

Heavy Metal Bioaccumulation in a Commercially Important Freshwater Fish, Tank Goby (*Glossogobius giuris*), from Lake Mainit, Philippines

Cresencio Cabuga Jr C^{1*}, Julito Puebla Jr A¹, Ailene Budiongan B¹,
Nathalie Daminar L²

¹Department of General Education, College of Industrial Technology and Teacher Education, Caraga State University, Cabadbaran City, Agusan Del Norte, Philippines, ²Research and Development, Innovation & Extension, Caraga State University, Cabadbaran City, Agusan Del Norte, Philippines. *Corresponding Author's Email: cccabuga@csucc.edu.ph

Abstract

Lake Mainit, shared by the provinces of Surigao del Norte and Agusan del Norte, represents a critical natural resource with high ecological significance. Tank Goby, locally known as Pijanga, is a native and economically important fish species in the lake. This study aimed to determine the concentrations of heavy metals in the muscle tissue of *Glossogobius giuris*. A total of nine adult specimens were collected, with body weights ranging from (72–100g) and total lengths from (18–21cm). Homogenized, skinless muscle tissues were analyzed following the standard protocols of the Official Methods of Analysis of AOAC International (21st edition) using modified Silver Diethyldithiocarbamate (SDDC) colorimetric method for Arsenic and Atomic Absorption Spectrophotometry for the rest of the metals. Results showed that the pattern of metal concentrations was as follows: Pb > Ni > Cr > As > Cd across the three sampling areas. Further, no statistically significant differences ($P > 0.05$) among Barangay Roxas, Canaway and San Pablo for most metals. The findings revealed that all detected heavy metals were below the permissible threshold limits, indicating that samples collected from the three barangays were within acceptable safety standards. These results suggest minimal contamination and indicate that the aquatic environment in the study areas remains relatively safe from excessive heavy metal accumulation. However, previous studies have reported heavy metal concentrations in this species that exceed permissible limits. Therefore, further investigation of other economically important fish species in the area, along with regular monitoring, is recommended to ensure continued food safety.

Keywords: Caraga, Freshwater, Limnology, Muscles, Staple Food, Tank Goby.

Introduction

Heavy metals are naturally occurring elements that can become significant pollutants in aquatic ecosystems through anthropogenic activities such as industrial and agricultural discharges, household waste, landfill erosion and other land-based activities. Because heavy metals are persistent and non-biodegradable, they can accumulate in aquatic organisms and may be transferred through food webs, posing potential risks to aquatic organisms and human consumers (1-3). The presence of heavy metals in aquatic environments is a significant concern due to their persistence and ability to undergo processes such as adsorption, sedimentation, dissolution and bioaccumulation. Unlike many organic pollutants, heavy metals cannot be readily degraded into harmless substances and may remain in the environment depending on water chemistry,

sediment properties and biological processes (4). Their mobility, persistence and bioavailability are influenced by environmental factors, including pH, temperature, dissolved oxygen, salinity, suspended particles and organic matter. These conditions can determine the extent to which metals remain available for uptake by aquatic organisms, thereby affecting their potential accumulation and ecological impacts (5). In aquatic ecosystems, sediments can serve as important reservoirs of heavy metals because metals released into the water column may bind to particulate materials and settle on the bottom. Changes in environmental conditions can subsequently remobilize these metals, making them available to aquatic organisms (6). Fish may be exposed to heavy metals through multiple pathways, including direct uptake from the water,

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ingestion of contaminated sediments and consumption of contaminated prey. The extent of metal accumulation varies among species and may be influenced by factors such as age, body size, feeding behavior, trophic position, habitat and environmental physicochemical conditions.

Because fish integrate contaminants from different components of aquatic ecosystems, they are considered useful bioindicators of heavy metal contamination and can reflect the presence and bioavailability of metals in water, sediments and food sources (7).

The assessment of heavy metals in edible fish is particularly relevant to environmental and public health because fish are an important source of animal protein and are frequently consumed by communities living near freshwater ecosystems. Although essential elements such as zinc and copper are required for normal physiological functions at appropriate concentrations, excessive exposure may cause adverse biological effects. Non-essential or potentially toxic metals such as arsenic, cadmium, lead and chromium may pose health concerns when exposure occurs at elevated levels. Consequently, determining metal concentrations in fish tissues and comparing them with established permissible limits provides useful information for evaluating environmental quality and potential risks associated with fish consumption (8, 9).

For lake ecosystems that support fisheries and local livelihoods, regular monitoring is essential because environmental conditions and anthropogenic activities can change over time. Baseline and periodic assessments can identify spatial variations in contamination, establish trends in metal accumulation and generate scientific evidence for resource management and public health protection. Moreover, assessing physicochemical characteristics alongside heavy metal concentrations provides a more comprehensive understanding of the environmental conditions that may influence metal distribution, mobility and accumulation in aquatic organisms.

Lake Mainit is the fourth largest and one of the deepest lakes in the Philippines, with a maximum depth of approximately 223 m and a surface area of about 172.40 km² (10). Located between the provinces of Agusan del Norte and Surigao del Norte, the lake provides important ecological, economic and livelihood resources to surrounding

communities. Numerous communities depend on its fisheries and other aquatic resources for food and income (11-14). However, anthropogenic activities, including mining, agricultural practices, agrochemical use, unsustainable fishing and the expansion of human settlements, may adversely affect the ecological condition of the lake (15, 16). Previous assessments have documented varying levels of heavy metals in the water, sediments and aquatic organisms of Lake Mainit, indicating the need for continued monitoring of contaminant levels and their potential ecological and public health implications (17-19).

The tank goby, locally known as pijanga, is a native and commercially important fish species in Lake Mainit (18). It is widely consumed and contributes to the food supply and livelihood of communities surrounding the lake (16). Its feeding behavior may also expose it to contaminants present in the aquatic environment. As a piscivorous species (20), *Glossogobius giuris* may accumulate heavy metals through its diet, making its tissues useful for assessing the occurrence of metal contamination and potential exposure through fish consumption (21, 22).

Previous studies have documented heavy metal accumulation in aquatic organisms from Lake Mainit. Heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni) and zinc (Zn) have been investigated in fish and sediments, with reported concentrations varying among locations and species (23, 24). In particular, previous research on *G. giuris* has reported the presence of several heavy metals in its muscle tissues, with concentrations differing from those observed in other fish species and sampling areas. These differences may be associated with variations in sampling location, environmental conditions, anthropogenic activities, feeding behavior and metal bioavailability (25).

Despite previous investigations, continued assessment of heavy metal accumulation in *G. giuris* remains important because the species is regularly consumed by communities surrounding Lake Mainit. Monitoring different sampling locations can provide updated information on the current status of heavy metal accumulation and help determine whether detected concentrations remain within established safety limits. Assessment of physicochemical water conditions

alongside heavy metal concentrations can also provide additional information on the environmental conditions of the sampling sites. Thus, this study was conducted to assess the physicochemical characteristics of the sampling sites and determine the concentrations of selected heavy metals in the muscle tissues of *Glossogobius giuris* from Lake Mainit, Philippines. Specifically, the study aimed to:

- determine the physicochemical parameters of water, including temperature, conductivity, pH, dissolved oxygen and total dissolved solids, across the selected sampling sites;
- quantify the concentrations of arsenic (As), cadmium (Cd), chromium (Cr), nickel (Ni) and lead (Pb) in the muscle tissues of *G. giuris*;
- compare the detected heavy metal concentrations among the three sampling sites; and
- assess the detected concentrations against established permissible threshold limits to

determine their potential implications for fish safety and environmental quality.

Methodology

Study Area

Lake Mainit, as shown in Figure 1, sustains fisheries that support the livelihoods of communities in the municipalities of Surigao del Norte (9°18' to 10°30' N and 125°15' to 126°15' E) and Agusan del Norte (9.0720° N, 125.4978° E) while the local economies surrounding the lake also depend heavily on adjacent agricultural production (21). The sampling stations namely: S1 (Barangay Roxas), S2 (Barangay Canaway) and S3 (San Pablo), where the fish was collected. These areas are relatively far and constitute the upper, middle and lower portions of the Lake. The upper and middle portions may receive more direct influence from tributaries and land-based inputs (agriculture, settlement), while the lower portion might reflect more integrated or downstream effects.

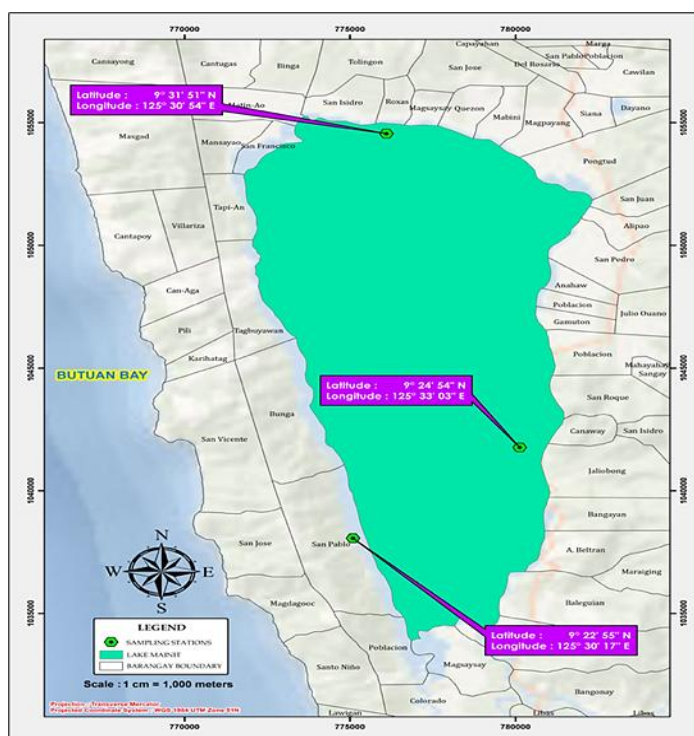


Figure 1: Map of the Study Area, Lake Mainit, Philippines

Physicochemical Parameters

Physicochemical water parameters, including temperature, conductivity, pH, total dissolved solids (TDS) and dissolved oxygen (DO), were measured concurrently with fish sampling at three stations, each with three replicates. At sites where fish were collected, three randomized trials were

conducted to ensure measurement reliability. Data were obtained using a multi-parameter water quality meter (EUTECH PCD) and analyzed with Paleontological Statistics Software (PAST), with results reported as mean $\pm$ standard error of the mean (SEM).

Collection and Processing of Fish Samples

A purposive sampling strategy was used to select three stations in Lake Mainit (9°25'57"N 125°31'22"E) Barangay Roxas (S1), Barangay Canaway (S2) and Barangay San Pablo (S3) representing the upper, middle and lower portions of the lake. *G. giuris* specimens were collected with the assistance of a local fisherman, with 3 adult (weights: 0.72 to 100g and lengths: 180 to 210cm) specimens collected from each station (9 specimens in total). The same collection and handling procedures were applied at all stations to ensure consistency. Fish length and weight were recorded and muscle tissues were collected and transported under chilled conditions for laboratory analysis (23, 26). Sampling was conducted under the necessary permits and regulations. The findings are therefore interpreted specifically for the three selected sampling stations and are not intended to represent the entire Lake Mainit.

Analysis of Levels of Arsenic Cadmium, Chromium Lead, Nickel in Fish Muscles

Homogenized, skinless fish muscle samples were transported under chilled conditions to the FAST Laboratory in Cagayan de Oro City for heavy metal analysis. Analytical procedures followed the Official Methods of Analysis of AOAC International (27), with appropriate sample digestion and preparation prior to instrumental determination. Arsenic (As) was quantified using the modified Silver Diethyldithiocarbamate (SDDC) colorimetric method, based on the AOAC procedure with modifications adopted for the present study. Cadmium (Cd), chromium (Cr), nickel (Ni) and lead (Pb) were determined using Atomic Absorption Spectrophotometry (AAS) following the applicable analytical procedures. Quality assurance and quality control (QA/QC) measures, including method blanks, duplicate analyses and certified reference materials, were employed to ensure analytical accuracy and precision. Laboratory detection limits for each analyte were also verified to meet applicable AOAC performance criteria. These procedures ensured the reliability and validity of the measured heavy metal concentrations in the *Glossogobius giuris* muscle tissues.

Limits of Detection and Quantification

The limits of detection (LOD) and limits of quantification (LOQ) were not determined for each

analyzed metal (As, Cd, Cr, Ni and Pb) based on the analytical method and laboratory quality-control procedures. However, the analytical reporting limits were 0.05 mg/kg for arsenic (As), 0.025 mg/kg for cadmium (Cd) and 0.25 mg/kg for chromium (Cr), lead (Pb) and nickel (Ni).

Regulatory Standards for Heavy Metal Concentrations in Fish Muscle

The concentrations of arsenic (As), cadmium (Cd), chromium (Cr), nickel (Ni) and lead (Pb) detected in the muscle tissues of *G. giuris* were evaluated against applicable regulatory limits for contaminants in fish and fishery products intended for human consumption. The analytical results were reported in mg/kg wet weight (ww) to ensure consistency with the units used in food-safety standards. The comparison of measured concentrations was based on the applicable standards and regulatory guidance of recognized food-safety authorities, particularly the Codex Alimentarius Commission (FAO/WHO) standards for contaminants in food. The standards were selected based on their applicability to fish muscle and fishery products intended for human consumption, rather than standards established for water, sediments, or other environmental matrices. Where a specific maximum level was not established for a particular metal fish category combination, the absence of an applicable regulatory limit was explicitly indicated rather than assigning a value from an unrelated food category.

Statistical Analysis

PAST (Paleontological Statistics Software) was used in testing the difference of means of the concentration and levels of As, Cd, Cr, Pb and Ni in the muscles. One-Way Analysis of variance (ANOVA) was used for testing the significant difference of the muscles. Data were presented as mean $\pm$ standard error mean (SEM) and were calculated using column statistics in PAST software. All data were analyzed using Graph Pad Prism 10.0.

Ethical Consideration

Specimens of *G. giuris* were collected from Lake Mainit, Philippines, under the necessary permits and in compliance with applicable local regulations. Sample handling and laboratory analyses were conducted following established ethical and biosafety guidelines.

Results and Discussion

Physicochemical Characteristics of Water Across the Sampling Sites

Table 1 shows the physicochemical parameters of water measured across three sampling sites in Lake Mainit, Philippines. Conductivity values ranged from (215 to 240 $\mu\text{S}/\text{cm}$), which fall well within the acceptable limits prescribed by national standards. These readings indicate a moderate ionic concentration, characteristic of many freshwater systems in the Philippines. Comparable conductivity levels have been reported in the Marilao River and Urdaneta tributaries, where similar values were attributed to the presence of naturally occurring minerals rather than significant anthropogenic pollution (21). Dissolved oxygen (DO) concentrations exhibited apparent spatial variation, with the northern and middle reaches recording (4.41 mg/L and 3.96 mg/L,) respectively both below the 5 mg/L threshold set by the Department of Environment and Natural Resources (12). In contrast, the southern section registered a higher DO concentration of (7.84 mg/L), exceeding the standard limit. The reduced DO levels in the upper (Barangay Roxas) and middle (Barangay Canaway) reaches may be attributed to organic loading, low water flow and consequently limited aeration, factors that are known to depress oxygen availability in tropical streams (25). Similar longitudinal patterns have been documented in the Marilao–Meycauayan–Obando River System, where midstream segments displayed oxygen depletion linked to domestic and agricultural effluents (26). The elevated DO observed in the lower stream may, therefore, reflect enhanced re-aeration processes associated with riffles, increased turbulence, or the inflow of oxygen-rich tributaries. Ecologically, such oxygen deficiencies in the upper and middle portions could impose physiological stress on sensitive macroinvertebrates and fish species, potentially reducing biodiversity and favoring more tolerant taxa (27).

Meanwhile, the pH values, ranging from (7.97 to 8.03,) were within the optimal range for most

freshwater biota. The slightly alkaline conditions observed are typical of tropical freshwater ecosystems and are likely influenced by carbonate buffering (28). Temperature readings between (28 and 28.7°C) are consistent with those reported for Laguna de Bay and several inland rivers in Mindanao (24). While these temperatures are generally conducive to aquatic life, they may reduce oxygen solubility, potentially exacerbating the low DO concentrations observed in slower-flowing sections of the stream. These values are comparable to those reported for upland river systems in Mindanao with limited agricultural runoff (28). Total Dissolved Solids (TDS) levels, ranging from (125 to 131 mg/L) indicated low concentrations of dissolved substances, suggesting minimal salinity and a low degree of anthropogenic influence.

Generally, the physico-chemical profile of the Lake Mainit tributary stream indicates a moderately impacted ecosystem. The reduced DO in the northern and middle portions implies organic enrichment or restricted hydrological flow. In contrast, the acceptable values of conductivity, TDS, pH and temperature indicate the absence of substantial ionic or chemical pollution. Based on Philippine freshwater ecological assessments, such conditions correspond to a “fair” ecological status, wherein tolerant species dominate over more sensitive taxa (27). The assessment of physicochemical parameters across the three sampling sites of Lake Mainit reveals a system that remains generally compliant with established water quality standards, yet exhibits localized stressors that may impact the ecological balance. The low dissolved oxygen (DO) concentrations in the upper and middle reaches are of particular concern, as they fall below the regulatory threshold and may indicate organic enrichment, reduced flow velocity, or biochemical oxygen demand (BOD) from organic matter decomposition. Such oxygen limitation can significantly impact aquatic community structure, reducing the abundance of sensitive taxa, such as Ephemeroptera, Plecoptera and Trichoptera (EPT) and favoring pollution-tolerant species (28).

Table 1: Physicochemical Characteristics Across the Three Sampling Sites in Lake Mainit, Philippines

Parameters	Standard DAO 2016-08	Barangay Roxas	Barangay Canaway	Barangay San Pablo	Remarks
Conductivity	100-2000 uS/cm	215.67 ± 28.61	216 ± 27.74	240 ± 7.02	Within the permissible limits
Dissolve Oxygen	>5mg/L	4.41 ± 0.03	3.96 ± 0.24	7.84 ± 0.14	Within the permissible limits
pH	6.5-8.5	7.98 ± 0.12	7.97 ± 0.01	8.03 ± 0.04	Within the permissible limits
Temperature	26-30 °C	28.67± 0.33	28.67 ± 0.33	28.00 ± 0.58	Within the permissible limits
Total Dissolve Solids	<1000mg/L	131.33 ± 1.33	125.33 ± 0.67	126.67 ± 1.76	Within the permissible limits

Conversely, the southern area (Barangay San Pablo) exhibited relatively higher DO levels, suggesting improved aeration and hydrodynamic mixing, which ripples or tributary inflows may have enhanced. The stability of pH, conductivity and TDS across all sites reflects a chemically balanced environment with low ionic pollution, aligning with conditions reported in other relatively unpolluted Philippine freshwater systems (24, 25). The observed temperature range is characteristic of tropical streams and, while generally suitable for aquatic organisms, may exacerbate DO depletion in areas with poor circulation (29). From an ecological perspective, these findings suggest that Lake Mainit's tributary system is moderately impacted, displaying early signs of stress that are likely driven by localized organic inputs or hydrological modifications. The physico-chemical parameters indicate that while the water quality remains within acceptable limits, the biological integrity of the system could be at risk if DO levels continue to decline. Maintaining adequate oxygenation is critical for sustaining biodiversity and supporting essential ecosystem functions such as nutrient cycling and primary production.

Heavy Metal Concentrations in the Muscle Tissues of *G. giuris*

Table 2 shows that Arsenic (As) was detected in *G. giuris* from all three sites, with the highest concentration in Barangay Canaway (0.015 mg/kg). This finding is consistent with previous

studies reporting low but detectable arsenic accumulation in freshwater fish (30-32). The variation among sites may be associated with differences in local contamination sources, sediment characteristics and feeding conditions, particularly since *G. giuris* is a bottom-associated species. Cadmium (Cd) was detected only in Barangay Canaway (0.003 mg/kg), suggesting possible localized exposure. Similar spatial variations in cadmium accumulation have been reported in freshwater fish and may result from differences in sediment chemistry, anthropogenic inputs and bioaccumulation processes. Meanwhile, chromium (Cr) was detected at all sites, with the highest concentration in Barangay Roxas (0.021 mg/kg). Its distribution differed from that of arsenic, suggesting that the metals may have different sources or environmental pathways. Generally, the relatively low concentrations indicate limited heavy-metal accumulation in the muscle tissues of the sampled fish. However, the spatial differences emphasize the need to assess water, sediments and prey organisms to better identify contamination sources and potential ecological risks in Lake Mainit. Comparable observations were reported in freshwater ecosystems in the Philippines where heavy metal concentrations in aquatic organisms remained below international safety standards, reflecting limited anthropogenic contamination and relatively stable environmental conditions (11, 33).

Table 2: Heavy Metal Concentrations in the Muscles Tissues of *G. giuris* Collected from Three Sampling Sites in Lake Mainit, Philippines

Heavy Metals	Threshold (mg/kg)	Barangay Roxas	Barangay Canaway	Barangay San Pablo	Regulatory Standard
As	0.050	0.012 ± 0.003	0.015 ± 0.004	0.010 ± 0.002	Codex Alimentarius Commission, CXS 193-1995; applicable inorganic arsenic provisions
Cd	0.025	ND	0.003 ± 0.001	ND	Codex Alimentarius Commission, CXS 193-1995 / applicable food category
Cr	0.250	0.021 ± 0.006	0.018 ± 0.005	0.020 ± 0.004	No specific Codex Maximum Level identified for chromium in fish muscle
Ni	0.250	0.030 ± 0.008	0.025 ± 0.007	0.028 ± 0.006	No specific Codex Maximum Level identified for nickel in fish muscle
Pb	0.250	0.040 ± 0.010	0.035 ± 0.009	0.038 ± 0.008	Codex Alimentarius Commission, CXS 193-1995;

Note: Values are expressed as mean ± SEM in mg/kg wet weight. ND = Not Detected. Analytical reporting limits: As = 0.050 mg/kg, Cd = 0.025 mg/kg and Cr, Ni and Pb = 0.250 mg/kg. Analytical procedures followed AOAC International, 21st ed. (2019).

Previous research has shown that muscle tissue generally accumulates lower concentrations of heavy metals than metabolically active organs such as the liver and gills (34), which supports the finding that non-detects in *G. giuris* muscle do not necessarily reflect the complete absence of metals in the environment. Studies in nearby Mindanao lakes have also reported low muscle concentrations of Pb, Ni and Cd in native fish species where anthropogenic pressures are limited (35), consistent with the present results. Furthermore, the benthic feeding behavior of *G. giuris* often exposes the species to sediment-associated contaminants; however, non-detects may indicate either low sediment contamination or poor metal bioavailability due to strong adsorption to sediment particles, a process well-documented in tropical lake systems (36). The findings suggest that the current metal exposure risk to human consumers is low; however, consistent with earlier recommendations by Philippine ecotoxicological studies (37, 38), continued multi-tissue monitoring, sediment assessment and the use of more sensitive analytical methods remain essential to detect any future changes linked to mining, agricultural runoff, or watershed development. The presence of Pb, Ni, Cr, As and Cd in Lake Mainit

may result from both natural and anthropogenic sources. Natural inputs may arise from the weathering and erosion of metal-bearing rocks and soils, which can transport naturally occurring metals through tributaries into the lake (39). Anthropogenic sources may include mining activities, agricultural runoff, agrochemical and fertilizer application, domestic wastes and settlement-related activities. These potential sources are particularly relevant in the Lake Mainit watershed, where mining areas occur near tributaries and extensive agricultural and residential areas surround portions of the lake. Previous studies have documented heavy metals in the surface water, sediments and aquatic organisms of Lake Mainit (11, 20). It was also identified agricultural activities as a potential source of Cd through fertilizer and pesticide inputs, (11) while reported higher metal accumulation in *G. giuris* from areas associated with mining, agriculture, residential activities and tributary inputs (21). In the present study, the relatively higher Pb and Ni concentrations may therefore reflect localized watershed inputs and/or natural geochemical processes. However, because source-apportionment analyses were not conducted, these pathways should be considered potential rather than definitive sources.

Table 3: One-way ANOVA Results of Heavy Metal Concentrations in the Muscles Tissues of *G. giuris* Collected from Three Sampling Sites in Lake Mainit, Philippines

Heavy metal	F-statistic	df	Exact P-value	η^2	Interpretation
As	0.655	2.24	0.5284	0.0518	Not significant
Cr	0.091	2.24	0.9134	0.0075	Not significant
Ni	0.128	2.24	0.8809	0.0105	Not significant
Pb	0.078	2.24	0.9256	0.0064	Not significant

Note: df = Degree of Freedom, η^2 = effect size.

Table 3 presents the results of the one-way ANOVA, which showed no significant differences in the concentrations of As, Cr, Ni and Pb in the muscle tissues of *G. giuris* among the three sampling sites in Lake Mainit ($p > 0.05$). Arsenic showed the largest effect size ($\eta^2 = 0.0518$), although this remained small and statistically non-significant ($F = 0.655$, $p = 0.5284$). Chromium ($F = 0.091$, $p = 0.9134$, $\eta^2 = 0.0075$), nickel ($F = 0.128$, $p = 0.8809$, $\eta^2 = 0.0105$) and lead ($F = 0.078$, $p = 0.9256$, $\eta^2 = 0.0064$) likewise showed very small effect sizes. These findings indicate that the observed concentrations of the analyzed heavy metals were relatively consistent across the three sampling sites, suggesting no significant spatial variation in metal accumulation in *G. giuris* muscle tissues during the study period.

However, the findings of the present study in Figure 2 differ from those of a previous study (21), which reported an increasing order of heavy metal concentrations in *G. giuris* muscle tissue: Cd (not detected) < Pb (0.05 mg/kg) < As (0.17 mg/kg) < Ni (0.35 mg/kg) < Cu (0.99 mg/kg) < Cr (1.43 mg/kg) < Zn (50.12 mg/kg). At the same time, a study in Lake Lanao reported that heavy metals arsenic, cadmium, chromium, mercury and lead

accumulated in the muscle tissue of the fish (*G. giuris*) at concentrations within safe limits (40). Characteristically, the carnivorous feeding habit of the fish influence to bioaccumulation, making it a reliable bioindicator with a high capacity to accumulate heavy metals from the surrounding aquatic environment (41-43). Moreover, the fish samples in the previous study were collected from a different sampling area than that used in the present study (43). The five sampling stations (Tagbuyawan, Magtiaco, Jaliobong, Dinarawan, Kalinawan) were associated with varying anthropogenic activities, with both small- and large-scale mining operations currently active in Magtiaco and Tagbuyawan, areas located near several river tributaries. Additionally, a hydro-power facility is located near the lake and discharges wastewater directly from a tunnel into the Lake. The Kalinawan River outlet in Barangay Colorado, Jabonga, is bordered by extensive agricultural areas, including rice paddies and plantations of maize, watermelon and squash and is subject to annual flooding (44). These areas are also residential zones with access to fishery resources and are used for transportation via boats and fuel-powered vehicles (11).

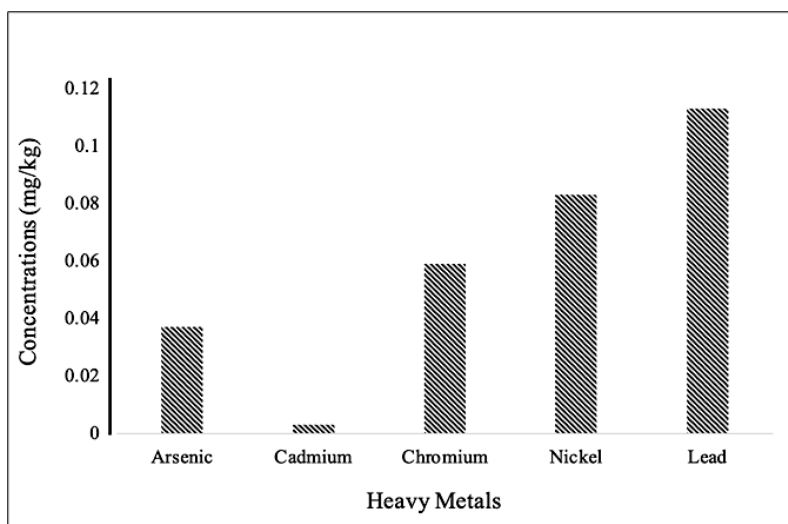


Figure 2: Concentrations of Heavy Metals in the muscles of *G. giuris*

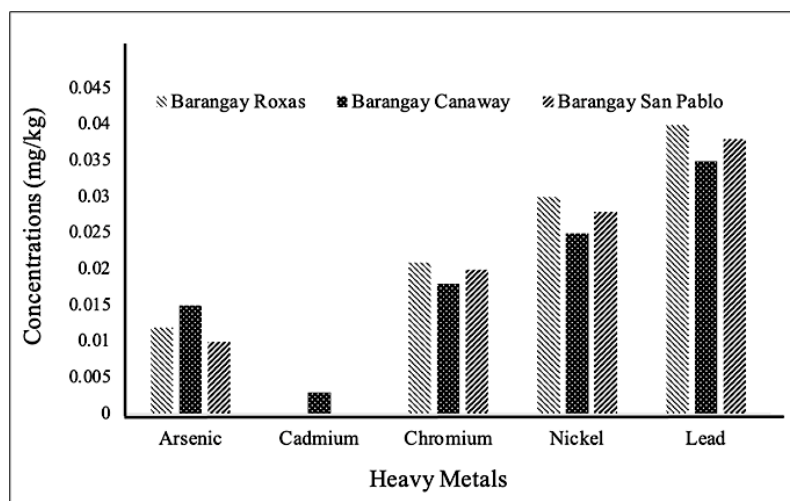


Figure 3: Concentrations of Heavy Metals Across the Three Sampling Areas

Specifically, lead (Pb) accumulation in the muscle tissues of three major fish species *O. niloticus*, *G. giuris* and *C. striata* collected from the same area was relatively low and remained below the established permissible limits (45). Additionally, heavy metal concentrations were detected in *C. striata* from the lake, with levels occurring in the following descending order: Zn > Cu > Cr > Ni > As > Pb > Cd. Notably, the concentrations of these metals exceeded the recommended safe limits (23). Similarly lead, cadmium and mercury were detected in the Lakes water, though at non-alarming levels (20, 46). In contrast, sediment analysis revealed heavy metal concentrations in the order of Pb > Cd > Hg, exceeding standard limits (24). While these metals were not detected in fish samples, Lake Mainit's surrounding intensive agriculture may contribute cadmium from phosphate fertilizers and pesticides, potentially leaching into the lake (20). Although the study detected no measurable levels of these metals, the results indicate that fish samples from the study areas are safe for human consumption. Yet, heavy metal bioaccumulation in fish is affected by multiple factors, such as body size, sex, reproductive stage, feeding habits, swimming patterns and habitat conditions (47, 48). Nevertheless, the potential presence of these metals remains a concern, as their cumulative effects may pose risks to human health (49). Despite the results of the study, Lake Mainit is persistently influenced by various anthropogenic activities in its surrounding areas, including mining, unsustainable fishing practices, the use of agrochemicals and the expansion of human

settlements, all of which may have intensified the lake's current condition (12).

The heavy metal concentrations in Figure 3 indicated that arsenic, cadmium, chromium, nickel and lead in the sampled areas of Lake Mainit remained below the established threshold limits, suggesting a relatively low ecological risk in the lake ecosystem. However, the observed presence of nickel and lead at comparatively higher concentrations across Barangay Roxas, Barangay Canaway and Barangay San Pablo may still reflect potential influences from anthropogenic activities such as agricultural runoff, domestic wastes and nearby mining-related operations within the Lake Mainit watershed. Previous studies in Lake Mainit and other freshwater ecosystems in Mindanao reported that continuous exposure to trace heavy metals may gradually affect aquatic organisms through bioaccumulation and trophic transfer despite concentrations remaining within permissible limits (8, 50). Moreover, heavy metals are persistent environmental pollutants that can accumulate in sediments and aquatic biota over time, potentially affecting biodiversity, water quality and fisheries productivity if not regularly monitored (51). Thus, although the present findings suggest that the ecological condition of Lake Mainit remains within safe standards, continuous environmental monitoring and strengthened conservation efforts are essential to prevent future ecological degradation and maintain the ecological integrity of the lake ecosystem.

Several toxic heavy metals, are lead, thallium, cadmium and antimony, are widely used in industrial processes and are recognized as

substantial contributors to environmental pollution (51). Exceeding the recommended threshold levels of these metals may constitute a potential health risk. Heavy metals may induce toxicity in various human organs, leading to adverse effects such as nephrotoxicity, neurotoxicity, hepatotoxicity, dermal toxicity and cardiovascular toxicity, among others (52). Excessive levels of both essential and non-essential trace elements can lead to physiological or morphological abnormalities, as well as genetic mutations, potentially inhibiting growth or triggering mutations (53). Environmental pressures, including uncontrolled mining, unsustainable agricultural practices, human activities, soil erosion and improper fishing methods, have intensified pollution and ecological risks in Lake Mainit (20). Moreover, the lake is a valuable natural resource with significant ecological. It is reassuring to note that these fish remain safe for consumption, which is important since many communities around the lake rely on fish harvests as a primary source of livelihood. Generally, the findings demonstrate that the heavy metal levels across the three barangays do not pose immediate ecological or public health concerns. However, continuous monitoring is still recommended considering that heavy metals are persistent pollutants capable of bioaccumulation in aquatic organisms over time (46, 54) importance and serves as a vital communal asset for the provinces of Surigao del Norte and Agusan del Norte (7).

Conclusion

The present study demonstrated that the concentrations of arsenic (As), cadmium (Cd), chromium (Cr), nickel (Ni) and lead (Pb) in the muscle tissues of *G. giuris* collected from Barangay Roxas, Barangay Canaway and Barangay San Pablo, Lake Mainit, were below the applicable permissible limits for fish and fishery products. No statistically significant differences in As, Cr, Ni and Pb concentrations were observed among the three sampling sites, indicating relatively comparable levels of metal accumulation in the muscle tissues of *G. giuris* within the sampled areas. The physico-chemical characteristics of the water were generally within acceptable ranges, although dissolved oxygen concentrations at Barangay Roxas and Barangay Canaway were below the

recommended threshold. These findings suggest that, during the sampling period, heavy-metal accumulation in the edible muscle tissues of *G. giuris* did not indicate an immediate food-safety concern at the selected sites.

Several limitations should, however, be considered when interpreting these findings. The study was based on a relatively small number of fish specimens ($n = 9$), with only three specimens collected from each of the three sampling stations. In addition, the investigation was conducted at selected sites and during a limited sampling period; consequently, the results should not be generalized to the entire Lake Mainit ecosystem or interpreted as representative of seasonal patterns of metal accumulation. The assessment was also restricted to muscle tissues, which may not fully reflect metal accumulation in other metabolically active tissues such as the liver and gills. Moreover, potential sources of heavy metals were inferred from the environmental context and previous studies, but source-apportionment analyses were not performed; therefore, the contribution of specific natural or anthropogenic sources cannot be established from the present data.

Future investigations should employ larger sample sizes, broader spatial coverage and repeated sampling across wet and dry seasons to determine temporal and spatial variability in heavy-metal accumulation. Comparative assessment of multiple commercially important fish species and different tissues, together with concurrent analysis of water, sediments and prey organisms, would provide a more comprehensive understanding of metal bioavailability, uptake and trophic transfer within Lake Mainit. The application of more sensitive analytical techniques and source-apportionment approaches is also recommended to improve the detection of trace-level contaminants and identify their probable origins. Long-term environmental monitoring integrating heavy-metal concentrations with physicochemical and sediment characteristics would further strengthen the assessment of contamination trends and ecological risks. Such evidence would support science-based fisheries management, environmental monitoring and the protection of aquatic ecosystem integrity and public health in communities dependent on Lake Mainit fisheries.

Abbreviations

AAS: Atomic Absorption Spectrophotometry, FAO: Food Agriculture Organization, QA: Quality Assurance, QC: Quality Control, WHO: World Health Organization.

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Author Contributions

Cresencio Cabuga Jr C: Writing – Original Draft, Review and Editing, Julito Puebla Jr A: Data Analysis, Ailene Budiongan B: Sampling Procedure, Nathalie Daminar L: Supervision.

Conflict of Interest

The authors declare no conflict of interests.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Artificial Intelligence (AI) Assistance

Artificial intelligence (AI) tools were used solely to assist with language editing, grammar improvement and manuscript organization. The authors retain full responsibility for the accuracy, interpretation, originality and integrity of the content presented in this manuscript.

Ethics Approval

Fish specimens used in this study were obtained from local fishers operating in Lake Mainit, Philippines, under the necessary collection permits and in compliance with applicable regulations. All laboratory procedures were performed following established ethical and biosafety guidelines.

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