Human Exposure Risk Assessment of Heavy Metals in Periophthalmus papillio (mudskipper), Bille Creek: Probabilistic Risk Approach

Davies Ibienebo Chris[1], Omonuwe Victor[1], Sibe Lebari[2], and Enyi Ikpechi Ovundah[3]
[1]Department of Fisheries, University of Port Harcourt, P.M.B 500272, Port Harcourt, Rivers State, Nigeria
[2]Biochemistry/Chemistry Technology, School of Science Laboratory Technology, University of Port Harcourt, Choba, Rivers State, P.M.B. 5323, Nigeria
[3]Department of Biology, faculty of Natural and Applied Sciences, Ignatius Ajuru University of Education, Port Harcourt, Nigeria
Corresponding Email: davies.chris@uniport.edu.ng

Abstract
This study systematically evaluated the concentrations and potential human health risks of cadmium (Cd), lead (Pb), arsenic (As), and copper (Cu) in Periophthalmus papillio (mudskipper) from Bille Creek, Degema LGA, Rivers State, Nigeria. Using Atomic Absorption Spectrophotometry (AAS) and USEPA (2011) probabilistic risk models, contamination levels, non-carcinogenic (HQ, HI), and carcinogenic (TCR) risks were determined. Results showed Cu (4.432–4.439 mg/kg) > Pb (0.097–0.099 mg/kg) > Cd (0.036–0.037 mg/kg) > As (0.031 mg/kg). All values were below WHO limits (Cd: 0.05; Pb: 0.3; As: 0.1; Cu: 10 mg/kg), indicating low contamination. Estimated Daily Intake (EDI) was higher in children (Cd: 0.047868–0.049198; Pb: 0.128979–0.131638; Cu: 5.893143–5.902451; As: 0.04122 mg/kg/day) than adults (Cd: 0.010258–0.010542; Pb: 0.027638–0.028208; Cu: 1.262816–1.264811; As: 0.008833 mg/kg/day). HQ values were <1, with Cu showing the highest (0.050592 in adults; 0.236098 in children). HI ranged 0.050637–0.050716 (adults) and 0.236307–0.236674 (children), indicating no non-carcinogenic risk. Carcinogenic Risk (CR) and Total Cancer Risk (TCR) ranged from 1×10^{-6} to 1×10^{-4}, within USEPA's acceptable range. Thus, P. papillio from Bille Creek is safe for consumption, but ongoing monitoring and regulation of industrial discharges are recommended to prevent future accumulation of toxic metals and safeguard aquatic and human health.

Keywords: Periophthalmus papillio, Heavy metals, Bille Creek, Hazard Quotient (HQ), Total Cancer Risk (TCR), Niger Delta

1.0 Introduction

Aquatic ecosystems constitute over two-thirds of the Earth's surface, fulfilling an indispensable role in regulating global climate and providing essential resources vital for human sustenance, including food and water supplies (Häder et al., 2020). However, in recent decades, the contamination of creeks and rivers by various chemicals has become a major environmental concern, particularly in the Niger Delta region of Nigeria. This pollution not only threatens public water supplies but also disrupts aquatic life and ecological balance (Lawal, 2020). Freshwater resources are crucial for drinking, sanitation, agriculture, and industry, while marine water serves in the production of cosmetics, fertilizers, and other additives (Häder et al., 2020).

Unfortunately, pollution, industrial impacts, and human activities remain the major sources of aquatic degradation in the Niger Delta (Bashir et al., 2020; Chris et al., 2024). Natural processes and anthropogenic activities such as domestic sewage, agricultural runoff, mining, and industrial effluent introduce heavy metals into aquatic systems (Khatri et al., 2015). These pollutants persist in the environment and accumulate in aquatic organisms, posing severe ecological and health risks. According to Häder et al. (2020), ecosystems provide vital services such as recreation, transportation, and food production, but growing human pressures are increasingly threatening them. Chris et al. (2014) reported that anthropogenic activities contribute to climate change, rising sea surface temperatures, overfishing, and coastal pollution, all of which harm aquatic systems. Lv et al. (2020) highlighted that heavy metal bioaccumulation and variations in physicochemical parameters are critical environmental issues in the Niger Delta (Davies et al., 2024).

Parameters such as pH, salinity, dissolved oxygen, and temperature influence aquatic life distribution and productivity (Chris et al., 2023). Changes in these factors alter species composition and ecosystem dynamics, thereby affecting the stability of the Niger Delta coast (Sih et al., 2012). Nigeria's status as a leading oil producer has led to frequent oil spills, environmental degradation, and heavy metal pollution of rivers, sediments, and aquatic organisms (Ukhurebor et al., 2021). Runoffs from agricultural, industrial, and domestic activities have further contaminated water bodies, threatening aquatic biodiversity and public health (Davies & Ekperusi, 2021). Sediments act as both sinks and potential secondary sources of contamination, storing toxic metals such as lead (Pb), copper (Cu), cadmium (Cd), and arsenic (As), which bioaccumulate in aquatic organisms (Akankali & Davies, 2021; Davies & Ekperusi, 2021).

This contamination endangers edible fish species like the mudskipper (*Periophthalmus papillio*), an important protein source for local communities (Emenike et al., 2021; Fida et al., 2023). Long-term exposure to trace metals such as Cu, Pb, and Cd can cause gastrointestinal disorders, neurotoxicity, kidney damage, and cancer (Obasi & Akundinobi, 2020; Manwani et al., 2022). This study therefore aims to evaluate the biotoxicity of persistent heavy metals in *Periophthalmus papillio* along the Bille Creeks in Degema Local Government Area, Rivers State. It assesses concentrations of Pb, Cd, Cu, and As in fish tissues, estimates human health risks through parameters such as hazard indices and target hazard quotients, and determines the potential cancer risk associated with their consumption.

2.0 Materials and Methods

2.1 Study Area and Sampling

The research was conducted along Bille Creek, located within the Degema Local Government Area of Rivers State, Nigeria (Figure 1). Bille Creek is hydraulically significant, connecting the Bille community to the Sombrero River and sustaining local livelihood through fishing and domestic water use.1 The area features a tropical climate, characterized by high humidity and consistent temperatures, with an average annual high of 29.79°C and low of 22.8°C.1 The environmental context is defined by ongoing industrial activity, as the Bille community hosts several major oil exploration companies, including Shell, New Cross, and Eroton, which contributes to recurrent hydrocarbon pollution events and environmental disputes.

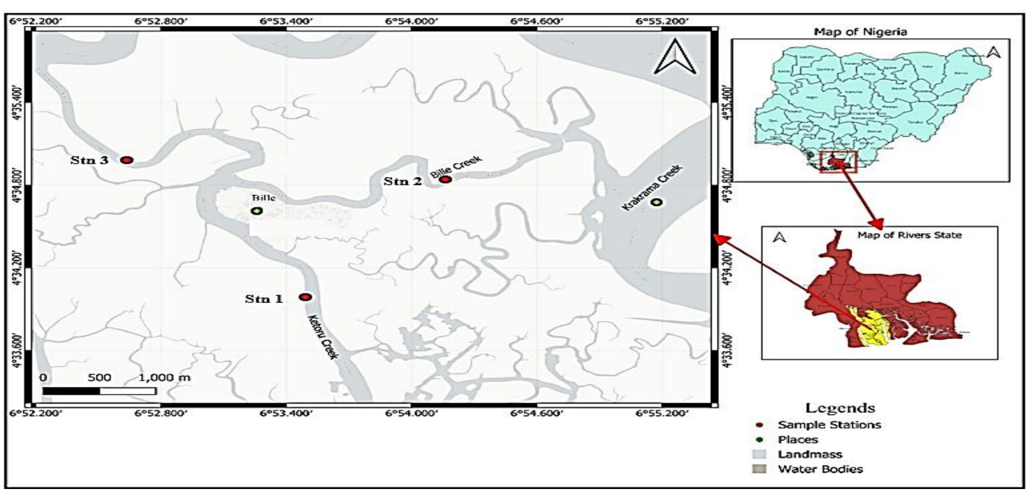

Figure 1: Map showing the research area.

2.2 Analytical Procedures and Quality Control

Fresh mudskipper (*Periophthalmus papillio*) samples were collected from local fishers at three sampling stations along the creek. The species was identified following Powell (1983), and measurements of length and weight were recorded. The fish samples were preserved in ice to maintain freshness and transported to the laboratory for digestion and analysis. The concentrations of lead (Pb), copper (Cu), cadmium (Cd), and arsenic (As) were determined using a UNICAM Solaar 969 Atomic Absorption Spectrometer (AAS). All analytical procedures followed standard methods for the determination of heavy metals in aquatic organisms to ensure data accuracy and reproducibility.

2.3 Statistical Analysis

Data generated were statistically analyzed using Microsoft Excel and one-way Analysis of Variance (ANOVA) to test for significant differences ($p < 0.05$) in the concentrations of metals among sampling stations.

2.3.1 Human Health Risk Assessment (HHRA) Models (USEPA, 2011)

The potential health risks associated with dietary intake of *P. Papillio (*mudskipper) from the Bille Creek were quantified using a probabilistic risk assessment approach derived from standard models and guidelines published by the United States Environmental Protection Agency (USEPA 1999, 2001,2004. 2011).

2.3.2 Estimated Daily Intake (EDI)

The Estimated Daily Intake (EDI) is an expression of the average quantity of metal ingested daily through fish consumption (Moldovan et al., 2020; USEPA, 2001, 2004, 2011). It was computed using the formula below:

$$EDI = \frac{(Cw \times SA \times Kp \times ET \times EF \times ED \times CF)}{BW x AT} \qquad (1)$$

Where EDI is the daily dose (mg/L), Cw is the metal concentration (mg/L), SA is the exposed surface area (1800 cm² for adults and 6600 cm² for children), Kp is the permeability coefficient (0.0001 cm/h), ET is the exposure time (0.58 h/event for adults, 1 h/event for children), EF is exposure frequency (350 days/year), ED is exposure duration (70 years for adults, 6 years for children), CF is the conversion factor (0.001 L/cm³), BW is body weight (70 kg for adults, 15 kg for children), and AT is the average exposure time (24,500 days for adults, 2,100 days for children) (USEPA 2001, 2004). The model's parameters were explicitly differentiated between adults and children to capture the disparity in physiological vulnerability. The use of a significantly lower body weight (BW) and a shorter average time (AT) for children amplifies the resulting EDI value, providing a conservative assessment that highlights the sensitivity of this population group to environmental contaminants.

2.3.3 Non-Carcinogenic Risk Assessment: Hazard Quotient (HQ) and Hazard Index (HI)

The Hazard Quotient (HQ) determines the non-carcinogenic risk arising from exposure to a single heavy metal, calculated as the ratio of the chronic daily intake (CDI) to the reference dose (RfD).

$$HQ = \frac{CDI}{RfD} \quad (2)$$

Where CDI is the chronic daily intake (mg/kg/day) and RfD_o is the oral reference dose (mg/kg/day). An HQ value greater than 1 indicates potential health risks, while HQ less than 1 implies safety (USEPA 1999).

The Hazard Index (HI) reflects the combined non-carcinogenic risk resulting from exposure to multiple metals. It is expressed as:

$$HI = \sum_{i=1}^{n} HQ/THQ \quad (3)$$

Where, HI is the hazard index for the overall toxic risk and n equals the total number of elements under consideration; If HI for non-carcinogenic adverse effect due to ingestion (mudskipper) exposures is lower than one (HI < 1.0), then no chronic risks are expected to occur but if HI is greater than one (HI > 1.0), possible chronic risk arising from the ingestion (mudskipper) exposures could manifest (Moldovan *et al.*, 2020)

2.3.4 Carcinogenic Risk Assessment: Total Cancer Risk (TCR)

The Total Cancer Risk (TCR) estimates the lifetime probability of developing cancer from exposure to carcinogenic metals through fish consumption. Its formula is as follows:

$$TCR = \frac{(Efr \times ED \times FIR \times C \times CSF)}{(BW \times AT)} \quad (4)$$

Where, AT is the average time for carcinogens (days/year × ED); Efr is the exposure frequency (days/year); ED is the exposure duration (years); FIR is the food ingestion rate (g/day); CSF is the oral carcinogenic slope factor derived from the Integrated Risk Information System by the USEPA (2012); Bw is the average body weight (kg); AT is the average exposure time for non-carcinogens (days/year × ED); The calculated TCR value $<10^{-6}$ Is negligible, and values within 10^{-6} and 10^{-4} are acceptable values whereas values $>10^{-4}$ are unacceptable.

3.0 Results

3.1 Heavy Metal Concentrations and Regulatory Compliance

The analysis of heavy metals (Cd, Pb, As, and Cu) in *Periophthalmus papillio* from Bille Creek revealed variations in concentration across the sampling stations, with copper exhibiting the highest mean value, followed by lead, cadmium, and arsenic. As presented in Table 3.1, copper recorded the highest concentration, ranging from 4.432 ± 0.922 mg/kg at Site 1 to 4.439 ± 0.921 mg/kg at Site 2, while cadmium ranged between 0.036 ± 0.004 mg/kg and 0.037 ± 0.004 mg/kg. Lead concentrations varied slightly from 0.097 ± 0.007 mg/kg to 0.099 ± 0.007 mg/kg, whereas arsenic was the least abundant, with a uniform concentration of 0.031 ± 0.003 mg/kg across all sites. The mean concentrations of all metals were below the WHO (2011) and USEPA (2012) permissible limits, suggesting that *P. papillio* from Bille Creek may currently be safe for consumption.

Table 3.1: Spatial Variations of Heavy metals in the Mudskipper (*Periophthalmus papillio*) from Bille Creek (mg/kg, wet weight)

Parameter	Site 1	Site 2	Site 3	WHO Limit (mg/kg)	USEPA Limit (mg/kg)
Cd	0.036 ± 0.004[a]	0.036 ± 0.004[a]	0.037 ± 0.004[a]	0.05	0.04
Pb	0.098 ± 0.007[a]	0.097 ± 0.007[a]	0.099 ± 0.007[a]	0.3	0.3
As	0.031 ± 0.003[a]	0.031 ± 0.003[a]	0.031 ± 0.003[a]	0.10	0.10
Cu	4.432 ± 0.922[a]	4.439 ± 0.921[a]	4.434 ± 0.922[a]	10	10

Note: Values are expressed as mean ± standard deviation. Identical superscripts ([a]) within rows indicate no statistically significant difference ($p < 0.05$).

3.2 Estimated Daily Intake (EDI)

The calculated EDI values (Table 3.2) quantified the dietary exposure of the local population to the studied heavy metals. The results demonstrate a clear vulnerability differential based on age, with children exhibiting substantially higher EDI values across all metals compared to adults, owing to their smaller body mass and higher relative food intake.

The highest EDI values for cadmium (0.049198 mg/kg/day for children and 0.010542 mg/kg/day for adults) and lead (0.131638 mg/kg/day for children and 0.028208 mg/kg/day for adults) were recorded at Site 3. Copper had the highest EDI at Site 2 (5.902451 mg/kg/day for children and 1.264811 mg/kg/day for adults), while arsenic remained consistent across sites (0.04122 mg/kg/day for children and 0.008833 mg/kg/day for adults). These results indicate that Cu and Pb contributed most to dietary exposure risk, though still within safe limits.

Table 3.2: Estimated Daily Intake (EDI) of Heavy metals in *Periophthalmus papillio* Across Sites (mg/kg/day)

	Adults			**Children**		
Metal (mg/kg)	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Cd	0.010258	0.010258	0.010542	0.047868	0.047868	0.049198
Pb	0.027923	0.027638	0.028208	0.130309	0.128979	0.131638
As	0.008833	0.008833	0.008833	0.04122	0.04122	0.04122
Cu	1.262816	1.264811	1.263386	5.893143	5.902451	5.895803

3.3 Non-Carcinogenic Risk Assessment (HQ and HI)

The assessment of non-carcinogenic risk demonstrated that the consumption of *P. papillio* poses negligible acute or chronic health concerns under current conditions. The Hazard Quotient (HQ) values for all four heavy metals in both adults and children (Table 3.3) were significantly below the safety threshold of unity (1) as established by USEPA (2004, 2011).

Copper contributed the most to HQ values, particularly at Site 2 (0.050592 for adults and 0.236098 for children). The combined HI values ranged from 0.050637 to 0.050716 in adults and 0.236307 to 0.236674 in children, confirming negligible health risks.

Table 3.3: Hazard Quotients (HQ) of Heavy metals in *P. papillio* for Adults and Children

	Adults			Children		
Metal (mg/kg)	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Cd	1.03E-05	1.03E-05	1.05E-05	4.79E-05	4.79E-05	4.92E-05
Pb	0.000112	0.000111	0.000113	0.000521	0.000516	0.000527
As	2.65E-06	2.65E-06	2.65E-06	1.24E-05	1.24E-05	1.24E-05
Cu	0.050513	0.050592	0.050535	0.235726	0.236098	0.235832

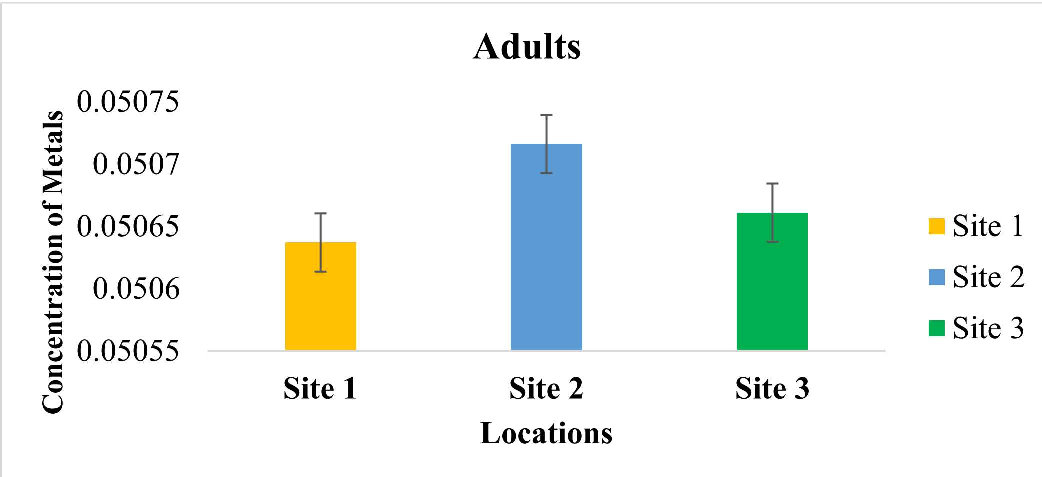

Figure 2: Hazard Index (HI) of Heavy metals in *P. papillio* for adults

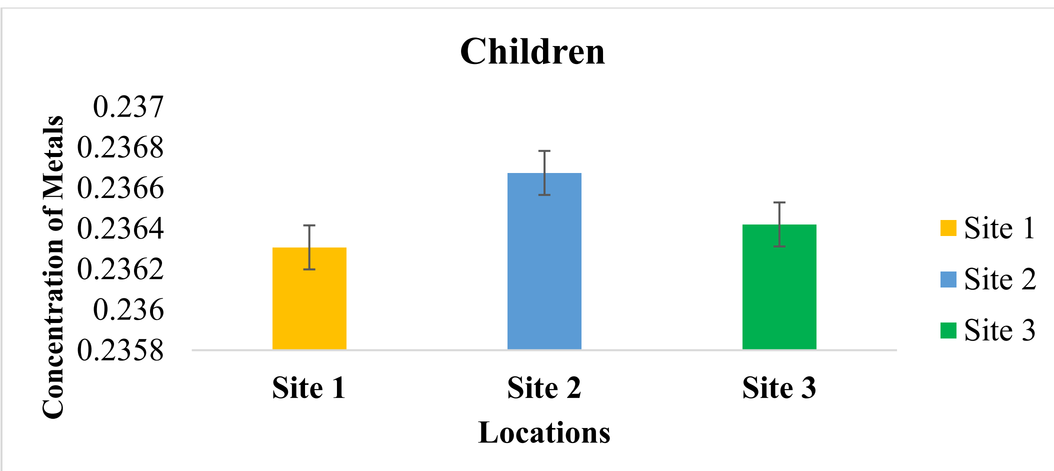

Figure 2: Hazard Index (HI) of Heavy metals in *P. papillio* for Children

3.4 Carcinogenic Risk Assessment (CR and TCR)

The Carcinogenic Risk (CR) values, shown in Table 3.4, indicate that Cd, Pb, and As posed no significant cancer risk, as all values were below the USEPA tolerable range of 1E−04. The highest CR values were observed at Site 3, with Cd (3.99E−06 for adults; 1.87E−05 for children) and As (3.98E−06 for adults; 1.86E−05 for children), suggesting slightly elevated but still tolerable risk levels. Overall, children showed higher CR values than adults, indicating greater susceptibility to trace element exposure through dietary intake. These findings reveal that the highest lifetime probability of developing cancer due to the consumption of *P. papillio* by children is 1:10,000 and 1:1,000,000 by adult consumers over their lifetime of exposure.

Table 3.4: Carcinogenic Risk (CR) of Heavy metals in *P. papillio* for Adults and Children

	Adults			Children		
Metal (mg/kg)	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Cd	3.91E-06	3.91E-06	3.99E-06	1.82E-05	1.82E-05	1.87E-05
Pb	9.52E-07	9.44E-07	9.61E-07	4.43E-06	4.39E-06	4.48E-06
As	3.98E-06	3.98E-06	3.98E-06	1.86E-05	1.86E-05	1.86E-05

4.0 Discussion

Metal Accumulation Dynamics and Bioindicator Confirmation

The concentrations of cadmium (Cd), lead (Pb), arsenic (As), and copper (Cu) in *Periophthalmus papillio* from Bille Creek were all within the permissible limits recommended by WHO (2011) and USEPA (2012).

The observed hierarchy of metal accumulation, with copper (Cu) concentrations (4.432–4.439 mg/kg) significantly exceeding 0.036–0.037 mg/kg, 0.097–0.099 mg/kg, and 0.031 mg/kg, respectively of the non-essential toxic metals (Cd, Pb, As), provides crucial insight into the bioaccumulation processes in Bille Creek.Copper is an essential micronutrient, actively regulated by aquatic organisms for crucial metabolic functions, including respiration and enzymatic activity. Its relatively high accumulation is further linked to its geochemical behavior; copper readily complexes with dissolved organic matter, forming stable organo-metallic compounds that enhance its bioavailability to organisms. This relatively high accumulation is consistent with the observations of Anandkumar et al. (2018), who reported elevated Cu concentrations in edible fish species from the Niger Delta. Remarkably, low concentrations of Cd and Pb below WHO (2012) regulatory limits of 0.05 mg/kg and 0.3 mg/kg, for Cd and Pb were observed, despite the proximity of significant industrial and petroleum operations, reflect limited direct anthropogenic inputs or effective pollution attenuation within the creek.

Similar low-level metal accumulations were reported by Akankali et al. (2022) in fish species from the Bonny Estuary, reinforcing that bioaccumulation in *P. papillio* may be influenced more by sediment–water interactions than by direct pollution events. The relatively higher accumulation of copper can also be attributed to its geochemical behavior in aquatic systems. Copper tends to complex with dissolved organic matter, forming stable organo-metallic compounds that are more bioavailable to benthic organisms. Since *P. papillio* is a mudskipper species that spends considerable time foraging on benthic substrates, sediment-associated metals are readily ingested through feeding. This ecological behavior makes the species a suitable bioindicator of sediment contamination. Similar conclusions were drawn by Chris et al. (2023), who observed elevated Cu accumulation in benthic-feeding catfish species compared to pelagic fishes. On the other hand, the relatively lower Cd and Pb concentrations may be linked to their strong association with fine sediments and particulate matter, which may not be as easily assimilated through the mudskipper's dietary pathway.

Exposure Scenerio of Children and Adults to *P. Papillio from Bille*

As shown in Table 3.2, the Estimated Daily Intake (EDI) values were higher in children than in adults, reflecting children's greater food intake relative to body weight. Among the studied elements, copper again showed the highest EDI values (5.893143–5.902451 mg/kg/day for children and 1.262816–1.264811 mg/kg/day for adults), followed by lead and cadmium. The lowest EDI values were observed for arsenic (0.04122 mg/kg/day for children and 0.008833 mg/kg/day for adults). Despite these differences, all EDI values were within the provisional tolerable daily intake (PTDI) range established by FAO/WHO (2021), implying no significant health risk from dietary exposure to the metals through mudskipper consumption. This agrees considerable with Markmanuel, et al. (2022), who observed similar EDI trends in Niger Delta fish species. The higher EDI in children highlights their vulnerability to environmental contaminants, emphasizing the need for more stringent food safety monitoring to protect this sensitive group. Furthermore, the observed EDI pattern suggests that the local population consuming *P. papillio* as part of their diet is not at immediate risk of metal-induced toxicity.

However, continuous exposure, even at low doses, may result in chronic accumulation in tissues over time. According to WHO (2012), prolonged intake of Cu beyond recommended limits may lead to gastrointestinal distress, while excessive Pb or Cd accumulation may impair kidney and neurological functions. Hence, periodic biomonitoring is vital to ensure that trace metal concentrations remain within safe thresholds as anthropogenic activities in the Niger Delta continue to expand.

Non-Carcinogenic Risk Assessment and Vulnerability

The non-carcinogenic risk assessment, represented by the Hazard Quotient (HQ) and Hazard Index (HI), is presented in Table 3.3. HQ values for all metals in both adults and children were below threshold limit, suggesting no significant health concern. Copper recorded the highest HQ (0.050592 for adults and 0.236098 for children), while arsenic recorded the lowest (2.65E−06 for adults and 1.24E−05 for children). The total HI values (0.050637–0.050716 for adults and 0.236307–0.236674 for children) were also below 1, confirming that cumulative exposure to Cd, Pb, As, and Cu does not pose a non-carcinogenic risk. According to WHO (2011) and Thomsen et al. (2022), an HI > 1 indicates a potential non-cancer health concern, whereas HI < 1 denotes a tolerable exposure level. These results agree with Ukwo et al. (2020), who reported similarly low HI values in shellfish from the Niger Delta.

The higher HQ and HI in children compared to adults indicate that children are more prone to non-carcinogenic health risks due to their lower body mass and higher consumption rate relative to body weight. This finding corroborates the report of Kaba and Kılıç (2024), who emphasized that children's metabolic and developmental differences make them more susceptible to trace metal exposure even when concentrations are within acceptable limits. Nonetheless, since all HQ and HI values in this study are <1, there is no indication of chronic toxicity through the consumption of *P. papillio* from Bille Creek. However, It is significant to evaluate the risk source. This study reveals that copper drives approximately 99% of the non-carcinogenic risk (HQ). Notably, Cu is an essential element, the toxicological concern at these current, safe levels is related to potential essential metal overload, which may cause gastrointestinal distress in extreme cases, rather than the severe neurotoxicity or nephrotoxicity typically associated with Pb or Cd. Since the estimated daily exposure to Cu is within the established provisional tolerable limits, the body's homeostatic mechanisms are currently capable of managing the burden. Any future environmental stressor that compromises the detoxification or excretion capacity of the local consumers, however, could rapidly transform this essential element into a health threat.

Long-Term Carcinogenic Risk Management

The carcinogenic risk (CR) results, as shown in **Table 3.4** falls well within the USEPA's acceptable lifetime risk bracket of 10E-6 to 10-4 confirming that intake of Cd, Pb, and As via mudskipper poses no immediate or chronic cancer threat under current conditions.

The highest CR values were recorded for Cd (3.99E−06 for adults; 1.87E−05 for children) and As (3.98E−06 for adults; 1.86E−05 for children), while Pb exhibited the lowest (9.61E−07 for adults; 4.48E−06 for children). These results indicate slightly higher risks in children, likely due to their lower body weight and higher relative intake. A CR value of 1×10^{-2} implies that one individual in every 100 exposed persons may develop cancer during their lifetime, while a CR value of 1×10^{-4} corresponds to one in 10,000 individuals, and 1×10^{-6} corresponds to one in 1,000,000 individuals (USEPA, 2012). Given that the CR values in this study fall between 1×10^{-6} and 1×10^{-4}, the Total Cancer Risk (TCR) of this study implies that at most one individual out of every 10,000 to 1,000,000 people consuming *P. papillio* from Bille Creek may develop cancer over a lifetime of exposure. This range is considered tolerable and negligible according to USEPA (2012) guidelines, confirming that the fish is safe for human consumption, at least for now. These findings are in harmony with those of Tarinimi et al. (2025), who reported low cancer risk indices for heavy metals in African catfish from fish ponds surrounding Port Harcourt, Nigeria. The low TCR observed could be associated with the self-purifying ability of aquatic ecosystems and the dilution effect caused by tidal flushing in the Niger Delta's estuarine waters.

Such processes reduce the residence time of pollutants and limit bioavailability to aquatic organisms. However, considering that oil and gas exploration, urbanization, and artisanal fishing are major activities within the Bille Creek axis, the observed minimal contamination should not justify complacency. Metals can accumulate gradually, and long-term exposure, even at low concentrations, could still result in bioaccumulation and biomagnification through the food chain (Oros, 2025).

5.0 Conclusion

This study evaluated the concentrations of cadmium (Cd), lead (Pb), arsenic (As), and copper (Cu) in Periophthalmus papillio from Bille Creek and assessed their potential health risks to consumers. The results revealed that all metal concentrations were below the WHO (2011) and USEPA (2012) permissible limits, indicating minimal contamination. Estimated Daily Intake (EDI), Hazard

Quotient (HQ), and Hazard Index (HI) values for both adults and children were less than 1, suggesting no significant non-carcinogenic risk. Similarly, the Total Cancer Risk (TCR) values ranged between 1×10^{-6} and 1×10^{-4}, implying that at most one individual out of every 10,000 to 1,000,000 consumers may develop cancer over a lifetime, a level considered negligible by USEPA standards. Overall, the findings confirm that P. papillio from Bille Creek is safe for human consumption. However, continuous environmental monitoring and stricter control of industrial discharges are recommended to sustain this safety level and prevent potential heavy metal accumulation in the future.

References

Akankali, J. A., & Davies, I. C. (2021). Heavy metals and physicochemical parameters evaluation in the upper reaches of Bonny River, Niger Delta, Nigeria. *Journal of Applied Sciences and Environmental Management, 25(8),* 1341-1348.

Akankali, J. A., Davies, I. C., & Blessing, D. I. (2022). Assessment of Sawmill and other Associated Wastes on the Water Quality of Ilo-abuchi Creek, Rivers State, Niger Delta. *Asian Journal of Fisheries and Aquatic Research, 17*(4), 1-13.

Anandkumar, A., Nagarajan, R., Prabakaran, K., Chua Han, B., & Rajaram, R. (2018). Human health risk assessment and bioaccumulation of trace metals in fish species collected from the Miri coast, Sarawak, Borneo. *Marine Pollution Bulletin, 133*, 655–663. https://doi.org/10.1016/j.marpolbul.2018.06.033

Bashir, I., Lone, F. A., Bhat, R. A., Mir, S. A., Dar, Z. A., & Dar, S. A. (2020). Concerns and threats of contamination on aquatic ecosystems. *Bioremediation and biotechnology: sustainable approaches to pollution degradation, 5*, 1-26.

Chris, D. I., Amaewhule, E. G., & Onyena, A. P. (2024). Estimation of potential health risks on metals and metalloids contaminants in black goby (*Gobius niger*) consumption in selected niger Delta coast, nigeria. *Journal of Trace Elements and Minerals, 8*, 1-7.

Chris, D. I., Onyena, A. P., & Sam, K. (2023). Evaluation of human health and ecological risk of heavy metals in water, sediment and shellfishes in typical artisanal oil mining areas of Nigeria. *Environmental Science and Pollution Research, 30*(33), 80055-80069.

Chris, D. I., Wokeh, O. K., Lananan, F., & Azra, M. N. (2023). Assessment of Temporal Variation of Water Quality Parameters and Ecotoxic Trace Metals in Southern Nigeria Coastal Water. *Polish Journal of Environmental Studies*, *32*(5), 4493-4502.

Davies, I. C., & Ekperusi, A. O. (2021). Evaluation of heavy metal concentrations in water, sediment and fishes of New Calabar River in Southern Nigeria. *Journal of Limnology and Freshwater Fisheries Research, 7*(3), 207-218.

Davies, I. C., Ibienebo, D. I., & Yusuf, S. (2024). Environmental Impact Assessment of Trace Metals Contaminated Water, Fish, and Sediments from Riparian Communities in the Niger Delta Region, Nigeria.

Emenike, E. C., Iwuozor, K. O., & Anidiobi, S. U. (2021). Heavy metal pollution in aquaculture: sources, impacts and mitigation techniques. *Biological Trace Element Research, 1,* 1-17.

FAO/WHO (2021). Joint FAO/WHO expert committee on food additives. Summary report of the ninety-first meeting of JECFA (Safety evaluation of certain food additives and contaminants). Available at: http://apps.who.int/food-additives-contaminants-jecfa-database/Home/Chemical/1376

Fida, M., Li, P., Wang, Y., Alam, S. K., & Nsabimana, A. (2023). Water contamination and human health risks in Pakistan: a review. *Exposure and Health, 15*(3), 619-639.

Häder, D. P., Banaszak, A. T., Villafañe, V. E., Narvarte, M. A., González, R. A., & Helbling, E. W. (2020). Anthropogenic pollution of aquatic ecosystems: Emerging problems with global implications. *Science of the Total environment, 713*, 1-6.

Kaba S, & Kılıç S. (2024). Investigation of trace element levels and toxic metals in obese children: A single-center experience. *Turkish Archives of Pediatrics, 59*(4), 390-396.

Khatri, N., & Tyagi, S. (2015). Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in Life Science, 8*(1), 23-39.

Lawal, O. (2020). Spatially constrained clustering of nigerian states: Perspective from social, economic and demographic attributes. *International Journal of Environment and Geoinformatics, 7(1), 68-79*

Lv, M., Luan, X., Liao, C., Wang, D., Liu, D., Zhang, G., & Chen, L. (2020). Human impacts on polycyclic aromatic hydrocarbon distribution in Chinese intertidal zones. *Nature Sustainability*, *3*(10), 878-884

Manwani, S., Vanisree, C. R., Jaiman, V., Awasthi, K. K., Yadav, C. S., Sankhla, M. S., & Awasthi, G. (2022). Heavy metal contamination in vegetables and their toxic effects on human health. Sustainable Crop Production: *Recent Advances*, *181*, 1-5

Markmanuel, D. P., Amos-Tautau, B. M. W., & Songca, S. P. (2022). Tin concentrations and human health risk assessment for children and adults in seafood and canned fish commonly consumed in Bayelsa State, Nigeria. *Journal of Applied Sciences and Environmental Management, 26*(7), 1263-1269.

Moldovan, A., Hoaghia, M. A., Kovacs, E., Mirea, I. C., Kenesz, M., Arghir, R. A., & Moldovan, O. T. (2020). Quality and health risk assessment associated with water consumption, a case study on karstic springs. *Water, 12*(12), 3510.

Obasi, P. N., & Akudinobi, B. B. (2020). Potential health risk and levels of heavy metals in water resources of lead–zinc mining communities of Abakaliki, southeast Nigeria. *Applied Water Science, 10(7), 1-23.*

Oros, A. (2025). Bioaccumulation and trophic transfer of heavy metals in marine fish: ecological and ecosystem-level impacts. *Journal of Xenobiotic*, *15*(59), 1-10. https://doi.org/10.3390/ jox15020059

Powell, C. B. (1983). Fresh and brackish water shrimps of economic importance in the Niger Delta. University of Port Harcourt, Port Harcourt, Nigeria. Conference item. 254 – 285. http://hdl.handle. net/1834/21107

Sih, A., Cote, J., Evans, M., Fogarty, S., & Pruitt, J. (2012). Ecological implications of behavioural syndromes. *Ecology Letters, 15*(3), 278-289.

Tarinimi, J.T., Imomotimi, T.A., Return, O., & Christopher, U.E. (2025). Health risk assessment of heavy metals in African Catfish (*Clarias gariepinus*) from fish ponds in Port Harcourt, Rivers State, Nigeria. *Journal of Applied Chemical Science International*, *16*(1), 1-10

Thomsen, S. T., Assunção, R., Afonso, C., Boué, G., Cardoso, C., Cubadda, F., & Pires, S. M. (2022). Human health risk–benefit assessment of fish and other seafood: a scoping review. *Critical Reviews in Food Science and Nutrition*, *62*(27), 7479-7502.

Ukhurebor, K. E., Athar, H., Adetunji, C. O., Aigbe, U. O., Onyancha, R. B., & Abifarin, O. (2021). Environmental implications of petroleum spillages in the Niger Delta region of Nigeria: a review. *Journal of Environmental Management, 293, 1-2.*

Ukwo, S.P., Chidi, F.E., & Kuyik, S.A. (2020). Hazard indices and human health risks associated with toxic element contaminants in Bivalve Shellfish from Niger Delta, *Nigeria. Archives of Ecotoxicology, 2*(4), 61-68. https://doi.org/10.36547/ae.2020.2.4.61-68

USEPA (2004). Risk Assessment Guidance for Superfund Volume I: human Health Evaluation Manual (Part E). U.S.*Environmental Protection Agency. Available Online.*

USEPA, (2001). Baseline Human Health Risk Assessment Vasquez Boulevard and I-70 Superfund Site Denver CO. U.S. *Environmental Protection Agency.*

USEPA, (1999). Screening Level Ecological Risks Assessment Protocol for Hazardous Waste Combustion Facilities. Toxicity Reference Values, Appendix E. Usepa, 2000. *Riskbased Concentration Table.*

USEPA (2011a). *Exposure factors handbook: 2011 edition* (Report No. EPA/600/R-09/052F). National Center for Environmental Assessment. https://www.epa.gov/expobox/exposure-factors-handbook-2011-edition

USEPA. (2012). Guidelines for carcinogenic risk assessment. The EPA official guidance on cancer risk assessment method and interpretation. Available at: https://www.epa.gov/riskguidelines-cancernogen-risk-assessment

WHO (2011). Guidelines for Drinking-water Quality: Incorporating 1st and 2nd Addenda, Vol. 1 Recommendations (3rd ed.). *Geneva: World Health Organization*