Original Article

Assessment of heavy metals and human health risk in shrimps collected from different farms at City of Mati, Davao Oriental

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ABSTRACT

Heavy metals are naturally occurring elements whose concentrations may increase due to anthropogenic activities, posing risks to ecosystems and human health. This study investigated the concentrations of cadmium, chromium, iron, lead, manganese, and nickel in water, sediment, and shrimp (tissue and shell) samples from selected farms in Barangays Dahican and Dawan, City of Mati, Davao Oriental, Philippines. Atomic Absorption Spectrometry was used for heavy metal study, and potential non-carcinogenic health risks were assessed using the target hazard quotient (THQ) and hazard index (HI), following the US Environmental Protection Agency guidelines. Results showed that chromium and nickel levels in water from both farms exceeded the allowable thresholds set by the Department of Environment and Natural Resources. In sediments, chromium, iron, lead, and manganese levels in Dahican exceeded World Health Organization (WHO) limits, whereas Dawan showed elevated levels of chromium, iron, and manganese, with nickel surpassing National Oceanic and Atmospheric Administration standards. In shrimp tissue, chromium in Dahican and manganese in Dawan exceeded WHO limits, while iron remained within safe limits. Cadmium, lead, and nickel were either undetected or below detection limits in shrimp tissue and shell samples from both farms. Despite the elevated concentrations of some metals in the samples, the THQ and HI were below one, indicating that long-term, continuous intake of shrimp from the two farms is unlikely to pose any significant health hazards. Nonetheless, continuous monitoring and management of

heavy metals in shrimp farming remain essential to prevent future contamination risks and safeguard environmental and public health.

Keywords: atomic absorption spectrometry, bioaccumulation, hazard index, target hazard quotient, shrimp contamination, vannamei

INTRODUCTION

Heavy metals, naturally found in trace amounts within the Earth's crust, can become hazardous when their concentrations increase. Heavy metals such as iron (Fe), manganese (Mn), cadmium (Cd), chromium (Cr), and nickel (Ni) are essential for various biological functions; however, at elevated levels, they become toxic (Singh et al. 2024; Jomova et al. 2025). Lead (Pb) poses risks due to its ability to bioaccumulate in organisms and biomagnify through food chains, even at low concentrations, causing severe damage to vital organs, and in extreme cases, death (Perumal et al. 2021). Contaminated food exceeding recommended heavy metal levels can pose health concerns (Jomova et al. 2025), prompting local and international agencies like the World Health Organization (WHO), National Oceanic and Atmospheric Administration (NOAA), and Department of Natural Resources Administrative Order (DENR-DAO) No. 2016-08 to establish safety limits.

FAO (2022) and Macusi et al. (2022) highlighted that shrimp farming has become a rapidly growing sector within the global aquaculture industry. In the Philippines, the Bureau of Fisheries and Aquatic Resources (BFAR) registered 941 farms cultivating *Penaeus vannamei* (Boone, 1931), a highly valued shrimp species, covering 3,372.62 ha. Region XI alone is home to 22 of these farms, with 16 located in the City of Mati, Davao Oriental (BFAR 2022). Vannamei farms in the City of Mati utilize water from Pujada Bay, a bay that encompasses coastal barangays (Sorrosa et al. 2014; Li 2021). *Penaeus vannamei* is highly valued for its nutritional benefits (Ogello and Munguti 2016; Liu et al. 2021), particularly its rich protein content and essential minerals, which contribute to its vital role in the local economy (Sultana et al. 2022; Ujjania et al. 2022).

In the City of Mati, Davao Oriental, several shrimp farms are located along the shores of Pujada Bay (Pilotos and Bualan 2024), which has been declared a Protected Seascape and Landscape in Davao Oriental under Proclamation No. 451. These farms rely on the same water source. After operations, these shrimp farms discharge wastewater directly into the bay. According to Ali et al. (2019) and Wang et al. (2023), runoffs from surrounding areas can introduce substantial levels of heavy metals. In addition, it is also indicated that mining activities may further contribute to the accumulation of heavy metals in the aquatic environments (Takarina et al. 2018; Wang et al. 2019). This is particularly relevant as mining operations are occurring in proximity to Pujada Bay.

Building on these identified sources of contamination, aquaculture systems are increasingly exposed to multiple environmental pressures that may compromise water quality and food safety. Aquaculture practices themselves can contribute to environmental pollution through the use of feeds, pond inputs, and management interventions (Turlybek et al. 2025). In addition, external factors such as mining-related activities within connected watersheds and other anthropogenic sources including residential runoff, transportation, and land use changes, may introduce heavy metals into water bodies utilized for shrimp farming (Arshad et al. 2024).

In the context of vannamei farms in the City of Mati, Davao Oriental, these systems may face potential contamination risks due to their exposure to such multiple sources. These farms are influenced by surrounding residential activities, transportation, and water inputs, which may serve as pathways for heavy metal introduction. Moreover, tea seed powder is commonly applied during pond preparation to improve water quality. However, tea saponin has been reported to desorb heavy metals from sediments, increasing their bioavailability and potentially leading to greater accumulation in shrimp (Yu and He 2018).

Given these interacting sources and processes, assessing heavy metal concentrations in water, sediments, and shrimp tissues is crucial for evaluating potential human health risks and ensuring the environmental sustainability of aquaculture in Davao Oriental. In view of these concerns, this study was conducted to investigate the potential heavy metal contamination in selected vannamei farms in the City of Mati, Davao Oriental. Specifically, this study aimed to determine the concentrations of heavy metals (Fe, Mn, Pb, Cd, Cr, Ni) in water, sediment, and shrimp (tissue and shell) samples. Furthermore, the study evaluated the potential human health risks of consuming shrimps contaminated with heavy metals. This research addresses the environmental and health impacts of heavy metal contamination for safer and more sustainable shrimp farming practices.

METHODS

Study Site

This study was conducted in Barangays Dahican and Dawan, City of Mati, Davao Oriental, Philippines (Figure 1). The vannamei farm in Dahican spans a total area of 5,500 m^2, comprising three shrimp ponds and one fishpond. To prepare shrimp culture in this farm, the water from the previous culture cycle is drained into another pond, and the residual matter is utilized as fertilizer. The ponds are thoroughly dried before refilling with fresh seawater to prevent white spot disease outbreaks. The seawater is chlorinated in a separate pond for at least five days to create a sterile environment before transferring shrimp into the culture ponds. Before being introduced to the ponds, the shrimp are kept in a nursery for 20 days.

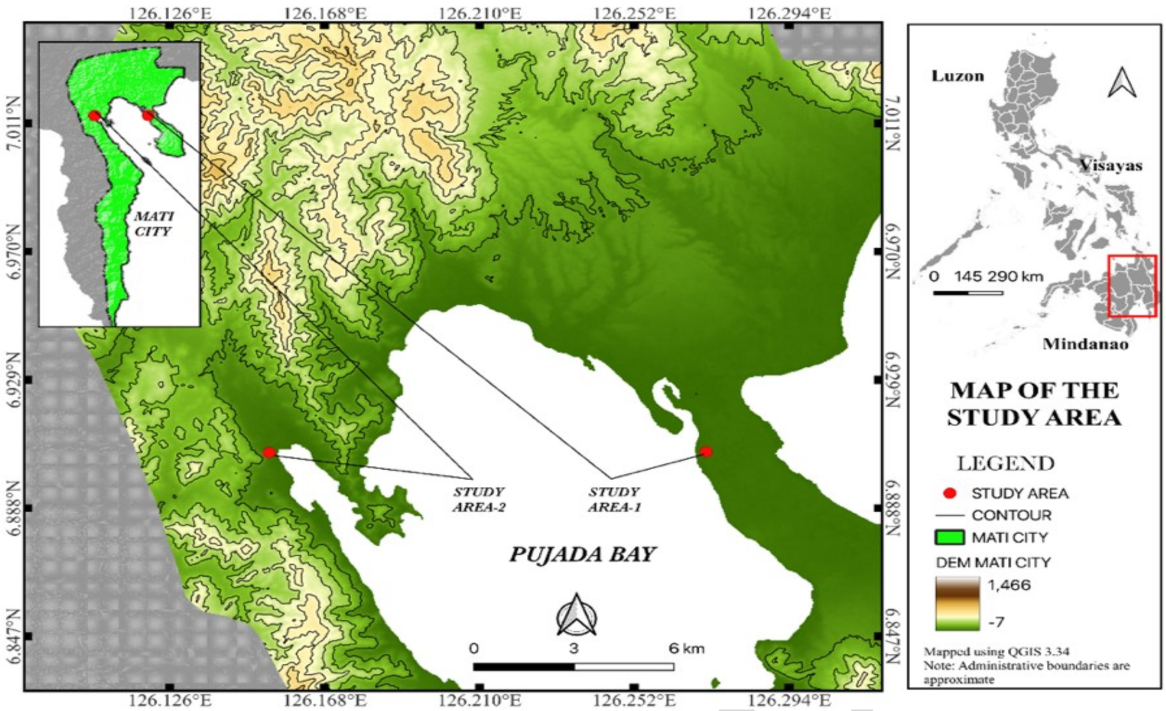

Figure 1. The study areas of the selected shrimp farms in the City of Mati, Davao Oriental.

The Dawan farm is adjacent to Balete Bay, a protected embayment with abundant mangrove stands, seagrass beds, and rich coral reef systems that support diverse marine life. The farm has been operational for nearly six years and occupies a one-hectare area with two shrimp ponds. It is located approximately 18 kilometers from the city proper and utilizes seawater directly from the bay as the primary water source. Prior to stocking, the farm applies tea seed (Camella seed powder) to eliminate unwanted organisms and potential pathogens in the ponds. Unlike the Dahican farm, it does not operate a nursery. Newly purchased fry is directly introduced into the culture ponds. After each harvest, the ponds are drained and allowed to dry, and accumulated sediments, uneaten feed, and organic debris on the pond bottom are removed in preparation for the next culture season.

Sample Collection and Preparation

Water, sediment, shrimp tissue, and shell samples were collected from the two study sites at four sampling stations. The procedures for collecting the samples were uniformly applied across both study sites. Since there was no fixed harvest schedule, all samples were collected approximately two weeks before the actual harvest, while the water level was still high, as the water would be drained immediately after harvesting.

Water samples. Water samples were collected using acid-washed plastic bottles with a depth of 50 cm. Before collection, the bottles were thoroughly rinsed with HNO_3 (69.5%, Expert Q, ACS, ISO) manufactured by Scharlab (Spain) to minimize metal cation precipitation and adsorption (Mishra et al. 2019). The acid-washed plastic bottles were rinsed with pond water before filling with the desired amount using a one-liter plastic container. To reduce contamination, the samples were then poured into a 4-L polypropylene container. At each site, a one-gallon homogenized water sample was collected from each of the four sampling stations. Each sample was labeled with the time, date, and collection location. The bottles were immediately stored in a cooler for transport to the Davao Oriental State University–Regional Integrated Coastal Management Center XI (RIC XI) laboratory. They were placed in a refrigerator for preservation until analysis.

Sediment samples. Sediment samples were collected using a PVC pipe. The pipe was pushed into the sediment and carefully controlled not to exceed a depth of 50 cm (Biswas et al. 2021). The sediment samples were collected from four sampling stations and sealed in polyethylene bags, each labeled with the station number. The bags were then placed in a container for transport to the Davao Oriental State University–Science Laboratory. Four bags, each weighing one kilogram, were collected and labeled. Upon arrival at the laboratory, the sediment samples were allowed to air dry and pulverized using a laboratory mortar to reduce them to a fine powder. A composite sample was further ground to ensure uniformity. One kilogram of the homogenized sample was separated and placed in a Ziplock bag, ready for analysis.

Shrimp samples. Shrimp samples were collected using a nylon mesh net with floats, leads, and rope for effective deployment and retrieval. Half a kilogram of shrimp was collected at each farm's four sampling stations, resulting in a total of 2 kg from both farms. The shrimp were placed in a plastic bucket before they were transferred to a sealed polyethylene bag labeled with the location, weight, and collection date. The bags were then placed in a cool box for transport to the laboratory. The shrimp samples were stored in a cool box and placed in a freezer at a temperature range of 0-4°C at the RIC XI Laboratory. After four months, the samples were then transferred to the Science Laboratory, where they were carefully peeled to separate the muscle tissue (flesh) from the exoskeleton (shell). Both portions were labeled, placed in the freezer, and after three days, delivered to Davao Analytical Laboratories, Inc. (DALINC) for heavy metal analysis. The prepared samples were maintained under controlled temperatures during transit.

Heavy Metal Analysis

Water samples. Davao Analytical Laboratories, Inc. employed the SMEWW 3111B method for water samples, utilizing the Direct Air-Acetylene Flame technique per the standard protocol outlined in the 23rd edition of Standard Methods for the Examination of Water and Wastewater.

The water sample was filtered through a 0.45 μm filter paper to separate the suspended matter from the sample of interest. The filtrate was then treated with concentrated HNO_3 to a pH < 2. This is to prevent the metals in the matrix from precipitating out of the solution. The Atomic Absorption Spectrometer (AAS) was set up to optimize the parameters needed for the air-acetylene flame. Meanwhile, the prepared blank and standard solutions (multi-element standards) were aspirated into the flame to establish the calibration curve. Lastly, the prepared samples were also aspirated directly into the flame to determine the metal concentration present in the sample matrix.

Sediment samples. Sediment analysis employed the USEPA 3050B method, which involved acid digestion of sediments, sludge, and soil, to determine the levels of heavy metals. This method followed the standard protocols for soil, fertilizer, plant tissue, and water analysis as outlined in the 17th edition of the Official Method of Analysis (Association of Official Analytical Chemists (AOAC) 2000). A standard reference material (SRM) 2710a of the National Institute of Standards and Technology (NIST) was utilized in the analysis.

One gram (1 g) of the sediment sample was digested using nitric acid, 1:1 HNO_3, and heated at 95°C ± 5°C until brown fumes in the solution ceased. The digestate was then cooled down and treated with 30% hydrogen peroxide (H_2O_2). Gentle heating was applied to facilitate the breakdown of organic matter in the matrix while controlling the foaming. Subsequently, the solution was heated to reduce the volume to ~5.0 mL and allowed to cool. Once cooled, hydrochloric acid (HCl) was added to the matrix and brought to a boil for a short period of time. The resulting solution was diluted with reagent water to a 100 mL final volume. A calibration curve was established using the blank and standard solutions. Finally, the sample was subjected to instrumental analysis to determine the concentration of the metals of interest.

Shrimp samples. For shrimp shell and tissue examination, the laboratory utilized the Dry-Ashing Atomic Absorption Spectrometry method using Atomic Absorption Spectroscopy purchased from Shimadzu Corporation (Japan) to determine the levels of heavy metals, also following the Official Method of Analysis (AOAC 2000). A reference material, NIST-RM 8259, was employed in the analysis.

One gram (1 g) of the homogenized sample was placed into a clean, pre-ashed crucible. The sample was charred in a hot plate over a low flame to remove moisture and volatile organic matter. The sample was transferred to a muffle furnace and heated at 550°C until the remaining organic matter was oxidized, leaving an ash. The crucible was allowed to cool. Nitric acid was added to the crucible to dissolve the ash. The solution was diluted to a final volume of 100 mL and filtered to remove any insoluble residue in the matrix. The filtrate was then subjected to an AAS for analysis after the calibration curve (blank and standard solutions) was established.

Potential Human Health Risk Assessment

The Total Hazard Quotient (THQ) indicates the potential non-carcinogenic health risk for the population exposed to any pollutants or contaminants present in food (Ortiz-Moriano et al. 2024). Previous risk assessment studies indicate that the ingestion dose is assumed to be equivalent to the absorbed contaminant dose (Traina et al. 2019).

THQ was calculated using the following formula:

$$THQ = \frac{E_D \times F_{IR} \times E_F \times C_i}{R_{FD} \times W_{AB} \times T_A} \times 10^{-3} \quad (1)$$

Where:

ED = Exposure duration (average life span, 72.32 years)

FIR = Daily ingestion rate (2.43 mg person^{-1} day^{-1})

EF = Exposure frequency (365 days year^{-1})

Ci = Concentration of respective heavy metal (mg kg^{-1})

RFD = Reference dose of individual metal (0.001 mg kg^{-1} for Cd, 1.5 mg kg^{-1} for Cr, 0.02 mg kg^{-1} for Ni (USEPA 2018)

WAB = Average body weight for an adult consumer (58 kg for Philippines) based on the mean weight of Filipinos (Garcia et al. 2020)

TA = Average exposure time, calculated as ED x EF (Biswas et al. 2021).

A THQ value above 1 suggests that the dose equals or exceeds the oral reference dose. This means a population exposed to this dose through shrimp consumption could experience significant health risks (Traina et al. 2019). It also indicates that further measures may be required to reduce the risk of adverse health effects (Yaradua et al. 2019; Biswas et al. 2021; Ahmed et al. 2023).

Since humans are often exposed to multiple contaminants simultaneously, with potential combined or interactive effects, the hazard index was also calculated as the sum of the THQ of the metals under study.

$$HI = THQ\,(Cd) + THQ\,(Cr) + THQ\,(Ni) + THQ\,(Fe) + THQ\,(Pb) + THQ\,(Mn) \quad (2)$$

Where:

HI = Overall Hazard Index, a comprehensive measure of the combined health risks associated with exposure to multiple contaminants

THQ (Cd) = the Total Hazard Quotient for cadmium, indicating the health risk specifically associated with exposure to Cd

THQ (Cr) = the Total Hazard Quotient for chromium, indicating the health risk associated with Cr exposure

THQ (Ni) = the Total Hazard Quotient for nickel, indicating the health risk associated with Ni exposure

THQ (Pb) = the Total Hazard Quotient for lead, indicating the health risk associated with Pb exposure

THQ (Fe) = the Total Hazard Quotient for iron, indicating the health risk associated with Fe exposure

THQ (Mn) = the Total Hazard Quotient for manganese, indicating the health risk associated with Mn exposure

When a HI exceeds 1, it signifies a significant health risk associated with consuming contaminated shrimp. In such instances, it becomes imperative to implement appropriate measures to reduce or eliminate exposure to heavy metals (Sarkar et al. 2016; Biswas et al. 2021; Ahmed et al. 2023).

To mitigate the health risks posed by heavy metal contamination, the WHO and the Food and Agriculture Organization (FAO) established the maximum recommended limits for each heavy metal (Biswas et al. 2021) (Table 1).

Table 1. Maximum recommended limits for heavy metal consumption in humans, as defined by the World Health Organization and Food and Agriculture Organization.

Heavy Metals	**Maximum recommended limits** (JECFA 2021)
Cadmium (Cd)	1 mg kg^{-1}
Chromium (Cr)	0.05 mg kg^{-1}
Iron (Fe)	100 mg kg^{-1}
Lead (Pb)	2 mg kg^{-1}
Manganese (Mn)	1 mg kg^{-1}
Nickel (Ni)	1 mg kg^{-1}

Data Analysis

Heavy metal concentrations, specifically Fe, Mn, Pb, Cd, Cr, and Ni in water, sediment, shrimp tissue, and shrimp shell samples, were determined from composite samples, each formed by pooling and homogenizing samples collected from four sampling stations within each study area, yielding a single concentration value for each sample type at each farm. The resulting concentration values were compared descriptively against established regulatory standards, including the DENR Administrative Order (DAO) No. 2016-08 for water quality, and the permissible limits set by the WHO, the NOAA, and FAO for sediment and shrimp samples, respectively. The non-carcinogenic human health risk was evaluated through the calculation of the THQ and HI for each heavy metal as described above. Concentrations below the detection limit (BDL) were recorded as not detected (ND) and were excluded from THQ and HI calculations.

RESULTS

Heavy Metals in Water

Water samples collected from selected vannamei shrimp farms in the City of Mati, Davao Oriental exhibited varying levels of heavy metals (Table 2). Cadmium, Fe, Pb, and Mn were consistently low, with concentrations below 0.020 mg L^{-1} at two locations. Chromium was recorded at 0.060 mg L^{-1} in both areas. Nickel exhibited the highest concentrations, ranging from 0.700 to 0.740 mg L^{-1} across the two sampling sites.

Table 2. Levels of heavy metals (mg L^{-1}) in water samples collected from selected vannamei shrimp farms in City of Mati, Davao Oriental, showing comparisons to permissible limits defined by the Department of Environment and Natural Resources Administrative Order (DAO) No. 2016-08.

Location	Cadmium	Chromium	Iron	Lead	Manganese	Nickel
Dahican	< 0.001	< 0.060	< 0.020	< 0.020	< 0.020	0.700
Dawan	< 0.001	< 0.060	< 0.020	< 0.020	< 0.020	0.740
Department of Environment and Natural Resources Administrative Order (DENR 2016)	0.005	0.050	1.500	0.050	0.040	0.060

Heavy Metals in Sediment

The levels of heavy metals (mg kg^{-1}) in the sediment samples from selected vannamei shrimp farms in the City of Mati, Davao Oriental are presented in Table 3. Iron and Mn were elevated in both farms, with Fe ranging from 400 mg kg^{-1} in Dahican to 20,000 mg kg^{-1} in Dawan, and Mn from 12.20 mg kg^{-1} to 396 mg kg^{-1}, respectively. Lead was detected in Dahican at 17.90 mg kg^{-1}, but was not detected in Dawan. Chromium concentrations varied, with 0.65 mg kg^{-1} recorded in Dahican and 13.40 mg kg^{-1} in Dawan. Nickel was not detected in Dahican but was notably high in Dawan at 46 mg kg^{-1}. Cadmium was not detected in either location.

Table 3. Levels of heavy metals (mg kg^{-1}) in the sediment samples from selected vannamei shrimp farms in City of Mati, Davao Oriental, showing comparisons to permissible limits defined by the World Health Organization and National Oceanic and Atmospheric Administration. ND–Not Detected.

Location	Cadmium	Chromium	Iron	Lead	Manganese	Nickel
Dahican	ND	0.65	400	17.90	12.20	ND
Dawan	ND	13.40	20,000	ND	396	46
World Health Organization (EPA 2018)	0.1	0.03-0.3	5.00	5.00	0.2	-
National Oceanic and Atmospheric Administration (Buchman 2008)	0.68	52.3	-	30.2	-	15.9

Heavy Metals in Shrimp

The levels of heavy metals (mg kg^{-1}) in shrimp samples varied between locations (Table 4). In Dahican, shrimp tissue contained 0.19 mg kg^{-1} of Cr, 5.80 mg kg^{-1} of Fe, and 0.82 mg kg^{-1} of Mn, while Cd, Pb, and Ni were not detected. The shell samples from the same site had 5.10 mg kg^{-1} of Fe and 0.66 mg kg^{-1} of Mn, with all other metals being undetected. In Dawan, shrimp tissue exhibited Fe and Mn levels, with 19.3 mg kg^{-1} of Fe and 1.20 mg kg^{-1} of Mn, respectively, while Cd, Cr, Pb, and Ni were not detected. The shell samples from Dawan contained 3.10 mg kg^{-1} of Fe and 0.43 mg kg^{-1} of Mn, with other metals not detected.

Table 4. Levels of heavy metals (mg kg^{-1}) in shrimp tissue and shell samples from selected vannamei shrimp farms in City of Mati, Davao Oriental, showing comparisons to permissible limits defined by the World Health Organization and Food and Agriculture Organization. ND–Not Detected.

Location	Sample	Cadmium	Chromium	Iron	Lead	Manganese	Nickel
Dahican	Tissue	ND	0.19	5.80	ND	0.82	ND
	Shell	ND	ND	5.10	ND	0.66	ND
Dawan	Tissue	ND	ND	19.3	ND	1.20	ND
	Shell	ND	ND	3.10	ND	0.43	ND
World Health Organization, Food and Agriculture Organization (JECFA 2021)		1.00	0.05	100.00	2.00	1.00	1.00

Potential Human Health Risks of Heavy Metal Contamination

Target Hazard Quotient (THQ). The THQs for all analyzed heavy metals in shrimp samples from both farms were determined to be less than one (Table 5).

Table 5. Calculated target hazard quotient (THQ) in shrimp tissue and shell and their hazard index (HI) collected from selected shrimp vannamei farms in the City of Mati, Davao Oriental. *Concentration was undetected or below the detection limit; THQ and HI could not be computed.

Heavy Metals	Sampling Site				THQ Recommended Limit (FAO and WHO)
	Farm 1		Farm 2		
	Tissue	Shell	Tissue	Shell	
Cadmium (Cd)	*	*	*	*	1
Chromium (Cr)	5.31E-06				1
Iron (Fe)	0.034	0.03	0.115	0.018	1
Lead (Pb)	*	*	*	*	1
Manganese (Mn)	0.000197	0.000245	0.000359	0.000129	1
Nickel (Ni)	*	*	*	*	1
Hazard Index	**0.06**	**0.036**	**0.146**	**0.019**	**1**

Hazard Index (HI). Shrimp samples collected from Dahican and Dawan exhibited below one in both tissue and shell (Table 5).

DISCUSSIONS

Heavy Metals in Water

Heavy metals naturally occur on the Earth's crust and are enhanced through natural processes such as weathering rocks (Tchounwou et al. 2012; Begum and Simpson 2022; Mitra et al. 2022). However, anthropogenic operations nearby, such as mining, industrial effluents, agricultural wastes, and domestic wastewater, also influence their increasing concentrations to a great extent (Begum and Simpson 2022; Georgaki and Charalambous 2023; Georgaki et al. 2023). The lack of suitable treatment for these wastes leads to contamination in species like shrimp (Tahiluddin et al. 2025). The presence of heavy metal content in aquaculture products poses a significant threat to food security (Takarina et al. 2018). The elevated concentration of Ni in the water samples is particularly concerning due to the proximity of the sampling site to Pujada Bay, as mining activities have been reported. This geographic setup could facilitate the accumulation of pollutants, including heavy metals, in the water column and sediments (Macusi et al. 2019).

High doses of heavy metals may lead to severe serious health risks if orally ingested (Idris et al. 2020; Mitra et al. 2022). In small amounts, they are required for maintaining good health, but in larger amounts, they can become toxic or dangerous. For instance, Cr is an essential nutrient required for sugar and fat metabolism (Vincent 2019). However, it is also noted to have damaging effects on the kidneys, lungs, and liver (Vo Ngoc et al. 2020; Pandiyan et al. 2021; Georgaki et al. 2023). Nickel, on the other hand, is a component of certain enzymes involved with chemical reactions and may assist with iron absorption (Genchi 2020). However, high doses of Ni exposure can cause nausea, stomach cramps, vomiting, and even diarrhea (Buxton et al. 2019). Nonetheless, previous studies have not reported any severe health conditions resulting from skin contact with these metals (Javed and Usmani 2013; Hirose et al. 2021).

Given these potential health effects, understanding the concentrations of heavy metals in aquatic environments becomes essential. The levels of Cd, Fe, Pb, and Mn in this study are found to be within acceptable limits set by international water quality guidelines. This suggests that the water quality meets the standards for these metals. However, their presence in the water sample needs further monitoring since it may cause adverse effects when present excessively (Jaishankar et al. 2014).

Heavy Metals in Sediments

The present study showed elevated levels of Cr, Fe, Pb, and Mn in the water samples collected from both farms in the City of Mati, Davao Oriental. As these metals tend to bioaccumulate in living tissues (Ali et al. 2019), the results indicate a potential threat to the health of aquatic organisms and humans. According to Mani et al. (2015), 80% of pollutants from freshwater environments are directed to the marine environment, a factor not accounted for in the WHO's permissible limit set for freshwater sediment. Apart from natural sources like weathering rocks and minerals, excess Fe, Mn, and Ni in sediments could be attributed to anthropogenic activities (Idrus and Ding 2026). The presence of heavy metals, particularly Cr, Fe, and Mn, may be partly attributed to excessive feed application, as suggested by previous studies (Adekanmbi et al. 2021; Sultana et al. 2022). Aquaculture feeds, usually in the form of dried pellets, are known to contain these essential elements and other nutrients, such as minerals, vitamins, proteins, and lipids, for the proper growth of farmed aquatic organisms

(Truong et al. 2022; Júnior et al. 2023). Moreover, Hidayati et al. (2020) reported that Mn is one of the trace minerals found in the commercial diet sources of *Litopenaeus vannamei* (Boone 1931), with concentrations ranging from 25.9 to 132.2 ppm.

The elevated concentrations of Ni observed in Dawan farm indicate an increased ecological risk associated with shrimp farming operations. The farm's proximity to a national road and suburban houses suggests that municipal activities and vehicle emissions may be significant sources of pollution (Arshad et al. 2024). Vehicles emit heavy metals in the form of fine particulate matter, through the combustion of fuel, engine oil, and tires, as well as from various non-exhaust sources, such as tire and brake wear and road surface abrasion (Begum and Simpson 2022). Additionally, discharges from the neighboring community can be transported to the pond because the farm uses a water pump for its water supply. These activities may contribute to the build-up of Ni in the pond's bottom sediments, as suspended metals from outside the farm can be drawn in by the strong water currents driven by the pump and eventually settle within the farm (Kinuthia et al. 2020; Pandiyan et al. 2021). Pollution in pond sediments can harm both aquatic life and humans because harmful substances can enter the food chain. This usually happens when farms do not manage waste properly or rely too much on artificial feeds to increase production (Olayinka-Olagunju et al. 2021; Hossain et al. 2023).

The absence of Pb in Dawan and Ni in Dahican sediments suggest diverse local pollution sources or distinct geochemical conditions in influencing metal accumulation and mobility (El-Sharkawy et al. 2025). Despite mining operations near Dahican, the absence of Ni in its sediment suggests complex environmental factors at play. Additionally, other anthropogenic contributions, including residential activities in Dawan, may have influenced these findings.

Heavy Metals in Shrimp

In the present study, shrimp are likely to accumulate more heavy metals (Cr in Dahican) from sediments than from water samples, as sediments are more concentrated than water samples. However, the low levels of Fe and Mn in the shrimp tissue and shell are probably due to the shrimp's low accumulation of heavy metals and the farm's management practices since shrimp's accumulation of metals depends on external factors (soluble metals, physiochemical properties, interactions with metals, feeding habits, sediment, and food) and internal factors (individual differences, body size, growth stage, sex, age) (Sharifi et al. 2017; Takarina et al. 2018). Additionally, the early-harvest practice on the farms where this study was conducted may contribute to minimal accumulation of heavy metals in shrimp (Arisekar et al. 2022). The timing of harvest in these farms depends largely on the shrimp's size and weight, as well as the arrival of the purchaser; thus, there is no fixed timeframe or set harvest schedule. According to the Department of Agriculture (2022), shrimp are typically harvested within three months of the start of cultivation. While few studies directly examine the relationship between heavy metal accumulation and shrimp culture duration, this early or flexible harvesting practice might reduce the shrimp's exposure time to environmental pollutants. Hence, even though shrimp feed contains a significant level of heavy metals (Arisekar et al. 2022), this management practice could help reduce the metal accumulation in shrimp. Although the heavy metal concentrations in this study remain within acceptable limits set by regulatory bodies, human exposure to these levels may still result in mild to severe health effects depending on the extent and duration of exposure (Sakar et al. 2016; Zhang et al. 2018).

Moreover, larger shrimp are reported to accumulate higher levels of heavy metals (Ramos-Miras et al. 2023). The shrimp in the present study were harvested within three months of culture, during which they did not have sufficient time to grow and absorb more heavy metals from the surrounding water and sediments. Furthermore, shrimp actively prefer to absorb essential elements, such as calcium, copper, and iron, for growth and survival (Dayal et al. 2013; Ramos-Miras et al. 2023) instead of the non-essential elements like Pb, which have no metabolic role in living organisms and can disrupt normal cellular functions and signaling pathways, affecting a variety of cellular processes (Aytekin et al. 2019). This energy-consuming selective absorption of vital nutrients over harmful substances is a defense mechanism against toxins (Ramos-Miras et al. 2023), further supporting the absence of Pb accumulation in the present study.

Meanwhile, Cr concentration showed noticeable differences between Dawan and Dahican across both sediment and shrimp tissue samples. In sediment samples, Dawan exhibited a high concentration of 13.40 mg kg^{-1} of Cr, compared to Dahican's 0.65 mg kg^{-1}. Both locations had sediment Cr levels exceeding WHO limits. Dawan's water samples also showed Cr levels above the environmental thresholds. However, a notable contrast emerges in shrimp tissue: Dahican shrimp contained 0.19 mg kg^{-1} of Cr, surpassing WHO limits, whereas Cr was undetected in the tissue and shell samples from Dawan. This discrepancy can be attributed to several factors influencing Cr availability and form. While Dawan's sediments possess higher total Cr, it is likely present in less bioavailable form, such as the stable and less soluble trivalent Cr (Cr^{3+}) bound within chromite or clay minerals, than the highly toxic, mobile, and bioaccumulative hexavalent form (Cr^{6+}) (Pađan et al. 2019; Merrot et al 2021). Conversely, the lower sediment Cr in Dahican, which still exceeded WHO limits, led to detectable levels in shrimp tissue. This could be due to the sources of contamination in Dahican, such as wastewater discharge from aquaculture farms and mining operations, introducing Cr in a more bioavailable or toxic form. Coastal sediments can be enriched with Cr from such industrial and domestic effluents, and its persistence and potential for bioaccumulation in the food chain are significant concerns (Pandiyan et al. 2020; El-Sharkawy et al. 2025). The behavior of Cr in sediments is largely influenced by its chemical form, particularly its oxidation-reduction status, and the surrounding geochemical conditions (Dhanakumar and Mohanraj 2019; Sricharoenvech et al. 2024).

Potential Human Health Risks of Heavy Metal Contamination

The THQ estimates the potential health risks associated with accumulated heavy metal concentrations in humans from consuming shrimp contaminated with heavy metals (Biswas et al. 2021). All heavy metal values in both shrimp farms are within the acceptable value (THQ <1) (Table 5). This denotes non-carcinogenic effects from the ingestion of these heavy metals individually.

Shrimp samples taken in Dahican and Dawan showed hazard indices (HI), both in tissue and shell, within the acceptable limit (HI <1). This trend implies a low probability of developing carcinogenic effects from continuous shrimp consumption. Hence, shrimp from farms in the City of Mati are safe for continuous consumption, provided they comply with the regulatory limits. The relatively low risk values may be attributed to the implementation of proper aquaculture management practices, including regulated feeding, water quality monitoring, and sediment remediation, which have been shown to minimize heavy metal accumulation in shrimp (Ali et al. 2019; Ramos-Mitra et al. 2023; Ahmed et al. 2023).

In aquaculture systems, the increasing levels of heavy metals are linked to various sources. Potential sources include contaminated or polluted water, feed additives, pond liners, and the desorption of heavy metals from the sediments (Alam et al. 2002; Hossain et al. 2023). Although elements such as Fe and Mn are essential nutrients for shrimp growth and development (Truong et al. 2023), their elevated levels can be toxic (Frías-Espericueta et al. 2003). This is particularly relevant as shrimp are benthic organisms that feed on seafloor sediments, making them more susceptible to metal accumulation than certain fish species (Hossain et al. 2022). Additionally, shrimp size and age influence metal accumulation, with older and larger shrimp tending to accumulate higher levels of potentially toxic elements due to extended exposure to environment and dietary factors (Ramos-Miras et al. 2023). Practices such as early harvesting may therefore help mitigate this risk.

Despite these findings, a key limitation of this study is that some heavy metal concentrations were below the detection limit (BDL) of the analytical instrument and were excluded from THQ and HI calculations. This may result in an underestimation of actual exposure and associated health risks, rendering the reported values conservation estimates. The use of substituted values for BDL data has been shown to introduce systematic bias, suppress variance, and compromise data interpretation (USEPA 2002; Antweiler and Taylor 2008). To address this limitation, future studies should employ more sensitive analytical techniques, such as Inductively Coupled

Plasma-Optical Emission Spectroscopy (ICP-OES) or Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), to improve the detection and quantification of trace metal concentrations.

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Grammarly Premium was utilized for grammar, spelling, punctuations, and style editing. The authors reviewed and revised the AI-assisted outputs and take full responsibility for the accuracy and integrity the published work.

ETHICAL CONSIDERATIONS

Since this study did not involve human subjects, it was exempted from requiring ethical review.

DECLARATION OF COMPETING INTEREST

The authors declare that there are no competing interests to any authors.

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