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Journal of Biotropical Research and Nature Technology Vol. 5 No. 1 (2026) https://doi.org/10.47352/jbrnt.2964-0431.452

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Research Article

Bioaccumulation of Heavy Metals Fe, Cu, and Mn in Mozambique Tilapia (*Oreochromis mossambicus*) from Situ Tlajung Hilir, Gunung Putri, Bogor

Widya Kartika Laksmawati, Mia Azizah*, Nurlela, Sufrizal Ihsan Latief

Received : June 25, 2026	Revised : June 28, 2026	Accepted : June 29, 2026	Online : June 29, 2026

Abstract

Freshwater ecosystems located near urban, industrial, and residential areas are vulnerable to heavy metal contamination derived from anthropogenic activities, including industrial discharge, domestic wastewater, and surface runoff. These contaminants may accumulate in aquatic organisms and potentially affect food safety when contaminated fish are consumed. This study evaluated the concentrations of iron (Fe), copper (Cu), and manganese (Mn) in the edible muscle tissue of Mozambique tilapia (*Oreochromis mossambicus*) collected from Situ Tlajung Hilir, Bogor Regency, Indonesia. Fish samples were obtained from three purposively selected locations representing areas influenced by community activities, industrial operations, and domestic wastewater discharge. Heavy metal concentrations were determined using Atomic Absorption Spectroscopy (AAS) following wet digestion of dried muscle tissues. The concentrations of Fe, Cu, and Mn varied among sampling locations, with Fe showing the highest accumulation, followed by Cu and Mn. Based on dry weight measurements, Fe concentrations ranged from 66.14 to 621.39 mg kg^{-1}, Cu from 0.87 to 21.27 mg kg^{-1}, and Mn from 5.14 to 6.18 mg kg^{-1}. Although numerical differences were observed among sampling locations, statistical analysis indicated that these differences were not significant, suggesting high within-site variability and limited statistical power due to the small number of biological replicates. The elevated concentrations of metals in fish muscle indicate that *O. mossambicus* from Situ Tlajung Hilir has accumulated Fe, Cu, and Mn, possibly reflecting the influence of surrounding anthropogenic activities. However, direct identification of contamination sources requires further analysis of water, sediment, and physicochemical parameters. These findings provide preliminary evidence of heavy metal bioaccumulation in fish from an urban freshwater ecosystem and highlight the need for continuous environmental monitoring and future human health risk assessment.

Keywords: Atomic Absorption Spectroscopy, bioaccumulation, freshwater pollution, heavy metals; *Oreochromis mossambicus*

1. INTRODUCTION

Heavy metal contamination has become a major environmental concern due to rapid industrialization, urbanization, and increasing anthropogenic activities. Industrial effluents, metal-processing industries, agricultural runoff, and domestic wastewater continuously introduce heavy metals into aquatic ecosystems. Unlike many organic pollutants, heavy metals are persistent, accumulate in sediments, and can subsequently enter aquatic food webs through bioaccumulation, posing ecological and human health risks [1,7].

Fish are widely recognized as effective bioindicators of heavy metal pollution because they continuously interact with contaminated water, sediments, and food resources. Heavy metals accumulated in fish tissues not only reflect environmental contamination but also represent a potential pathway of human exposure through fish consumption [3,4,13]. Consequently, monitoring heavy metal concentrations in edible fish species has become an important approach for evaluating freshwater ecosystem quality and food safety [1,2].

Among the various heavy metals occurring in aquatic environments, iron (Fe), copper (Cu), and manganese (Mn) were selected because they are environmentally relevant to the characteristics of the study area. Situ Tlajung Hilir is surrounded by industrial facilities, vehicle repair workshops, commercial areas, and residential settlements, all of which may contribute Fe-, Cu-, and Mn-containing wastes through industrial effluents, urban runoff, corrosion products, and domestic wastewater [1,8,9]. These metals are widely used in manufacturing processes, metal fabrication, machinery maintenance, electrical components, and construction materials, making them common contaminants in rapidly urbanizing freshwater ecosystems [1,9]. Although Fe, Cu, and Mn are essential trace elements required for oxygen transport, enzymatic activity, and bone

development, excessive accumulation may induce oxidative stress, neurological disorders, liver dysfunction, and other adverse effects in aquatic organisms and humans [1,7,11,14]. Therefore, evaluating the accumulation of these metals in edible fish species provides important information for assessing environmental contamination as well as potential food safety risks.

Mozambique tilapia (*Oreochromis mossambicus*) is one of the most widely consumed freshwater fish species in Indonesia and is considered a suitable bioindicator because of its relatively sedentary behavior, omnivorous feeding habits, and ability to accmulate contaminants from the surrounding environment [3,6]. Situ Tlajung Hilir, located in Gunung Putri District, Bogor Regency, is surrounded by rapidly expanding industrial, commercial, and residential areas that may contribute heavy metal inputs into the aquatic ecosystem through industrial discharge, urban runoff, and domestic wastewater.

Previous studies have investigated heavy metal contamination in freshwater ecosystems; however, most have focused primarily on water and sediment quality or on highly toxic non-essential metals such as Pb, Cd, and Hg. Information regarding the accumulation of essential heavy metals (Fe, Cu, and Mn) in edible *Oreochromis mossambicus* inhabiting Situ Tlajung Hilir remains limited. Moreover, previous studies have rarely evaluated the spatial distribution of these essential metals in fish collected from small urban freshwater ecosystems that are simultaneously influenced by industrial, commercial, and residential activities. By focusing on Fe, Cu, and Mn bioaccumulation in an economically important freshwater fish species from Situ Tlajung Hilir, this study provides baseline evidence of spatial contamination patterns in an urban freshwater ecosystem and contributes scientific information that can support future environmental monitoring and human health risk assessment in rapidly urbanizing regions. Therefore, this study aimed to determine the concentrations and spatial distribution of Fe, Cu, and Mn in *O. mossambicus* collected from Situ Tlajung Hilir using Atomic Absorption Spectroscopy (AAS).

2. MATERIALS AND METHODS

2.1. Materials

A purposive sampling approach was employed to select the sampling locations. Three sampling points were established based on the dominant anthropogenic activities surrounding Situ Tlajung Hilir. Sampling Point A represented an area characterized by intensive community activities, Sampling Point B was located adjacent to industrial facilities, and Sampling Point C was situated near residential areas receiving domestic wastewater discharges. This sampling strategy was adopted to represent different potential sources of heavy metal contamination within the study area.

The chemicals used for sample preparation and digestion included concentrated nitric acid (HNO_3, 65%), hydrogen peroxide (H_2O_2, 30%), deionized water, and Whatman No. 41 filter paper.

The equipment employed in this study consisted of a Shimadzu AA-7000 Atomic Absorption Spectrophotometer (AAS), analytical balance, laboratory glassware, drying oven, desiccator, blender, sieve (80 mesh), digestion tubes, and a water bath.

2.2. Methods

2.2.1. Study Area and Sample Collection

Fish samples were collected from Situ Tlajung Hilir using a purposive sampling approach. Three sampling locations were selected based on the dominant anthropogenic activities surrounding the lake. Sampling Point A represented an area with intensive community activities, Point B was located near industrial facilities, and Point C was situated close to domestic wastewater discharge from residential areas. For each sampling location, three individual fish were analyzed as

biological replicates (n = 3). Each sample was measured in duplicate, and the duplicate readings were averaged before statistical analysis.

Fresh fish specimens were captured from each sampling location and immediately placed in labeled polyethylene bags. The samples were subsequently stored in a cooler box and transported to the laboratory for further analysis.

2.2.1. Sample Preparation

Sample preparation was performed according to the AOAC (2005) method with slight modifications [20]. Nine individual *Oreochromis mossambicus* collected from three sampling locations (three biological replicates per location) were used for heavy metal analysis. The sampled fish had body weights ranging from 176 to 193 g (Table 1).

Scales, skin, viscera, bones, and other non-edible tissues were removed, and only the dorsal muscle tissue was used for heavy metal analysis. The muscle tissues were thoroughly rinsed with deionized water to remove adhering debris and surface contaminants. The cleaned muscle tissues were cut into small pieces, homogenized, and dried in a drying oven at 65°C for 24 h until a constant weight was achieved.

The dried samples were ground into a fine powder using a laboratory blender and passed through an 80-mesh sieve to obtain a uniform particle size. The homogenized powdered samples were stored in clean, acid-washed, airtight polyethylene containers in a desiccator until acid digestion and subsequent Atomic Absorption Spectrophotometry (AAS) analysis.

2.2.2. Sample Digestion

Heavy metal extraction was performed using the wet digestion method. Approximately 5 g of dried fish tissue was accurately weighed and transferred into a digestion tube. Subsequently, 20 mL of concentrated HNO_3 (65%) and 10 mL of H_2O_2 (30%) were added to the sample.

The mixture was heated in a water bath at 60–70°C for 2–3 h until a clear solution was obtained. After cooling to room temperature, the digested solution was filtered through Whatman No. 41 filter paper. The filtrate was transferred into a 50 mL volumetric flask and diluted to volume using 5% HNO_3 solution. The resulting solution was homogenized prior to instrumental analysis.

2.2.3 Preparation of Standard Solutions

Stock standard solutions of Fe, Cu, and Mn (1000 mg L^{-1}) were used to prepare calibration standards. Intermediate standard solutions (100 mg L^{-1} and 10 mg L^{-1}) were prepared by serial dilution with deionized water.

Working standard solutions with concentrations of 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0 mg L^{-1} were prepared from the intermediate solution. Calibration curves were generated for each metal, and the linearity of the calibration was evaluated using the coefficient of determination (R^2). Calibration curves with R^2 values greater than 0.98 were considered acceptable for quantitative analysis.

Calibration curves were prepared for Fe, Cu, and Mn using a series of standard solutions. The calibration equations were $y = 0.09617x - 0.00015$ for Fe, $y = 0.16868x - 0.00072$ for Cu,

Table 1. Biological Characteristics of *Oreochromis mossambicus* Used in This Study.

Sampling Location	Fish ID	Fish Weight (g)
Site A	A1	193
Site A	A2	192
Site A	A3	186
Site B	B1	188
Site B	B2	190
Site B	B3	184
Site C	C1	181
Site C	C2	180
Site C	C3	176

Table 2. Calibration parameters of the Atomic Absorption Spectrophotometer (AAS) used for determining Fe, Cu, and Mn concentrations.

Metal	Calibration equation	R^2
Fe	y = 0.09617x − 0.00015	0.9984
Cu	y = 0.16868x − 0.00072	0.9999
Mn	y = 0.24156x − 0.00023	0.9997

and y = 0.24156x − 0.00023 for Mn, with coefficients of determination (R^2) of 0.9984, 0.9999, and 0.9997, respectively (Tabel 2). These values indicated good linearity for quantitative AAS analysis.

2,2,4. Determination of Heavy Metals

The concentrations of Fe, Cu, and Mn in digested fish samples were determined using Atomic Absorption Spectrophotometry (AAS; Shimadzu AA-7000). Measurements were performed at the specific analytical wavelengths recommended for each metal according to the manufacturer's operating procedures. Heavy metal concentrations were expressed as milligrams per kilogram (mg/kg) on a dry weight (dw) basis because fish muscle samples were oven-dried to constant weight prior to acid digestion and Atomic Absorption Spectroscopy (AAS) analysis.

2.2.5. Data Analysis

Heavy metal concentrations obtained from AAS measurements were calculated from the calibration curves and expressed as milligrams per kilogram (mg kg^{-1}) on a dry weight (dw) basis, using this following equation:

$$Heavy\ metal\ concetration = \frac{AAS\ consentration\ \left(\frac{mg}{Kg}\right) - Volume\ (mL)}{weight\ of\ the\ dried\ sample\ (kg)}$$

The measured concentrations were compared with guideline values and international food safety references. Comparisons with standards reported on a wet weight (ww) basis were interpreted cautiously because the present study used dry weight concentrations [18], [19].

Heavy metal concentrations were expressed as mean ± standard deviation. Differences among sampling locations were evaluated using one-way ANOVA when data met normality assumptions, whereas the Kruskal–Wallis test was applied when normality assumptions were not satisfied. A significance level of $p < 0.05$ was used.

3. RESULTS AND DISCUSSIONS

3.1. Iron (Fe) Concentration in Oreochromis mossambicus

The mean iron (Fe) concentrations in the muscle tissues of *Oreochromis mossambicus*,

Figure 1. The concentration of iron (Fe).

calculated from three biological replicates at each sampling location, ranged from 66.14 to 621.39 mg kg^{-1}. The highest mean Fe concentration was observed at Sampling Point A (621.39 mg kg^{-1}), followed by Sampling Point B (230.17 mg kg^{-1}) and Sampling Point C (66.14 mg kg^{-1}), as shown in Figure 1. These results indicate spatial variations in contamination levels within the study area, which are likely influenced by differences in surrounding anthropogenic activities.

The Fe concentration detected at Sampling Points A and B exceeded the maximum permissible limit of 100 mg kg^{-1} for fishery products. The elevated concentration at Point A may be associated with intensive community activities, vehicle repair workshops, and commercial establishments surrounding the area. Meanwhile, Point B is located near industrial facilities that may contribute iron-containing wastes through wastewater discharge and surface runoff.

Iron accumulation in fish is regulated by both environmental bioavailability and physiological homeostasis. Dissolved Fe can be absorbed primarily through the gills, whereas particulate-bound Fe may enter the digestive tract through ingestion of contaminated food and sediments. Under oxic conditions, Fe is generally present as insoluble oxides; however, changes in pH and redox potential may increase its solubility and bioavailability, thereby enhancing uptake by aquatic organisms [8], [9]. Although fish possess physiological mechanisms to regulate essential metals such as Fe, prolonged exposure to elevated environmental concentrations may exceed these regulatory capacities, resulting in tissue accumulation and oxidative stress [1,7,14].

The accumulation of Fe in fish tissues can occur through direct absorption from water, ingestion of contaminated food, and interaction with sediment-associated contaminants. Persistent heavy metals can enter aquatic food webs through bioaccumulation and biomagnification processes, resulting in elevated concentrations in higher trophic organisms [1]. Recent studies have also demonstrated that sediment-bound metals remain bioavailable to fish and may contribute significantly to long-term contamination even when dissolved concentrations appear relatively low [6].

Although iron is an essential micronutrient required for oxygen transport and cellular metabolism, excessive exposure may induce oxidative stress and tissue damage in aquatic organisms. Elevated iron concentrations have also been associated with adverse health effects in humans when exposure occurs continuously over prolonged periods [7,15].

3.2. Copper (Cu) Concentration in Oreochromis mossambicus

The mean copper (Cu) concentrations in fish tissues, calculated from three biological

Figure 2. Copper (Cu) Concentration.

replicates at each sampling location, ranged from 0.87 to 21.27 mg kg^{-1}. The highest mean concentration was observed at Sampling Point B (21.27 mg kg^{-1}), followed by Sampling Point A (1.41 mg kg^{-1}) and Sampling Point C (0.87 mg kg^{-1}), as shown in Figure 2. This pattern suggests that industrial activities surrounding Point B may represent an important source of copper contamination.

Copper is widely used in various industrial applications, including metal plating, electrical equipment manufacturing, pigments, pesticides, and alloy production [9]. Consequently, industrial effluents frequently contain elevated copper concentrations that may enter adjacent freshwater ecosystems. Similar findings have been reported in urban and industrial watersheds where copper contamination was strongly associated with industrial discharge and surface runoff [8].

The significantly higher Cu concentration detected at Point B may reflect increased bioavailability of copper within the aquatic environment. Copper accumulation in fish is influenced by several environmental factors, including pH, dissolved oxygen, organic matter content, and water hardness. Under favorable conditions, dissolved copper can be readily absorbed through fish gills and digestive tissues [5].

Copper is generally more bioavailable than iron because it predominantly occurs as dissolved ionic species or organic complexes that can be readily absorbed through fish gills and intestinal tissues. The bioavailability of Cu is strongly influenced by water chemistry, particularly pH, dissolved organic matter, hardness, and dissolved oxygen. Lower water hardness and reduced competition with other cations may increase Cu uptake through branchial ion transport pathways [5,6]. Once absorbed, copper is transported to the liver, where it is involved in essential metabolic processes; however, excessive exposure may overwhelm physiological regulation, leading to oxidative stress, enzyme inhibition, and impaired growth and reproduction [3,10,12].

Fish continuously interact with contaminated water, sediments, and food resources throughout their life cycle, making them effective bioindicators of copper pollution [3]. Previous studies have demonstrated that excessive copper accumulation may impair respiration, enzyme activity, growth performance, and reproductive functions in fish populations [10].

Furthermore, copper-induced oxidative stress has been identified as a major mechanism

Figure 3. Manganese (Mn) Concentration.

underlying heavy metal toxicity. Excessive copper exposure promotes the formation of reactive oxygen species (ROS), leading to cellular damage and physiological dysfunction [12]. Therefore, the elevated Cu concentration observed in this study may indicate potential ecological risks for aquatic organisms inhabiting Situ Tlajung Hilir.

3.3. Manganese (Mn) Concentration in Oreochromis mossambicus

The mean manganese (Mn) concentrations in fish tissues, calculated from three biological replicates at each sampling location, ranged from 5.18 to 6.18 mg kg^{-1}. The highest mean concentration was observed at Sampling Point C (6.18 mg kg^{-1}), followed by Sampling Point B (5.21 mg kg^{-1}) and Sampling Point A (5.18 mg kg^{-1}), as shown in Figure 3. All measured concentrations exceeded the recommended limit of 1 mg kg^{-1}, indicating widespread manganese contamination throughout the study area.

Unlike copper contamination, which appeared concentrated around industrial activities, manganese contamination was detected at relatively similar levels across all sampling locations. This pattern suggests the presence of multiple contamination sources, including industrial discharge, domestic wastewater, urban runoff, and natural geological weathering processes.

Environmental factors strongly influence manganese mobility and bioavailability. Under low-oxygen and reducing conditions, manganese compounds stored in sediments may be released into the water column, thereby increasing their availability for uptake by aquatic organisms [6]. Consequently, fish may accumulate manganese through direct absorption from water, ingestion of contaminated sediments, and consumption of contaminated prey organisms.

Manganese is an essential trace element involved in enzymatic reactions and bone formation. However, excessive exposure may result in neurotoxicity, liver dysfunction, behavioral alterations, and other adverse health effects [11]. Recent reviews have further highlighted the potential relationship between chronic manganese exposure and neurological disorders in both humans and aquatic organisms [2].

Unlike Fe and Cu, manganese is relatively mobile under reducing conditions and may be released from sediments into the overlying water when dissolved oxygen decreases. Consequently, Mn bioavailability is strongly controlled by sediment geochemistry and redox conditions rather than by direct industrial inputs alone [8,9]. Fish absorb manganese primarily through the gills and gastrointestinal tract. Although Mn is an essential cofactor for numerous enzymes involved in antioxidant defense and bone metabolism, excessive accumulation may disrupt metal homeostasis, interfere with calcium metabolism, and induce neurotoxic effects through oxidative damage to nervous tissues [2,11,14].

Mean concentrations of Fe, Cu, and Mn in *Oreochromis mossambicus* collected from three sampling locations (Table 3). Values are presented as mean ± standard deviation (SD) based on three biological replicates (n = 3). Each biological replicate represents one individual fish, and duplicate AAS measurements were averaged prior to statistical analysis. Differences among sampling locations were evaluated using the Kruskal–Wallis test for Fe and Cu because normality assumptions were not satisfied, whereas one-way ANOVA was applied for Mn. Statistical significance was accepted at $p < 0.05$.

Prior to statistical analysis, duplicate AAS measurements obtained for each fish were averaged to produce a single value for each biological replicate. Data are presented as mean ± standard deviation (SD) of three biological replicates (n = 3). The Shapiro–Wilk test was used to assess data normality, while homogeneity of variances was evaluated using Levene's test. One-way ANOVA was applied when the assumptions of normality and homogeneity were satisfied; otherwise, the non-parametric Kruskal–

Table 3. Mean (±SD) heavy metal concentrations in *Oreochromis mossambicus* collected from Situ Tlajung Hilir and results of statistical comparison among sampling locations.

Metal	(Mean ± SD)			p-value
	Site A	Site B	Site C	
Fe	621.39 ± 947.83	230.17 ± 120.85	66.14 ± 7.31	0.148
Cu	1.41 ± 1.38	21.27 ± 30.84	0.87 ± 0.44	0.086
Mn	5.14 ± 3.76	5.21 ± 1.31	6.18 ± 3.29	0.894

Wallis test was used. Statistical significance was set at $p < 0.05$.

Although Fe concentrations were numerically highest at Sampling Point A, statistical analysis showed that the differences among sampling locations were not significant (p = 0.148). This result was mainly influenced by the high variability among individual fish collected from Sampling Point A, indicating that Fe accumulation may be heterogeneous within the same location.

Copper concentrations showed the largest numerical difference among sampling locations, with the highest mean observed at Sampling Point B. However, the Kruskal–Wallis test indicated that this difference was not statistically significant (p = 0.086). The relatively low p-value suggests a tendency toward spatial variation, although the limited number of biological replicates and high within-site variability reduced the statistical power to detect significant differences.

Manganese concentrations were relatively uniform across the three sampling locations, and no statistically significant differences were detected (p = 0.894). This finding suggests that Mn accumulation was relatively homogeneous throughout the study area and may reflect diffuse environmental inputs or natural geochemical processes rather than localized contamination.

Although numerical differences in Fe and Cu concentrations were observed among sampling locations, statistical analyses indicated that these differences were not significant (p > 0.05). This finding suggests that the apparent spatial variation should be interpreted cautiously because the observed differences may reflect substantial variability among individual fish rather than consistent differences among sampling locations. The relatively small number of biological replicates (n = 3) and the presence of highly variable individual concentrations reduced the statistical power to detect significant spatial differences. In contrast, Mn exhibited relatively uniform concentrations across the study area, indicating more homogeneous accumulation patterns.

3.4. Environmental Interpretation of Heavy Metal Accumulation

The different accumulation patterns observed for Fe, Cu, and Mn likely reflect differences in their environmental behavior and physiological regulation in fish. Iron exhibited the greatest spatial variation, with the highest concentration recorded at Sampling Point A, which may indicate localized inputs associated with intensive community activities, vehicle repair workshops, and commercial areas. In contrast, copper reached its highest concentration at Sampling Point B, suggesting that nearby industrial activities may increase the availability of dissolved Cu species that are more readily absorbed through branchial ion transport pathways. Manganese displayed relatively uniform concentrations among sampling locations, indicating that its distribution may be influenced by diffuse anthropogenic inputs together with sediment geochemistry, redox conditions, and natural weathering processes rather than by a single point source [1,5,6,8,11]. Nevertheless, because heavy metal concentrations in water and sediments as well as physicochemical parameters were not measured, these interpretations should be regarded as plausible explanations rather than direct evidence of contamination sources. Overall, the findings demonstrate that metal accumulation in fish is

governed not only by contamination sources but also by metal-specific physicochemical properties, environmental bioavailability, and physiological uptake mechanisms.

Heavy metals accumulated in fish tissues may subsequently be transferred through aquatic food webs and ultimately reach human consumers. Fish consumption is widely recognized as one of the primary pathways through which environmental contaminants enter the human body [13]. Recent studies have reported that chronic exposure to heavy metals through contaminated fish consumption may contribute to oxidative stress, kidney dysfunction, neurological disorders, cardiovascular diseases, and increased cancer risk [12,14].

The observed contamination levels emphasize the importance of implementing effective pollution control strategies and continuous environmental monitoring programs in Situ Tlajung Hilir. Such efforts are essential to reduce heavy metal inputs, protect aquatic biodiversity, maintain fishery resources, and safeguard public health.

3.5. Limitations

This study has several limitations. First, sampling was conducted only once and therefore does not represent seasonal variation. Second, heavy metal concentrations in water and sediments, as well as physicochemical parameters such as pH, dissolved oxygen, temperature, and organic matter, were not measured, preventing direct assessment of contamination pathways and limiting the ability to establish causal relationships between environmental contamination and metal accumulation in fish. Third, biological characteristics of fish, including age and sex, were not evaluated. Finally, human health risk indices such as Estimated Daily Intake (EDI) and Target Hazard Quotient (THQ) were not calculated. Future studies should integrate environmental matrix analyses, water quality parameters, and human health risk assessment to provide a more comprehensive understanding of heavy metal contamination and its potential impacts.

4. CONCLUSIONS

This study determined the concentrations of iron (Fe), copper (Cu), and manganese (Mn) in the edible muscle tissues of *Oreochromis mossambicus* collected from Situ Tlajung Hilir, Bogor Regency, Indonesia. The results showed that Fe, Cu, and Mn were detected in fish samples from all sampling locations, indicating the accumulation of these metals in the studied fish species. Although numerical differences in metal concentrations were observed among sampling locations, statistical analysis showed that these differences were not significant. Therefore, the apparent spatial variation should be interpreted cautiously, particularly considering the small number of biological replicates and the high variability among individual fish.

The observed metal concentrations may reflect the influence of environmental pressures around the lake, including urban, residential, and industrial activities. However, direct relationships between specific contamination sources and metal accumulation in fish tissues could not be established because heavy metal concentrations in water, sediments, industrial effluents, domestic wastewater, and physicochemical parameters were not measured in this study. Thus, the interpretation of possible contamination sources remains inferential rather than causal. Overall, the findings provide preliminary evidence of Fe, Cu, and Mn bioaccumulation in *O. mossambicus* from an urban freshwater ecosystem and support the potential use of this species as a bioindicator for monitoring heavy metal contamination. Future studies should include seasonal sampling, larger sample sizes, analysis of water and sediment matrices, measurement of physicochemical water quality parameters, and quantitative human health risk assessment to better identify contamination pathways, evaluate ecological

implications, and assess potential food safety risks.

AUTHOR INFORMATION

Corresponding Author

Mia Azizah - Biology Study Program, Faculty of Science and Technology, Universitas Islam Negeri Syarif Hidayatullah, Jakarta, 15412 (Indonesia);

orcid.org/0000-0002-0615-9018

Email : mia.azizah@uinjkt.ac.id

Author(s)

Widya Kartika Laksmawati - Agribusiness Department, Faculty of Science and Technology, Universitas Islam Negeri Syarif Hidayatullah, Jakarta, 15412 (Indonesia);

orcid.org/0009-0007-5161-4335

Nurlela - Pusat Riset Bahan Baku Obat dan Obat Tradisional, Badan Riset dan Inovasi Nasional (BRIN), Bogor, 16911 (Indonesia);

Sufrizal Ihsan Latief - Chemistry Study Program, Faculty of Science and Technology, Universitas Nusa Bangsa, Bogor, 16166 (Indonesia);

Author Contributions

W.K.L: methodology design sampling, visualization, and writing–original draft preparation. M.A: conceptualization, methodology, supervision, validation, project administration, and review of the manuscript. N: methodology, laboratory analysis, validation, resources, and review of the manuscript. S.I.L: methodology, instrumental analysis, laboratory analysis and writing–review and editing. All authors have read and approved the final version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

DECLARATION OF GENERATIVE AI

Not applicable.

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