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Multi-Species Bioaccumulation and Risk Assessment of Heavy Metals in a Tropical Industrial Coastline: Sentinel-Based Insights from the Philippines

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ABSTRACT

This research applies an integrated biomonitoring framework that combines bioaccumulation metrics (BSAF, BAF) and toxicological risk indices (EDI, HQ) to assess heavy metal contamination (Pb, Cd, and Hg) along a tropical industrial coastline in Iligan City, Philippines. Multi-trophic bioindicators (*Anadara* sp., *Terapon jarbua,* and *Padina* sp.) were analyzed across three coastal sites to trace sediment-associated and waterborne exposure pathways. Pb exhibited distinctive accumulation patterns, with sediment concentrations ranging from 5.37 to 5.43 mg/kg, closely matching those detected in Anadara sp. (5.40–5.79 mg/kg) and exceeding the levels observed in *T. jarbua* (2.33–3.38 mg/kg). This affirms its role as an effective sentinel for sediment-associated Pb exposure and highlights the link between sediment and biota. Significant differences among environmental compartments (Kruskal-Wallis, $p < 0.05$) further indicate pathway-specific uptake, with bivalves linked to sediment exposure and fish reflecting mixed trophic and waterborne inputs. Risk assessment showed higher exposure in *Anadara* sp. (HQ = 0.206) than in *T. jarbua* (HQ = 0.183), with bivalve concentrations exceeding Philippine regulatory limits but remaining within EU thresholds. Despite this, HQ values < 1 indicate no immediate non-carcinogenic risk under current consumption assumptions. Cd and Hg were below detection limits, including in the macroalgae sample, *Padina* sp., identifying Pb as the primary contaminant of concern. By integrating bioaccumulation and exposure metrics, this research provides a systems-based framework for tracing contaminant pathways and assessing seafood safety in rapidly urbanizing tropical coastal systems.

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INTRODUCTION

Heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg) naturally enter coastal systems through rock weathering, volcanic activity, and sediment transport (Tchounwou et al., 2012; Gavas et al., 2026; Guan et al., 2026). Human activities—industrial discharge, urban runoff, and mining—greatly amplify these inputs. Persistent and toxic, these metals bioaccumulate and move through aquatic food webs (Tchounwou et al., 2012; Gavas et al., 2026; Guan et al., 2026). These metals are non-essential and hazardous, with harmful effects on organisms and humans even at low concentrations (Rafi et al., 2021; Afzaal et al., 2022; Taslima et al., 2022). Through bioaccumulation and biomagnification, such pollutants pose serious risks to ecosystem integrity and public health (Adani et al., 2022; Pan and Han, 2023; Guan et al., 2026; Farukuzzaman et al., 2026).

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Biomonitoring with aquatic organisms—particularly fish and mollusks—is a reliable approach for assessing metal contamination, as these bioindicators reflect the biologically available fraction of pollutants (Gerhardt, 2002; Holt, 2010; Parmar et al., 2016; Adani et al., 2022; Singh and Gupta, 2021; Chahouri et al., 2023; Swam et al., 2023; Jolaosho et al., 2024; Taslima et al., 2022; Gao et al., 2025). Unlike chemical measurements, they integrate exposure across environmental compartments, providing a more comprehensive view of contamination. Multi-species monitoring enhances ecological representation and improves early detection in complex coastal systems (Lee et al., 2021; Amin et al., 2022; Donaher et al., 2024; Farukuzzaman et al., 2026). Benthic bivalves such as *Anadara* sp. indicate sediment-associated exposure (Khatri and Tyagi, 2015; Swam et al., 2023; Niloy et al., 2024; Gavas et al., 2026), while demersal fish like *T. jarbua* integrate dietary and waterborne pathways across variable salinity patterns (Zhang et al., 2012; Lakshmanasenthil et al., 2013; Authman et al., 2015).

Ecotoxicological studies increasingly integrate bioaccumulation metrics with human health risk assessments. In Malaysia's Santubong Estuary, for instance, BAF, Igeo, and health indices (HRI, HI) were combined to evaluate Cd and Pb risks in water, sediment, fish, and prawn (Lee et al., 2021). Similar approaches applied to *R. philippinarum* in China used dietary risk metrics such as EDI, THQ, and HQ, revealing potential health risks from mollusk consumption under elevated Pb exposure (Yang et al., 2013; Islam et al., 2018; Zhang et al., 2012; Niloy et al., 2024; Farukuzzaman et al., 2026). In the Red Sea, Amin et al. (2022) further demonstrated species-specific differences in Pb uptake across fish, crabs, and squid using bioaccumulation factors, linking environmental exposure pathways with human health risk assessments across multiple trophic levels.

In the Philippines, research on metal contamination and health risks is increasing, yet most studies remain species-specific. Toxicological risk metrics such as THQ, HI, and EDI have been applied to *O. niloticus, C. macrocephalus, C. fluminea,* and *Mytilus* (Oquiñena-Paler and Ancog, 2014; Dela Cruz et al., 2017; Raju et al., 2021; Merencillo et al., 2024; Balingit et al., 2024; Villacarlos et al., 2025). International studies emphasize combining bioaccumulation metrics with health risk indices across environmental compartments, yet multi-trophic indicators—such as benthic bivalves, demersal fish, and macroalgae—are still underutilized in tropical industrial coasts, despite their relevance for ecosystem and public health.

To address this gap, the present research applies an integrated multi-species approach that traces contaminant movement across environmental compartments using Biota–Sediment Accumulation Factor (BSAF) and Bioaccumulation Factor (BAF) (McGeer et al., 2003; DeForest et al., 2007; Burkhard, 2009; Djikanović et al., 2018; Jolaosho et al., 2024), alongside human exposure metrics such as Estimated Daily Intake (EDI) and Hazard Quotient (HQ). By linking ecological bioaccumulation with human health risk assessment (Maynard, 2000; Islam et al., 2018; Zhang et al., 2012; Niloy et al., 2024; Jolaosho et al., 2024; Farukuzzaman et al., 2026), this approach provides a systems-based evaluation of contaminant transfer across trophic levels in a tropical industrial coastline.

Pb bioaccumulation was assessed using co-occurring mollusk and fish bioindicators to link environmental exposure with seafood safety directly. Ancillary screening for Cd, Hg, and *Padina* sp. was also performed; although concentrations were below detection limits (BDL), their inclusion provides baseline data for future multi-contaminant assessments and reinforces Pb as the primary contaminant of concern in the research area.

MATERIALS AND METHODS

Iligan City in Northern Mindanao is a highly industrialized coastal system, with cement factories, steel plants, food processing facilities, and port infrastructure concentrated along its southeastern shoreline (Castañeto and Lacuna, 2015). These activities contribute to metal inputs

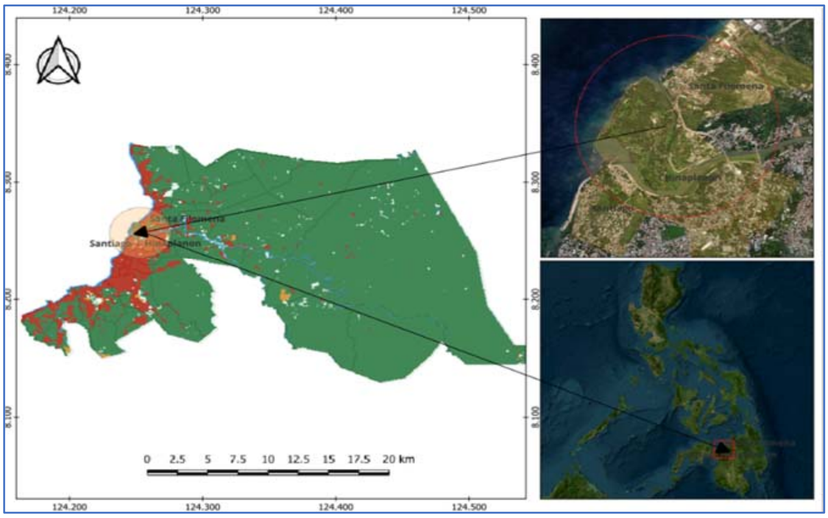

Fig. 1. Map of the research area in Iligan City, Northern Mindanao, Philippines, showing the spatial distribution of the three sampling, representing varying degrees of potential heavy metal exposure.

Fig. 2. Representative bioindicator species collected from the three sampling stations in Iligan Bay: (a) *T. jarbua* (marine fish) and (b) *Anadara* sp. (bivalve mollusks). These species were selected for their ecological relevance and capacity to bioaccumulate lead (Pb).

Padina sp. was included in the sampling but is not illustrated, as it functioned as a supporting primary producer indicator and yielded values below detection limits

through industrial discharge, urban runoff, and watershed transport. Three sites were selected to represent varying levels of anthropogenic influence, based on land use, proximity to pollution sources, and satellite-verified field observations.

Santa Filomena is the most industrialized site, adjacent to multiple manufacturing facilities and the abandoned ILICOCO plant, with additional inputs from Lugait, Kiwalan, and Dalipuga. Hinaplanon is less industrial but receives pollutants via the Mandulog River, which drains urban and resource-extraction areas (De Guzman et al., 2015). Santiago is primarily residential yet exposed to runoff from built-up zones. Sampling was conducted at low tide in November 2023 under consistent tidal conditions to ensure comparability.

Biological and environmental sampling

To assess site-specific metal uptake and trophic transfer, three bioindicator species were selected: *Anadara* sp., a benthic bivalve, *T. jarbua*, referred locally as *'bugaong,'* a demersal, catadromous fish, and macroalgae *Padina* sp. (Figure 2). These species were collected from each sampling site based on their ecological roles, commercial importance, local abundance, and known capacity for heavy metal bioaccumulation in coastal environments. *Padina* sp.

samples were collected opportunistically near sediment and water sampling points to represent primary producer exposure within the same environmental setting.

At each site, biological samples were composited to represent integrated exposure, ensuring representative tissue concentrations for each location. Immediately after collecting, samples were rinsed with ambient seawater to remove sediments, epiphytes, and debris. About 1 kg of whole *Anadara* sp. (with shells) was collected at each site, roughly 25–30 individuals depending on size, while 1 kg of *T. jarbua* equated to around 6–10 specimens. Biological samples were stored at −20 °C before analysis to preserve tissue integrity and minimize post-collection alteration.

Specimen identification was initially guided by local fishers and later validated by faculty at Mindanao State University–Naawan. Although locally referred to as *"Balinsala*," morphological traits aligned more closely with *A. granosa* than *A. antiquata* or *"Litob*". In the absence of molecular or morphometric confirmation, specimens are conservatively reported as *Anadara* sp. throughout this paper.

Surface sediments (0–5 cm) were collected using a PVC corer from three spatially distinct sampling points per site. Sediment samples from each point were processed and analyzed separately, with each sample measured in triplicate to ensure analytical precision. Water samples were collected from the same points using sterile 500 mL polyethylene bottles, while biota and sediments were stored in polyethylene bags. Samples were labeled and transported on ice. Upon arrival at the laboratory, water samples were stored at 4 °C, while sediment samples were air-dried before further processing.

All sample collection, including tissue preparation and extraction, was conducted using non-metallic materials to minimize contamination and interaction with heavy metals. These procedures are consistent with established protocols emphasizing contamination control and a standardized handling outlined in the USEPA (2001) module.

Biological and environmental media sample preparation

Whole soft tissues of bivalves were analyzed, noting that predators typically consume the entire mollusk body, making full-tissue quantification more ecologically realistic for trophic transfer assessments (Yam et al., 2020; Niloy et al., 2024; Jolaosho et al., 2024). While fish samples were deboned, edible tissues were retained, excluding the digestive tract and gonads, for analysis to align with human dietary exposure pathways. Samples were air-dried for 24 hours, and then oven-dried at 60 °C until a constant weight was reached, homogenized, and analyzed in triplicate.

Sediment samples were processed separately to ensure they remained representative. Dried sediments were mixed and sieved to <63 µm using a non-metallic sieve to separate the geochemically active fraction. These procedures adhere to sediment handling and processing protocols to ensure consistent samples and reliable analysis (U.S. EPA, 2001; Siddique et al., 2025; Farukuzzaman et al., 2026; Guan et al., 2026).

Following (Roa et al., 2010; Yam et al., 2020; Niloy et al., 2024; Siddique et al., 2025; Farukuzzaman et al., 2026), a 1 g homogenized sample of biota and sediments was placed in a glass beaker and digested with 5 mL (1+1) HNO_3 and 10 mL (1+4) HCl. The beaker was covered with a ribbed watch glass and heated under reflux at about 95 °C in a fume hood for 30 minutes, avoiding vigorous boiling to prevent losing volatile components. Once cooled, the digested samples were transferred and diluted to 100 mL with reagent water, then mixed thoroughly.

For water samples, a 100 mL water sample was filtered and transferred to a beaker. 5 mL of concentrated HNO_3 was added, and the sample was gently heated to near boiling on a hot plate until it reduced to 10 mL without drying out. More HNO_3 was added until digestion was complete, indicated by a clear, light-colored solution. The digest was cooled, rinsed with deionized water, and filtered with the same filter used in the initial filtration. The filtrate was transferred and diluted to 100 mL in a volumetric flask.

Heavy metal detection

Heavy metal concentrations were quantified using Microwave Plasma–Atomic Emission Spectroscopy (MP-AES, Agilent 4200), calibrated with certified standards following Perkins (1996). All analyses were conducted at the Mindanao State University – Institute of Fisheries Research and Development (MSU-IFRD), Naawan, Philippines.

Quality control samples (QCS) were analyzed throughout the procedure to verify calibration performance, using the same acid matrix as the standards but prepared independently in accordance with USEPA (1979) guidelines, and in Jolaosho et al. (2024). Detection limits were established at 0.10 mg/kg for solid samples and 0.001 mg/L for water, consistent with Skoog et al. (2017). Values below these thresholds were classified as below detection limit (BDL) and interpreted as concentrations below analytical sensitivity rather than absence of contaminants.

Ecological risk assessment

The ecological risk of Pb bioaccumulation was evaluated by relating tissue concentrations to those in sediments and water. Biota–Sediment Accumulation Factor (BSAF) was calculated as the ratio of tissue concentration to sediment concentration, while the Bioaccumulation Factor (BAF) was defined as the ratio of tissue concentration (mg/kg) to ambient water concentration (mg/L), following standard coastal biomonitoring approaches (Burkhard, 2009; DeForest et al., 2007; Djikanović et al., 2018; Jolaoshoet al., 2024), calculated using the equation:

$$BSAF = C_b/C_s$$
$$BAF\ (L/kg) = C_b/C_w$$

Where: BAF = bioaccumulation factor (L/kg), BSAF = biota-sediment accumulation factor (dimensionless), Cb = concentration of metal in fish (µg/g dw), Cs = concentration of metal in sediment (µg/g dw), and Cw = concentration of metal in water (mg/L).

Statistical analysis

Normality and variance were first tested using Shapiro–Wilk and Levene's tests. When parametric assumptions were met, one-way ANOVA was applied, followed by Tukey's HSD for post-hoc comparisons. Because several datasets did not satisfy normality or homogeneity criteria, non-parametric approaches were adopted, with Kruskal–Wallis used for group comparisons and Mann–Whitney U for pairwise tests. Statistical significance was set at $p < 0.05$.

Toxicological risk assessment

Toxicological risk assessment followed U.S. Environmental Protection Agency (EPA) protocols outlined in the Risk Assessment Guidance for Superfund (RAGS; USEPA, 1989), employing Estimated Daily Intake (EDI) and Hazard Quotient (HQ) to evaluate non-carcinogenic risks. The reference dose (RfD) for Pb was set at 0.0035 mg/kg/day, consistent with values from IRIS (USEPA, 2004) and the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2011), following approaches used in prior studies (Islam et al., 2018; Fang et al., 2020; Yam et al., 2020; Niloy et al., 2024; Jolaosho et al., 2024; Farukuzzaman et al., 2026).

The EDI estimates the average daily Pb intake through seafood consumption and was calculated as: $EDI = \frac{C \times IR}{BW}$

The HQ, which indicates a potential health risk, was computed as: $HQ = \frac{EDI}{RfD}$

Where: C = Pb concentration in tissue (mg/kg ww); IR = ingestion rate (0.03 kg/day for

Table 1. Summary of the Pb results detected from the selected bioindicator species, sediment (mg/kg), and water samples (mg/L).

Sites	*Anadara* sp.	*T. jarbua*	Sediments	Water
Santiago	5.46 ± 0.11	2.33 ± 0.14	5.38 ± 0.03	0.013 ± 0.002
Hinaplanon	5.40 ± 0.02	3.15 ± 0.11	5.37 ± 0.03	0.018 ± 0.001
Santa Filomena	5.79 ± 0.10	3.38 ± 0.12	5.43 ± 0.05	0.022 ± 0.003

Note: Cd and Hg concentrations across all matrices, including Padina sp., were below detection limits (0.10 mg/kg for solids; 0.001 mg/L for water) and were therefore excluded from quantitative analyses.

mollusks, 0.05 kg/day for fish); BW = body weight (60 kg, average adult). HQ ≥ 1 indicates a potential health risk. Site-averaged Pb concentrations were used to calculate EDI and HQ values for clarity in reporting in the main text.

Tissue Pb concentrations measured on a dry-weight basis were converted to wet-weight concentrations using a dry-matter conversion factor of 0.26. Site-averaged Pb concentrations were used for the dietary exposure assessment. Pb concentrations in Anadara sp. and T. jarbua were compared with the applicable national food-safety standard (BFAR, 2001) and relevant Codex Alimentarius maximum levels for lead (CXS 193-1995). Dietary exposure and noncarcinogenic risk were subsequently assessed using the EDI and HQ framework described above.

RESULTS AND DISCUSSION

The subsequent section highlights lead (Pb) levels in sediment and biotic tissues from three Iligan City coastal sites. Pb concentrations across environmental compartments are summarized in Table 1. These data establish the basis for evaluating compartment-specific accumulation, spatial variation, and associated exposure risks. Each outcome is considered in relation to ecological exposure pathways, bioaccumulation, and seafood safety.

Sediment as the primary reservoir

Pb concentrations in surface sediments were consistently detected across all three sites, with mean values of 5.38 ± 0.03 mg/kg at Station 1, 5.37 ± 0.03 mg/kg at Hinaplanon, and slightly higher at 5.43 ± 0.05 mg/kg at Santa Filomena (Table 1). The consistent distribution suggests persistent, diffuse contamination influenced by terrestrial runoff, atmospheric deposition, and industrial inputs.

Sediment characteristics further influence Pb retention. The research area is dominated by fine-grained sediments (i.e., silt and clay fractions) derived from weathered terrestrial materials and coastal depositional processes. These materials, often associated with aluminosilicate minerals and organic matter, enhance the adsorption and accumulation of metals such as Pb, reinforcing the role of sediments as long-term contaminant reservoirs (Adani et al., 2022; Donaher et al., 2024; Guan et al., 2026).

Compared with other studies, Pb levels in Iligan Bay are lower than those reported in Manila Bay (14.49 mg/kg; Olivares et al., 2019), Bafa Lake, Türkiye (13.75 mg/kg; Algul and Beyhan, 2020), the Lahug River, Cebu (6.22–39.33 mg/kg; Alburo and Villegas 2025), and urban rivers in Leyte (6.23–21.36 mg/kg; Siddique et al., 2025). Nevertheless, the consistent detection across all stations indicates a chronic contamination pattern with potential for trophic transfer.

In contrast to riverine systems, where elevated concentrations are often linked to direct point-source discharges, the coastal pattern observed in Iligan reflects cumulative inputs from diffuse terrestrial runoff, watershed processes, and atmospheric deposition.

Bivalve mollusk as a benthic sentinel

Pb concentrations in *Anadara* sp. tissues were consistently elevated across stations, ranging from 5.40 ± 0.02 mg/kg at Hinaplanon to 5.46 ± 0.11 mg/kg at Santiago, with a maximum of 5.79

± 0.10 mg/kg at Santa Filomena (Table 1). This pattern closely reflects the relatively uniform Pb levels observed in surface sediments across the research sites, indicating a strong linkage between sediment contamination and biological uptake. The slightly higher concentration at Station 3 likely corresponds with localized inputs from stormwater-driven runoff, which can mobilize Pb from urban and industrial surfaces into coastal waters.

As sedentary benthic filter-feeders, *Anadara* sp. integrate exposure across multiple environmental compartments, including direct sediment contact, suspended particulate ingestion, and water filtration (Khatri and Tyagi, 2015; Singh and Gupta, 2021; Chahouri et al., 2023; Jolaosho et al., 2024; Donaher et al., 2024). This sediment–biota coupling highlights their sensitivity to the bioavailable fraction of Pb within the benthic system and explains the close correspondence between sediment concentrations and tissue accumulation.

Their consistent accumulation patterns reinforce the use of bivalves as key indicators for tracing sediment-associated contamination and trophic transfer in coastal systems (Khatri and Tyagi, 2015; Januar et al., 2019; Singh and Gupta, 2021; Swam et al., 2023; Chahouri et al., 2023; Niloy et al., 2024; Jolaosho et al., 2024; Gavas et al., 2026).

Crescent-banded grunter (T. jarbua, Forsskål 1775) as an integrative indicator

Pb was consistently detected in *T. jarbua* across all stations, ranging from 2.33 ± 0.14 mg/kg at Santiago to 3.38 ± 0.12 mg/kg at Santa Filomena (Table 1), exceeding concentrations reported in the Bay of Bengal (0.80 ± 0.16 mg/kg; Lakshmanasenthil et al., 2013) and indicating elevated exposure under industrialized coastal conditions.

As a benthic–demersal species, *T. jarbua* integrates Pb exposure across both sediment-associated and waterborne pathways through feeding as well as gill and dermal uptake (Zhang et al., 2012; Authman et al., 2015). This multi-pathway uptake reflects coupling between benthic and pelagic compartments, particularly in systems influenced by runoff and sediment disturbance.

The higher concentrations observed at Station 3 further suggest sensitivity to localized inputs, such as stormwater-driven pulses. By occupying a mid-trophic position, *T. jarbua* provides a link between environmental contamination and potential dietary exposure, supporting its use as a sentinel for both ecosystem condition and human health risk in coastal systems (Zhang et al., 2012; Lakshmanasenthil et al., 2013; Authman et al., 2015).

Ancillary findings: Macroalgae (Padina sp.) As the primary producer baseline

Padina sp., along with all Cd and Hg measurements, were below detection limits (0.10 mg/kg), indicating concentrations below analytical sensitivity rather than ecological absence. These BDL values likely reflect lower inputs or dilution effects within the research area (Skoog et al., 2017). While limiting quantitative comparison, the inclusion of *Padina* sp. extends trophic coverage by representing primary producer pathways. In contrast, consistent Pb detection across biota and sediments reinforces Pb as the dominant contaminant and highlights system-level differences in metal behavior. Previous studies confirm that *Padina* can accumulate metals under elevated loading (Supardi and Puspito-Nugroho, 2019; Ho and Bantoto-Kinamot, 2021).

Ecological risk assessment

BSAF and BAF values (Figure 4a and 4b) reveal distinct Pb accumulation patterns between bivalves and fish, reflecting differences in exposure pathways across environmental compartments. *Anadara* sp. exhibited BSAF values consistently >1.0 (1.01–1.07), indicating Pb uptake at or above sediment concentrations (Figure 4a).

As a sedentary benthic filter-feeder inhabiting fine-grained substrates, *Anadara* maintains prolonged contact with contaminated sediments, facilitating uptake through both particulate ingestion and diffusive exchange. In contrast, *T. jarbua* showed lower BSAF values (0.43–

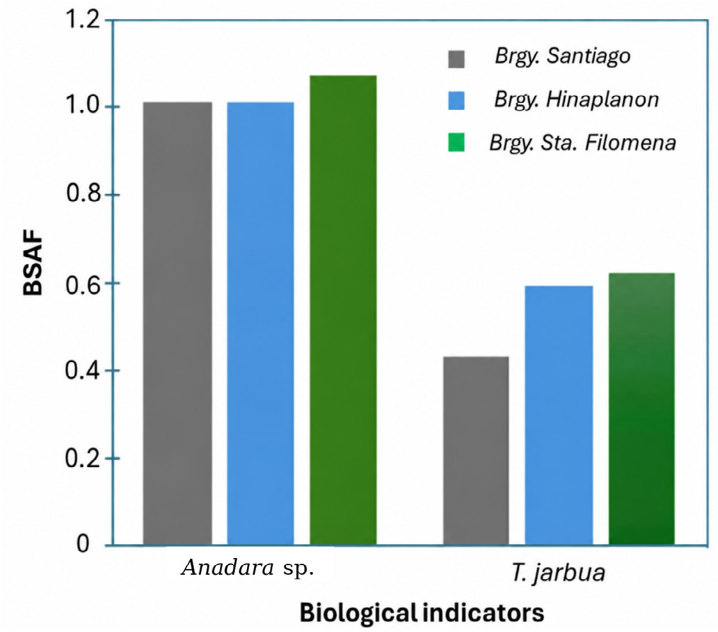

Fig. 4a. Biota–Sediment Accumulation Factor (BSAF) of Pb for *Anadara* sp. and *T. jarbua* across sampling sites, indicating sediment-associated uptake patterns.

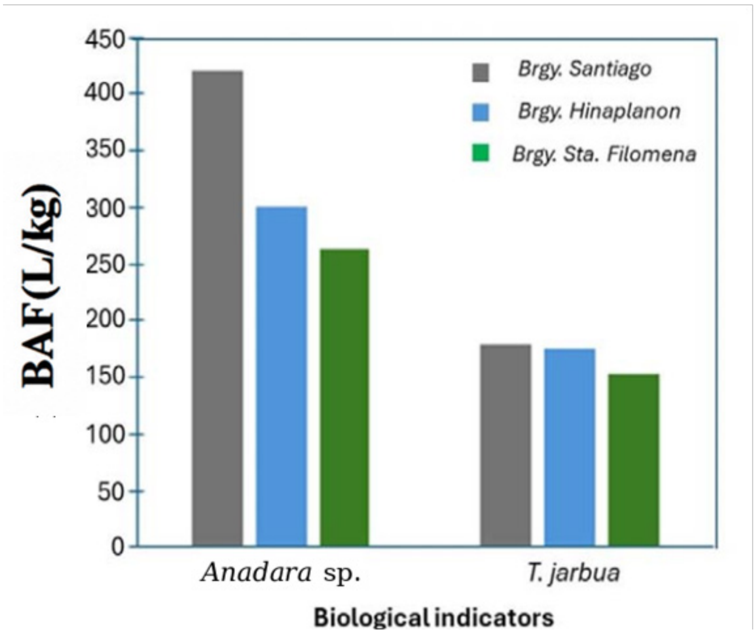

Fig. 4b. Bioaccumulation factor (BAF) of Pb for *Anadara* sp. and *T. jarbua* across sampling sites, reflecting dissolved-phase exposure pathways.

0.62), indicating weaker sediment coupling and greater reliance on trophic and waterborne exposure pathways.

Similar patterns have been reported, with bivalves closely tracking sediment contamination, while demersal fishes exhibit lower sediment fidelity and stronger dietary-mediated metal acquisition (Burkhard, 2009; Authman et al., 2015; Gupta and Banerjee, 2016; Djikanović et al., 2018; Chahouri et al., 2023).

Table 2. Statistical differences in Pb concentrations across environmental compartments

Comparison	Test	p-value
All compartments	Kruskal–Wallis	1.81×10^{-5} ***
Anadara vs *T. jarbua*	Mann–Whitney U	0.0023 **
Anadara vs Sediment		1.000 ns
Anadara vs Water		0.0032 **
T. jarbua vs Sediment		0.016 *
T. jarbua vs Water		0.145 ns

*Non-parametric tests were used due to violations of normality and homogeneity of variance (see Supplementary Table S4). Significance levels ns = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.*

Waterborne exposure insights

Although waterborne Pb was not the primary focus, BAF values provide insight into dissolved-phase exposure pathways. BAF values ranged from 263.2–420.0 L/kg for *Anadara* sp. and 153.6–179.2 L/kg for *T. jarbua* (Figure 4b). While these values are below the threshold of 1,000 L/kg threshold for strong waterborne bioaccumulators, they indicate measurable uptake from the dissolved phase, particularly in *Anadara* sp.

The higher BAF observed in *Anadara* likely reflects continuous filtration and prolonged residence within Pb-exposed microhabitats, facilitating sustained interaction with dissolved contaminants. In contrast, lower BAF values in *T. jarbua* suggest reduced reliance on dissolved uptake and greater influence of dietary and sediment-associated pathways, consistent with its mobility and feeding behavior (Arnot and Gobas, 2006).

The observed species-specific accumulation patterns reflect a linked exposure continuum from environmental sources to biological uptake. Sediments act as the primary reservoir of Pb, with the bivalve mollusk capturing sediment-associated exposure, while the fish integrates waterborne and trophic pathways. As emphasized in Burkhard (2009), DeForest et al. (2007), and McGeer et al., 2003, Jolaosho et al., 2024 bioaccumulation factors for metals are highly variable and often inversely related to exposure concentrations, with uptake regulated by physiological processes, dietary pathways, and environmental bioavailability rather than simple direct relationships with environmental concentrations.

Statistical results

Inferential analyses assessed Pb variation across *Anadara* sp., *T. jarbua*, sediments, and water. Shapiro–Wilk and Levene's tests indicated deviations from normality and homogeneity, supporting non-parametric methods. A Kruskal–Wallis test confirmed significant differences among compartments ($p < 0.001$), with post hoc results showing higher Pb in sediments and *Anadara* sp. relative to water and *T. jarbua*. No significant differences were observed between sediments and Anadara sp., or between fish and water (Table 2).

This structure reflects compartment-specific exposure pathways. The similarity between sediments and *Anadara* sp. indicates strong sediment–biota coupling via benthic uptake of bioavailable Pb. In contrast, lower and comparable levels in *T. jarbua* and water suggest weaker sediment linkage and greater reliance on trophic and dissolved-phase pathways. Overall, these patterns show Pb partitioning across compartments and species-specific uptake, underscoring the value of multi-indicator approaches for resolving contaminant dynamics in industrial coastal systems.

Toxicological risk and regulatory compliance assessment in seafood bioindicators

Estimated daily intake (EDI) values of Pb from *Anadara* sp. and *T. jarbua* were 0.000722 and 0.000640 mg/kg/day, respectively, both well below the chronic oral reference dose (0.0035 mg/kg/day; USEPA, 2004; Joint FAO/WHO Expert Committee on Food Additives [JECFA], 2011. Corresponding hazard quotients (HQ) of 0.206 and 0.183 (Table 3) indicate no immediate

Table 3. Estimated Daily Intake (EDI) and Hazard Quotient (HQ) of lead (Pb) through consumption of *Anadara* sp. and *T. jarbua*, with comparison to local and international maximum limits (MLs) for Pb in seafood commodities.

Commodity	Pb Tissue (mg/kg/ww)	EDI (mg/kg/day)	HQ	ML: EU Regulation 1881/2006 (mg/kg)	ML: DA- FAO 210-01 (mg/kg)	Portion of the commodity to which the ML applies
Mollusk	1.443	0.000722	0.206	1.50	0.50	(whole tissue)
Fish	0.768	0.000640	0.183	0.30	0.50	Whole tissue (excluding digestive tract)

Other regulatory guidelines, such as PNS 194:2022 and Codex CXS 193-1995, were excluded from the comparison table for bivalve mollusks due to the absence of Pb-specific MLs for this commodity. All raw data and detailed computations of toxicological risk assessments (EDI and HQ) are available in the supplementary materials accompanying this manuscript

non-carcinogenic risk under current exposure conditions.

Although current HQ values remain below critical thresholds, the consistent detection of Pb across environmental compartments and biota indicates persistent trophic-level contamination. This suggests that risk is controlled not only by concentration thresholds but also by cumulative exposure pathways and ecological connectivity.

Although these findings do not indicate acute toxicity, they highlight the need for continued biomonitoring of benthic species in coastal areas exposed to industrial or urban runoff. According to Maynard (2000), chronic exposure to sub-threshold levels of Pb can still lead to cumulative health effects, and long-term Pb exposure may lead to neurodevelopmental and cognitive impairments, particularly in children.

CONCLUSION

Pb contamination in Iligan City shows a clear pathway from sediment to biota, with sediments acting as the primary reservoir. *Anadara* sp. reflects sediment-associated exposure, while *T. jarbua* integrates trophic and waterborne inputs, linking environmental conditions to potential human exposure.

By combining bioaccumulation (BSAF, BAF) with exposure indicators (EDI, HQ), this study improves the interpretation of contaminant transfer across compartments and supports multi–indicator, cross–trophic monitoring. However, these results represent a temporal snapshot. Variability in hydrodynamics, seasonal inputs, and episodic discharge may alter exposure pathways and bioavailability, underscoring the need for continued, system-based monitoring to support adaptive seafood safety and coastal management.

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CONFLICT OF INTEREST

The authors hereby affirm that they have no conflicts of interest related to the publication of this paper.

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Conceptualization: April Joy Montejo, Dr. Rey Y. Capangpangan; Methodology: Dr. Elnor C. Roa, Dr. Rey Y. Capangpangan, April Joy Montejo, Aida D. Perpetua, Sonnie A. Vedra; Validation: Dr. Elnor C. Roa, Dr. Rey Y. Capangpangan, April Joy Montejo; Formal Analysis: April Joy Montejo; Investigation: April Joy Montejo, Christian Dela Torre, Margie Rose Olbenario, Reycyl Guia, Jade Coñado, Jomar Besoña; Data Curation: April Joy Montejo, Christian Dela Torre, Margie Rose Olbenario, Reycyl Guia, Jade Coñado, Jomar Besoña; Original Draft Preparation: April Joy Montejo; Writing – Review & Editing: April Joy Montejo, Dr. Rey Y. Capangpangan; Supervision: Dr. Rey Y. Capangpangan

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