcentration factor (BCF) of 8.85 in roots and 6.97 in leaves. *R. mucronata* had a BCF of 5.75 in roots and 2.09 in leaves, while *B. gymnorrhiza* demonstrated a root BCF of 28.8 and leaf BCF of 28.4. Translocation factor (TF) analysis revealed that *A. marina* had the highest TF (1.27), indicating phytostabilization as its primary mechanism. Meanwhile, *R. mucronata* and *B. gymnorrhiza* exhibited phytoextraction characteristics due to higher metal translocation efficiency. These findings highlight the distinct phytoremediation strategies among species.

ABSTRAK

Kontaminasi logam berat di kawasan pesisir perkotaan menjadi ancaman serius bagi lingkungan, dengan timbal (Pb) sebagai salah satu polutan paling persisten dan berbahaya. Hutan mangrove, yang berfungsi sebagai penyangga alami antara daratan dan laut, memiliki potensi dalam mereduksi pencemaran logam berat melalui mekanisme fitoremediasi. Penelitian ini mengevaluasi potensi fitoremediasi tiga spesies mangrove—*Avicennia marina, Rhizophora mucronata,* dan *Bruguiera gymnorrhiza*—di kawasan pesisir yang terkontaminasi Pb di kawasan pesisir Wonorejo dan Gunung Anyar, Surabaya, Indonesia. Sampel sedimen, akar, dan daun dikumpulkan menggunakan metode survei dan purposive random sampling. Analisis fisikokimia mencakup tekstur tanah, pH, konduktivitas listrik (EC), dan konsentrasi Pb. Hasil penelitian menunjukkan bahwa konsentrasi Pb dalam sedimen di Gunung Anyar mencapai 12,0 ppm, lebih tinggi dibandingkan Wonorejo sebesar 4,05 ppm. *A. marina* menunjukkan akumulasi Pb tertinggi dengan faktor biokonsentrasi (BCF) sebesar 8,85 pada akar dan 6,97 pada daun. *R. mucronata* memiliki BCF sebesar 5,75 pada akar dan 2,09 pada daun, sedangkan *B. gymnorrhiza* menunjukkan BCF akar sebesar 28,8 dan BCF daun sebesar 28,4. Analisis faktor translokasi (TF) menunjukkan bahwa *A. marina* memiliki TF tertinggi (1,27), yang mengindikasikan bahwa mekanisme utama fitoremediasi yang terjadi adalah fitostabilisasi. Sementara itu, *R. mucronata* dan *B. gymnorrhiza* menunjukkan karakteristik fitoekstraksi dengan efisiensi translokasi logam yang lebih tinggi. Temuan ini menyoroti strategi fitoremediasi spesifik dari masing-masing spesies.

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INTRODUCTION

Heavy metal contamination in coastal environments poses a severe threat to ecological stability and public health. Among various toxic pollutants, lead (Pb) is one of the most persistent and hazardous heavy metals, known for its ability to bioaccumulate in marine organisms and enter the food chain, ultimately impacting human health (Phaenark et al., 2024). Industrial activities, urban expansion, and waste discharge have led to increasing Pb concentrations in coastal sediments, disrupting nutrient cycles and degrading aquatic ecosystems (El-Sharkawy et al., 2025). In addition to endangering marine biodiversity, Pb contamination can weaken the structural integrity of coastal habitats, making them more vulnerable to environmental stressors such as erosion and extreme weather events (Lincoln et al., 2022; Doelle & Puthucherril, 2023).

Indonesia, home to more than 3.36 million hectares of mangrove forests, harbors the largest mangrove ecosystem in the world, constituting approximately 20.37% of the global total (Indonesian Ministry of Environment and Forestry [KLHK], 2023). These coastal forests play a crucial role in stabilizing shorelines, preventing seawater intrusion, and acting as natural buffers against tidal waves and tsunamis (Harris et al., 2018). Mangroves are also efficient carbon sinks, absorbing atmospheric CO_2 and mitigating the effects of climate change caused by anthropogenic emissions (Friess et al., 2019). Furthermore, mangrove ecosystems facilitate nutrient cycling, supporting biodiversity and enhancing coastal productivity (Alongi, 2018). However, despite their ecological significance, Indonesian mangroves have experienced severe degradation due to land conversion for aquaculture, agriculture, and infrastructure development. Studies by Mughofar et al. (2018) and Goldberg et al. (2020) indicate that according to FAO data (2020), Indonesia has significantly contributed to mangrove loss in Asia, with an accelerating degradation rate over the past three decades.

One of the most pressing environmental challenges in mangrove ecosystems is heavy metal contamination, particularly from lead (Pb), which accumulates in sediments and plant tissues. The ability of mangroves to tolerate and remediate heavy metals through phytoremediation has been recognized, but research on their effectiveness in urban coastal areas remains limited. While previous studies (Chakraborty et al., 2013; Kaewtubtim et al., 2016; Banerjee et al., 2018) have demonstrated that mangroves can accumulate heavy metals, most have taken a broad ecological perspective without quantitatively assessing individual species' efficiency in urban coastal environments with high contamination levels. Additionally, limited research has been conducted in Surabaya, an industrialized city experiencing severe Pb pollution in its mangrove forests.

This study evaluates the phytoremediation potential of *A. marina, R. mucronata*, and *B. gymnorrhiza* in accumulating Pb in contaminated urban coastal environments. By analyzing Pb concentrations in sediments, roots, and leaves, this research aims to quantify the species-specific capacity for heavy metal uptake and assess their role in mitigating Pb contamination. The findings will provide scientific insights to support conservation strategies and offer recommendations for managing Pb-contaminated coastal areas. Ultimately, this study contributes to the development of environmental rehabilitation frameworks for polluted urban mangrove ecosystems, particularly in Surabaya.

MATERIALS & METHODS

Study area and sampling locations

This study was conducted in Surabaya, Indonesia, between May and August 2024, focusing on the mangrove ecosystems of Wonorejo and Gunung Anyar. Observations were carried out at two designated locations within each area: Wonorejo (7°18'42.06" S, 112°50'39.08" E) and Gunung Anyar (7°19'56.89" S, 112°49'53.95" E). The selection of these sites was based on their exposure to urban pollution and heavy metal contamination, particularly from industrial and domestic waste, which has been documented as a major environmental concern in coastal areas (Adimalla et al., 2020; Wu et al., 2022).

Mapping and spatial data processing were conducted at the SDL Studio Laboratory, while chemical and physical analyses of soil and sediment samples were performed in the Physics and Chemistry Laboratories of the Faculty of Agriculture, UPN "Veteran" East Java. The equipment and materials used in this study included soil augers for sediment collection, knives for plant sample extraction, Avenza Maps software for geospatial mapping, and ArcGIS Pro 10.8 (Esri, USA) for spatial analysis. Soil texture was determined using the pipette method, while chemical properties such as pH (Bench Top pH Meter model PL 700 PV, Taiwan) and electrical conductivity (EC) (HANNA HI9813-5, Romania) were analyzed following standard laboratory protocols by book of technical manual from the Indonesian soil research center.

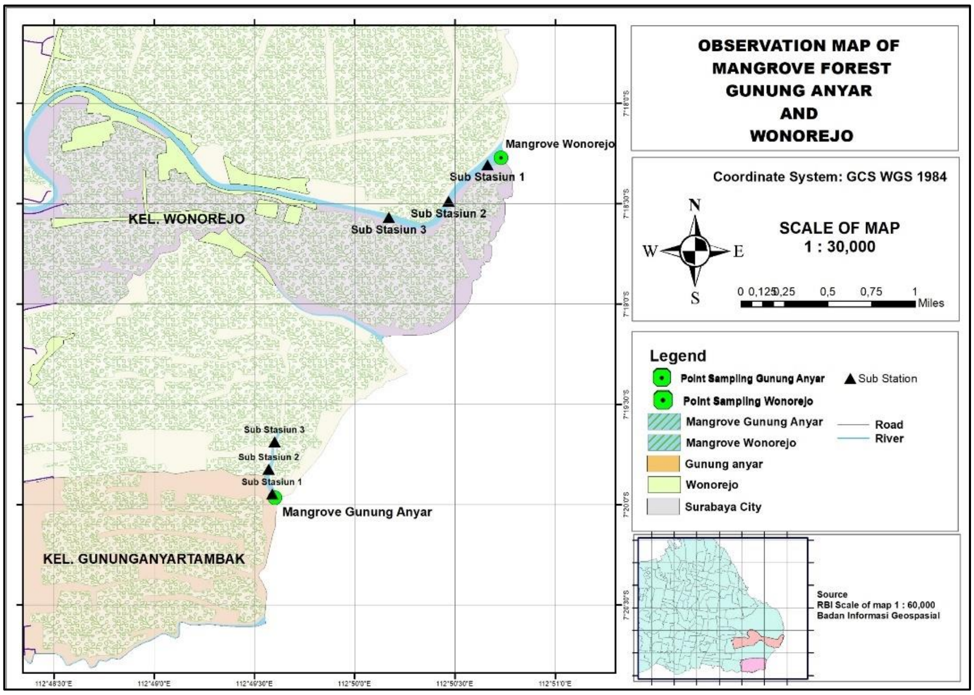

Figure 1. Sampling location of mangrove at Gunung Anyar and Wonorejo, Surabaya, Indonesia

Sampling and laboratory analyses

A survey method approach was employed to characterize the physiographic conditions and describe the actual field environment of the study sites. Sampling locations were selected using purposive random sampling, following the methodology outlined by Mahfud et al. (2013), to ensure representative data collection. The study considered three distinct mangrove zones within each site, which are typically classified based on their relative proximity to water and substrate conditions. The Avicennia zone was located closest to the waterline, where salinity levels tend to be highest. The Rhizophora zone represented the transitional area between water and land, where moderate salinity levels and periodic tidal flooding occur. The Bruguiera zone was the most inland zone, characterized by less frequent tidal influence and higher organic matter accumulation. Sampling was conducted at three sub-zone stations within each location, with a 1-kilometer interval from the river estuary to capture variations in heavy metal accumulation across the gradient of mangrove zonation.

For laboratory analysis, the concentration of lead (Pb) in sediments, roots, and leaves of the three mangrove species—*A. marina*, *R. mucronata*, and *B. gymnorrhiza*—was quantified using the HNO_3:$HClO_4$ extraction method, a widely recognized approach for metal digestion in environmental samples (Ji et al., 2025). The extracted Pb content was then analyzed using a Shimadzu AA-7000 Atomic Absorption Spectrophotometer (AAS) (Shimadzu, Japan) to determine the metal concentrations in different sample matrices.

Statistical analysis

To assess potential differences in heavy metal accumulation in mangrove roots between the two study sites, an independent sample t-test was applied. This statistical test was chosen due to it s effectiveness in comparing mean differences between independent groups in environmental and biological studies (Agbangba et al., 2024). The analysis was conducted using IBM SPSS Statistics software, which provided insights into the significance of variations in Pb accumulation between Wonorejo and Gunung Anyar, Surabaya, Indonesia.

Furthermore, the concentration of Pb in plants and sediments was evaluated using the Bio-Concentration Factor (BCF) and Translocation Factor (TF) equations, which are widely used to assess metal mobility within plant systems and their accumulation efficiency in contaminated environments (Usman et al., 2013; Li et al., 2025). BCF values were calculated to determine the ability of mangrove roots to absorb Pb from sediments, while TF values were used to assess the capacity of mangrove species to translocate Pb from roots to aerial parts such as stems and leaves. These indices provide critical insights into whether a particular species primarily functions as a phytoextractor (high TF) or a phytostabilizer (high BCF but low TF), which has important implications for phytoremediation strategies in heavy metal-contaminated coastal areas.

RESULTS & DISCUSSIONS

Characteristic of contaminated soil

Soil texture plays an important role in soil science because it greatly affects soil quality and fertility. Soil texture refers to the composition of sand, silt, and clay particle sizes, with each fraction affecting the soil's capacity to retain water, aeration, and nutrient availability (Dewiyanti et al., 2021; Aditya & Wijayanti, 2023). Based on the results of the study in Table 1 the sediment texture in the Wonorejo and Gunung Anyar mangrove areas mostly consists of silt fractions, ranging from 67–87%. In areas with dense mangrove vegetation, the soil texture tends to be silty clay loam, formed from the decomposition of organic litter and the binding of silt and clay particles by mangrove roots, so that over time it forms a muddy layer (Wang et al., 2021). This soil texture is also influenced by currents and tides, because water currents carry smaller particles more easily than larger particles.

Table 1. Physico-chemical characteristics of soil in mangrove areas

No	Mangrove locations	Zones	Fraction (%)			Texture	pH		EC
			Sand	Silt	Clay		H_2O	KCl	dS/m
1	Gunung anyar	*Avicennia*	6	70	24	Silt clay	7.81	7.10	8.14
		Rhizophora	2	71	27	Silt clay loam	8.14	7.53	14.8
		Bruguierra	7	74	19	Silt clay loam	7.75	6.95	6.54
2	Wonorejo	*Avicennia*	1	68	31	Silt clay	8.12	7.31	16.18
		Rhizophora	8	67	25	Silt clay	7.41	6.81	15.53
		Bruguierra	1	87	12	Silt clay loam	7.24	6.57	12.69

The pH of the soil is a crucial factor in evaluating the condition of mangrove ecosystems, especially since mangroves are found in coastal regions where seawater has an impact. Research findings indicate pH fluctuations throughout several zones. The potential pH in KCl solution (pH KCl) ranges from 6 to 7, while the actual soil pH (pH H_2O) ranges from 7 to 8. The pH of H_2O in the mangrove region of Gunung Anyar ranges from 7.75 to 8.14, whereas the pH of KCl varies between 6.95 and 7.53. In Wonorejo, the pH of H_2O varies from 7.24 to 8.12, whereas the pH of KCl goes from 6.57 to 7.31. The findings suggest that the soil in both areas is predominantly neutral to alkaline, which is optimal for mangrove development (Dookie et al., 2024). (Fajar et al., 2013). Fajrin et al. (2016) state that when mangrove regions are near populated areas or land that is often subjected to human activity, the pH of the soil may become more acidic.

Electrical conductivity (EC) is a critical parameter for assessing the quality of mangrove soil, as it is a measure of the soil's capacity to conduct electrical current, which is influenced by the concentration of ions in the soil (Chaikaew & Chavanich, 2017). Analysis results indicate that EC values in mangrove sediments at Gunung Anyar and Wonorejo differ among various vegetation zones, exhibiting higher values in proximity to water sources. According to Nichols et al. (2019) and Drewry et al. (2021) the absorption rate of heavy metals in sediments can be significantly influenced by the EC or salinity levels, which are crucial for the overall health of the mangrove ecosystem and the preservation of soil biophysical quality.

Contaminated heavy metal in mangrove

Lead (Pb) is a heavy metal that has a bluish gray color with soft and malleable properties. With a low melting point of around 327.5°C and a boiling point of 1.740°C, Pb metal tends to easily accumulate in mangrove sediments which are influenced by the type of substrate, root structure, and the ability of mangroves to bind metals. Mangrove roots can absorb heavy metals, including Pb, from sediments and store them in plant tissues which can help reduce pollutant levels. However, high Pb concentrations can have a negative impact on the health of mangroves and surrounding organisms (Khotimah et al., 2024). Table 2 shows the results of Pb heavy metal content in Wonorejo and Gunung Anyar mangroves.

Table 2. Concentration of Pb in sediment and mangrove at Gunung Anyar and Wonorejo

Location	Zones	Weeks	Pb (ppm)		
			Sediment	Leaf	Root
Gunung Anyar	*Avicennia*	1	12.08	2.02	1.59
	Rhizophora		2.58	1.23	0.45
	Bruguiera		5.35	1.36	0.19
	Avicennia	2	3.58	2.54	3.09
	Rhizophora		2.54	0.18	0.73
	Bruguiera		5.22	0.18	0.72
	Avicennia	3	0.70	0.71	0.98
	Rhizophora		8.78	1.23	0.72
	Bruguiera		7.03	0.97	0.97
	Avicennia	4	4.56	2.09	1.43
	Rhizophora		8.78	1.24	0.45
	Bruguiera		8.22	0.95	0.71
Wonorejo	*Avicennia*	1	4.04	0.58	1.02
	Rhizophora		4.2	0.61	0.76
	Bruguiera		5.27	0.81	2.18
	Avicennia	2	4.05	0.37	1.06
	Rhizophora		5.22	0.92	0.42
	Bruguiera		6.09	0.57	1.85
	Avicennia	3	5.22	0.87	0.74
	Rhizophora		4.45	0.42	0.46
	Bruguiera		4.08	0.93	2.31
	Avicennia	4	5.11	0.52	1.03
	Rhizophora		4.33	0.45	0.43
	Bruguiera		4.02	0.92	2.72

The results of heavy metal Pb in Table 2 show a significant difference in Pb concentration between the Gunung Anyar and Wonorejo locations, especially in the Avicennia zone. In the first w eek, the Pb concentration in the Gunung Anyar sediment was recorded at 12.0 ppm, exceeding the 4.05 ppm observed in Wonorejo. This indicates an increase in local pollution levels or differences in the ability of mangroves to absorb heavy metals. Human activities and industrial waste can cause an increase in lead (Pb) levels in Gunung Anyar. The concentration of Pb in mangrove leaves in Gunung Anyar was 2.01 ppm, while in Wonorejo it was recorded at 0.58 ppm. The ability of mangroves to transfer metals from roots to leaves shows their potential for bioaccumulation in the phytoremediation process of heavy metals in polluted coastal environments. The results showed that in general Gunung Anyar showed a higher level of lead pollution compared to Wonorejo. This may be due to the proximity of the area to industrial pollution sources or increased transport of polluted particles by water flow.

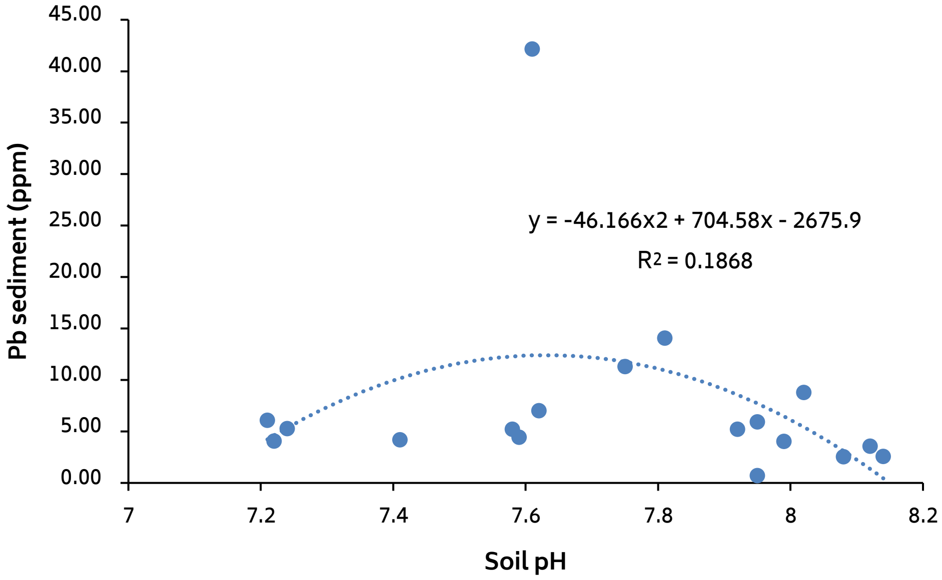

Figure 2. Interaction between Pb in sediment and pH

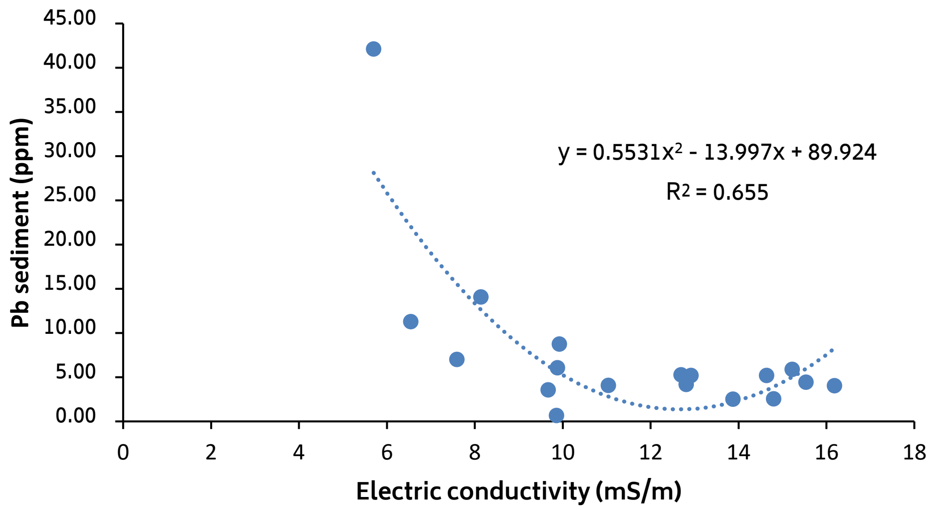

Figure 3. Interaction between Pb in sediment and EC

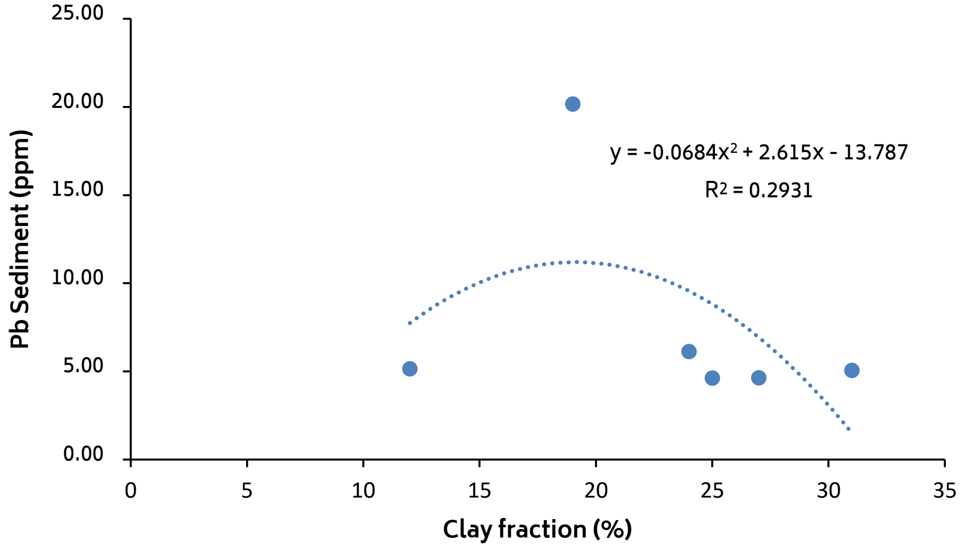

Figure 4. Interaction between Pb in sediment and soil texture (clay fraction)

Based on the graphic in Figures 2, 3, and 4, the results of the correlation analysis examine the relationship between total Pb concentration in mangrove sediment soil in the Wonorejo and Gunung Anyar areas with various environmental factors, including clay fraction, soil pH, and Electrical Conductivity (EC). Figure 4 the results showed that the clay fraction had a coefficient of determination (R^2) of 0.2931 or around 29.31%, indicating a weak relationship with total Pb concentration. These results imply that additional factors, such as organic matter and salinity levels, can also affect the presence of Pb in sediments. The texture of the clay fraction is known to have a high adsorption capacity for heavy metals due to its large surface area and negative charge. Thus, in general, it can reduce the mobility of heavy metals such as Pb (Ugwu & Igbokwe, 2019). However, in the Wonorejo and Gunung Anyar mangrove ecosystems, the high organic matter content can allow the formation of stable complexes with Pb, thereby reducing the adsorption capacity of clay (Hurum et al., 2023).

Furthermore, at the Figure 2 explain the coefficient of determination for soil pH is 0.1868 indicating that pH explains only about 18.68% of the variation in Pb concentration, showing that pH is not a primary factor in Pb distribution. High organic matter content in mangrove soil allows complex formation with Pb, thus decreasing its mobility and making Pb less available to plants or organisms (Lian et al., 2022). Additionally, the fluctuating salinity and anaerobic conditions characteristic of mangrove soils affect the form and mobility of heavy metals (Hu et al., 2021). The anaerobic conditions in the sediment promote Pb deposition as stable sulfide forms that are insoluble, even with pH changes. The presence of clay minerals in mangrove soils also plays a significant role in Pb adsorption, strengthening the metal's attachment to the sediment matrix (Meng et al., 2016; Adimalla et al., 2020).

In addition, Figure 3 shows that the Electrical Conductivity Value (EC) has a determination coefficient of 0.655, which means that around 65.5% of the variation in Pb concentration can be explained by the variation in EC, which shows a moderate correlation between EC and Pb concentration in mangrove sediment soil. This high EC value indicates an increase in salinity which can affect the solubility of heavy metals such as Pb. An environment with a high EC value can increase the solubility of metals because there are competing ions. Thus, it can inhibit the absorption of Pb on the soil surface and can reduce the availability of Pb in the dissolved phase (Setyaningrum et al., 2018; Zhang et al., 2021)

Bioconsentration factor (BCF) and translocation factor (TF)

Bioconcentration Factor (BCF) analysis in mangroves provides an overview of the capacity of various mangrove species to absorb and accumulate heavy metals from sediment and water in coastal areas. In Table 3, the results of the study show the results of variations in BCF values of lead (Pb) among the mangrove species studied. This indicates differences in the heavy metal accumulation capacity of each species. In the Gunung Anyar mangrove ecosystem, in the *Avicennia* zone, the concentration of Pb in sediment is 14.0 ppm, with a root BCF of 8.85 and a leaf BCF of 6.97. These results reveal that *Avicennia* plants have a high Pb accumulation capacity, especially in the roots which can play a dominant role in the heavy metal accumulation process (Hidayah & Rachman, 2023). In the *Rhizophora* zone, the Pb content in the sediment is lower (2.57 ppm), with a root BCF of 5.75 and a leaf BCF of 2.09, which means it shows a significant but lower absorption capacity compared to *Avicennia*. In the *Bruguiera* zone, the concentration of Pb metal in the sediment reached 8.22 ppm with a very high root BCF of 28.8. According to Mentari et al. (2022) state that *Brugruiera* plants can indicate an extraordinary ability to accumulate heavy metals in their roots. While the leaf BCF value was recorded at 28.4.

Table 3. BCF and TF analysis in mangroves at Gunung Anyar and Wonorejo

Location	Zones	Weeks	BCF root	BCF	BCF leaf	BCF	TF	TF type
Gunung Anyar	*Avicennia*	1	8.86	High	6.97	High	1.27	Phytoextraction
	Rhizophora		5.76	High	2.09	High	2.75	Phytoextraction
	Bruguiera		28.89	High	3.92	High	7.36	Phytoextraction
	Avicennia	2	1.16	Moderate	1.41	Moderate	0.82	Phytostabilization
	Rhizophora		3.60	High	13.82	High	0.26	Phytostabilization
	Bruguiera		7.26	High	28.43	High	0.26	Phytostabilization
	Avicennia	3	0.71	Low	0.99	Low	0.72	Phytostabilization
	Rhizophora		12.2	High	7.12	High	1.71	Phytoextraction
	Bruguiera		7.23	High	7.24	High	1.00	Phytostabilization
	Avicennia	4	3.19	High	2.18	High	1.46	Phytoextraction
	Rhizophora		19.51	High	7.08	High	2.76	Phytoextraction
	Bruguiera		11.58	High	8.65	High	1.34	Phytoextraction
Wonorejo	*Avicennia*	1	3.96	High	6.97	High	0.57	Phytostabilization
	Rhizophora		5.53	High	6.89	High	0.82	Phytostabilization
	Bruguiera		2.42	High	6.59	High	0.37	Phytostabilization
	Avicennia	2	3.81	High	10.92	High	0.35	Phytostabilization
	Rhizophora		12.43	High	5.67	High	2.19	Phytoextraction
	Bruguiera		3.29	High	10.68	High	0.31	Phytostabilization
	Avicennia	3	7.05	High	6.22	High	1.18	Phytoextraction
	Rhizophora		9.67	High	10.6	High	0.91	Phytostabilization
	Bruguiera		1.77	Moderate	4.39	High	0.40	Phytostabilization
	Avicennia	4	4.96	High	9.83	High	0.52	Phytostabilization
	Rhizophora		10.07	High	9.62	High	1.05	Phytoextraction
	Bruguiera		1.48	Moderate	4.37	High	0.34	Phytostabilization

The results of the Translocation Factor (TF) explained significant variations among species in their ability to translocate heavy metals from the roots to the upper part of the plant. These results indicate that the TF value is influenced by mangrove species, environmental conditions, sediment types, pollution levels, and salinity. These variables have affected the efficiency of heavy metal transfer from roots to leaves. The evaluation of TF for various mangrove species in Gunung Anyar and Wonorejo showed that the ability to translocate heavy metals varied in both locations. Based on the data in

Table 3, it shows that the analysis in Gunung Anyar explained the variation in TF among *Avicennia*, *Rhizophora*, and *Bruguiera* species. In the first week, Avicennia showed a TF of 1.27, which then decreased to 0.82 in the second week, indicating a decrease in translocation ability. *Rhizophora* showed an initial TF of 2.75 in the first week but decreased significantly to 0.26 in the second week. Bruguiera recorded the highest TF in the first week, with a value of 7.36. According to Ganeshkumar et al. (2019) this variation shows that each species has a quite different capacity for phytoextraction of heavy metals from soil to plant tissue, which indicates a species-specific accumulation mechanism in mangroves.

The potential of A. marina, R. mucronata*, and* B. gymnorrhiza *in phytoremediation of Pb*

Phytoremediation is a biotechnology method that utilizes plants to reduce pollutants and has proven to be very effective in overcoming and accumulating heavy metal pollution, especially in mangrove ecosystems that are very susceptible to the accumulation of hazardous substances, such as lead (Pb). Figure 5 shows the types of mangroves, namely *Avicennia*, *Rhizophora*, and *Bruguiera*, which are mangrove plants that have significant potential in the phytoremediation process in the Wonorejo and Gunung Anyar mangrove forests. Avicennia species are commonly found in mangrove habitats and have important abilities in absorbing heavy metals from the environment (Hossain et al., 2022). The results of a study on Avicennia in Gunung Anyar and Wonorejo found the highest Pb levels in sediments in Gunung Anyar, with a root BCF of 8.85. According to Dajam et al. (2024) stated that *A. marina* has an ideal capacity to absorb lead (Pb) from contaminated sediments through the bioaccumulation process in plant roots, this indicates that the level of translocation is minimal to aerial tissue, including to leaves.

Figure 5. Mangrove species that have the potential as phytoremediation agents (1) *Avicennia*, (2) *Rhizhopora*, (3) *Brugruiera* in Gunung Anyar and Wonorejo Mangrove Forest

This is in line with previous studies showing that Avicennia can accumulate heavy metals in its root tissue (Sarath & Puthur, 2021). In environments with low Pb concentrations, such as Wonorejo, the phytostabilization mechanism is more dominant with metals tending to persist in the roots (Ghasemi et al., 2018). Rhizophora and other mangrove species also show high potential as phytoremediation agents. In Gunung Anyar, Rhizophora has a fairly high root BCF, averaging 1.23, indicating significant Pb accumulation in the roots compared to other tissues, along with an average TF of 2.09. The results of the study by (dos Santos Garcia et al., 2021) & (Hossain et al., 2022) found that *A. marina* has the ability to translocate lead (Pb) from its roots to leaves through a heavy metal transport pathway involving heavy metal ATPase (HMA) proteins. Accumulation of Pb in leaves reduces toxicity to the roots, with Translocation Factor (TF) values approaching or exceeding one under certain conditions. Consequently, *A. marina* is a useful phytoremediation agen t that can control lead distribution without seriously harming the physiological system of the plant. In Wonorejo mangrove, variations in

BCF and TF values indicate different responses influenced by environmental conditions. Such as the level of contaminants and sediment quality in the mangrove environment (Setyawan, 2022). High TF in Rhizophora indicates that this species can translocate heavy metals to the upper part of the plant, thus facilitating further remediation processes (Yap & Al-Mutairi, 2023). Bruguiera plants are another mangrove species studied in Gunung Anyar and Wonorejo, showing substantial phytoremediation potential results, with high root BCF in Wonorejo (2.18) but lower in Gunung Anyar (0.185). Although BCF is lower, TF is high in Gunung Anyar (7.36) As an important component of phytoextraction. Bruguiera plants show the capacity to transmit lead (Pb) from roots to leaves. Pb is absorbed by the roots, transported through the xylem, and accumulated in the leaves with the help of heavy metal transporters such as heavy metal ATPase (HMA). This process can clean the roots and stems of plants while maintaining their growth. This shows how effective and beneficial Bruguiera is for phytoremediation of polluted mangrove ecosystems (Adhikari et al., 2023; Yadav & Sharma, 2021). In addition, in the Wonorejo mangrove, Bruguiera plants often work well as phytostabilizing agents with lower TF. According to Rahman et al. (2024) explained that what causes Pb to accumulate is mostly in the roots. Overall, this study explains that each mangrove species has a unique role in phytoremediation which is certainly influenced by local environmental conditions, such as sediment quality and contaminant levels. This study supports the strategic use of various mangrove species in environmental restoration programs tailored to local needs, especially in coastal ecosystems contaminated with heavy metals (Garbisu & Alkorta, 2001; Manikasari & Mahayani, 2018)

CONCLUSIONS

This study demonstrates that mangrove species exhibit distinct phytoremediation mechanisms for lead (Pb) contamination, influenced by species type and local environmental conditions. *A. marina* is most effective for phytostabilization, trapping Pb in its roots, while *R. mucronata* facilitates phytoextraction, translocating Pb to its leaves. *B. gymnorrhiza* adapts flexibly, acting as a phytostabilizer at low contamination levels and a phytoextractor under higher contamination. These findings emphasize the need for species-specific strategies in coastal restoration programs, where *A. marina* is prioritized in high-contamination zones and *R. mucronata* or *B. gymnorrhiza* in moderate-to-low contamination areas. Strengthening legal protections, community engagement, and environmental education is essential for sustainable mangrove conservation. Beyond pollution mitigation, mangrove phytoremediation enhances ecosystem resilience, supports biodiversity, and strengthens coastal defense against environmental stressors. Future research should explore long-term phytoremediation efficiency and interactions with other ecological factors.

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