JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(8), 219–237
https://doi.org/10.12911/22998993/204088
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.04.06
Accepted: 2025.05.26
Published: 2025.06.10

Spatial distribution of heavy metal lead concentration in soil and mangrove plants in the mangrove forests of Surabaya City: A case study of Gunung Anyar and Wonorejo mangroves

Haidar Fari Aditya[1], Dinna Hadi Sholikah[1*], Ahmad Mustapha Mohamad Pazi[2], Fina Dwi Permatasari[1]

[1] Department of Agrotechnology, Faculty of Agriculture, University of Pembangunan Nasional Veteran Jawa Timur, Rungkut Madya Street, Surabaya City, East Java, Indonesia
[2] Department Forestry Science, Faculty of Agricultural and Forestry Sciences, Universiti Putra Malaysia Bintulu Sarawak Campus, 97000 Bintulu, Sarawak, Malaysia
* Corresponding author's e-mail: dinna.hadi.fp@upnjatim.ac.id

ABSTRACT

Mangrove forests are vital coastal ecosystems that provide shoreline protection, support biodiversity, and sequester carbon. However, urbanization and industrial activities have led to the introduction of heavy metal contaminants, especially lead (Pb), posing significant threats to ecosystem health. This study examines Pb concentration in Gunung Anyar and Wonorejo mangroves in Surabaya, two key areas for coastal defence that are increasingly exposed to Pb pollution. From January to March 2024, samples were collected from sediments, roots, and leaves of *Avicennia marina*, *Rhizophora mucronata*, and *Bruguiera gymnorrhiza* using purposive random sampling at nine observation points. Pb content was analyzed using Atomic Absorption Spectrophotometry and spatial analysis of Pb distribution analysis using ArcGIS 10.8. The results showed that Pb concentrations were highest in Gunung Anyar, reflecting the impact of industrial activities, with the highest Pb levels found in soil (14.22 ppm), roots (1.57 ppm), and leaves (2.21 ppm) of *Avicennia marina*. Soil pH, electrical conductivity, organic matter, and clay content were identified as key factors influencing Pb uptake and retention, with neutral pH and higher organic matter supporting greater Pb accumulation. The study emphasizes the role of mangrove ecosystems in bioremediation, highlighting their potential to mitigate coastal pollution through phytoremediation. This research underscores the importance of monitoring and conserving mangrove ecosystems to enhance their role in pollution management and coastal health.

Keywords: lead concentration, plant mangrove, pollution, root, leaves, sediment.

INTRODUCTION

Mangroves are crucial coastal ecosystems that provide numerous ecological services (Huxham et al., 2017), including acting as natural barriers against coastal erosion (Winterwerp et al., 2020), supporting biodiversity, and sequestering carbon (Rahman et al., 2021; Vierros, 2017). However, these ecosystems are increasingly threatened by anthropogenic heavy metal concentration, primarily due to urbanization and industrial activities (Chai, Li, Ding, et al., 2019; Kulkarni et al., 2018; Proshad et al., 2024). Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are introduced into mangrove ecosystems primarily through industrial discharges, urban runoff, and agricultural practices (Araújo et al., 2022; Onyena et al., 2024).

Lead is a toxic heavy metal that poses significant risks to ecosystem health and local communities, particularly in mangrove areas. The accumulation of Pb in both soil and plants can harm biodiversity and human health, making it a critical environmental concern. The influx of heavy metals into mangrove environments poses significant risks to their health and functionality, as well as to the organisms that inhabit these areas (Anu et al., 2024; Palit et al., 2022). The accumulation process of mangrove plants can reduce the accumulation of heavy metals in the environment by absorption, cation exchange, filtration, and chemical changes from the roots (Hossain et al., 2022). However, the high concentration of heavy metals in mangrove plants can cause physiological and biochemical changes in plant cells (Y.-Y. Zhou et al., 2021) that impact the environmental ecological system (Sangur et al., 2021). The behavior of mangrove plants under stress from heavy metals includes anti-oxidant stress (Cabañas-Mendoza et al., 2023), osmotic stress (Acharya et al., 2023), photosynthesis inhibition (Afzal et al., 2023), growth inhibition, and increased mortality (Dan et al., 2022). Mangroves are increasingly recognized for their unique ability to filter pollutants, which positions them as effective bioindicators of environmental concentration (Rahman et al., 2024). Potentially toxic metals in the mangroves of the Sundarbans in Bangladesh due to anthropogenic influences from urbanization, industrialization, shipping, shipbuilding, and metallurgical industries as the main causes of pollution. The order of contamination is Pb > Ni > Cd > Fe > Mn > Zn > Cu (Islam et al., 2022).

However, limited research exists on Pb concentration in mangrove forests in Southeast Asia, especially in urbanized areas like Surabaya City. This study investigates the distribution of Pb concentration in the soils and mangrove plants of Gunung Anyar and Wonorejo mangrove forests in Surabaya City, Indonesia. Recent studies have shown that mangroves are capable of bioaccumulating pollutants such as heavy metals, which can reflect the concentration levels in the surrounding environment (de Lacerda et al., 2022).

The Gunung Anyar and Wonorejo mangrove forests are located in Surabaya, a city that has experienced rapid industrial growth. These forests serve as vital habitats for various species and protect the coastal areas from erosion and storm surges (Luthansa et al., 2021). Despite their ecological significance, these mangrove ecosystems are exposed to anthropogenic pollution, including heavy metals such as Pb, which are introduced through industrial effluents and urban runoff (Aljahdali and Alhassan 2020; Chai et al. 2019b; Sharma et al., 2021). Recent research highlights that mangrove plants are effective in accumulating heavy metals, making them useful for environmental monitoring (Yadav et al., 2023). Understanding the distribution of Pb concentration in these areas is essential for assessing the health of the mangrove ecosystem and ensuring its continued ecological function (Chowdhury & Maiti, 2016; Islam et al., 2022). This ability is essential for mitigating pollution and maintaining the ecological balance within these sensitive ecosystems (Chanda & Akhand, 2023; Y.-S. Wang & Gu, 2021). However, the accumulation of Pb and other heavy metals can also pose significant risks to the health of mangrove flora and fauna, as well as to the overall ecosystem services they provide (Kulkarni et al., 2018; Luthansa et al., 2021). Research indicates that anthropogenic activities, such as industrial discharges, aquaculture, and urban runoff, significantly contribute to Pb concentration in mangrove areas (Chai et al., 2019a; P. Li et al., 2022).

So, it is necessary to analyze the level of Pb concentration in mangrove areas at Wonorejo and Gunung Anyar that are affected by urbanization and industry. In Wonorejo, studies have indicated that this area has accumulated significant heavy metals, particularly Pb and copper, due to its proximity to industrial activities and urban runoff. The presence of Pb in mangrove sediments can Pb to bioaccumulation in mangrove species such as *Avicennia marina*, which has been identified as a potential agent for phytoremediation of heavy metals (Rachmawati et al., 2018). n Gunung Anyar, similar concerns regarding heavy metal concentration have been raised. The region's mangrove ecosystems are vulnerable to pollution from nearby urban and industrial activities, which can Pb to increased levels of Pb in sediments and biota (Alhassan & Aljahdali, 2021; Maharani et al., 2019). The accumulation of heavy metals in mangrove sediments not only poses risks to the plants and animals that inhabit these areas but also affects the overall health of the coastal ecosystem, which plays a vital role in carbon sequestration and coastal protection (Yam et al., 2020). The findings will contribute to a better understanding of how Pb concentration affects mangrove ecosystems, helping to inform policy and management strategies for these critical habitats (Onyena & Sam, 2020). Furthermore, this study will provide data that can be used for future conservation efforts, particularly in urban coastal regions, where the pressure from pollution continues to rise (Dong et al., 2024).

This study aims to assess the extent of Pb concentration in Gunung Anyar and Wonorejo mangrove forests and examine its distribution in soil and mangrove plants. By investigating the correlation between Pb concentrations in different locations and the mangrove species present, this research will provide valuable insights into the ecological impact of heavy metal pollution in urban coastal ecosystems. So, it can be used to mitigate mangrove degradation that impacts biodiversity sustainability and coastal community welfare.

MATERIAL AND METHODS

Site location

This research was conducted in the mangrove areas in the Wonorejo and Gunung Anyar Village, Rungkut Subdistrict, Surabaya City, East Java, from January to March 2024. The research locations are shown in Figure 1, which displays nine observation points in each mangrove area.

Experimental design

The method used in this research is the survey method, which aims to describe the actual conditions of the location and analyze the causes of certain phenomena (Minasny & McBratney, 2016). The observation points were determined using a purposive random sampling method, which involves selecting sampling locations based on predefined criteria and specific considerations relevant to the research objectives (Kidd et al., 2015; L. Zhang et al., 2022). The sampling points were selected based on two types, there are based on stations (Gunung Anyar (P1) and Wonorejo (P2)) and zone of site-specific tree

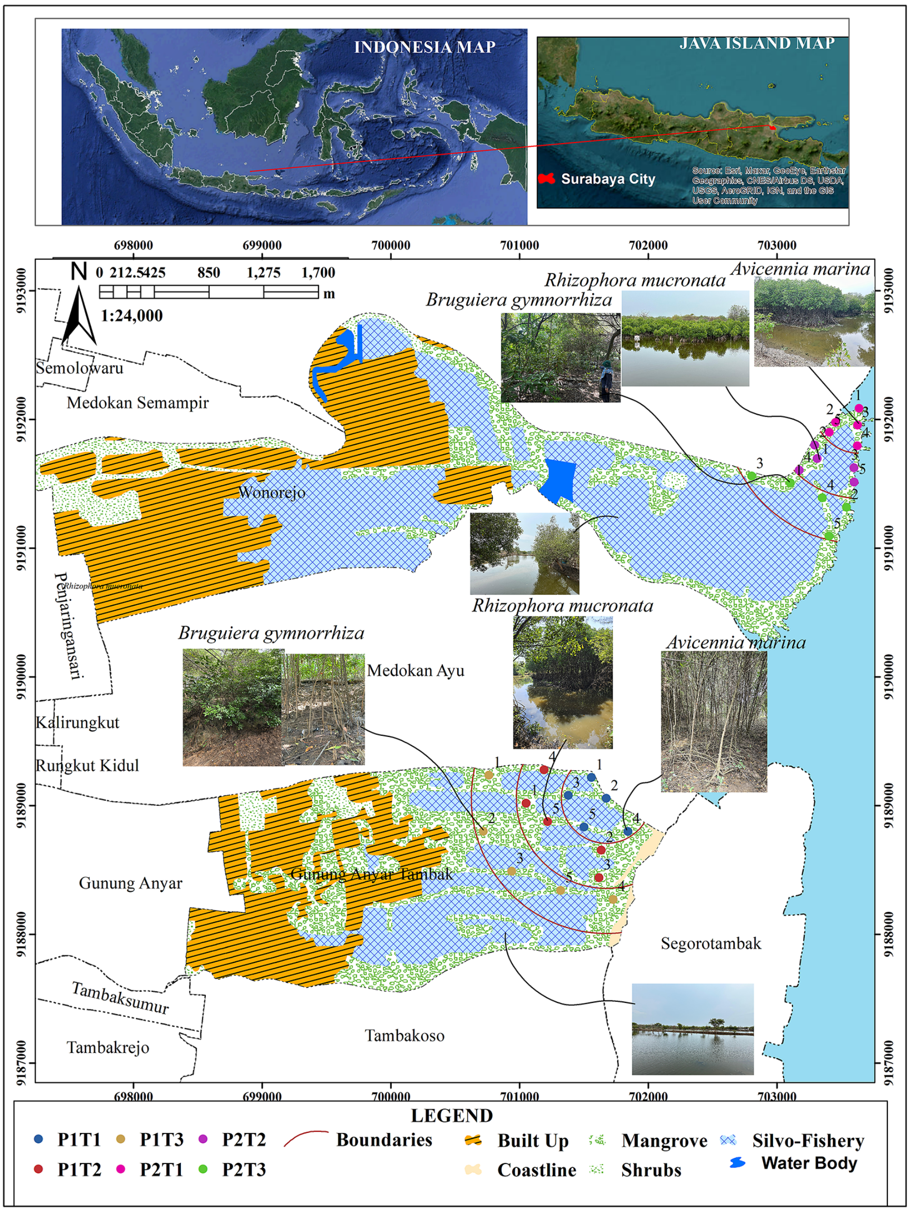

Figure 1. Point observation map of mangrove area in Gunung Anyar and Wonorejo Village, Rungkut Subdistrict, Surabaya City, East Java

plants of the mangrove ecosystem (the *Avicennia marina* zone (T1), the *Rhizophora mucronata* zone (T2), and the *Bruguiera gymnorrhiza* zone (T3)). Each station was divided into three sub-stations, with each sub-station positioned at 350 m intervals from the river mouth to the sampling point. Determination of sample points at the sub-station took 5 points randomly.

Sampling was carried out over four weeks to provide a more comprehensive representation of the mangrove ecosystem. Each sub-station represents a different vegetation zone, namely the *Avicennia* zone (water), the *Rhizophora* zone (water and land), and the *Bruguiera* zone (land). Data sampling was performed by measuring the heavy metal Pb content in sediment, roots, and leaves of mangrove plants, namely *Avicennia marina, Rhizophora mucronata,* and *Bruguiera gymnorrhiza.* The samples included leaves and roots of mangrove trees and sediments. Sampling of roots and leaves were sampled from trees with the same trunk and height and diameters of about 15–25 cm. The roots of the mangrove trees have an irregular shape, and they expand around the trunk outside the sediments. Root samples were collected from three with an appearance that was as similar as possible. The roots were cut and harvested around mangrove trees (which were visible). The size of the root sample in submerged conditions of the substrate taken is 0.4–1 cm in diameter with a length of 10 cm. The approximate weight of the samples was 200 g after drying and sifting (J. Wang et al., 2021). Trees with a healthy appearance and no damage were selected. Leaf with lengths from 4 to 6 cm was selected. Leaves were randomly collected from the middle to two-thirds of the canopy. Samples were collected from three trees with an appearance that was as similar as possible. The amount of the leaf sample collected each time was about 0.5 kg. This sample weighed approximately 200 g after drying and sifting (Safari et al., 2018). Sediment sampling was done in the form of a soil auger using a soil drill. Sediment collection is done right under the shade of mangrove trees that have been sampled roots and leaves (at a distance of 50 cm). Sediment samples with an area of 10×10 cm^2 were collected from a depth of 10 to 15 cm at several points around the tree. The wet weight of each sediment sample was about 400 g (Tamis et al., 2021). The tools and materials used during the study included knives, scissors, mobile phones, Avenza Map, stationery, shovels, labels, plant leaf samples, roots, and soil sediments.

Laboratory analysis

The sediments were stored in nylon bags and kept in the laboratory at 4 °C for < 4 h. In the laboratory, tests on moisture content, water content, and water content were conducted. In the laboratory, tests such as H_2O pH, electrical conductivity (EC), soil texture, soil organic matter (SOM), and Pb concentration (Maghsodian et al., 2021). The determination of Pb content in the sediment, roots, and leaves of mangrove plants can be analyzed using the ashing method and an atomic absorption spectrophotometer (AAS) flame test method in line with the Indonesian National Standard (2004) (Ferreira et al., 2018).

Spatial analysis

The preparation of the base map starts with the classification of land cover using the Supervised method from Sentinel 2A imagery using the ArcGIS 10.8 application (Ma et al., 2017; Phiri et al., 2020). Land cover classification is used as a determinant of observation points focused on mangroves in coastal areas, as well as analyzing the influence of land use that dominates around mangrove areas. After that, the preparation of survey maps through overlay analysis of base maps and secondary maps (Jia et al., 2017). The Pb distribution map is prepared using the zoning area of mangrove species by buffer area (Brumberg et al., 2021). Buffer building on vector features is a computationally intensive process to divide the vector dataset into a specific form of zoning. The computational intensity of each feature must be accurately stimulated based on the range of distances used based on the center point. In this research, the center point is the coastline. Therefore, determining the concentration of Pb in each zone is carried out using the zoning of existing conditions of mangrove vegetation using a multi-ring buffer that emphasizes the algorithmic aspects of spatial data-based geometry (Guo et al., 2020).

After the distribution of Pb concentrations is complete, it is necessary to classify the concentration of Pb in sediment, roots, and mangrove plants using the King Ma method. The King Ma method is used to determine the class interval (Irawan et al., 2019), so it is easier to categorize the Pb range class in each zone. Calculation of class interval (Ki) is done by determining the highest value (Xt) and the lowest value (Xr), then dividing by the number of classes to be used (n). The King Ma method formula is as follows :

$$Ki = \frac{[Xt - Xr]}{n} \quad (1)$$

Statistical analysis

Statistical analysis was used to evaluate Pb heavy metal concentration variation between Gunung Anyar and Wonorejo mangrove areas. In addition, the correlation between Pb content in sediments, roots, and leaves of mangrove plants and physicochemical parameters should be analyzed. This analysis determined the parameters associated with Pb content at each location. Statistical analysis using the 5% Analysis of Variance test, 5% Duncan test, and correlation using the Rstudio application (Grömping, 2015).

RESULTS AND DISCUSSION

Soil characteristics in Gunung Anyar and Wonorejo Mangrove

The accumulation of Pb concentration can be measured in sediments and plant parts, including roots and leaves. Soil properties include physical (clay fraction), chemical (pH H_2O, EC), and biological. This discussion focuses on a comparative analysis of substrate physicochemical properties and heavy metal (Pb) concentration in sediment and plants (Table 1) and related parameters in different mangrove species of *Avicennia marina, Rhizophora mucronata,* and *Bruguiera gymnorrhiza* from these two areas.

The binding of heavy metals in soil fractions is significantly influenced by the physical and chemical characteristics of the soil, particularly the clay fraction, which exhibits a greater capacity for heavy metal adsorption than dust and sand fractions. This is primarily attributed to clay minerals' high specific surface area and cation exchange capacity. Research indicates that clay has a unique ability to interact with heavy metal ions through multiple complex mechanisms, including ion exchange and surface adsorption. Colloidal minerals with a negative charge are particularly effective in adsorbing cations, including heavy metals such as Pb and Cd (Tako et al., 2024). The interaction mechanisms involve both ion exchange processes and surface complexation. This proclivity for adsorption explains that the mobility and speciation of heavy metals in soils are largely governed by these adsorption characteristics influenced by soil texture (Gao & Li, 2022). Heavy metals were predominantly found in fine soil particles, aligning with the general trend of heavier metals being retained more effectively in smaller, clay-sized soil fractions (J. Zhang et al., 2021).

pH is an important factor affecting the solubility and availability of heavy metals in mangrove soils. High soil acidity in mangrove areas can increase the solubility and availability of heavy metals, leading to increased Pb uptake by mangrove species (del Refugio Cabañas-Mendoza et al., 2020). Meanwhile, a slightly alkaline pH can reduce Pb uptake by mangrove plants ((Harifia et al., 2022). This suggests an inverse relationship between soil pH and Pb availability, emphasizing the importance of maintaining optimal pH levels to reduce Pb accumulation. Electrical conductivity indicates the salinity level of soil particles (Banón et al., 2021). Soils with high salinity Pb to high levels of mobility and availability of heavy metals in soil particles (Suska-Malawska et al., 2022). Anthropogenic factors, including industrial pollution, can modify the physicochemical characteristics of mangrove sediments, thus

Table 1. Pb content (ppm) and physical-chemical properties of soil in mangrove areas

Treatment	Pb content (ppm)			pH H_2O	EC (µS/cm)	SOM (%)	Clay (%)
	Soil	Leaves	Root				
P1T1	11.51 ± 0.72	1.76 ± 0.28	0.66 ± 0.28	7.52 ± 0.23	6.54 ± 0.11	2.70 ± 0.10	24.40 ± 1.85
P1T2	2.68 ± 0.33	1.42 ± 0.34	0.48 ± 0.09	8.34 ± 0.28	13.85 ± 0.88	2.48 ± 0.10	17.40 ± 1.02
P1T3	14.22 ± 0.19	2.21 ± 0.33	1.57 ± 0.07	7.45 ± 0.22	8.23 ± 0. 08	2.06 ± 0.04	25.80 ± 1.72
P2T1	5.18 ± 0.25	0.98 ± 0.13	0.51 ± 0.13	7.66 ± 0.18	12.34 ± 0.68	4.58 ± 0.06	30.40 ± 2.06
P2T2	4.38 ± 0.29	0.56 ± 0.11	0.54 ± 0.08	7.35 ± 0.14	15.30 ± 0.43	3.20 ± 0.03	14.20 ± 1.47
P2T3	4.04 ± 0.14	0.94 ± 0.09	2.49 ± 0.22	7.51 ± 0.15	11.17 ± 0.10	5.42 ± 0.06	23.80 ± 1.94

affecting pH and EC (X. Zhou et al., 2022). SOM can affect heavy metals' retention and binding capacity in the sediment matrix, thus affecting the overall concentration of metals found in mangrove environments (Wu et al., 2022).

Spatial variability in Pb concentrations across mangrove ecosystems can also be attributed to physical and chemical gradients along estuarine and coastal environments. Pb concentrations increased as the study site moved further away from the estuary due to differences in hydrodynamics and sediment deposition (Luthansa et al., 2021). Mangrove sediments and associated vegetation in areas influenced by industrial and urban discharges show different contamination patterns (Chanda et al., 2021). The significant inter-site variation in accumulated heavy metal concentrations of Pb is related to changes in antioxidant enzyme activity and overall mangrove health in the Central Red Sea mangrove ecosystem (Alhassan & Aljahdali, 2021).

In addition to sediment characteristics, variations in Pb uptake and accumulation in different parts of the mangrove plant (roots, stems, and leaves) show different accumulation patterns. Several studies have shown that different parts of the mangrove plant (roots, stems, and leaves) exhibit different accumulation patterns. While roots often act as the main reservoir for Pb, leaves and stems also accumulate measurable concentrations (Maharani et al., 2019; Rumanta, 2019). This differential distribution, influenced by physiological adaptations and translocation mechanisms of Pb within the plant, tends to be higher in *Avicennia marina* roots than in other heavy metals such as cadmium (Cd) (Sari et al., 2023). Such variation underscores the importance of understanding intra-plant metal partitioning to assess ecological risk.

Pb distribution in mangrove ecosystems is not uniform across spatial gradients or among different vegetative components. Variations in Pb concentrations among different sites can be attributed to several factors, including proximity to pollution sources, sediment properties, and the inherent physiological ability of mangrove species to absorb, translocate, and sequester heavy metals. Increased Pollution Load Index (PLI) values in the State of Egypt at various sites such as tourist villages and the seaport, the dunes, mangrove swamp, healthy mangrove area of *Avicennia marina*, and human activities, had the highest concentrations of heavy metal concentrations in the areas of tourist villages and the seaport and human activities, suggesting that local sediment characteristics and contamination by anthropogenic activities play an important role in determining Pb levels (Alharbi et al., 2023). In addition, Pb concentrations in mangrove areas with more mangrove populations in the Andaman mangrove forests of Chidayatapu and Kalapathar dominated by *Rhizophora* species and Burmanala dominated by *Bruguiera* species were significantly lower compared to other areas with lower mangrove vegetation populations and also without mangroves. This suggests that local environmental conditions and urban discharge patterns may cause substantial differences in Pb concentrations across sites (Mishra & Manish, 2018).

The data presented reflects soil characteristics and the ability of mangrove plants to accumulate heavy metal Pb based on six treatments (P1T1 to P2T3). The highest Pb content in soil was found in treatment P1T3 at 14.22 ppm, followed by P1T1 (11.51 ppm). However, in leaves and roots, Pb values tended to be lower than in soil, indicating that the heavy metal accumulation process in plant tissues has a certain limit, although the P1T3 treatment also showed the highest Pb in roots (1.57 ppm) and leaves (2.21 ppm). This shows the ability of mangroves to absorb heavy metals under certain conditions, especially in areas with high concentration (Hossain et al., 2022; J. Wang et al., 2021).

The actual pH parameter significantly affected Pb bioavailability in the soil. In treatment, P1T2, the highest pH (8.34) indicates that alkaline soil conditions can affect Pb availability to plants, with relatively lower Pb content in leaves and roots. In contrast, treatments with near neutral pH such as P1T1 and P2T3 tended to show higher Pb accumulation in plant tissues. The heavy metals tend to be more bound to soil particles under alkaline conditions, making them less available for uptake by roots (Feng et al., 2021; Naz et al., 2022a).

Treatment P1T2 had the highest EC (13.85 mS/cm) reflecting the high concentration of ions in the soil but was not necessarily followed by increased Pb content in plant tissues (Dittmann et al., 2022; Othaman et al., 2020). In contrast, lower EC values such as in P1T1 (6.54 mS/cm) and P1T3 (8.23 mS/cm) showed higher Pb accumulation in leaves and roots (Chai, Li, Ding, et al., 2019; Chandrasekhar & Ray, 2019). This suggests that in addition to EC, other factors such as soil substrate and organic matter content also play an important role in the heavy metal uptake process (Huang et al., 2020). Soil organic matter composition and clay content also influence the Pb retention process in the soil (Borggaard et al., 2019; Y. Li et al., 2024). The P2T3 treatment has the highest SOM (5.42%), which supports the retention of Pb in the soil through the chelation mechanism, while the highest clay content in P2T1 (30.40%) strengthens the soil's capacity to absorb heavy metals.

Organic matter can improve soil structure and enhance the soil's capacity to retain heavy metals like Pb (Hamid et al., 2020). The chelation process involves the formation of stable complexes between organic compounds and Pb ions adsorption, which reduces the mobility and bioavailability of Pb in the soil (Elnajdi et al., 2023; Jimenez et al., 2021). Increased organic matter content correlates with higher retention capacities for heavy metals, including Pb, due to the adsorption properties of organic compounds (Stefanowicz et al., 2020). Organic matter derived from mangrove vegetation, such as *Bruguiera gymnorhiza*, is particularly effective in binding Pb. The organic acids and phenolic compounds secreted by the roots of mangroves can form chelates with Pb, thereby immobilizing them in the soil matrix (Osland et al., 2020). This combination of soil properties suggests that soil with high organic matter content and sufficient clay fraction can be an effective medium to reduce heavy metal pollution, with mangroves serving as efficient bioremediation agents.

Spatial distribution of Pb in Gunungayar and Wonorejo Mangrove

The spatial distribution of Pb content in Gunungayar and Wonorejo areas is divided into three categories: Pb content (ppm) in soil, leaves, and roots of mangrove plants (Figure 2). Each concentration level is shown with a color scale indicating the level ranging from very low to very high. This map provides a detailed picture of the spatial variation of Pb concentration in different areas, which can be utilized for environmental analysis or soil and vegetation management planning.

The distribution of Pb content in soil shows that areas with very high concentrations (>12.15 ppm) are in the Gunung Anyar area. In contrast, the Wonorejo area has low to moderate Pb content. This suggests that anthropogenic activities or major sources of pollution are highest in the Gunung Anyar area. Based on Figure 1, the distance between the mangrove area (P1T3) and the built-up area is relatively nearby (<200 m). In Gunung Anyar mangrove areas the nearest to anthropogenic activities with *Bruguiera gymnorrhiza* can accumulate higher Pb. In addition, the Gunung Anyar Mangrove Area is found to have

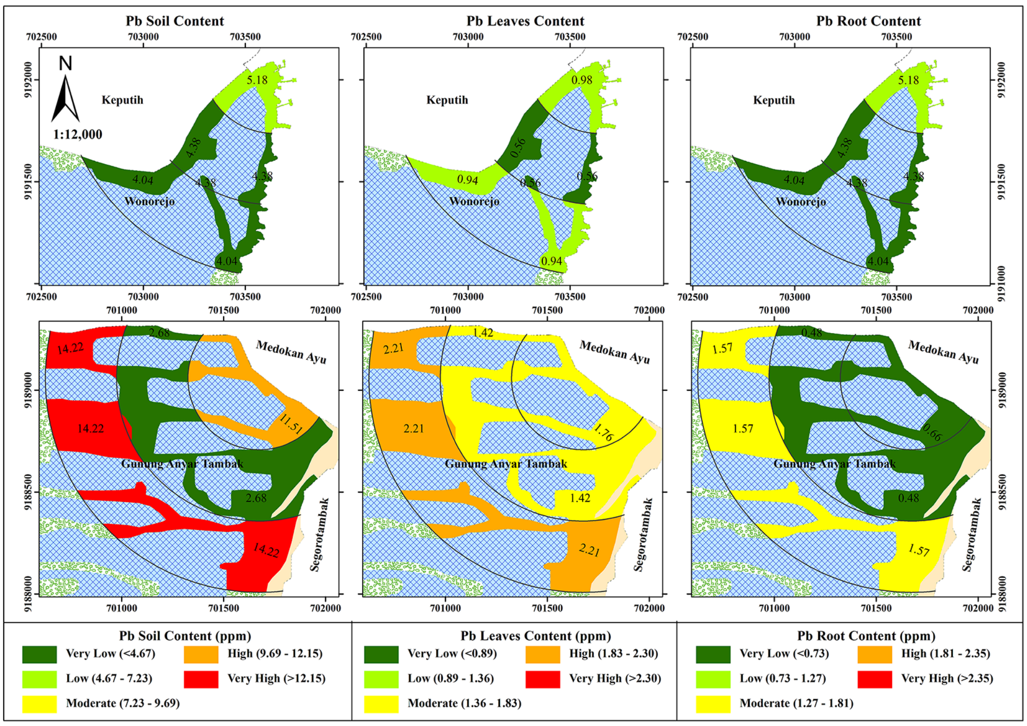

Figure 2. Spatial distribution of Pb in Gunung Anyar and Wonorejo Mangrove

many transportation activities using ships, thus triggering higher Pb accumulation. Whereas in Wonorejo Mangrove Area, the geospatial shape of the area is elongated and the distance between mangrove areas (P2T3) is quite far, so the accumulation of Pb from anthropogenic factors is lower. This distribution pattern shows different Pb content based on pollution sources from industrial activities, activities from settlements, and transportation from ships that contribute to increasing Pb levels in the soil. This distribution is important to note because soil is the main medium that can potentially transmit pollutants to plants (S. Liu et al., 2020; Zwolak et al., 2019). Variations in Pb accumulation concentrations in soil can also be influenced by the physicochemical properties of soil (C. Li et al., 2019; Pan et al., 2020). Accumulation in mangrove soils is the structure and composition of microbial communities. Microbial diversity in mangrove soils is shaped by biogeographical, anthropological, and ecological factors, including nutrient cycling and organic or inorganic compounds. These microbial communities can influence the bioavailability of Pb through various biochemical processes, such as the transformation of organic matter and the degradation of pollutants (M. Liu et al., 2019; Tong et al., 2019).

Pb concentrations in mangrove sediments, roots, and leaves show significant variations due to complex interactions between plant physiology, sediment characteristics, and environmental conditions. Studies have shown that sediments usually exhibit higher Pb concentrations than mangrove plants' above-ground parts, especially roots and leaves. Studies have shown that Pb concentrations in sediments are generally greater than those found in roots and leaves of mangrove species. Pb and Cd levels in sediments of Tulehu mangrove exceeded those in leaves and stems, confirming that sediments can accumulate heavy metals more effectively than plant tissues (Natsir et al., 2019). Sediments consistently showed higher levels of metals, including Pb, than mangrove leaves, although they noted variations influenced by local conditions in Central Red Sea Mangrove, Egypt (Alhassan & Aljahdali, 2021). Heavy metal accumulation tends to be higher in roots than in sediments over long periods because roots can immobilize heavy metals (Titah & Pratikno, 2020). Roots often harbor higher concentrations of Pb, and the ability to move this metal to aerial parts such as leaves is limited. Mangrove species such as *Avicennia germinans* and *Laguncularia racemosa* in Ria Calestun Biosphere Reserve, Mexico can accumulate Pb in roots and translocate minimal amounts to leaves by phyto-stabilization strategies (del Refugio Cabañas-Mendoza et al., 2020). This leads to a phenomenon where Pb concentrations at Pekalongan mangrove area in roots often significantly exceed those in leaves; as noted in various studies, some species were recorded to accumulate Pb levels as high as 3.658 mg/kg in roots, in stark contrast to much lower concentrations in leaves (Soenardjo & Mentari, 2023). Anthropogenic activities, such as industrial discharge and agricultural runoff, contribute to Pb concentration in mangrove ecosystems. The introduction of pollutants through these activities can Pb to elevated Pb levels in the soil, which may adversely affect the health of mangrove vegetation and associated wildlife (Lin et al., 2020). The higher anthropogenic influence exhibits increased Pb concentrations, which can be detrimental to both soil health and the overall ecosystem (J. Li et al., 2017; Shih et al., 2019). Furthermore, the spatial variation of Pb concentration within mangrove areas can be attributed to factors such as hydrology, sediment characteristics, and vegetation types (Chai, Li, Tam, et al., 2019; Shi et al., 2019). Pb accumulation tends to be higher in areas with poor drainage or where sedimentation rates are low, as these conditions can Pb to greater retention of contaminants (Al-Akeel et al. 2021). Additionally, the types of vegetation present can influence Pb dynamics, as different mangrove species have varying capacities for Pb uptake and retention (Ghanbari et al., 2019).

The distribution of Pb in mangrove leaves is influenced by a variety of biotic and abiotic factors, including the species of mangrove, environmental conditions, and the specific mechanisms of metal uptake and translocation within the plant (Kulkarni et al., 2018; Maurya & Kumari, 2021). Research indicates that different mangrove species exhibit varying capacities for Pb accumulation, which can be attributed to their physiological and morphological traits. One significant factor affecting Pb distribution in mangrove leaves is the species-specific ability to accumulate heavy metals (Victório et al., 2024; Y.-Y. Zhou et al., 2021).

Very high levels of Pb in leaves (>2.30 ppm) only occurred in Gunung Anyar while concentrations in Wonorejo were lower. This variation indicates that Pb uptake by plants is more dependent on local environmental factors or the specific adaptability of mangrove plants in the region. It may also reflect bioaccumulation effects and interactions between soil and vegetation types (de Lacerda et al., 2022; Thanh-Nho et al., 2019). *Avicennia marina* plants can absorb Pb higher than others. *Avicennia* sp. and *Rhizophora* sp. are particularly effective at accumulating Pb in their leaves, with *Rhizophora* sp. demonstrating higher average Pb concentrations compared to other species (Dajam et al., 2024; Lang et al., 2023; Yap & Al-Mutairi, 2023).

Species-specific accumulation is often linked to the structural characteristics of the roots, which act as barriers to limit the translocation of Pb to above-ground parts (Asare et al., 2023; Vignesh et al., 2024). Additionally, the bioconcentration factor (BCF) and translocation factor (TF) values vary among species, indicating that some mangroves are more efficient at moving Pb from roots to leaves (Basri et al., 2024; S. U. Rahman et al., 2024; J. Wang et al., 2021).

The highest concentration of Pb in roots was found in Gunung Anyar. The Wonorejo area has low to moderate root Pb content. However, roots tend to show higher levels of Pb accumulation than leaves mangrove, reflecting the role of roots as the first organ in direct contact with pollutants in the soil (Alharbi et al., 2023). Elevated levels of Pb in the roots of *Avicennia marina* compared to its leaves indicate the critical role of mangrove roots in heavy metal accumulation (Hossain et al., 2022). This highlights the importance of root uptake mechanisms in controlling Pb distribution in plants and its impact on the food chain (Feng et al., 2021; Gupta et al., 2024). As the first organ in direct contact with soil pollutants, mangrove roots act as a barrier, limiting the translocation of heavy metals to the aerial parts of the plant (Feng et al., 2021; Kumar et al., 2020).

This function helps reduce heavy metal toxicity in sensitive tissues, enhancing the plant's overall survival in contaminated environments. Additionally, environmental factors such as salinity and sediment composition influence Pb uptake. High salinity (Table 1) conditions often promote increased root biomass allocation, which enhances the plant's ability to absorb and store heavy metals like Pb (Sinsin et al., 2022). Sediment characteristics, including texture and organic matter content, also affect the bioavailability of Pb, altering its uptake efficiency by mangrove roots (Pittarello et al., 2019; Ray et al., 2021). These interactions suggest that mangrove species have developed specialized mechanisms to optimize Pb absorption under different environmental conditions, reinforcing their role in mitigating heavy metal concentration in coastal ecosystems.

Different characteristic Pb based on vegetation and location

There are significant differences in the concentration of Pb in the soil of various types of mangroves in two research locations, namely Gunung Anyar (P1) and Wonorejo (P2). In Gunung Anyar, the treatment involving *Rhizophora mucronata* (P1T2) showed the highest Pb concentration, reaching 14.22 ppm, while *Avicennia marina* (P1T1) at the same location had a Pb concentration of 11.51 ppm. The high concentration of Pb in Gunung Anyar, especially in *Rhizophora mucronata* plants, can be associated with several environmental factors that increase the bioavailability of heavy metals in the soil, such as soil pH and electrical conductivity (EC). These factors directly affect the mobility and solubility of Pb in the soil, making it more accessible to plant roots and thus increasing its absorption by mangrove species (Analuddin et al., 2017; Robin et al., 2022).

In particular, soil pH can affect Pb ionization and its interaction with other elements, while EC can increase the movement of Pb ions in the soil, thus facilitating its uptake by plant roots (Figure 3). These results suggest that certain environmental conditions, such as pH and EC, may contribute to higher Pb bioaccumulation in *Rhizophora mucronata* in Gunung Anyar, compared to other mangrove species. On the other hand, the Wonorejo location showed lower Pb concentrations in all treatments, with the highest Pb concentration found in *Avicennia marina* (P2T1) at 5.18 ppm. Followed by *Bruguiera gymnorrhiza* (P2T3) at 4.38 ppm and *Rhizophora mucronata* (P2T2) at 4.04 ppm. The relatively lower Pb concentration in Wonorejo may be associated with the higher organic matter content in the soil at this location, which plays an important role in reducing the bioavailability and mobility of heavy metals. Organic matter in the soil can act as a natural barrier to metal uptake by plants by adsorbing and complexing them with metal ions, thereby reducing their mobility and making them less available for plant uptake (Uchimiya et al., 2020; Thakur et al., 2022). Research conducted by (Gerke, 2018; Azhar et al., 2022) has shown that the presence of organic compounds in the soil, such as humic substances, can form stable complexes with

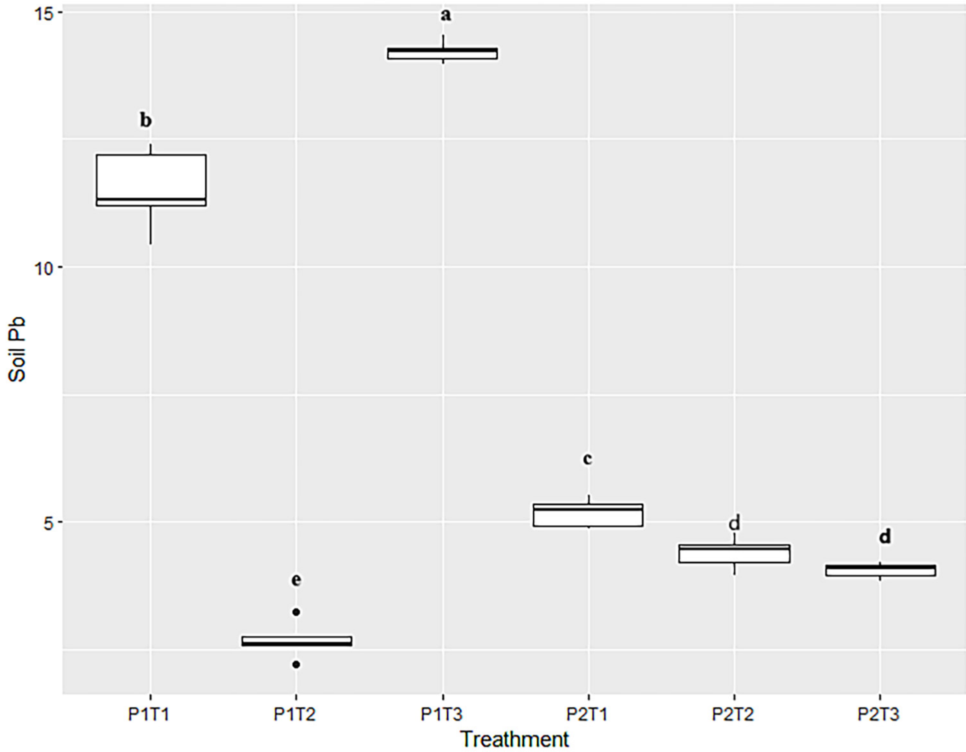

Figure 3. Differences in soil Pb content across different mangrove vegetation and sites

heavy metals, preventing them from dissolving into the soil solution and reaching plant roots. In addition, high organic content can improve soil structure, increase root growth, and facilitate the formation of mangrove vegetation which can further reduce the impact of metal concentration on plant health. This suggests that the presence of organic matter in the soil in Wonorejo may be one of the main factors contributing to the lower Pb concentrations observed in mangrove plants at this location. The lower Pb concentration results in Wonorejo may also reflect differences in hydrodynamic conditions between the two locations. Gunung Anyar is located in an area that may be more affected by anthropogenic activities, such as industrial waste discharge or runoff from urban areas that may Pb to higher concentrations of heavy metals in the soil. In contrast, Wonorejo may experience less direct exposure to these pollutants due to its location or the types of activities occurring in the surrounding area. These variations in concentration sources may also play an important role in determining the extent of Pb accumulation in the soil at both sites.

The differences in Pb concentrations between the two sites highlight the complex interactions of environmental factors that influence the bioaccumulation of heavy metals in mangrove ecosystems (Xie et al., 2022). The bioaccumulation potential of various mangrove species, particularly *Rhizophora mucronata* and *Avicennia marina*, appears to be strongly influenced by soil characteristics and the species' ability to tolerate and accumulate metals. In Gunung Anyar, *Rhizophora mucronata* tends to accumulate more Pb, possibly due to its ability to tolerate more extreme soil conditions or the greater efficiency of its root system in absorbing available nutrients and contaminants. On the other hand, *Avicennia marina* at both locations showed relatively lower Pb bioaccumulation, which may be due to differences in plant physiological responses to heavy metal stress, such as their ability to sequester metals in their tissues or compartmentalize them in vacuoles to prevent toxic effects. In addition to soil properties and species characteristics, other factors such as moisture level, soil texture, and redox conditions may also play an important role in determining Pb accumulation in mangrove soils (Hu et al., 2021). Redox conditions which are influenced by groundwater levels and tidal cycles, may affect the species, providing insights into how mangrove ecosystems can be managed and restored in the face of environmental pollution.

Relationship of Pb on sediment, leaves, and roots to physio-chemical subtrat

The results of this study reveal a significant relationship between Pb concentrations in soil, roots, and leaves and various environmental factors, including soil pH and electrical conductivity (EC). A perfect negative correlation (-1.0) was observed between EC and Pb concentration in the soil, indicating that an increase in electrical conductivity is inversely related to the concentration of Pb (Figure 4). This phenomenon can be explained through the ionic mobilization mechanism, where higher EC facilitates the movement of metal ions, such as Pb, within the soil. Increased conductivity enhances the solubility of these ions, making them more easily transported by water, which, in turn, reduces their concentration in the soil. This process accelerates the leaching of Pb ions from the soil, decreasing their retention and potentially lowering the risk of bioaccumulation in plant tissues (Kumar et al., 2020; Collin et al., 2022). Thus, the presence of higher EC can enhance the mobility of Pb in the soil, which subsequently affects its availability to plants. Additionally, a strong negative correlation (-0.7) was found between the soil organic matter (SOM) content and EC, supporting previous studies that emphasized the role of organic matter in immobilizing heavy metals through chemical interactions. Soil organic matter can absorb and bind metal ions, including Pb, thereby reducing their mobility within the soil. As such, the presence of organic matter acts as a natural barrier to the movement of heavy metals, preventing their further spread into the surrounding environment. Consequently, the organic fraction of the soil plays an important role in reducing the bioavailability of toxic metals, limiting their entry into plant roots, and minimizing potential groundwater concentration (Hou et al., 2020; Padhye et al., 2023).

The results of this study demonstrate that an increase in organic matter content in soil can reduce the mobility of heavy metals and enhance the soil's capacity to act as an absorber of these contaminants. Furthermore, this study revealed a strong positive correlation (0.9) between the concentration of Pb in the soil (Soil_Pb) and the concentration of Pb in the leaves (Leaves_Pb), indicating that higher Pb concentrations in the soil significantly influence the accumulation of Pb in plant tissues, particularly in the leaves. This result is consistent with the findings of (Gupta et al., 2024)

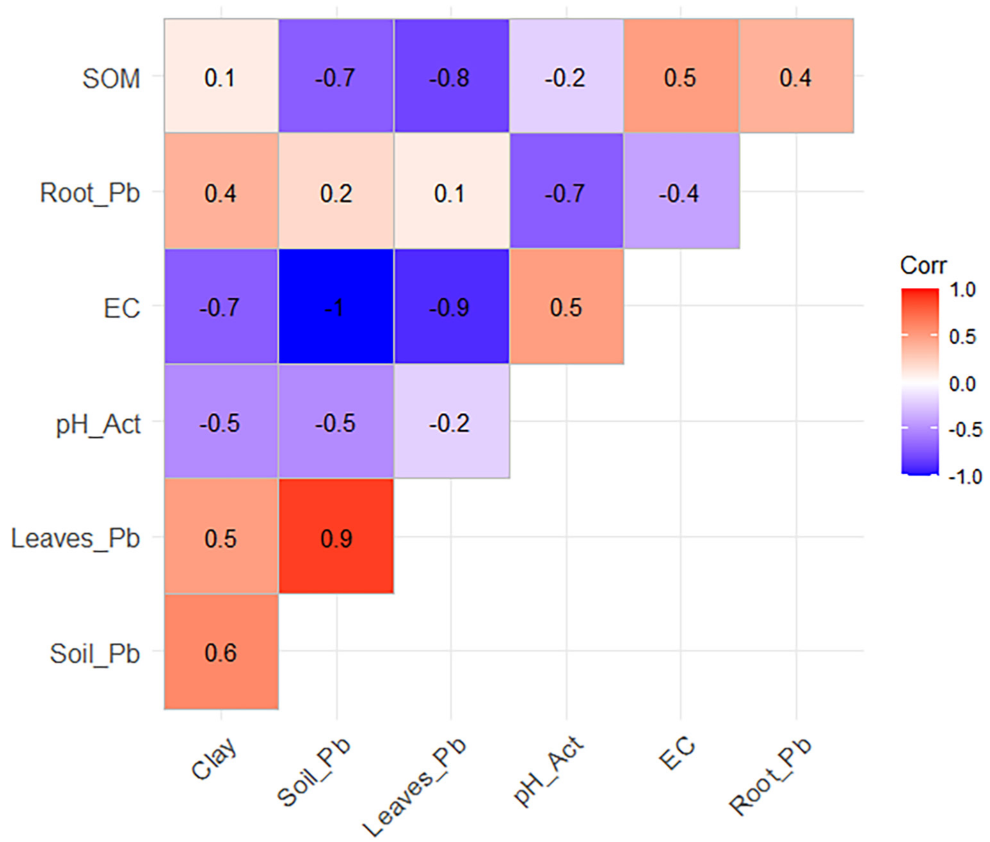

Figure 4. Correlation of Pb on sediment, leaves, and roots to physio-chemical subtrat

stated that soil Pb levels are a key determinant of Pb bioaccumulation in plants. As the concentration of Pb in the soil increases, the likelihood of Pb being absorbed by plant roots and subsequently transported to the leaves also rises. The relationship between soil Pb levels and Pb concentrations in plant tissues is direct, underscoring the critical role of soil concentration in determining the extent of heavy metal accumulation in plants.

The relationship between soil organic matter and electrical conductivity significantly influences the availability and accumulation of Pb in mangrove plant leaves. SOM is an important matrix in mangrove ecosystems that can adsorb, complex and immobilize Pb through its various organic compounds. This interaction reduces the fraction of Pb available in the sediment, thus limiting its uptake by mangrove roots and eventual translocation to leaves (Romero-Mujalli & Melendez, 2023). The interaction between SOM and EC becomes increasingly important when considering the phytoremediation potential of mangrove species. High EC conditions can increase or decrease the capacity of SOM to sequester Pb, thereby altering the bioconcentration factor (BCF) and translocation factor (TF) observed in mangrove leaf tissues (Sait et al., 2023).

Furthermore, a moderately strong negative correlation (-0.70) was found between Pb concentrations in roots and soil pH. This suggests that Pb solubility decreases in soils with higher pH (more alkaline), reducing its bioavailability to plant roots. Pb tends to precipitate at higher pH levels into less soluble forms, making it less available for plant absorption. Soil pH directly affects the chemical form of heavy metals, which influences the rate and extent of metal absorption by plants (Laghlimi et al., 2015; Yu et al., 2023). In more alkaline soils, Pb may exist in forms such as Pb hydroxide or Pb carbonate, which are less mobile and more difficult for plants to absorb. This relationship underscores the importance of managing soil pH to control the availability of toxic metals in contaminated soils, particularly in ecosystems where heavy metal concentration poses risks to plant health and productivity. The study by (Kicińska et al. 2022) indicates that the effect of soil pH on metal solubility shows that acidification can increase the solubility of heavy metals, thereby enhancing their availability to plants. Conversely, managing pH levels toward neutral or slightly alkaline conditions can reduce the solubility of metals like Pb, thus decreasing their absorption by plants. This highlights the importance of pH management in mitigating the risks associated with heavy metal concentration, particularly in agricultural soils where Pb concentration can impact crop yield and food safety.

Moreover, the significant relationship between Pb concentrations in the soil, roots, and leaves also emphasizes the importance of soil management practices in controlling the bioavailability and bioaccumulation of heavy metals. One of the most effective strategies for reducing heavy metal concentration in soils is the management of soil organic matter and pH. Since organic matter can significantly influence the mobility of heavy metals, adding organic amendments such as compost, biochar, or other organic materials can help reduce the mobility of Pb in the soil. Organic matter functions as a sorbent, binding Pb and preventing its leaching into groundwater or uptake by plant roots (Dhiman et al., 2020). Soil amendments designed to alter soil pH, such as applying lime to increase pH in acidic soils, can also play a crucial role in reducing the bioavailability of heavy metals like Pb. By adjusting soil pH to more neutral or alkaline conditions, Pb solubility can be reduced, limiting its absorption by plants and minimizing its potential harmful effects on plant health and growth (Kushwaha et al., 2018; Naz et al., 2022b). This approach has the potential to be an important component of remediation strategies in areas frequently contaminated with heavy metals, particularly in agricultural land and mangroves exposed to Pb concentration.

CONCLUSIONS

The highest Pb content (plants and sediments) was found in Gunung Anyar, which was influenced by anthropogenic factors and the distance of the built-up area. On the other hand, the absorption of Pb metals in *Avicennia marina, Rhizophora mucronata, and Bruguiera gymnorrhiz*a plants showed varying capacities. The results of *Avicennia marina* plants show the highest accumulation in their root systems. One of the advantages of this research is its contribution to understanding the role of mangroves as natural bioremediation agents in coastal environments. The spatial distribution of Pb offers a practical basis for environmental monitoring and pollution control policies.

Acknowledgement

This research was funded by the Internal Research Grant of UPN "Veteran" Jawa Timur through the research contract SPP/102/UN.63.8/LT/V2024. We extend our gratitude to the Research and Community Service Institution (LPPM) of UPN "Veteran" Jawa Timur for the financial support that made this study possible.

REFERENCES

1. Acharya, S., Pradhan, M., Mahalik, G., Babu, R., Parida, S., Mohapatra, P. K. (2023). Abiotic stress tolerance in mangroves with a special reference to salinity. *Plant Sci. Today*, *10*(2), 58–68.
2. Afzal, M. R., Naz, M., Wan, J., Dai, Z., Ullah, R., Rehman, S. U. R., Du, D. (2023). Insights into the mechanisms involved in lead (Pb) tolerance in invasive plants—The current status of understanding. *Plants*, *12*(11), 2084. https://doi.org/10.3390/plants12112084
3. Al-Akeel, K. A., Al-Fredan, M. A., Desoky, E.-S. M. (2021). Impact of wastewater discharge on the plant diversity, community structure and heavy metal pollution of range plants in eastern Saudi Arabia. *Saudi Journal of Biological Sciences*, *28*(12), 7367–7372. https://doi.org/10.1016/j.sjbs.2021.08.059
4. Alharbi, B. M., Abdulmajeed, A. M., Jabbour, A. A., Hashim, A. M. (2023). Eco-Physiological Responses of Avicennia marina (Forssk.) Vierh. To trace metals pollution via intensifying antioxidant and secondary metabolite contents. *Metabolites*, *13*(7), 808. https://doi.org/10.3390/metabo13070808
5. Alhassan, A. B., Aljahdali, M. O. (2021). Sediment metal contamination, bioavailability, and oxidative stress response in mangrove Avicennia marina in central Red Sea. *Frontiers in Environmental Science*, *9*, 691257. https://doi.org/10.3389/fenvs.2021.691257
6. Aljahdali, M. O., Alhassan, A. B. (2020). Ecological risk assessment of heavy metal contamination in mangrove habitats, using biochemical markers and pollution indices: A case study of Avicennia marina L. in the Rabigh lagoon, Red Sea. *Saudi Journal of Biological Sciences*, *27*(4), 1174–1184. https://doi.org/10.1016/j.sjbs.2020.02.004
7. Analuddin, K., Sharma, S., Septiana, A., Sahidin, I., Rianse, U., Nadaoka, K. (2017). Heavy metal bioaccumulation in mangrove ecosystem at the coral triangle ecoregion, Southeast Sulawesi, Indonesia. *Marine Pollution Bulletin*, *125*(1–2), 472–480.
8. Anu, K., Sneha, V., Busheera, P., Muhammed, J., Augustine, A. (2024). Mangroves in environmental engineering: Harnessing the multifunctional potential of Nature's coastal architects for sustainable ecosystem management. *Results in Engineering*, 101765. https://doi.org/10.1016/j.rineng.2024.101765
9. Araújo, P. R. M., Biondi, C. M., do Nascimento, C. W. A., da Silva, F. B. V., Ferreira, T. O., & de Alcântara, S. F. (2022). Geospatial modeling and ecological and human health risk assessments of heavy metals in contaminated mangrove soils. *Marine Pollution Bulletin*, *177*, 113489. https://doi.org/10.1016/j.marpolbul.2022.113489
10. Asare, M. O., Száková, J., & Tlustoš, P. (2023). Mechanisms of As, Cd, Pb, and Zn hyperaccumulation by plants and their effects on soil microbiome in the rhizosphere. *Frontiers in Environmental Science*, *11*, 1157415. https://doi.org/10.3389/fenvs.2023.1157415
11. Azhar, U., Ahmad, H., Shafqat, H., Babar, M., Munir, H. M. S., Sagir, M., Arif, M., Hassan, A., Rachmadona, N., Rajendran, S. (2022). Remediation techniques for elimination of heavy metal pollutants from soil: A review. *Environmental Research*, *214*, 113918.
12. Banón, S., Álvarez Martín, S., Bañón, D., Ortuño Gallud, M. F., Sánchez-Blanco, M. J. (2021). *Assessment of soil salinity indexes using electrical conductivity sensors*. https://digital.csic.es/handle/10261/258493
13. Basri, A., Aras, S., Samawi, M. F. (2024). Bioconcentration and translocation of heavy metals in Mangrove Avicennia sp. And Rhizophora sp. in diesel powel plant. *Ecological Engineering & Environmental Technology*, *25*(9). https://doi.org/10.12912/27197050/190754
14. Borggaard, O. K., Holm, P. E., Strobel, B. W. (2019). Potential of dissolved organic matter (DOM) to extract As, Cd, Co, Cr, Cu, Ni, Pb and Zn from polluted soils: A review. *Geoderma*, *343*, 235–246. https://doi.org/10.1016/j.geoderma.2019.02.041
15. Brumberg, H., Beirne, C., Broadbent, E. N., Zambrano, A. M. A., Zambrano, S. L. A., Gil, C. A. Q., Gutierrez, B. L., Eplee, R., Whitworth, A. (2021). Riparian buffer length is more influential than width on river water quality: A case study in southern Costa Rica. *Journal of Environmental Management*, *286*, 112132. https://doi.org/10.1016/j.jenvman.2021.112132
16. Cabañas–Mendoza, M. del R., Andrade, J. L., Sauri-Duch, E., Hernández-Terrones, L., Fuentes, G., & Santamaría, J. M. (2023). Lead tolerance of Laguncularia racemosa is associated to high proline accumulation and high antioxidant capacities. *Biometals*, *36*(4), 887–902. https://doi.org/10.1007/s10534-023-00488-8
17. Chai, M., Li, R., Ding, H., Zan, Q. (2019a). Occurrence and contamination of heavy metals in urban

mangroves: A case study in Shenzhen, China. *Chemosphere*, *219*, 165–173. https://doi.org/10.1016/j.chemosphere.2018.11.160

18. Chai, M., Li, R., Tam, N. F. Y., Zan, Q. (2019b). Effects of mangrove plant species on accumulation of heavy metals in sediment in a heavily polluted mangrove swamp in Pearl River Estuary, China. *Environmental Geochemistry and Health*, *41*, 175–189. https://doi.org/10.1007/s10653-018-0107-y
19. Chanda, A., Akhand, A. (2023). Challenges towards the Sustainability and Enhancement of the Indian Sundarban Mangrove's Blue Carbon Stock. *Life*, *13*(8), 1787. https://doi.org/10.3390/life13081787
20. Chanda, A., Swain, S., Das, S., Seal, A., Ghosh, T., Hazra, S. (2021). Spatial variation of heavy metal accumulation in the sediments adjacent to different mangrove plant species within a mixed mangrove stand. *Soil and Sediment Contamination: An International Journal*, *30*(5), 548–568. https://doi.org/10.1080/15320383.2020.1867505
21. Chandrasekhar, C., Ray, J. G. (2019). Lead accumulation, growth responses and biochemical changes of three plant species exposed to soil amended with different concentrations of lead nitrate. *Ecotoxicology and Environmental Safety*, *171*, 26–36. https://doi.org/10.1016/j.ecoenv.2018.12.058
22. Chowdhury, A., Maiti, S. K. (2016). Assessing the ecological health risk in a conserved mangrove ecosystem due to heavy metal pollution: A case study from Sundarbans Biosphere Reserve, India. *Human and Ecological Risk Assessment: An International Journal*, *22*(7), 1519–1541. https://doi.org/10.1016/j.sjbs.2020.02.004
23. Collin, S., Baskar, A., Geevarghese, D. M., Ali, M. N. V. S., Bahubali, P., Choudhary, R., Lvov, V., Tovar, G. I., Senatov, F., Koppala, S. (2022). Bioaccumulation of lead (Pb) and its effects in plants: A review. *Journal of Hazardous Materials Letters*, *3*, 100064.
24. Dajam, A. S., Keshta, A. E., Bindajam, A. A., Eid, E. M. (2024). Bioaccumulation of Heavy metals in mangrove (Avicennia marina): Predictive uptake modeling and phytoremediation potential. *Journal of Soil Science and Plant Nutrition*, *24*(3), 6085–6098. https://doi.org/10.1007/s42729-024-01962-z
25. Dan, S. F., Udoh, E. C., & Wang, Q. (2022). Contamination and ecological risk assessment of heavy metals, and relationship with organic matter sources in surface sediments of the Cross River Estuary and nearshore areas. *Journal of Hazardous Materials*, *438*, 129531. https://doi.org/10.1016/j.jhazmat.2022.129531
26. de Lacerda, L. D., Ward, R. D., Borges, R., Ferreira, A. C. (2022). Mangrove trace metal biogeochemistry response to global climate change. *Frontiers in Forests and Global Change*, *5*, 817992. https://doi.org/10.3389/ffgc.2022.817992
27. del Refugio Cabañas-Mendoza, M., Santamaría, J. M., Sauri-Duch, E., Escobedo-GraciaMedrano, R. M., Andrade, J. L. (2020). Salinity affects pH and lead availability in two mangrove plant species. *Environmental Research Communications*, *2*(6), 061004.
28. Dhiman, J., Prasher, S. O., ElSayed, E., Patel, R., Nzediegwu, C., Mawof, A. (2020). Use of polyacrylamide superabsorbent polymers and plantain peel biochar to reduce heavy metal mobility and uptake by wastewater-irrigated potato plants. *Transactions of the ASABE*, *63*(1), 11–28.
29. Dittmann, S., Mosley, L., Stangoulis, J., Nguyen, V. L., Beaumont, K., Dang, T., Guan, H., Gutierrez-Jurado, K., Lam-Gordillo, O., McGrath, A. (2022). Effects of extreme salinity stress on a temperate mangrove ecosystem. *Frontiers in Forests and Global Change*, *5*, 859283. https://doi.org/10.3389/ffgc.2022.859283
30. Dong, W. S., Ismailluddin, A., Yun, L. S., Ariffin, E. H., Saengsupavanich, C., Maulud, K. N. A., Ramli, M. Z., Miskon, M. F., Jeofry, M. H., Mohamed, J. (2024). The impact of climate change on coastal erosion in Southeast Asia and the compelling need to establish robust adaptation strategies. *Heliyon*. https://doi.org/10.1016/j.heliyon.2024.e25609
31. Elnajdi, A., Berland, A., Haeft, J., Dowling, C. (2023). Influence of soil pH, organic matter, and clay content on environmentally available Lead in soils: A case study in Muncie, Indiana, USA. *Open Journal of Soil Science*, *13*(10), 414–430. https://doi.org/10.4236/ojss.2023.1310019
32. Feng, R., Wang, L., Yang, J., Zhao, P., Zhu, Y., Li, Y., Yu, Y., Liu, H., Rensing, C., Wu, Z. (2021). Underlying mechanisms responsible for restriction of uptake and translocation of heavy metals (metalloids) by selenium via root application in plants. *Journal of Hazardous Materials*, *402*, 123570. https://doi.org/10.1016/j.jhazmat.2020.123570
33. Ferreira, S. L., Bezerra, M. A., Santos, A. S., dos Santos, W. N., Novaes, C. G., de Oliveira, O. M., Oliveira, M. L., Garcia, R. L. (2018). Atomic absorption spectrometry–A multi element technique. *TrAC Trends in Analytical Chemistry*, *100*, 1–6. https://doi.org/10.1016/j.trac.2017.12.012
34. Gao, Y., & Li, X. (2022). Effects of bentonite addition on the speciation and mobility of Cu and Ni in soils from old mine tailings. *Sustainability*, *14*(17), 10878. https://doi.org/10.3390/su141710878
35. Gerke, J. (2018). Concepts and misconceptions of humic substances as the stable part of soil organic matter: A review. *Agronomy*, *8*(5), 76.
36. Ghanbari, M., Jami, M., Moghadam, M. S., Domig, K. J. (2019). Exploring the microbial diversity in oil-contaminated mangrove sediments using 16S rRNA metagenomics. *bioRxiv*, 735290. https://doi.org/10.1101/735290

37. Grömping, U. (2015). Using R and RStudio for data management, statistical analysis and graphics. *Journal of Statistical Software*, *68*, 1–7. https://doi.org/10.1201/b18151

38. Guo, M., Han, C., Guan, Q., Huang, Y., Xie, Z. (2020). A universal parallel scheduling approach to polyline and polygon vector data buffer analysis on conventional GIS platforms. *Transactions in GIS*, *24*(6), 1630–1654. https://doi.org/10.1111/tgis.12670

39. Gupta, M., Dwivedi, V., Kumar, S., Patel, A., Niazi, P., Yadav, V. K. (2024). Lead toxicity in plants: Mechanistic insights into toxicity, physiological responses of plants and mitigation strategies. *Plant Signaling & Behavior*, *19*(1), 2365576.

40. Hamid, Y., Tang, L., Hussain, B., Usman, M., Lin, Q., Rashid, M. S., He, Z., Yang, X. (2020). Organic soil additives for the remediation of cadmium contaminated soils and their impact on the soil-plant system: A review. *Science of The Total Environment*, *707*, 136121. https://doi.org/10.1016/j.scitotenv.2019.136121

41. Harifia, R., Irham, M., Rusdi, M. (2022). Chemical analysis of mangrove land in north Aceh. *IOP Conference Series: Earth and Environmental Science*, *1116*(1), 012083. https://iopscience.iop.org/article/10.1088/1755-1315/1116/1/012083/meta

42. Hossain, M. B., Masum, Z., Rahman, M. S., Yu, J., Noman, M. A., Jolly, Y. N., Begum, B. A., Paray, B. A., Arai, T. (2022). Heavy metal accumulation and phytoremediation potentiality of some selected mangrove species from the world's largest mangrove forest. *Biology*, *11*(8), 1144. https://doi.org/10.3390/biology11081144

43. Hou, D., O'Connor, D., Igalavithana, A. D., Alessi, D. S., Luo, J., Tsang, D. C., Sparks, D. L., Yamauchi, Y., Rinklebe, J., Ok, Y. S. (2020). Metal contamination and bioremediation of agricultural soils for food safety and sustainability. *Nature Reviews Earth & Environment*, *1*(7), 366–381.

44. Hu, B., Guo, P., Wu, Y., Deng, J., Su, H., Li, Y., Nan, Y. (2021). Study of soil physicochemical properties and heavy metals of a mangrove restoration wetland. *Journal of Cleaner Production*, *291*, 125965.

45. Huang, B., Yuan, Z., Li, D., Zheng, M., Nie, X., Liao, Y. (2020). Effects of soil particle size on the adsorption, distribution, and migration behaviors of heavy metal (loid) s in soil: A review. *Environmental Science: Processes & Impacts*, *22*(8), 1596–1615. https://doi.org/10.1039/D0EM00189A

46. Huxham, M., Dencer-Brown, A., Diele, K., Kathiresan, K., Nagelkerken, I., Wanjiru, C. (2017). Mangroves and people: Local ecosystem services in a changing climate. *Mangrove Ecosystems: A Global Biogeographic Perspective: Structure, Function, and Services*, 245–274. https://doi.org/10.1007/978-3-319-62206-4_8

47. Irawan, I. G. A., Diara, I. W., Bhayunagiri, I. (2019). Pemetaan potensi lokasi pengungsian akibat bencana letusan gunung agung di kabupaten karangasem berbasis sistem informasi geografis (sig). *Jurnal Agroekoteknologi Tropika ISSN*, *2301*, 6515.

48. Islam, M. M., Akther, S. M., Hossain, M. F., Parveen, Z. (2022). Spatial distribution and ecological risk assessment of potentially toxic metals in the Sundarbans mangrove soils of Bangladesh. *Scientific Reports*, *12*(1), 10422. https://doi.org/10.1038/s41598-022-13609-z

49. Jia, P., Cheng, X., Xue, H., Wang, Y. (2017). Applications of geographic information systems (GIS) data and methods in obesity-related research. *Obesity Reviews*, *18*(4), 400–411. https://doi.org/10.1111/obr.12495

50. Jimenez, L. C. Z., Queiroz, H. M., Otero, X. L., Nóbrega, G. N., Ferreira, T. O. (2021). Soil organic matter responses to mangrove restoration: A replanting experience in Northeast Brazil. *International Journal of Environmental Research and Public Health*, *18*(17), 8981. https://doi.org/10.3390/ijerph18178981

51. Kicińska, A., Pomykała, R., Izquierdo-Diaz, M. (2022). Changes in soil pH and mobility of heavy metals in contaminated soils. *European Journal of Soil Science*, *73*(1), e13203.

52. Kidd, D., Malone, B., McBratney, A., Minasny, B., Webb, M. (2015). Operational sampling challenges to digital soil mapping in Tasmania, Australia. *Geoderma Regional*, *4*, 1–10. https://doi.org/10.1016/j.geodrs.2014.11.002

53. Kulkarni, R., Deobagkar, D., Zinjarde, S. (2018). Metals in mangrove ecosystems and associated biota: A global perspective. *Ecotoxicology and Environmental Safety*, *153*, 215–228. https://doi.org/10.1016/j.ecoenv.2018.02.021

54. Kumar, A., Kumar, A., MMS, C.-P., Chaturvedi, A. K., Shabnam, A. A., Subrahmanyam, G., Mondal, R., Gupta, D. K., Malyan, S. K., Kumar, S. S. (2020). Lead toxicity: Health hazards, influence on food chain, and sustainable remediation approaches. *International Journal of Environmental Research and Public Health*, *17*(7), 2179.

55. Kushwaha, A., Hans, N., Kumar, S., Rani, R. (2018). A critical review on speciation, mobilization and toxicity of lead in soil-microbe-plant system and bioremediation strategies. *Ecotoxicology and Environmental Safety*, *147*, 1035–1045.

56. Laghlimi, M., Baghdad, B., El Hadi, H., Bouabdli, A. (2015). Phytoremediation mechanisms of heavy metal contaminated soils: A review. *Open Journal of Ecology*, *5*(8), 375–388.

57. Lang, T., Tam, N. F., Hussain, M., Ke, X., Wei,

J., Fu, Y., Li, M., Huang, X., Huang, S., Xiong, Z. (2023). Dynamics of heavy metals during the development and decomposition of leaves of Avicennia marina and Kandelia obovata in a subtropical mangrove swamp. *Science of The Total Environment*, *855*, 158700. https://doi.org/10.1016/j.scitotenv.2022.158700

58. Li, C., Sun, G., Wu, Z., Zhong, H., Wang, R., Liu, X., Guo, Z., Cheng, J. (2019). Soil physiochemical properties and landscape patterns control trace metal contamination at the urban-rural interface in southern China. *Environmental Pollution*, *250*, 537–545. https://doi.org/10.1016/j.envpol.2019.04.065
59. Li, J., Yang, L., Pu, R., Liu, Y. (2017). A review on anthropogenic geomorphology. *Journal of Geographical Sciences*, *27*, 109–128.
60. Li, P., Li, X., Bai, J., Meng, Y., Diao, X., Pan, K., Zhu, X., Lin, G. (2022). Effects of land use on the heavy metal pollution in mangrove sediments: Study on a whole island scale in Hainan, China. *Science of The Total Environment*, *824*, 153856. https://doi.org/10.1016/j.scitotenv.2022.153856
61. Li, Y., Wang, K., Dötterl, S., Xu, J., Garland, G., Liu, X. (2024). The critical role of organic matter for cadmium-lead interactions in soil: Mechanisms and risks. *Journal of Hazardous Materials*, *476*, 135123. https://doi.org/10.1016/j.jhazmat.2024.135123
62. Lin, C.-W., Kao, Y.-C., Chou, M.-C., Wu, H.-H., Ho, C.-W., Lin, H.-J. (2020). Methane emissions from subtropical and tropical mangrove ecosystems in Taiwan. *Forests*, *11*(4), 470. https://doi.org/10.3390/f11040470
63. Liu, M., Huang, H., Bao, S., Tong, Y. (2019). Microbial community structure of soils in Bamenwan mangrove wetland. *Scientific Reports*, *9*(1), 8406. https://doi.org/10.1038/s41598-019-44788-x
64. Liu, S., Yang, B., Liang, Y., Xiao, Y., Fang, J. (2020). Prospect of phytoremediation combined with other approaches for remediation of heavy metal-polluted soils. *Environmental Science and Pollution Research*, *27*, 16069–16085. https://doi.org/10.1007/s11356-020-08282-6
65. Luthansa, U. M., Titah, H. S., Pratikno, H. (2021). The ability of mangrove plant on lead phytoremediation at Wonorejo Estuary, Surabaya, Indonesia. *Journal of Ecological Engineering*, *22*(6), 253–268. https://doi.org/10.12911/22998993/137675
66. Ma, L., Li, M., Ma, X., Cheng, L., Du, P., Liu, Y. (2017). A review of supervised object-based land-cover image classification. *ISPRS Journal of Photogrammetry and Remote Sensing*, *130*, 277–293. https://doi.org/10.1016/j.isprsjprs.2017.06.001
67. Maghsodian, Z., Sanati, A. M., Ramavandi, B., Ghasemi, A., Sorial, G. A. (2021). Microplastics accumulation in sediments and Periophthalmus waltoni fish, mangrove forests in southern Iran. *Chemosphere*, *264*, 128543. https://doi.org/10.1016/j.chemosphere.2020.128543
68. Maharani, M. D. K., Hertika, A. M. S., Musa, M. (2019). Accumulation of heavy metals lead (Pb) and copper (Cu) in mangrove area of Avicennia marina in Manyar Subdistrict, Gresik District, East Java. *Research Journal of Life Science*, *6*(2), 104–113. https://doi.org/10.21776/ub.rjls.2019.006.02.4
69. Maurya, P., Kumari, R. (2021). Toxic metals distribution, seasonal variations and environmental risk assessment in surficial sediment and mangrove plants (A. marina), Gulf of Kachchh (India). *Journal of Hazardous Materials*, *413*, 125345. https://doi.org/10.1016/j.jhazmat.2021.125345
70. Minasny, B., McBratney, A. B. (2016). Digital soil mapping: A brief history and some lessons. *Geoderma*, *264*, 301–311. https://doi.org/10.1016/j.geoderma.2015.07.017
71. Mishra, A. K., Manish, K. (2018). Andaman mangrove sediments: Source of nutrients and sink of heavy metals. *bioRxiv*, 431262. https://doi.org/10.1101/431262
72. Natsir, N. A., Hanika, Y., Rijal, M., Bacthiar, S. (2019). Kandungan logam berat timbal (Pb) dan kadmium (Cd) pada air, sedimen dan organ mangrove di perairan Tulehu. *BIOSEL (Biology Science and Education): Jurnal Penelitian Science Dan Pendidikan*, *8*(2), 149–159.
73. Naz, M., Dai, Z., Hussain, S., Tariq, M., Danish, S., Khan, I. U., Qi, S., Du, D. (2022a). The soil pH and heavy metals revealed their impact on soil microbial community. *Journal of Environmental Management*, *321*, 115770. https://doi.org/10.1016/j.jenvman.2022.115770
74. Naz, M., Dai, Z., Hussain, S., Tariq, M., Danish, S., Khan, I. U., Qi, S., Du, D. (2022b). The soil pH and heavy metals revealed their impact on soil microbial community. *Journal of Environmental Management*, *321*, 115770.
75. Onyena, A. P., Folorunso, O. M., Nwanganga, N., Udom, G. J., Ekhator, O. C., Frazzoli, C., Ruggieri, F., Bocca, B., Orisakwe, O. E. (2024). Engaging one health in heavy metal pollution in some selected Nigerian Niger delta cities. A Systematic review of pervasiveness, bioaccumulation and subduing environmental health challenges. *Biological Trace Element Research*, *202*(4), 1356–1389. https://doi.org/10.1007/s12011-023-03762-5
76. Onyena, A. P., Sam, K. (2020). A review of the threat of oil exploitation to mangrove ecosystem: Insights from Niger Delta, Nigeria. *Global Ecology and Conservation*, *22*, e00961. https://doi.org/10.1016/j.gecco.2020.e00961
77. Osland, M. J., Feher, L. C., Spivak, A. C., Nestlerode, J. A., Almario, A. E., Cormier, N., From, A.

S., Krauss, K. W., Russell, M. J., Alvarez, F. (2020). Rapid peat development beneath created, maturing mangrove forests: Ecosystem changes across a 25-yr chronosequence. *Ecological Applications*, *30*(4), e02085. https://doi.org/10.1002/eap.2085

78. Othaman, N., Isa, M., Ismail, R., Ahmad, M., Hui, C. (2020). Factors that affect soil electrical conductivity (EC) based system for smart farming application*, 2203*(1). https://doi.org/10.1063/1.5142147

79. Padhye, L. P., Srivastava, P., Jasemizad, T., Bolan, S., Hou, D., Shaheen, S. M., Rinklebe, J., O'Connor, D., Lamb, D., Wang, H. (2023). Contaminant containment for sustainable remediation of persistent contaminants in soil and groundwater. *Journal of Hazardous Materials*, *455*, 131575.

80. Palit, K., Rath, S., Chatterjee, S., Das, S. (2022). Microbial diversity and ecological interactions of microorganisms in the mangrove ecosystem: Threats, vulnerability, and adaptations. *Environmental Science and Pollution Research*, *29*(22), 32467–32512.

81. Pan, X., Zhang, S., Zhong, Q., Gong, G., Wang, G., Guo, X., Xu, X. (2020). Effects of soil chemical properties and fractions of Pb, Cd, and Zn on bacterial and fungal communities. *Science of the Total Environment*, *715*, 136904. https://doi.org/10.1016/j.scitotenv.2020.136904

82. Phiri, D., Simwanda, M., Salekin, S., Nyirenda, V. R., Murayama, Y., Ranagalage, M. (2020). Sentinel-2 data for land cover/use mapping: A review. *Remote Sensing*, *12*(14), 2291. https://doi.org/10.3390/rs12142291

83. Pittarello, M., Busato, J. G., Carletti, P., Sodré, F. F., Dobbss, L. B. (2019). Dissolved humic substances supplied as potential enhancers of Cu, Cd, and Pb adsorption by two different mangrove sediments. *Journal of Soils and Sediments*, *19*, 1554–1565. https://doi.org/10.1007/s11368-018-2158-1

84. Proshad, R., Rahim, M. A., Rahman, M., Asif, M. R., Dey, H. C., Al, M. A., Islam, M., Idris, A. M. (2024). Utilizing machine learning to evaluate heavy metal pollution in the world's largest mangrove forest. *Science of The Total Environment*, *951*, 175746. https://doi.org/10.1016/j.scitotenv.2024.175746

85. Rachmawati, R., Yona, D., Kasitowati, R. D. (2018). Potential of Avicennia alba as an Agent of Phytoremediation heavy metal (Pb and cu) in Wonorejo, Surabaya. *Jurnal Kelautan: Indonesian Journal of Marine Science and Technology*, *11*(1), 80–87. https://doi.org/10.21107/jk.v11i1.3341

86. Rahman, M. M., Zimmer, M., Ahmed, I., Donato, D., Kanzaki, M., Xu, M. (2021). Co-benefits of protecting mangroves for biodiversity conservation and carbon storage. *Nature Communications*, *12*(1), 3875. https://doi.org/10.1038/s41467-021-24207-4

87. Rahman, S. U., Han, J.-C., Zhou, Y., Ahmad, M., Li, B., Wang, Y., Huang, Y., Yasin, G., Ansari, M. J., Saeed, M. (2024). Adaptation and remediation strategies of mangroves against heavy metal contamination in global coastal ecosystems: A review. *Journal of Cleaner Production*, 140868. https://doi.org/10.1016/j.jclepro.2024.140868

88. Ray, R., Mandal, S., González, A. G., Pokrovsky, O. S., Jana, T. (2021). Storage and recycling of major and trace element in mangroves. *Science of the Total Environment*, *780*, 146379. https://doi.org/10.1016/j.scitotenv.2021.146379

89. Robin, S. L., Marchand, C., Mathian, M., Baudin, F., & Alfaro, A. C. (2022). Distribution and bioaccumulation of trace metals in urban semi-arid mangrove ecosystems. *Frontiers in Environmental Science*, *10*, 1054554.

90. Romero-Mujalli, G., Melendez, W. (2023). Nutrients and trace elements of semi-arid dwarf and fully developed mangrove soils, northwestern Venezuela. *Environmental Earth Sciences*, *82*(1), 51. https://doi.org/10.1007/s12665-022-10701-5

91. Rumanta, M. (2019). The potential of rhizophora mucronata and sonneratia caseolaris for phytoremediation of lead pollution in Muara Angke, North Jakarta, Indonesia. *Biodiversitas Journal of Biological Diversity*, *20*(8). https://smujo.id/biodiv/article/view/4088

92. Safari, M., Ramavandi, B., Sanati, A. M., Sorial, G. A., Hashemi, S., Tahmasebi, S. (2018). Potential of trees leaf/bark to control atmospheric metals in a gas and petrochemical zone. *Journal of Environmental Management*, *222*, 12–20.

93. Sait, Y. C. B., Titah, H. S., Pratikno, H. (2023). Analysis of the Phytoremediation dynamic system of lead in mangrove plants at the Wonorejo River Estuary, Surabaya, Indonesia. *Ecological Engineering & Environmental Technology*, *24*. https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-cb64130e-ab0e-47a3-87a5-8eb7644ad683

94. Sangur, K., Leiwakabessy, F., Tuaputty, H., Tuwankotta, L. V., Samloy, S. V., Ratila, C., Salakory, O. B., Matulessy, C., Rumahlatu, D. (2021). Mudskipper as an indicator species for lead, cadmium and cuprum heavy metal pollution in the Mangrove, Ambon, Indonesia. *Journal of Ecological Engineering*, *22*(4), 1–19. https://doi.org/10.1016/j.marpolbul.2021.112900

95. Sari, S. H. J., Yona, D., Vidayanti, V., Ramadhan, F. (2023). Effectivity of bioaccumulation and translocation of heavy metals (Cd, Zn, and Pb) in Avicennia Marina growing at Wonorejo Mangrove Ecosystem, East Surabaya. *Journal of Environmental Engineering and Sustainable Technology*, *10*(02), 104–111.

96. Sharma, D., Rao, K., Ramanathan, A. (2021). A systematic review on the impact of urbanization and industrialization on Indian coastal mangrove ecosystem. *Coastal Ecosystems:*

Environmental Importance, Current Challenges and Conservation Measures, 175–199. https://doi.org/10.1007/978-3-030-84255-0_8

97. Shi, C., Ding, H., Zan, Q., Li, R. (2019). Spatial variation and ecological risk assessment of heavy metals in mangrove sediments across China. *Marine Pollution Bulletin*, *143*, 115–124. https://doi.org/10.1016/j.marpolbul.2019.04.043
98. Shih, S.-S., Ding, T.-S., Chen, C.-P., Huang, S.-C., Hsieh, H.-L. (2019). Landscape structured by physical settings and benthic polychaete and avifauna habitat uses in a mangrove-vegetated estuary. *bioRxiv*, 2019–12. https://doi.org/10.1101/2019.12.12.874008
99. Sinsin, L. C. B., Salako, K. V., Tohoun, R. J., Glèlè Kakaï, R. (2022). Survival, growth, and productivity of Rhizophora racemosa transplanted in natural ecosystems: Implications for mangrove restoration. *Wetlands*, *42*(6), 61. https://doi.org/10.1007/s13157-022-01583-1
100. Stefanowicz, A. M., Kapusta, P., Zubek, S., Stanek, M., Woch, M. W. (2020). Soil organic matter prevails over heavy metal pollution and vegetation as a factor shaping soil microbial communities at historical Zn–Pb mining sites. *Chemosphere*, *240*, 124922. https://doi.org/10.1016/j.chemosphere.2019.124922
101. Suska-Malawska, M., Vyrakhamanova, A., Ibraeva, M., Poshanov, M., Sulwiński, M., Toderich, K., Mętrak, M. (2022). Spatial and in-depth distribution of soil salinity and heavy metals (Pb, Zn, Cd, Ni, Cu) in arable irrigated soils in Southern Kazakhstan. *Agronomy*, *12*(5), 1207.
102. Tako, E., Baraj, E., Mele, A., Hoxha, V. (2024). Montmorillonite Clay as an Adsorbent for the Remediation of Cd (II) Ions in Aqueous Solutions: A Comparison With Pb (II) Ions. *Remediation Journal*, *34*(4), e21785. https://doi.org/10.1002/rem.21785
103. Tamis, J. E., Koelmans, A. A., Dröge, R., Kaag, N. H. B. M., Keur, M. C., Tromp, P. C., Jongbloed, R. H. (2021). Environmental risks of car tire microplastic particles and other road runoff pollutants. *Microplastics and Nanoplastics*, *1*(1), 10. https://doi.org/10.1186/s43591-021-00008-w
104. Thakur, M., Praveen, S., Divte, P. R., Mitra, R., Kumar, M., Gupta, C. K., Kalidindi, U., Bansal, R., Roy, S., Anand, A. (2022). Metal tolerance in plants: Molecular and physicochemical interface determines the "not so heavy effect" of heavy metals. *Chemosphere*, *287*, 131957.
105. Thanh-Nho, N., Marchand, C., Strady, E., Huu-Phat, N., Nhu-Trang, T.-T. (2019). Bioaccumulation of some trace elements in tropical mangrove plants and snails (Can Gio, Vietnam). *Environmental Pollution*, *248*, 635–645. https://doi.org/10.1016/j.envpol.2019.02.041
106. Titah, H. S., Pratikno, dan H. (2020). Chromium accumulation by avicennia alba growing at ecotourism mangrove forest in Surabaya, Indonesia. *Journal of Ecological Engineering*, *21*(2), 222–227.
107. Tong, T., Li, R., Wu, S., Xie, S. (2019). The distribution of sediment bacterial community in mangroves across China was governed by geographic location and eutrophication. *Marine Pollution Bulletin*, *140*, 198–203. https://doi.org/10.1016/j.marpolbul.2019.01.046
108. Uchimiya, M., Bannon, D., Nakanishi, H., McBride, M. B., Williams, M. A., Yoshihara, T. (2020). Chemical speciation, plant uptake, and toxicity of heavy metals in agricultural soils. *Journal of Agricultural and Food Chemistry*, *68*(46), 12856–12869.
109. Victório, C., dos Santos, M., Alves, G., Bento, J., dos S. Ferreira, B., da C. Souza, M., do C. de O. Arruda, R. (2024). Rapid detection of metals in red mangrove Rhizophora mangle leaves in a polluted environment in Brazil. *International Journal of Environmental Science and Technology*, *21*(4), 4157–4170. https://doi.org/10.1007/s13762-023-05271-3
110. Vierros, M. (2017). Communities and blue carbon: The role of traditional management systems in providing benefits for carbon storage, biodiversity conservation and livelihoods. *Climatic Change*, *140*(1), 89–100. https://doi.org/10.1007/s10584-013-0920-3
111. Vignesh, A., Amal, T. C., Sivalingama, R., Selvakumar, S., Vasanth, K. (2024). Unraveling the impact of nanopollution on plant metabolism and ecosystem dynamics. *Plant Physiology and Biochemistry*, 108598.
112. Wang, J., Wang, P., Zhao, Z., Huo, Y. (2021). Uptake and concentration of heavy metals in dominant mangrove species from Hainan Island, South China. *Environmental Geochemistry and Health*, *43*, 1703–1714. https://doi.org/10.1007/s10653-020-00717-w
113. Wang, Y.-S., Gu, J.-D. (2021). Ecological responses, adaptation and mechanisms of mangrove wetland ecosystem to global climate change and anthropogenic activities. *International Biodeterioration & Biodegradation*, *162*, 105248. https://doi.org/10.1016/j.ibiod.2021.105248
114. Winterwerp, J. C., Albers, T., Anthony, E. J., Friess, D. A., Mancheño, A. G., Moseley, K., Muhari, A., Naipal, S., Noordermeer, J., Oost, A. (2020). Managing erosion of mangrove-mud coasts with permeable dams–lessons learned. *Ecological Engineering*, *158*, 106078. https://doi.org/10.1016/j.ecoleng.2020.106078
115. Wu, D., Liu, H., Wu, J., Gao, X. (2022). Spatial distribution, ecological risk assessment and source

analysis of heavy metals pollution in urban lake sediments of Huaihe River Basin. *International Journal of Environmental Research and Public Health*, *19*(22), 14653.

116. Xie, Z., Zhu, G., Xu, M., Zhang, H., Yi, W., Jiang, Y., Liang, M., Wang, Z. (2022). Risk assessment of heavy metals in a typical mangrove ecosystem—A case study of Shankou Mangrove National Natural Reserve, southern China. *Marine Pollution Bulletin*, *178*, 113642. https://doi.org/10.1016/j.marpolbul.2022.113642
117. Yadav, K. K., Gupta, N., Prasad, S., Malav, L. C., Bhutto, J. K., Ahmad, A., Gacem, A., Jeon, B.-H., Fallatah, A. M., Asghar, B. H. (2023). An eco-sustainable approach towards heavy metals remediation by mangroves from the coastal environment: A critical review. *Marine Pollution Bulletin*, *188*, 114569. https://doi.org/10.1016/j.marpolbul.2022.114569
118. Yam, R. S., Fan, Y.-T., Tan, Z., Wang, T.-D., Chiu, C.-Y. (2020). Assessing impacts of metallic contamination along the tidal gradient of a riverine mangrove: Multi-metal bioaccumulation and biomagnification of filter-feeding bivalves. *Forests*, *11*(5), 504.
119. Yap, C. K., Al-Mutairi, K. A. (2023). Potentially toxic metals in the tropical mangrove non-salt secreting Rhizophora apiculata: A field-based biomonitoring study and phytoremediation potentials. *Forests*, *14*(2), 237. https://doi.org/10.3390/f14020237
120. Yu, H., Li, C., Yan, J., Ma, Y., Zhou, X., Yu, W., Kan, H., Meng, Q., Xie, R., Dong, P. (2023). A review on adsorption characteristics and influencing mechanism of heavy metals in farmland soil. *RSC Advances*, *13*(6), 3505–3519.
121. Zhang, J., Mu, G., Zhang, Z., Huang, X., Fang, H. (2021). Speciation variation and bio-activation of soil heavy metals (Cd and Cr) in rice-rape rotation lands in karst regions. *International Journal of Environmental Research and Public Health*, *18*(3), 1364. https://doi.org/10.3390/ijerph18031364
122. Zhang, L., Yang, L., Cai, Y., Huang, H., Shi, J., Zhou, C. (2022). A multiple soil properties oriented representative sampling strategy for digital soil mapping. *Geoderma*, *406*, 115531. https://doi.org/10.1016/j.geoderma.2021.115531
123. Zhou, X., Wang, Y.-P., Song, Z. (2022). Heavy Metal Contamination and Ecological Risk Assessments in Urban Mangrove Sediments in Zhanjiang Bay, South China. *ACS Omega*, *7*(24), 21306–21316. https://doi.org/10.1021/acsomega.2c02516
124. Zhou, Y.-Y., Wang, Y.-S., Inyang, A. I. (2021). Ecophysiological differences between five mangrove seedlings under heavy metal stress. *Marine Pollution Bulletin*, *172*, 112900. https://doi.org/10.1016/j.marpolbul.2021.112900
125. Zwolak, A., Sarzyńska, M., Szpyrka, E., Stawarczyk, K. (2019). Sources of soil pollution by heavy metals and their accumulation in vegetables: A review. *Water, Air, & Soil Pollution*, *230*, 1–9. https://doi.org/10.1007/s11270-019-4221-y