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Investigating the relationship between heavy metals concentration and soil fractions in Benoa Bay, Indonesia

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ABSTRACT

Heavy metal contamination in coastal environments is a persistent concern due to the ability of soils to act as long-term sinks for pollutants such as lead (Pb), cadmium (Cd), copper (Cu), and chromium (Cr). This study aims to investigate the relationship between heavy metal concentrations and soil particle size distribution in Benoa Bay, a semi-enclosed tropical bay in southern Bali, Indonesia. A total of nine surface soil samples were collected from different environmental settings, including areas near landfills, ports, mangroves, and open coasts. Soil fractions were analyzed using dry sieving and the pipette method, while metal concentrations were measured using flame Atomic Absorption Spectrophotometry (AAS) following wet acid digestion. Pearson correlation analysis was used to examine the statistical relationships between soil particle size and heavy metal content. The results showed that cadmium levels exceeded the ANZECC/ARMCANZ soil guideline (1.5 mg/kg) at several locations (S3, S5, and S9), indicating ecological risk. Strong positive correlations were found between heavy metals and fine soil fractions (fine clay: $r = 0.92$ for Cd; medium silt: $r = 0.98$ for Cr), while coarse fractions like gravel showed strong negative correlations (e.g., $r = –0.92$ for Cr). This study is limited to surface soils (0–30 cm) and does not address vertical distribution or seasonal variations. However, it provides important baseline data for environmental monitoring and pollution management. The findings have practical value in identifying contamination hotspots, informing landfill leachate control, and guiding soil remediation planning. This research also offers a deeper understanding of how soil texture influences metal retention, which is critical for developing effective coastal management strategies. This study is original in its integrated approach to combining granulometric and geochemical analysis in a tropical bay setting and highlights the significance of particle size in controlling heavy metal mobility and accumulation.

Keywords: heavy metals, soil particle size, Benoa Bay, coastal contamination.

INTRODUCTION

Heavy metal contamination has become a persistent environmental concern, particularly in coastal ecosystems where soils often act as long-term sinks (El-Sharkawy et al., 2025). Metals such as lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) are introduced into these environments through both natural processes and human activities, including urban runoff, industrial discharge, tourism, and port operations (Daripa et al., 2023). Unlike organic pollutants, heavy metals do not degrade over time and can remain in the environment for decades, gradually accumulating in soils and posing risks to benthic organisms and the broader food web (Gall et al.,2015; Butnariu, 2022). Soil plays a crucial role in the geochemical cycling of heavy metals in coastal areas. However, not all soil is created equality to retain or release metals is strongly influenced by the size and composition of its constituent particles (Zhang et al., 2014; Bao et al., 2023). Coarse particles like sand and gravel tend to have low adsorption capacity, while finer particles such as silt and clay provide greater surface area and reactive sites for metal binding (Gunawardana et al., 2014; Huang et al., 2020). This makes understanding the relationship between soil particle fractions and heavy metal concentrations crucial for assessing environmental quality and the potential bioavailability of these contaminants.

In many cases, heavy metals tend to bind more readily to finer particles due to their higher surface area, charge properties, and mineral composition (Huang et al., 2020). Clay and silt fractions are particularly important in this context, as they often contain organic matter and metal oxides that enhance metal retention (Diagboya et al., 2015; Refaey et al., 2017). Moreover, environmental factors such as pH, redox conditions, salinity, and hydrodynamics can influence metal mobility, making local soil characteristics an essential consideration in pollution studies (Zhang et al., 2014).

Benoa Bay, located on the southern coast of Bali, Indonesia, represents a typical tropical coastal system that has experienced significant environmental changes over the past few decades. Once dominated by mangroves and seagrasses, the bay has seen extensive land reclamation, infrastructure development, and increasing maritime activity. These changes have led to growing concerns over the degradation of water and soil quality in the area. Several studies have identified the presence of heavy metals in Benoa Bay (Mardani et al., 2018; Suteja et al., 2020; Putri et al., 2024), but limited attention has been given to their interaction with soil characteristics, particularly soil particle fractions.

Understanding how heavy metals interact with specific particle sizes in Benoa Bay is essential for several reasons. First, it helps identify zones of potential ecological risk—areas where fine soils may concentrate higher levels of contaminants (Putri et al., 2024). Second, it provides insight into the long-term stability of metal contamination: whether metals are likely to remain bound in the soil or become mobilized into the water column (Outridge and Wang, 2015). Finally, it supports the development of targeted strategies for environmental monitoring and remediation (Wang et al., 2021).

Studies from other coastal areas have consistently shown that finer soil fractions, especially clay and fine silt, tend to exhibit higher concentrations of heavy metals (Liu et al., 2006; Chen et al., 2016). For instance, research conducted in estuarine systems in Southeast Asia and Europe has demonstrated that clay-rich soils can retain metals through complexation and ion exchange mechanisms (Thinh et al., 2018; Putri, 2024). However, each coastal system is unique, and local variations in soil composition, pollution sources, and hydrodynamic processes can result in different spatial patterns of metal distribution. Therefore, site-specific research in Benoa Bay is necessary to clarify these interactions and their implications for environmental health.

This study aims to examine the relationship between heavy metal concentrations and soil particle fractions in Benoa Bay. Specifically, it analyzes the concentrations of Pb, Cd, Cu, and Cr in surface soils and evaluates their correlation with different particle size classes. Based on previous studies and the known adsorption properties of finer soil particles, we hypothesize that heavy metals will exhibit stronger positive correlations with fine silt and clay fractions, particularly fine clay, due to their high surface area and ion exchange capacity. Conversely, coarser particles such as gravel and sand are expected to show weaker or negative associations with metal concentrations. These expectations reflect the assumption that soil texture is a primary control on metal retention and distribution in tropical coastal systems.

The results of this study are expected to contribute to the broader understanding of soil-bound metal dynamics in tropical coastal systems. It will also serve as a valuable baseline for future environmental assessments in Benoa Bay, especially considering ongoing development and reclamation projects. Furthermore, findings from this work may inform policy and management decisions aimed at preserving the ecological integrity of Benoa Bay and similar environments throughout Indonesia and Southeast Asia.

METHODS

Site description

This research was conducted from September to December 2024 in the coastal waters of Benoa Bay, located in the southern part of Bali Island, Indonesia (Figure 1). Benoa Bay is a tropical semi-enclosed embayment that receives input from multiple rivers and is heavily influenced by both natural and anthropogenic activities, including port operations, landfill runoff, land reclamation, and urban development (Figure 1). The bay is bordered by dense mangrove forests in the southwest, tourism infrastructure along the eastern coast, and a major shipping port (Port of Benoa) near the central-northern area of the bay. A total of nine soil sampling stations (S1 to S9) were established to capture the spatial variation in soil characteristics and metal contamination. These stations were strategically distributed across different environmental settings, including areas close to the landfill (S5), near the port (S9), in mangrove-dominated regions (S1, S2, S3), transitional tidal flats (S4, S7), urban-influenced estuarine areas (S8), and open coastal zones exposed to higher wave energy (S6). All samples collected in this study were limited to surface soil only (0–30 cm).

Soil data collection

At each of the nine sampling stations (S1–S9) in Benoa Bay, three soil cores were collected within a 2-meter radius using a manual coring method as shown in Figure 2. A PVC pipe with a diameter of 10 cm was vertically inserted into the ground to a depth of 30 cm at each point to obtain approximately ±1 kg of wet soil. The three cores from each station were homogenized into a single composite sample, resulting in a total of nine composite surface soil samples. This approach was intended to reduce micro-scale spatial variability and to provide a representative sample of surface soil conditions at each station. The collected samples were transferred into labeled plastic bags to avoid contamination and ensure traceability. All samples were immediately stored in a cooling box under low-temperature conditions and transported to the laboratory for further analysis. These nine composite samples were subsequently used for

Figure 2. Ilustration of field soil sampling collected at S7

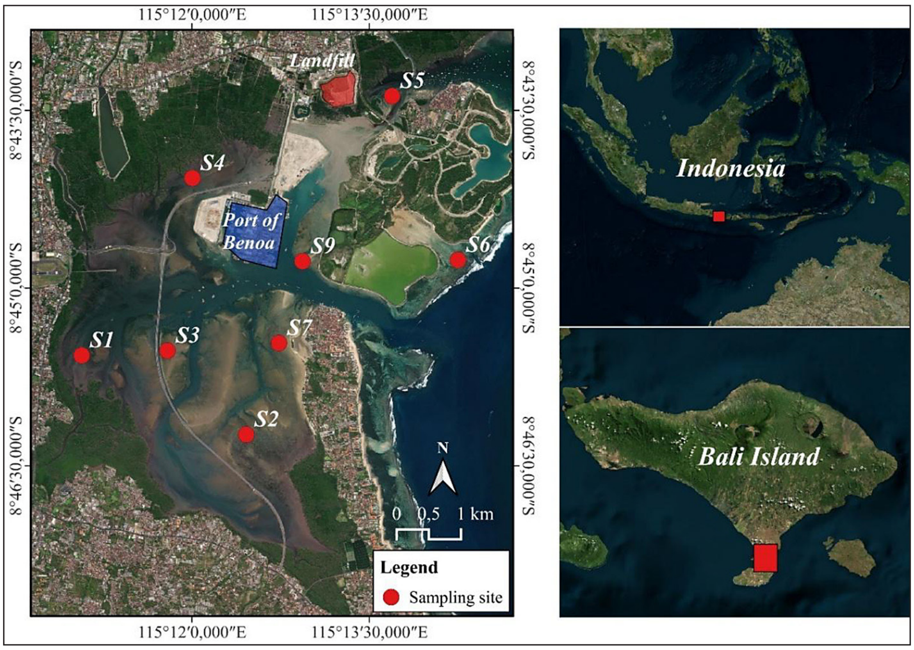

Figure 1. Distribution of soil sampling locations on Benoa Bay, Indonesia

both particle size analysis and heavy metal concentration measurements, and the resulting data were utilized in statistical correlation analyses to explore relationships between metal concentrations and soil fractions.

Laboratory analysis

In the laboratory, soil samples were oven-dried at 60 °C until constant weight and gently disaggregated using a ceramic mortar and pestle (Figure 3A and 3B). A 50-gram subsample was used for particle size analysis, which was conducted using a combination of dry sieving and the pipette/hydrometer method (Figure 3C and 3D). Sand fractions (> 63 µm) were separated using an ABM mechanical sieve shaker equipped with mesh sizes of 2 mm to 63 µm, allowing classification into gravel, very coarse sand, coarse sand, medium sand, fine sand, and very fine sand. For finer particles (< 63 µm), the pipette method was applied based on Stokes' Law, following organic matter removal with hydrogen peroxide (H_2O_2). Timed aliquots were extracted from a 1-liter sedimentation cylinder to determine the proportions of coarse silt, medium silt, fine silt, coarse clay, and fine clay. Particle size fractions were calculated as percentages of total dry weight using the Wentworth classification scale (Wentworth, 1922).

For heavy metal analysis, approximately 2 grams of oven-dried soil were digested using a mixture of concentrated H_2SO_4, H_2O_2, and HCl, following the APHA (2012) protocol as applied by Riani et al. (2018) (Figure 4A). The digested solution was filtered using Whatman No. 42 filter

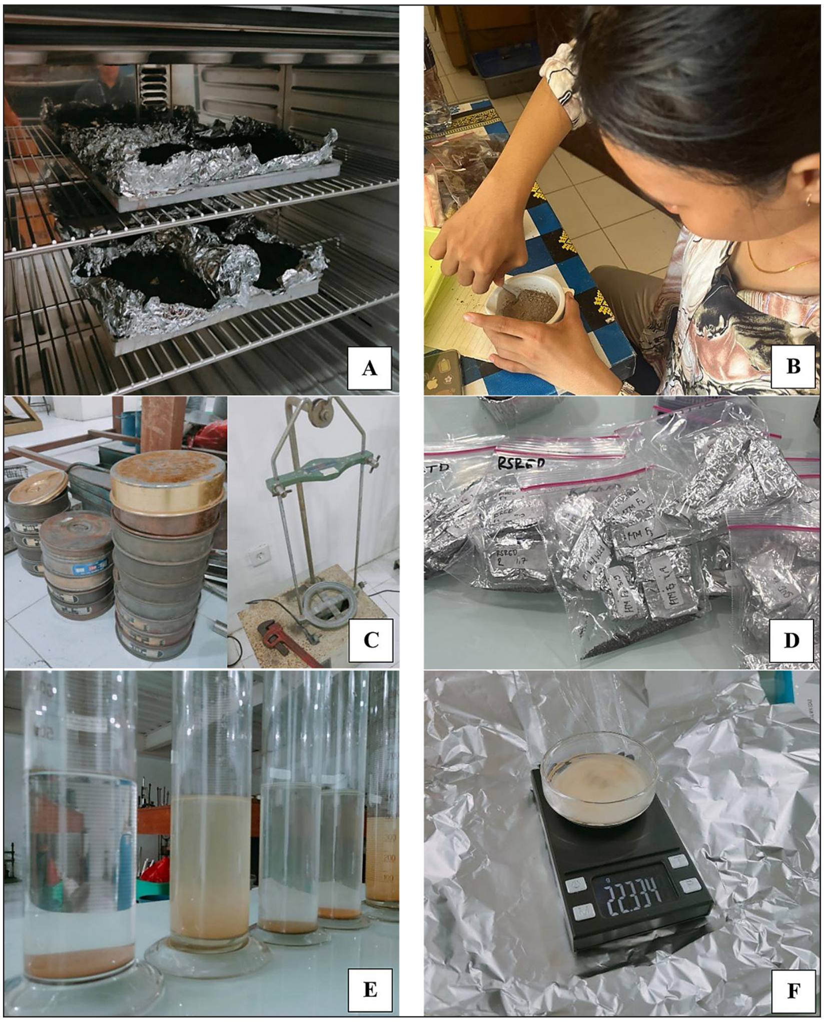

Figure 3. Laboratory procedures for soil particle size analysis, (A) oven-drying of soil samples at 60 °C, (B) gentle disaggregation using a ceramic mortar and pestle, (C) dry sieving of sand fractions using an ABM mechanical sieve shaker; (D) sieved soil fractions stored in aluminum foil, (E) pipette method for analyzing fine silt and clay fractions; (F) final weighing of oven-dried fine particles to determine soil type percentage

paper (2.5 μm pore size) (Figure 4B), diluted with deionized water to 50 mL (Figure 4C), and analyzed for Pb, Cd, Cu, and Cr concentrations using a flame Atomic Absorption Spectrophotometer (Agilent 200 Series AA) at the Soil Laboratory of Udayana University (Figure 4D).

Statistical analysis

The data were first tested for normality using the Shapiro-Wilk test ($\rho > 0.05$ for all variables), confirming suitability for parametric analysis. Pearson correlation coefficients (r) were then computed to assess the strength and direction of linear relationships between each heavy metal (Pb, Cd, Cu, Cr) and the ten soil particle size fractions. The significance of each correlation was determined at $\rho < 0.05$ and $\rho < 0.01$ levels using a two-tailed test in RStudio v4.0.2.

RESULT AND DISCUSSION

Heavy metal concentrations

The concentrations of four heavy metals (Pb, Cu, Cd, and Cr) in surface soils across the nine sampling stations in Benoa Bay (S1–S9) exhibit distinct spatial patterns, as illustrated in Figure 5. Pb concentrations ranged from 16.1 mg/kg at S6 to 27.5 mg/kg at S5, while Cu varied between 25.3 mg/kg at S6 and 45.3 mg/kg at S4. Cd showed the most critical values, with levels reaching 1.85 mg/kg at S5, 1.71 mg/kg at S3, and 1.6 mg/kg at S9. Cr concentrations were relatively low overall but peaked at 1.15 mg/kg in S5 and 1.05 mg/kg in S9, with the lowest concentration of 0.38 mg/kg observed at S6. These variations suggest that metal accumulation is strongly influenced by the environmental setting and proximity to anthropogenic

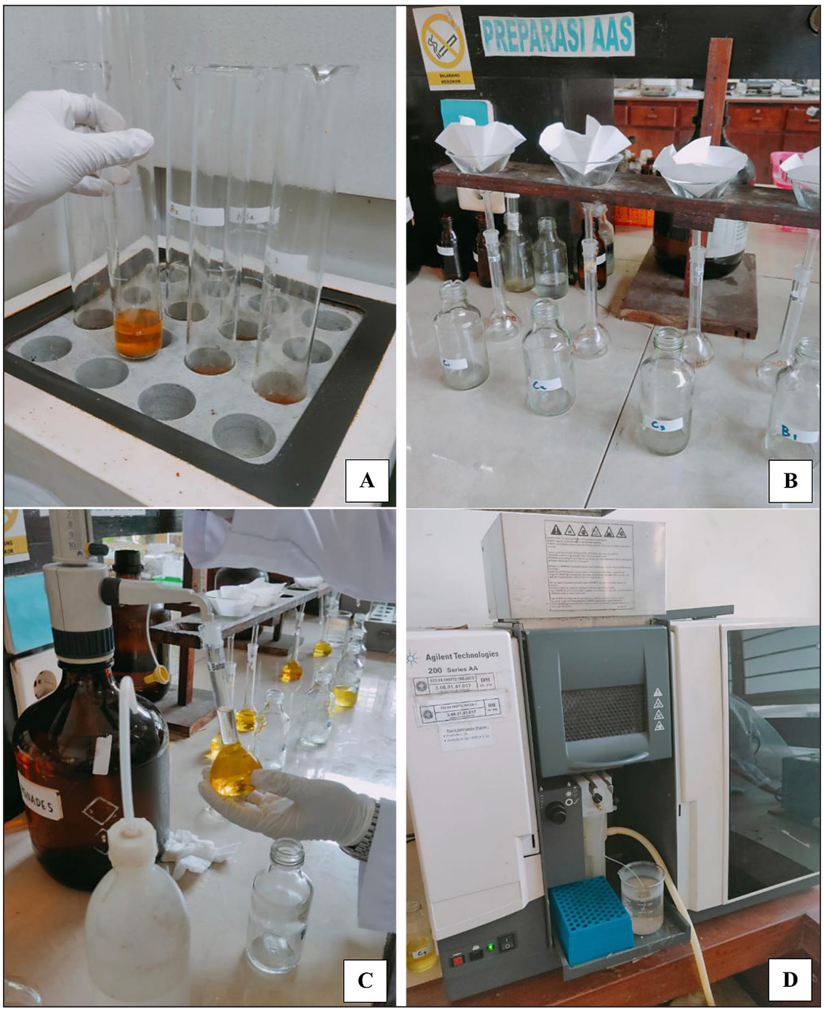

Figure 4. Laboratory procedures for heavy metal analysis, (A) soil digestion using a mixture of concentrated acids (H_2SO_4, H_2O_2, HCl); (B) filtration of the digested solution using Whatman No. 42 filter paper; (C) dilution of the filtrate with deionized water to a final volume of 50 mL; (D) measurement of metal concentrations (Pb, Cd, Cu, Cr) using atomic absorption spectrophotometry (AAS)

inputs. Notably, S5 consistently recorded the highest concentrations for Pb, Cd, and Cr, indicating it as a potential pollution hotspot.

A comparison with the ANZECC/ARMCANZ (2000) soil quality guidelines reveals that while concentrations of Pb (50 mg/kg), Cu (65 mg/kg), and Cr (80 mg/kg) remain well within acceptable thresholds across all stations, Cd levels exceeded the threshold value of 1.5 mg/kg at three locations: S3 (1.71 mg/kg), S5 (1.85 mg/kg), and S9 (1.60 mg/kg). These findings highlight cadmium as the primary pollutant of concern in Benoa Bay. The presence of over-limit Cd concentrations in one-third of the sampled stations implies an elevated risk to benthic ecosystems, particularly due to cadmium's known persistence, toxicity, and potential for trophic transfer. In contrast, the consistently low concentrations recorded at S6 reinforce the site's low-risk profile, possibly due to greater hydrodynamic flushing.

The elevated heavy metal concentrations observed at stations S5 and S9 are plausibly attributed to their proximity to significant pollution sources. Station S5 is located approximately 100 meters from an active landfill site, where leachate infiltration is likely to introduce cadmium and other metals into the surrounding environment. Similarly, S9 is situated near a busy coastal docking facility where maritime operations such as fuel handling, vessel maintenance, and antifouling paint usage are known contributors to metal inputs, particularly cadmium and chromium. The spatial alignment between elevated metal concentrations and these anthropogenic activities supports the hypothesis that site-specific sources are major drivers of soil contamination in Benoa Bay.

To contextualize the pollution status of Benoa Bay, a comparison was made with other coastal systems both regionally and globally (Table 1). Average metal concentrations in Benoa Bay soils (Pb: 22.0 mg/kg, Cd: 0.71 mg/kg, Cr: 0.98 mg/kg, Cu: 35.7 mg/kg) indicate a moderate level of contamination. Compared to the Red Sea (Pb: 60.5 mg/kg, Cr: 146.65 mg/kg) and Sicily, Italy (Cd: 25.6 mg/kg), Benoa Bay exhibits significantly lower pollution levels. However, Cd levels are higher than those reported for Palau (0.02 mg/kg) and the Gulf of Suez (0.55 mg/kg), suggesting that cadmium remains a site-specific concern. Within Indonesia, Cd concentrations in Benoa Bay are considerably lower than those in Sembilan Island, South Sulawesi (3.94 mg/kg), but higher than in Madura Waters (undetected). These comparisons reinforce the need for continued monitoring and source-specific mitigation efforts in the bay, particularly in the vicinity of landfill and port operations.

Soil texture and particle size distribution

The analysis of soil particle size fractions across the nine stations in Benoa Bay reveals

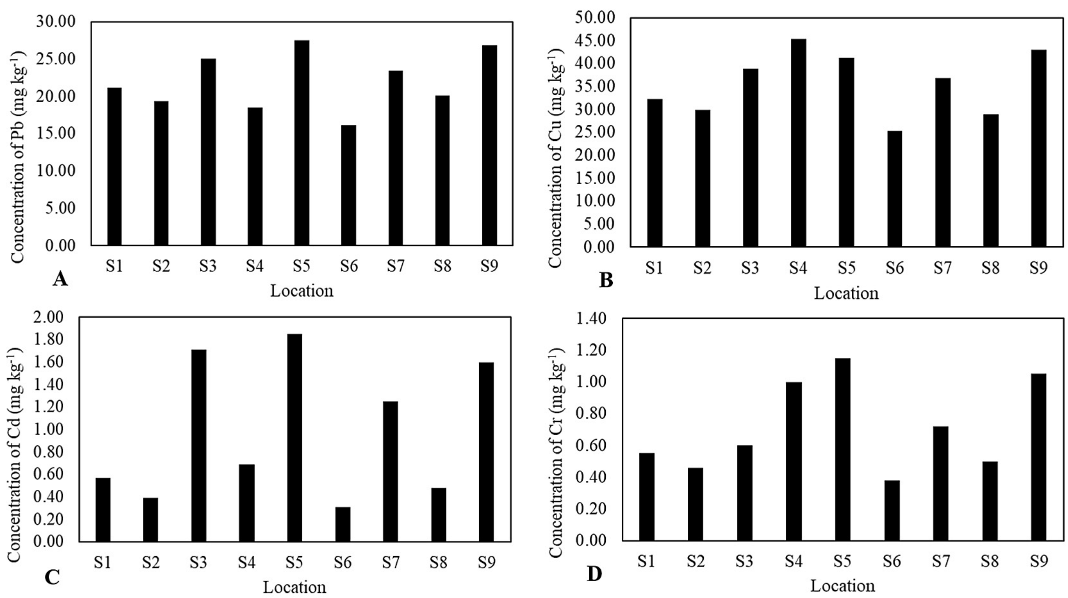

Figure 5. Spatial distribution of heavy metal concentrations in surface soils of Benoa Bay, Indonesia, where (A) Lead (Pb), (B) Copper (Cu), (C) Cadmium (Cd), and (D) Chromium (Cr), and Each bar represents the average concentration from a composite sample per location (S1–S9)

Table 1. Comparison of the average heavy metal concentrations to several locations

Location	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	References
Benoa Bay, Indonesia	22.00	0.71	0.98	35.72	This study
Red Sea, Sudan	60.5	0.22	146.65	N/A	Gaiballa, 2023
North Sumatra, Indonesia	12.15	0.37	16.29	6.95	Prartono et al., 2023
Sembilan Island, South Sulawesi	6.86	3.94	N/A	N/A	Rosalina et al., 2022
Madura Waters, Indonesia	2.01	N/A	N/A	4.35	Yona et al., 2021
Palau	1.0	0.02	61.1	8.0	Jeong et al., 2021
Coast of Sicily, Italy	8.91	25.6	11.89	64.4	Bonanno et al., 2020
Gulf of Suez, Egypt	1.73	0.55	N/A	5.10	Nour and El-Sorogy, 2020

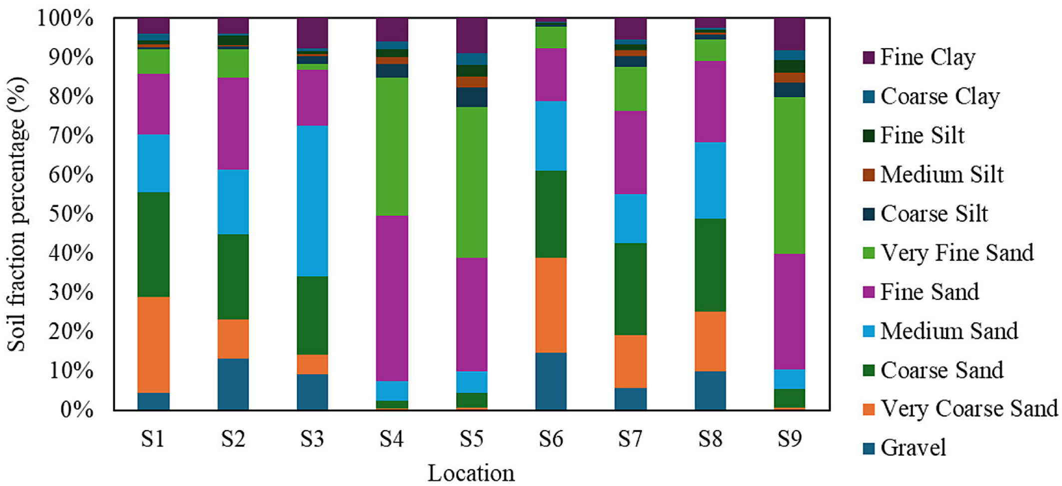

Figure 6. Percentage of soil fraction of each location in Benoa Bay, Indonesia

clear spatial variation in sediment texture (Figure 6), reflecting different depositional regimes and hydrodynamic energy conditions. Stations S1 and S6, for example, exhibited the highest proportion of coarse materials – S1 had a combined 57.8% of very coarse and coarse sand, while S6 had 14.9% gravel and 24.3% very coarse sand. These textures suggest high-energy conditions or proximity to coral debris, which typically limit metal adsorption due to low surface area.

In contrast, Stations S4, S5, and S9 were dominated by finer particles. S4 recorded 44.6% fine sand and 37.2% very fine sand, with only 0.1% gravel and negligible coarse sands – indicating a low-energy, depositional setting. S5 and S9 showed the highest percentages of fine clay (9.5% and 8.8%, respectively) and very fine sand (41.5% and 42.8%, respectively), suggesting high potential for heavy metal accumulation. These stations also correspond to elevated concentrations of Cd, Pb, and Cr, supporting the hypothesis that fine-textured soils with high surface area and cation exchange capacity act as effective sinks for metals (Chen et al., 2016; Zhang et al., 2014).

Meanwhile, Stations S2 and S3 represent transitional zones due to intermediate grain size distributions found (Bouchkara et al., 2024). S3 had the highest proportion of medium sand (41.3%), reflecting moderate energy conditions and possible episodic sediment input. While not as fine-textured as S5 and S9, S3 still showed elevated Cd concentrations (1.71 mg/kg), possibly due to the presence of 8.3% fine clay and 2.1% coarse silt that contribute to moderate adsorption capacity.

Overall, the spatial variation in soil texture across Benoa Bay plays a significant role in determining the retention, mobility, and distribution of heavy metals. Coarse-dominated soils such as at S6 exhibit low metal content due to limited binding surfaces, while finer soils at S5 and S9 act as accumulation zones—highlighting the importance of particle size analysis in understanding sediment-associated pollution patterns in coastal systems.

Relationship between heavy metal and soil fraction

The Pearson correlation analysis (Table 2) revealed clear and statistically significant relationships between soil particle size fractions and heavy metal concentrations. Coarser fractions (gravel, very coarse sand, and coarse sand) exhibited strong negative correlations with most metals. For instance, Cr showed the strongest inverse correlation with gravel ($r = -0.93$, $\rho = 0.0003$), followed by Cu with gravel ($r = -0.86$, $\rho = 0.0026$) and coarse sand ($r = -0.80$, $\rho = 0.0086$). These results indicate that coarse-textured soils tend to retain fewer heavy metals, likely due to lower surface reactivity and ion exchange capacity, as supported by Hu et al. (2018).

Conversely, finer soil fractions such as coarse silt, medium silt, and fine clay showed strong positive correlations with all four metals. Notably, Cr correlated very strongly with medium silt ($r = 0.98$, $\rho = 0.0001$) and coarse silt ($r = 0.97$, $\rho = 0.00001$), while Cd correlated most strongly with fine clay ($r = 0.92$, $\rho = 0.0002$). Similarly, Pb and Cu showed significant correlations with fine clay ($r = 0.89$ and $r = 0.87$, respectively; both $\rho = 0.0006$ and 0.0031). These findings are consistent with the principle that fine-grained soils provide higher specific surface area, organic matter content, and metal oxide coatings, which enhance their capacity to bind metal ions (Zhang et al., 2014; Refaey et al., 2017). The presence of multiple significant correlations across fine fractions suggests that metal retention is not limited to a single particle size but rather reflects a cumulative effect of interrelated fine materials. This further validates the hypothesis that soil texture is a dominant factor influencing the distribution and immobilization of heavy metals in coastal environments.

These relationships are not merely physical but are also influenced by geochemical factors, such as redox potential, mineral composition, and organic matter content, which play important roles in determining the stability, mobility, and binding affinity of metals in soils (Chen et al., 2016). The strong correlations observed between Pb and coarse silt ($r = 0.73$, $\rho = 0.0324$), medium silt ($r = 0.71$, $\rho = 0.0164$), and fine clay ($r = 0.89$, $\rho = 0.0617$) suggest that lead tends to bind preferentially to colloidal particles and accumulate in depositional zones rich in reactive surfaces (Huang et al., 2020). Furthermore, the consistency of significant positive correlations across several fine fractions underscores that metal retention is not confined to a single particle class but rather reflects a complex interaction among multiple fine-textured components. Overall, these findings confirm that soil texture and composition are critical factors in governing the geochemical behavior of heavy metals in dynamic coastal environments.

Environmental implications and scientific significance

The results of this study confirm that soil particle size distribution plays a fundamental role in controlling the accumulation of heavy metals in coastal environments. The strong positive correlations between fine fractions – such as fine clay, coarse silt, and medium silt – and heavy metals including Cd, Pb, Cu, and Cr indicate that finer-grained sediments act as efficient sinks for contaminants. These findings are especially important given that the highest concentrations of Cd, Pb, and Cr were found in stations located near known anthropogenic sources such as a landfill

Table 2. Pearson correlation of heavy metal and soil fraction

Location	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	References
Benoa Bay, Indonesia	22.00	0.71	0.98	35.72	This study
Red Sea, Sudan	60.5	0.22	146.65	N/A	Gaiballa, 2023
North Sumatra, Indonesia	12.15	0.37	16.29	6.95	Prartono et al., 2023
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Madura Waters, Indonesia	2.01	N/A	N/A	4.35	Yona et al., 2021
Palau	1.0	0.02	61.1	8.0	Jeong et al., 2021
Coast of Sicily, Italy	8.91	25.6	11.89	64.4	Bonanno et al., 2020
Gulf of Suez, Egypt	1.73	0.55	N/A	5.10	Nour and El-Sorogy, 2020

Note: *correlation significant at level $\rho < 0.05$, ** at $\rho < 0.01$.

(S5) and a port docking area (S9), highlighting the urgent need for targeted environmental monitoring and pollution mitigation strategies in such zones. Furthermore, the spatial variation in both texture and metal concentration reinforces the value of integrating granulometric analysis into baseline assessments in dynamic coastal systems like Benoa Bay.

From a scientific perspective, this study advances the understanding of geochemical and physical controls on metal retention in tropical coastal soils. While previous studies have often described metal pollution in surface sediments, fewer have quantitatively linked it to specific soil fractions using correlation analysis across a gradient of depositional environments (Mardani et al., 2018; Suteja et al., 2020; Putri et al., 2024). The combined use of detailed particle size analysis, multi-element heavy metal testing (Pb, Cu, Cd, Cr), and statistical correlation (Pearson) in this research provides an empirical model that can be replicated in other tropical bays facing similar pressures from urbanization, reclamation, or maritime activity. It also strengthens the mechanistic explanation that fine sediments offer higher surface area and metal-binding capacity through mineral and organic matter interactions.

Given the accelerating pace of coastal development in Indonesia, particularly in reclaimed and semi-enclosed bays such as Benoa Bay, the integration of sediment-based indicators into ongoing environmental monitoring frameworks is increasingly warranted. By adopting particle-size-informed risk assessments, stakeholders – including regulatory agencies, environmental consultants, and local governments – can better identify zones of ecological vulnerability and prioritize resources more effectively. Such evidence-based approaches will be vital for ensuring sustainable coastal management in the face of growing anthropogenic stressors.

CONCLUSIONS

This study demonstrates a clear and statistically supported relationship between heavy metal concentrations and soil particle size in Benoa Bay, Indonesia. Spatial analysis revealed that areas adjacent to anthropogenic sources – such as landfills and port facilities – consistently exhibited higher concentrations of Pb, Cu, Cd, and Cr, with cadmium notably exceeding soil quality guideline thresholds at several locations. Soil texture analysis further showed that heavy metals tend to accumulate in finer fractions – especially fine clay, medium silt, and coarse silt – due to their larger surface area and greater capacity for metal binding, as confirmed by strong positive Pearson correlations. Conversely, coarse fractions such as gravel and coarse sand were negatively correlated with metal concentrations, indicating a lower potential for retention.

These findings confirm the initial hypothesis that fine-grained soils act as dominant sinks for metal pollutants in semi-enclosed coastal systems. The integration of particle size analysis with heavy metal quantification and correlation analysis provides a novel approach for identifying contamination hotspots and understanding sediment-bound pollutant dynamics. This methodological framework contributes not only to the scientific understanding of coastal geochemistry but also offers practical value for environmental monitoring, particularly in regions undergoing rapid development and reclamation. Future research may expand on this by incorporating organic matter and redox-sensitive parameters to further refine metal retention models in tropical sediment environments.

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