

Marine Mollusks as Bioindicators of Heavy Metal Contamination in the Aquatic Ecosystem of Guang-guang, Pujada Bay, Philippines

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ABSTRACT

This study investigated heavy metal contamination in water, sediment, and five (5) marine mollusk species (*Periglypta puerpera*, *Codakia tigerina*, *Anadara antiquata*, *Canarium erythrinum*, and *Lambis millepeda*) within Guang-guang, Pujada Bay, Davao Oriental, Philippines, assessing their bioindicator potential for Cadmium (Cd), Chromium (Cr), Nickel (Ni), Iron (Fe), and Lead (Pb). Heavy metal concentrations were determined using Atomic Absorption Spectroscopy, and the study also evaluated associated ecological and human health risks. Analysis of water and sediment revealed generally low concentrations of these metals, although Cr in water (0.06 mg/L) notably exceeded the DENR DAO No. 2016-08 (2016) standard of 0.05 mg/L and the United States Environmental Protection Agency (US EPA) (2002) of 0.05 mg/L indicating possible contamination. Significantly, heavy metal concentrations in mollusk tissues varied, with *L. millepeda* exhibiting a Cd concentration of 0.2 mg/kg, surpassing both the Codex Stan 193-1995 (amended 2023) limit (0.1 mg/kg) and the EU 1881/2006 (2006) limit (0.05-0.1 mg/kg), thereby posing a potential health risk to consumers. Biota-Water Accumulation Factors (BWAf) and Biota-Sediment Accumulation Factors (BSAF) demonstrated considerable bioaccumulation (values >1) for Cd, Cr, and Ni across several species, particularly in *L. millepeda*, highlighting its pronounced capacity to concentrate these metals from its environment even when ambient levels are low. Fe also showed extremely high BWAf values across all species, while Pb exhibited limited accumulation. These findings underscore that low environmental metal concentrations do not necessarily prevent accumulation in biota, emphasizing the critical role of marine mollusks as effective bioindicators for heavy metal pollution. Therefore, continued monitoring of both environmental matrices and bioindicator species is crucial for safeguarding the marine ecosystem and ensuring seafood safety in Guang-guang, Pujada Bay.

Keywords: Aquatic Ecosystem, Bioaccumulation, Bioindicator, Heavy Metals, Mollusks.

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INTRODUCTION

Marine ecosystems are crucial for global biodiversity and human well-being, yet they face increasing threats from persistent and toxic heavy metal pollution (Ahamad *et al.*, 2024; El-Sharkawy *et al.*, 2025). These contaminants can bioaccumulate through the food chain, posing significant risks to aquatic life and human health (Oros *et al.*, 2025; Radomyski *et al.*, 2018). While

conventional environmental monitoring often relies on heavy metal concentrations in water and sediment, these measurements may not fully reflect the actual biological exposure and accumulation within marine organisms. This results in a limited understanding of true ecological impacts and potential human health risks (Artar *et al.*, 2024; DeForest *et al.*, 2007).

Marine mollusks, owing to their sessile nature and filter-feeding habits, are widely recognized as effective bioindicators capable of concentrating contaminants in their tissues. This characteristic provides a more integrated and accurate measure of environmental contamination than abiotic sampling alone (Azratul *et al.*, 2017; Boudammoussi *et al.*, 2024; Ong and Yunus, 2019). However, the extent to which low environmental concentrations translate into hazardous levels in edible mollusks, and the species-specific differences in accumulation, necessitates



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comprehensive investigation to safeguard seafood safety and public health (Primost *et al.*, 2017; Swaleh *et al.*, 2016).

Pujada Bay, located in the City of Mati, Davao Oriental, is known for its exceptional ecological significance, encompassing rich coral reefs, expansive seagrass beds, and thriving mangrove forests (Sanchez-Delute *et al.*, 2025), and holds the classification of a protected landscape and seascape (Terayama *et al.*, 2021; Wang *et al.*, 2023). Despite its ecological importance, existing studies in the bay have indicated concerns regarding heavy metal presence, with reports of non-essential heavy metals like Cd and Pb in sea hare egg strings exceeding established standards (Tayone, 2017), alongside other heavy metal assessments in marine mollusks in the region (Tayone *et al.*, 2020). While these findings highlight a potential threat, a comprehensive, species-specific assessment that quantifies multiple heavy metal concentrations across all abiotic compartments (water, sediment) and five (5) distinct marine mollusk species within Guang-guang, Pujada Bay remains largely unexplored. The lack of detailed data on species-specific bioaccumulation patterns, particularly using Biota-Sediment Accumulation Factors (BSAF) and Biota-Water Accumulation Factors (BWAf), impedes a full understanding of the ecological implications and potential health risks to human populations that rely on these marine resources.

This study aimed to evaluate the concentration levels of Cd, Cr, Ni, Fe, and Pb in the water column, sediment, and five (5) selected mollusk species (*Periglypta puerpera*, *Codakia tigerina*, *Anadara antiquata*, *Canarium erythrinum*, and *Lambis millepeda*) from Guang-guang, Pujada Bay. Moreover, this research assessed the potential of mollusks as bioindicators and thoroughly analyzed bioaccumulation dynamics using BSAF and BWAf. This robust approach yielded a detailed understanding of metal contamination, its transfer, and the associated ecological and human health risks, which is essential for developing informed conservation strategies and ensuring the long-term sustainability and seafood safety of this vital marine ecosystem.

METHODOLOGY

Pujada Bay in the City of Mati, Davao Oriental (Figure 1), recognized as one of the world's most beautiful bays, is a protected area known for its rich coral reefs, seagrass beds, and mangrove forests (Proclamation No. 431, 1994). Prior to the study, approval was secured from the Protected Area Management Board through PAMB Resolution No. 8, Series of 2025.

A preliminary site inspection and interview with the local guide were conducted prior to sample collection. Five (5) sampling stations were strategically selected for mollusk collection based on species abundance and habitat suitability. The collected mollusk species, along with their local names and coordinates, were: *P. puerpera* (Bug-atan) (Linnaeus, 1758) at 6.91346°N, 126.26539°E; *C. tigerina* (Tambayang) (Linnaeus, 1758) at 6.91974°N, 126.25918°E; *A. antiquata* (Litob) (Linnaeus, 1758)

at 6.91346°N, 126.26547°E; *C. erythrinum* (Aninikad) (Dillwyn, 1817) at 6.91337°N, 126.26551°E; and *L. millepeda* (Lima-lima) (Linnaeus, 1758) at 6.90944°N, 126.26188°E (Figure 2).

Sample collection, preparation, and heavy metal analysis

Water Samples

Water samples were collected at a depth of 50 cm and stored in acid-washed plastic bottles. To ensure a representative analysis of the study area, composite water samples were prepared by combining subsamples from the five sampling locations. The collected samples were immediately placed in a cooler for transport to the Davao Oriental State University laboratory, where they were acidified and refrigerated at 4°C until analysis (American Public Health Association [APHA] *et al.*, 2017).

At least 100 mL of a well-mixed, acid-preserved water sample was digested with concentrated HNO₃ by gentle evaporation and refluxing until a clear or stable digest was obtained, followed by the addition of HCl to dissolve any residues. The digest was cooled, filtered to remove insoluble materials, transferred to a 100 mL volumetric flask, and diluted to volume with distilled water. Metal determination was performed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) after proper instrument start-up, calibration with multi-element standard solution bracketing expected concentrations, and blank correction. Samples were aspirated via the autosampler, with intermittent nebulizer rinsing using dilute HNO₃, and analyzed at element-specific wavelengths within the optimum concentration range.

Sediment Samples

Sediment sampling was done using a plastic shovel. Similar to the water sampling procedure, composite sediment samples were prepared by combining subsamples from the five sampling locations to obtain a representative measure of sediment characteristics across the study area. A one (1) kg sediment sample was placed in a polyethylene Ziplock bag. The sediment sample underwent air-drying for three (3) days. The dried sediments were packed in a polyethene Ziplock bag with proper labelling until its analysis.

For the analysis of heavy metals (Cd, Cr, Ni, Fe, and Pb), sediment samples were first thoroughly mixed and sieved to ensure homogeneity. A 1 g dry-weight sample was digested with 1:1 HNO₃ and heated at 95±5°C, followed by repeated addition of concentrated HNO₃ (not exceeding 10 mL) until complete oxidation was achieved. The digest was reduced, treated with water and 30% H₂O₂ to complete oxidation, reheated to near dryness, and finally refluxed with concentrated HCl at 95±5°C for 15 min to complete digestion. The digestate was then filtered through Whatman No. 41 filter paper (or equivalent), the filtrate collected in a 100 mL volumetric flask, made up to volume with deionized

water, and subsequently analyzed for metal concentrations using Atomic Absorption Spectrophotometry (AAS).

Mollusk Samples

About 250 g per mollusk (tissue) were collected. The collection involved manual harvesting using plastic shovels. The samples were washed with distilled water, and the tissue was separated from the shell by cracking the shell open using a wooden hammer and a plastic knife. The soft tissue was stored in a ziplock and kept in the freezer set to -20°C (Ebol *et al.*, 2020) until analysis. The separated shells were buried in a 2-foot-deep hole to prevent odor and ensure proper decomposition. Since the shell is composed of calcium carbonate, it poses no environmental harm and will naturally break down without causing pollution.

Mollusk sample preparation followed Association of Official Analytical Chemists (AOAC) 972.23, wherein approximately five (5) g of sample was dried at 135-150°C, ashed at 500°C overnight, and treated with HNO₃ to obtain a clean, carbon-free ash. The ash was dissolved in 1 M HCl with heating, transferred to a 25 mL volumetric flask, diluted to volume with 1 M HCl, and the resulting solution was analyzed by AAS (AOAC, 2000).

Bioindicator Potential Determination

The BWAf as shown in equation 1 represents the ratio of the concentration of a heavy metal in the tissue of an aquatic organism to its concentration in the surrounding water, while the BSAf as shown in equation 2 refers to the ratio of the concentration of a heavy metal in the organism's tissue to that in the sediment (Louma and Rainbow, 2008; Wang *et al.*, 2012; Rainbow, 2002). These two indices are widely used to describe the ability of aquatic organisms to absorb and retain metals from their environment. They help determine the extent of bioaccumulation, reflecting the potential exposure risks to aquatic life and humans through seafood consumption, the availability of heavy metals in the aquatic system, and the role of organisms as indicators of metal contamination (Rainbow, 2002; Bryan and Langston, 1992; Li *et al.*, 2010).

Biota-Water Accumulation Factor

$$BWAf = \frac{[HM]_{mollusk}}{[HM]_{water}} \quad (\text{Equation 1})$$

Where [HM]_{mollusk} - is the heavy metal concentration of mollusk

Where [HM]_{water} - heavy metal concentration of water

Biota-Sediment Accumulation Factor

$$BSAf = \frac{[HM]_{mollusk}}{[HM]_{sediment}} \quad (\text{Equation 2})$$

Where [HM]_{mollusk} - is the heavy metal concentration of mollusk

Where [HM]_{sediment} - is the heavy metal concentration of sediment

Statistical Analysis

Heavy metal concentrations in water, sediment, and mollusk tissues were summarized using descriptive statistics and reported in mg/L for water and mg/kg for sediment and biota. The measured concentrations were directly compared with relevant environmental and food safety standards to evaluate compliance and potential ecological and human health risks. Furthermore, bioaccumulation was evaluated using the (BWAf) and (BSAf). Values greater than 1 indicate net accumulation, allowing assessment of each mollusk species' ability to concentrate metals from its environment.

RESULTS

Heavy Metal Concentrations

Water Samples

The assessment of heavy metal contamination in marine environments is vital due to the persistent and toxic nature of these pollutants, which can bioaccumulate through trophic levels and pose significant risks to both aquatic life and human health (Lin *et al.*, 2024; Mahmudiono *et al.*, 2024). Marine mollusks are recognized as effective bioindicators for heavy metal pollution in coastal areas due to their ability to concentrate contaminants within their tissues, providing a time-integrated measure of environmental contamination (Conti *et al.*, 2019; Fred *et al.*, 2019; Phuong, 2014; Primost *et al.*, 2017; Salah-Tantawy *et al.*, 2022; Sami *et al.*, 2020; Zongo *et al.*, 2022).

A water sample analysis from Guang-guang, Pujada Bay revealed that Cd concentrations were below both the Philippine Department of Environmental and Natural Resources Administrative Order No. 2016-08 (DENR DAO No. 2016-08) standard and the United States Environmental Protection Agency's (US EPA) recommended Criterion Continuous Concentration (CCC) for marine water. In contrast, Cr level exceeded both the DENR DAO No. 2016-08 (2016) standard of 0.05 mg/L and the US EPA (2002) of 0.05 mg/L. Pb concentrations were comparable to the DENR DAO No. 2016-08 (2016) standard and fell below the US EPA (2002) recommended CCC for marine water. Ni was detected; however, both Ni and Fe concentrations were within permissible limits and below the established standards. The elevated Cr concentration in the water column, although within some broader international guidelines, warrants attention due to its exceedance of both the DENR DAO 2016-08 (2016) and US EPA (2002) standard (Table 1).

Sediment Samples

In sediment samples from Guang-guang, Pujada Bay, the concentrations of most heavy metals were found to be low. Cd, Cr, Ni, and Pb levels were all significantly below the National Oceanic and Atmospheric Administration (NOAA) SQiRT tables (Buchman, 1999) Threshold Effect Level and Probable

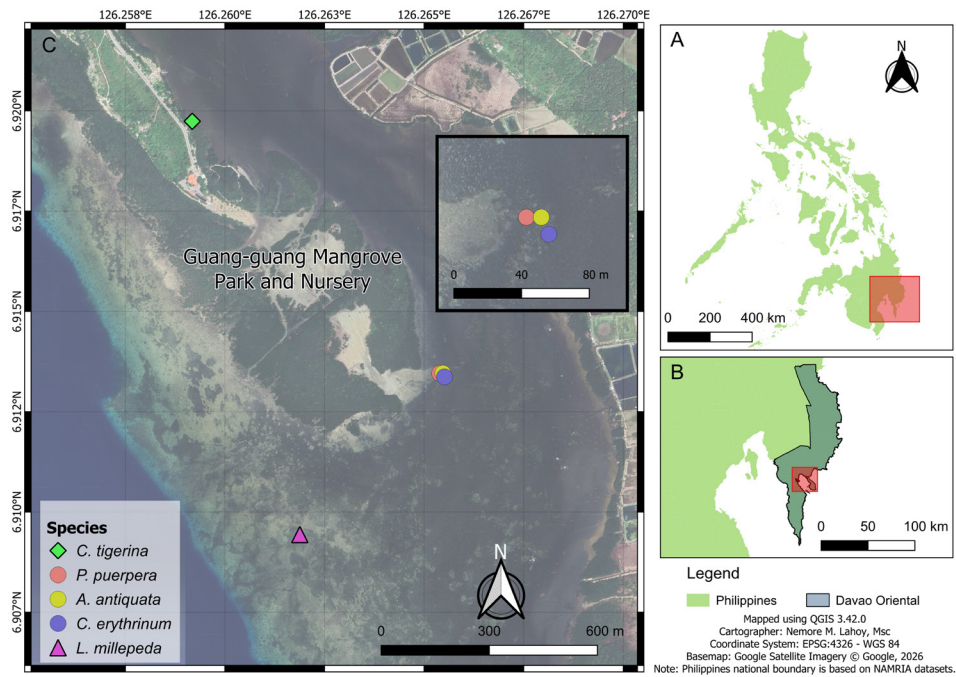


Figure 1: Map of the sampling site in Guang-guang, Dahican, Pujada Bay, City of Mati, Davao Oriental, Philippines.

Table 1: Concentration of heavy metals in water and sediment samples compared with environmental standards.

A. Water			
Heavy Metals	Concentration (mg/L)	DENR DAO Limit (mg/L)	US EPA (mg/L)
Cd	0.001	0.003	0.0093
Cr	0.06	0.05	0.05
Ni	0.02	0.2	0.022
Fe	0.02	1.5	-
Pb	0.01	0.01	0.0081
B. Sediment			
Heavy Metals	Concentration (mg/kg)	NOAA TEL Standard Limit (mg/kg)	NOAA PEL Standard Limit(mg/kg)
Cd	0.001	0.7	4.2
Cr	0.06	52.3	160
Ni	0.02	15.9	42.8
Fe	0.02	-	-
Pb	0.01	30.2	112

Note: No available standard (-).

Effect Level. For Fe, no specific NOAA TEL/PEL values were identified in the available literature for direct comparison. These consistently low levels across multiple heavy metals indicate good sediment quality at the time of sampling, suggesting a low immediate risk for benthic organisms (Ergen, 2020).

Mollusk Samples

The heavy metal concentrations in the mollusk samples, as summarized in Table 2, showed varying levels, particularly for Cd. While Cr, Ni, and Fe often lack specific standard limits in mollusk tissues for consumption, and Pb concentrations (0.01 mg/kg for

all species) were well below Codex Stan 193-1995 (amended 2023) and EU 1881/2006 (2006) limits of 0.3 mg/kg, Cd levels presented a concern. *L. millepeda* exhibited a Cd concentration of 0.2 mg/kg, which is twice the Codex Stan 193-1995 limit of 0.1 mg/kg and exceeds the EU 1881/2006 limit of 0.05-0.1 mg/kg for Cd in mollusks. *C. erythrinum* (0.09 mg/kg) and *A. antiquata* (0.07 mg/kg) also approached or slightly exceeded the upper range of the EU limit for Cd. In contrast, *P. puerpera* (0.02 mg/kg) and *C. tigerina* (0.02 mg/kg) showed lower Cd concentrations, remaining within acceptable international ranges. This highlights that even with relatively low environmental concentrations, certain mollusk species can accumulate metals to levels of concern for human consumption (Phuong, 2014; Primost et al., 2017; Sami et al., 2020).

Bioindicator Potential

Biota-Sediment Accumulation Factors

The BSAF and BWAf are critical for understanding how heavy metals transfer from the environment into marine organisms. Values greater than 1 indicate bioaccumulation, in which the organism concentrates the metal at a higher level than the surrounding matrix (Ahmed et al., 2017; Wang et al., 2025; Yu et al., 2022; Zhang et al., 2025).

The BSAF summarized in Table 3 revealed significant bioaccumulation of Cd, Cr, and Ni from sediment into the mollusks. *L. millepeda* exhibited exceptionally high BSAF values for Cd and Ni (62.5), indicating a strong capacity to accumulate

these metals from the sediment. Other species also showed considerable accumulation of Cd, such as *C. erythrinum* and *A. antiquata*. Cr also demonstrated bioaccumulation across most species, with *P. puerpera* showing a BSAF of 10. In contrast, Fe and Pb generally had BSAF values below 1, suggesting limited accumulation from sediment, possibly due to regulatory mechanisms or lower bioavailability in the sediment phase (Bakhshalizadeh, 2022).

Biota-Water Accumulation Factors

The BWAf in Table 3 showed similar patterns of accumulation from the water column. *L. millepeda* again displayed very high BWAf values for Cd and Ni, further confirming its pronounced ability to accumulate these elements from the dissolved phase. Significant BWAf values for Cd were also observed in *C. erythrinum* and *A. antiquata*. Cr also showed accumulation, with *P. puerpera* recording a BWAf of 20. Notably, Fe presented extremely high BWAf values across all species, with *L. millepeda* reaching 45100, and other species like *P. puerpera* and *A. antiquata* also demonstrated substantial water-to-biota transfer. This high Fe accumulation might be linked to its essential role in biological processes or specific environmental factors (Hu et al., 2022, 2023). Similar to BSAF, Pb showed very low BWAf values, indicating minimal accumulation from water. The high BSAF and BWAf values for Cd, Cr, and Ni, particularly in *L. millepeda*, underscore the effectiveness of these mollusks as bioindicators capable of concentrating metals even when ambient

Table 2: Heavy metal concentration (mg/kg) in selected mollusk species compared with regulatory standards.

Mollusk Species	Cd	Cr	Ni	Fe	Pb	Codex Stan 193-1995 (FAO/WHO)	EU 1881/2006
<i>P. puerpera</i>	0.02	1.2	0.04	68.6	0.01	Cd: 0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit	Cd: 0.05-0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit
<i>C. tigerina</i>	0.02	0.11	0.04	15.6	0.01	Cd: 0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit	Cd: 0.05-0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit
<i>A. antiquata</i>	0.07	0.21	0.04	68.4	0.01	Cd: 0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit	Cd: 0.05-0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit
<i>C. erythrinum</i>	0.09	0.14	0.04	30.1	0.01	Cd: 0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit	Cd: 0.05-0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit
<i>L. millepeda</i>	0.2	0.71	2.5	902	0.01	Cd: 0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit	Cd: 0.05-0.1, Pb: 0.3 Cr, Ni, Fe=No standard limit

Table 3: Biota-Sediment Accumulation Factor (BSAF) and Biota-Water Accumulation Factor (BWAf).

Mollusk	Biota-Sediment Accumulation Factor (BSAF)				
	Cd	Cr	Ni	Fe	Pb
<i>P. puerpera</i>	10	20	1	0.0786	0.0004
<i>C. tigerina</i>	10	1.8333	1	0.0179	0.0004
<i>A. antiquata</i>	35	3.5	1	0.0784	0.0004
<i>C. erythrinum</i>	45	2.3333	1	0.0345	0.0004
<i>L. millepeda</i>	100	11.8333	62.5	1.0332	0.0004
Mollusk	Biota-Water Accumulation Factor (BWAf)				
	Cd	Cr	Ni	Fe	Pb
<i>P. puerpera</i>	20	20	2	3430	1
<i>C. tigerina</i>	20	1.8333	2	780	1
<i>A. antiquata</i>	70	3.5	2	3420	1
<i>C. erythrinum</i>	90	2.3333	2	1505	1
<i>L. millepeda</i>	200	11.8333	125	45100	1

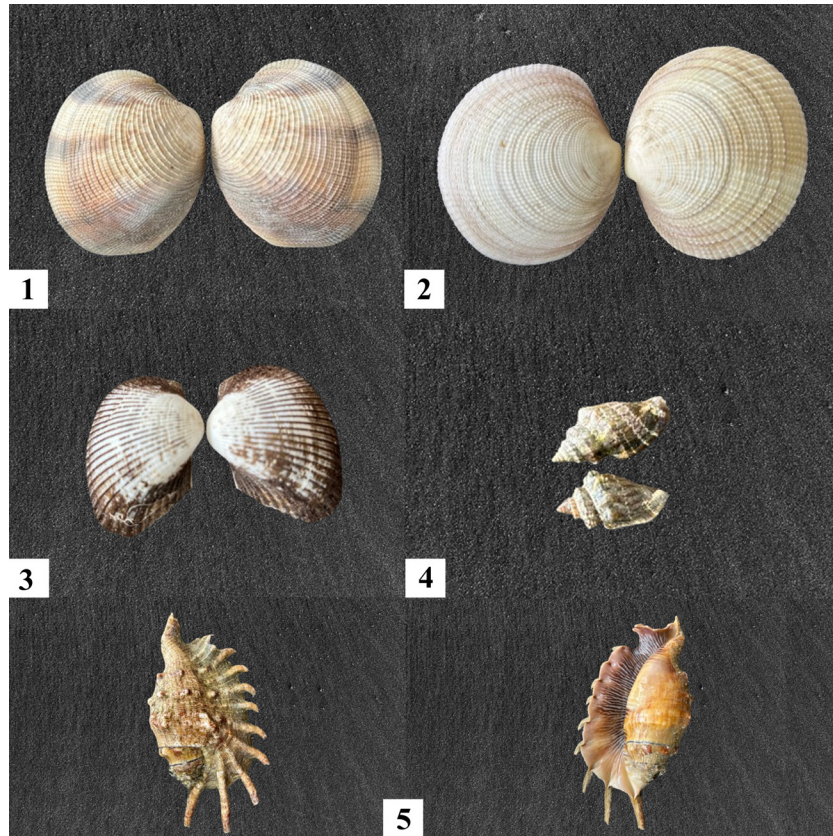


Figure 2: Selected mollusks collected from Guang-guang, Pujada Bay, City of Mati, Davao Oriental, Philippines: (1) *Periglypta puerpera* (Linnaeus, 1771), (2) *Codakia tigerina* (Linnaeus, 1758), (3) *Anadara antiquata* (Linnaeus, 1758), (4) *Canarium erythrinum* (Dillwyn, 1817), (5) *Lambis millepeda* (Linnaeus, 1758).

environmental concentrations are low (Conti *et al.*, 2019; Fred, 2019; Phương, 2014; Salah-Tantawy *et al.*, 2022; Zongo *et al.*, 2022).

DISCUSSION

The heavy metals enter the marine environment, primarily through various land-based human activities. These include industrial, municipal, and domestic wastewater effluents, as well

as surface runoff, which serve as primary pathways for heavy metals into marine ecosystems (Deocaris *et al.*, 2022; Diwa *et al.*, 2022; El-Sharkawy *et al.*, 2025). Rapid industrialization and urbanization, coupled with inadequate waste management in developing countries, significantly contribute to this pollution (Deocaris *et al.*, 2022; El-Sharkawy *et al.*, 2025). For instance, in the Philippines, industrial zones contribute to elevated Cd and Zn levels in coastal waters, including in Davao City and the Island Garden City of Samal (Aya-ay *et al.*, 2025). Mining activities, such

as those in Manicani, Guiuan, Eastern Samar, lead to Pb, Cu, and Ni pollution (Corales-Ultra *et al.*, 2019), while artisanal tailings from mining have impacted Mambulao Bay in Camarines Norte with various heavy metals (Gibaga *et al.*, 2024). Agricultural effluents and river influx, as seen in Manila Bay, also transport contaminants from land to coastal waters (Ebol *et al.*, 2020; Diwa *et al.*, 2022). Other identified sources include chemical enterprises, port operations, rock weathering, and metal smelting (Wang *et al.*, 2025).

In Guang-guang, Pujada Bay, the concentrations of heavy metals in water and sediment samples were generally low, with sediment levels consistently below established safety thresholds, indicating a relatively pristine abiotic environment at the time of sampling. However, an important exception was the elevated Cr detected in the water, which exceeded both DENR and US EPA standards, mirroring concerns found elsewhere in the Philippines, such as in dumpsite soil in Iligan City (Aja *et al.*, 2021). While the low heavy metal concentrations in sediment from Guang-guang, Pujada Bay are generally favorable compared to some other Philippine coastal areas, such as the moderately polluted fishpond sediments in Batan Bay, Aklan (Nillos *et al.*, 2020), or the highly contaminated Lake Mainit sediments with Ni (Laudiño *et al.*, 2024), or Manila Bay sediments with elevated concentrations (Olivares *et al.*, 2019; Prudente *et al.*, 1994), the presence of even low levels of metals in the water column can initiate the next critical stage which is bioaccumulation.

The journey of heavy metals continues as they are absorbed by marine organisms, a process known as bioaccumulation. Mollusks, in particular, are recognized as effective bioindicators due to their sessile nature and filtration feeding, which make them susceptible to accumulating contaminants from their environment (Phường, 2014; Zongo *et al.*, 2022; Azratul *et al.*, 2017; Kocabaş and Kocabaş, 2023). In Guang-guang, Pujada Bay, despite the generally low heavy metal levels in sediments, a significant concern arises from the high Cd concentrations found in *L. millepeda*. This observation aligns with findings in other Philippine mollusks, highlighting their consistent role as bioindicators; for instance, studies in Malita, Davao Occidental, have also investigated the bioaccumulation potential of marine bivalve seashells (Marquez and Avenido, 2022). Further local studies in Pujada Bay complement these findings by detailing species-specific bioaccumulation patterns, as seen in research on trace metal and nutrient composition in the egg strings of *Dolabella auricularia* (Tayone, 2017) and heavy metal concentrations and health risk assessments in selected mollusks (Tayone *et al.*, 2020). Sedimentation rates using sediment traps revealing high deposition rates influenced by upland runoff have also been studied in Pujada Bay (Sorrosa *et al.*, 2015).

The bioaccumulation of heavy metals, especially in food sources such as mollusks, poses significant risks implications to both ecological health and human consumers. The elevated Cd levels

in *L. millepeda* from Guang-guang, Pujada Bay, which exceed international food safety limits, strongly suggest a potential health risk to consumers, similar to findings in Indonesian green mussels for Pb, Hg, and Cd (Liu *et al.*, 2020). The consumption of bivalves with elevated heavy metal concentrations can pose significant human health risks, as evidenced by studies indicating high Hazard Index (HI) or Target Hazard Quotient (THQ) values for metals like Pb, Cd, and As in other regions (Li *et al.*, 2010; Lin *et al.*, 2024; Saleh *et al.*, 2021; Yu *et al.*, 2022). For example, a study in Manila Bay revealed considerable human health risk due to Pb in shellfish (Liu *et al.*, 2020), and in Marudu Bay, Malaysia, As intoxication was a concern from bivalve consumption despite low levels of other metals (Perelsonia *et al.*, 2017). In contrast, some studies in Malaysia and Thailand found THQ values below 1 for various metals in mussels, implying no significant health risks from individual metals (Denil *et al.*, 2017; Rajan and Ishak, 2017; Rattikansukha *et al.*, 2021; Tanhan *et al.*, 2022; Yap and Al-Mutairi, 2021).

The varying concentrations observed across water, sediment, and mollusks in Guang-guang, Pujada Bay underscore the complex interplay of environmental factors and anthropogenic influences, reflecting a global challenge (El-Sharkawy *et al.*, 2025; Yu *et al.*, 2022). Similar to the concerns in Guang-guang, Pujada Bay, other Southeast Asian countries also grapple with heavy metal contamination in seafood, with human health risk assessments in Pattani Bay, Thailand, revealing bioaccumulation in mollusks (Rattikansukha *et al.*, 2021), and Indonesian green mussels having levels exceeding maximum acceptable limits for various metals (Liu *et al.*, 2020). Studies in Malaysia also highlight Cd and Pb contamination in clams (Yona *et al.*, 2021). The issue of heavy metal bioaccumulation in marine organisms is a global concern, with studies on green mussels in Bangladesh finding Pb, Cd, and Hg concentrations (Hossen *et al.*, 2015). Positive correlations between metals such as Cd and Pb often indicate a common origin, such as industrial and municipal wastes (Hossen *et al.*, 2015). The effectiveness of mollusks as bioindicators, even in relatively clean environments, is a consistent finding across many international studies (Azratul *et al.*, 2017; Islam *et al.*, 2016; Ibrahim *et al.*, 2023), further emphasizing the need for continuous monitoring to safeguard both marine ecosystems and public health.

Biota-Sediment and Biota-Water Accumulation Factors

The BSAF, calculated as the ratio of metal concentration in biota tissue to that in sediment, is a critical index for assessing heavy metal bioavailability, transfer efficiency from sediments to organisms, and potential trophic magnification in marine food webs (Yu *et al.*, 2022; Kim *et al.*, 2025). Values >1 indicate net bioaccumulation, underscoring mollusks' role as effective biomonitors for sediment pollution even at low environmental levels, with implications for ecological risk and human health via seafood consumption (Sami

et al., 2020; Zhang *et al.*, 2025). Comparable high BSAF for Cd and Cr have been reported in gastropods (*Thais bitubercularis*, *Nerita lineata*) and bivalves from Malaysian and Kenyan coasts, confirming species-specific accumulation patterns influenced by feeding habits and sediment chemistry (Swaleh *et al.*, 2016; Zhang *et al.*, 2025; Ismail *et al.*, 2017). Although local Philippine studies specifically computing BSAF are scarce, bioaccumulation research on Asiatic clams (*Corbicula fluminea*) from Laguna de Bay showed positive correlations between sediment and tissue concentrations for several metals (e.g., Cu, Zn), indicating similar transfer dynamics (Diwa *et al.*, 2022), while bivalves in Davao Occidental demonstrated heavy metal uptake potential from coastal sediments (Marquez and Avenido, 2022).

Like BSAF, BWAf provides a key index for evaluating the bioavailability and transfer efficiency of heavy metals from the dissolved water phase to mollusk tissues, with values >1 signifying net bioaccumulation and highlighting the organisms' sensitivity to trace dissolved contaminants (Yu *et al.*, 2022; Zhang *et al.*, 2025). The elevated BWAf for Cd, Cr, and Ni observed here mirrors patterns in other coastal systems; for instance, bivalves in Daya Bay, China, exhibited BAF (equivalent to BWAf) values ranging from 286 to 89,362 for Cd, Cr, Cu, Zn, Pb, As, and Hg, attributed to filtration feeding and strong enrichment capacity, especially for Cr despite its non-essential status (Yu *et al.*, 2022). Similarly, the Mediterranean mussel *Mytilus galloprovincialis* from the Romanian Black Sea coast showed high BCF (bioconcentration factor, akin to BWAf) prioritizing Cu and Ni accumulation from seawater (Sami *et al.*, 2020). These comparable high BWAf/BAF/BCF values underscore species-specific accumulation influenced by feeding habits, metal speciation, and water chemistry, positioning mollusks such as *L. millepeda* and *P. puerpera* as robust biomonitors for early detection of waterborne metal pollution (Conti *et al.*, 2019; Zhang *et al.*, 2025). The exceptionally high Fe BWAf aligns with findings in Malaysian gastropods (*Nerita lineata*, *Thais bitubercularis*), where elevated tissue Fe reflects natural background levels and metabolic demands rather than pollution (Zhang *et al.*, 2025). Implications include potential trophic transfer to predators and human consumers via seafood, amplifying ecological and health risks even at low water concentrations, and emphasizing the need for routine mollusk-based monitoring in coastal management (Sami *et al.*, 2020; Yu *et al.*, 2022).

CONCLUSION

The findings from Guang-guang, Pujada Bay, reveal a complex picture where low heavy metal concentrations in water and sediment do not necessarily translate to low levels in marine biota. The elevated levels of Cd in certain mollusk species, such as *L. millepeda*, exceeding international food safety limits, along with high BSAF and BWAf values for Cd, Cr, and Ni, confirm the significant role of marine mollusks as bioindicators for heavy

metal pollution. The specific bioaccumulation patterns highlight species-specific differences in metal uptake and potential ecological and human health risks. Exceeding the DENR (2016) standard and US EPA (2002) for Cr levels in water also indicates a potential environmental concern. These results emphasize that direct environmental measurements alone may not fully capture the extent of heavy metal exposure within the ecosystem, and bioindicator species provide a more integrated and accurate assessment of environmental contamination. The potential health implications for consumers of these mollusks, especially regarding Cd, suggest a need for further monitoring and risk assessment in Guang-guang, Pujada. Continued monitoring of both environmental matrices and bioindicator species is crucial for safeguarding marine ecosystem health and ensuring the safety of seafood for coastal communities. The identified anthropogenic sources, ranging from industrial and agricultural runoff to mining activities, underscore the need for environmental management and stricter regulatory enforcement to mitigate heavy metal input into the bay.

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ABBREVIATIONS

AAS: Atomic Absorption Spectroscopy; **BSAF:** Biota-Sediment Accumulation Factor; **BWAf:** Biota-Water Accumulation Factor; **Cd:** Cadmium; **Cr:** Chromium; **DENR:** Department of Environmental and Natural Resources; **DOrSU:** Davao Oriental State University; **EU:** European Union; **Fe:** Iron; **ICP-OES:** Inductively Coupled Plasma Optical Emission Spectrometry; **Ni:** Nickel; **NOAA:** National Oceanic and Atmospheric Administration; **PAMB:** Protected Area Management Board; **Pb:** Lead; **PEL:** Probable Effect Level; **TEL:** Threshold Effect Level; **US EPA:** United States Environmental Protection Agency.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

SUMMARY

Heavy metals enter marine environments primarily through land-based human activities, including industrial, municipal, and domestic wastewater discharge, surface runoff, and mining operations (Deocaris *et al.*, 2022; Diwa *et al.*, 2022; El-Sharkawy *et al.*, 2025). In developing regions like the Philippines, rapid industrialization, urbanization, and insufficient waste management exacerbate contamination, contributing to elevated levels of Cd, Zn, Pb, Cu, and Ni in coastal waters (Aya-ay *et al.*, 2025; Corales-Ulta *et al.*, 2019; Gibaga *et al.*, 2024). Agricultural

effluents, riverine inputs, port activities, and metal processing further transport metals into marine ecosystems (Wang *et al.*, 2025; Ebol *et al.*, 2020; Diwa *et al.*, 2022). In Guang-guang, Pujada Bay, water and sediment analyses revealed generally low heavy metal concentrations, with sediment consistently below established safety thresholds, indicating a relatively pristine environment; however, Cr in the water exceeded national standards, signaling localized anthropogenic influence and the potential for bioaccumulation (Aja *et al.*, 2021; Nillos *et al.*, 2020; Laudiño *et al.*, 2024; Olivares *et al.*, 2019; Prudente *et al.*, 1994). Bioaccumulation in marine organisms, particularly mollusks, reflects their role as effective bioindicators due to filtration feeding and limited mobility (Phuong, 2014; Zongo *et al.*, 2022; Azratul *et al.*, 2017; Kocabaş and Kocabaş, 2023; Zafar *et al.*, 2023). In Pujada Bay, *L. millepeda* exhibited elevated Cd levels exceeding international food safety limits, highlighting potential health risks to consumers (Ghosn, 2019; Saleh *et al.*, 2021). Other species, including *C. erythrinum* and *A. antiquata*, showed moderate Cd accumulation, while Cr and Ni also demonstrated species-specific uptake (Tayone, 2017; Tayone *et al.*, 2020; Marquez and Avenido, 2022; Sorrosa *et al.*, 2015). Comparable patterns of metal accumulation have been observed in Southeast Asia, emphasizing mollusks' sensitivity to environmental contamination (Tanhan *et al.*, 2022; Saleh *et al.*, 2021; Hossen *et al.*, 2015; Islam *et al.*, 2016). These findings underscore the importance of continuous monitoring, as even low environmental concentrations can bioaccumulate in seafood, posing ecological and public health concerns (Kocabaş and Kocabaş, 2023; Kim *et al.*, 2025; Ibrahim *et al.*, 2023).

AUTHORS CONTRIBUTIONS

Hayma T. Usman was responsible for securing PAMB approval to conduct the study, performing the sample collection, field and laboratory work, data curation, and preparing the original draft. Conceptualization, funding acquisition, and writing contributors-including editing, polishing, and guidance- were provided by Janeth C. Tayone, Wilanfranco C. Tayone, Roselyn V. Regino, and France Guillian B. Rapiz. Statistical analysis was conducted by Ivan L. Saligumba

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