



## Bioaccumulation and Health Risk Assessment of Heavy Metals in Oysters (*Crassostrea gasar*) from Iko River Marine Ecosystem, Nigeria

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### Abstract

Heavy metal contamination is a major global problem threatening the sustainability of marine (aquatic) environments, biota species and humans who ingest resources from the contaminated ecosystems. This study aimed to investigate the seasonal variation, bioaccumulation, and associated human health risks of selected heavy metals in oysters (*Crassostrea gasar*) from Iko River marine ecosystem, Nigeria. The heavy metals considered are; zinc, lead, cadmium, copper, nickel, vanadium, cobalt and chromium. The heavy metals were determined using inductively coupled plasma – optical emission spectrometer (ICP-OES). The results indicated bioaccumulation of the metals determined in *Crassostrea gasar* in the order of magnitude (from the five sampling sites)  $Zn > Fe > V > Cu > Mn > Ni > Pb > Cr$ , whilst, Co, Ag and Cd were below detection limit. By the bioaccumulation factor (BCF) quality guidelines ranking scheme the present study has indicated that Zn, Mn, Cd, Pb, Ni, have low concerns ( $BCF < 250$ ) at the five sampling sites. This study demonstrates that *Crassostrea gasar* in Iko River significantly bioaccumulate heavy metals, with zinc showing the highest levels across seasons. Although Cd and Co were not detected, several metals exceeded recommended dietary limits, posing health risks to consumers. The findings highlight oysters as effective bioindicators and underscore the urgent need for regular monitoring and remediation strategies in Eastern Obolo coastal ecosystems.

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## 1.0 Introduction

Crude oil and gas exploration and production within Atlantic coastline of Iko river marine ecosystems, in Akwa Ibom State, Niger Delta, Nigeria, has been on for decades and are still ongoing given the current new investments in oil and gas activities in the Oil Mining License Field 13 (OML 13) (Ufikairom *et al.*, 2023). Consequent upon rapid urbanization and industrialization activities, there are reported cases of significant contaminations of Atlantic coastline of Iko river marine ecosystems by a number of organic and inorganic pollutants, including heavy metals and persistent organic pollutants (POP) (Enemugwem, 2009; Etesin *et al.*, 2013; Akpan *et al.*, 2019; Udoidiong, 2010; Naser, 2013; Nwaichi & Ntorgbo, 2016; Ubong *et al.*, 2020; Yawo & Akpan, 2001).

The sediments of Iko river have been assessed to be of acidic characteristics and predominantly of medium to fine grained sand ( $> 70\%$ ), and less of silt ( $< 15\%$ ) and clay ( $< 10\%$ ) indicating poor sink for heavy metal accumulation with accessibility to the biota (Etesin *et al.* 2013). Oil and gas exploration and exploitation activities are increasing, with accidental oil spills and gas flare, within and outside the ecosystems. The discharge and dumping of toxic wastes are expected to increase and be sustained for a long term, thus raising more concerns about the potential for significant pollution of the coastal marine ecosystems (Olujide, 2006; Benson & Etesin, 2007; Ubong *et al.*, 2020; EIA, 2020).

Recent studies indicate that heavy metal contamination is a major global problem threatening the sustainability of marine environments, biota species and humans who ingest resources from such contaminated ecosystems (Botta *et al.*, 2020; Naggar *et al.*, 2018; Weissmannova *et al.*, 2019; Alhjahdali & Alhassan, 2020; Liu *et al.*, 2021). Naggar *et al.* (2018) for instance was emphatic in describing the menace of heavy metals contamination of aquatic environments as “one of the highest problems that face human beings.” Aquatic

organisms exposed to these metals in their environment, absorb and bioaccumulate through various routes, such as respiration, ingestion, or direct contact with contaminated water (Morais *et al.*, 2012; Mok *et al.*, 2015; Manickavasagam *et al.*, 2019; Maher *et al.*, 2016). Heavy metals are among 129 contaminants (including organics, pesticides etc.) designated by the United States Environmental Protection Agency (US EPA) as priority pollutants based on their known or suspected carcinogenicity, mutagenicity, teratogenicity, or high acute toxicity of these contaminants which are regulated in most countries, including Nigeria (Tchobonoglous *et al.*, 2004; WHO, 2010). Heavy metals exhibit high toxicity when present beyond certain threshold concentrations (Ansari *et al.*, 2004; Fang *et al.*, 2003; Etesin *et al.*, 2021). The toxicity is enhanced by their non-degradable, persistent, and chemically reactive nature, as well as their high ability to accumulate and partition or sorb on to various environmental matrices (sediments, surface/pore water and biota tissues) (Ansari *et al.*, 2004; US EPA, 2023, 2007; Naggar *et al.*, 2018; Weissmannova *et al.*, 2019).

Heavy metal contamination of the environment may cause different kinds of stress, including death and disruption of the delicate balance in marine ecosystems' biodiversity due to their toxicity. Lead (Pb) exposure alone is reported to be causing about 3 % of cardiovascular diseases and 2 % of Ischæmic heart disease burden worldwide (WHO, 2010). Presently, Nigeria is ranked 5<sup>th</sup>, with an annual pollution-related death toll of 257, 093, among ten countries with the highest pollution-related deaths worldwide (Weiss, 2017). Niger Delta region is now rated as one of the five most petroleum polluted deltas in the world, with recent concern on the potential contamination of Eastern Obolo marine ecosystems by heavy metals (Etesin & Benson, 2007; Igbemi *et al.*, 2019; EIA, 2020; Ubong *et al.*, 2020; Tulcan *et al.*, 2021).

Some studies reported heavy metal contamination levels above the WHO standards which constitute considerable risk to biota and humans who source seafood from the aquatic ecosystems, raising a concern given the sustained exposure of Eastern Obolo marine ecosystem over several decades (Honda *et al.*, 1987; Juhl 2018; Igbemi *et al.*, 2019; Tuo *et al.*, 2019; Ubong *et al.*, 2020; Enemugwem, 2009; Chijioke *et al.*, 2018; Nworu *et al.*, 2019). Although previous studies assessed sediments and water quality, limited information exists on *Crassostrea gasar* as bioindicators for heavy metal risk assessment in this region.

The present study aimed to investigate the seasonal variation, bioaccumulation, and associated human health risks of selected heavy metals in oysters (*Crassostrea gasar*) from Iko River marine ecosystem, Nigeria. The heavy metals of concern in this study are cadmium Cd, lead Pb, zinc Zn, vanadium V, chromium Cr, manganese Mn, iron Fe, cobalt Co, nickel Ni, and copper Cu.

## 2.0 Materials and Methods

### 2.1 The Study Area

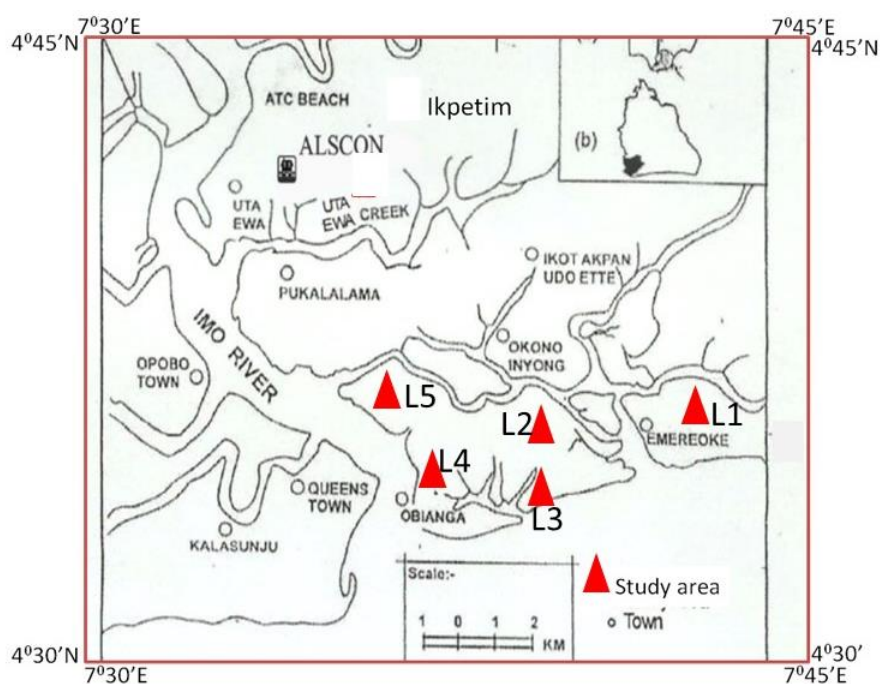
The Iko river ecosystem situates in Eastern Obolo Local Government Area of Akwa Ibom

State, which lies between latitudes 4°26' and 4°50' North and longitude 7°30' and 7°55' East (Fig. 1), within the equatorial region as well as the tropical mangrove belt (Etesin *et al.*, 2013; Igbemi *et al.*, 2019). As a Local Government Area in Akwa Ibom State, Nigeria, Eastern Obolo lies on the Atlantic coastline within the Gulf of Guinea, and is bound to the North by Mkpatt Enin, the South-East by Onna L.G.A, the West by Ikot Abasi LGA. and the south by the Atlantic Ocean (Enemugwem, 2009; Bessey *et al.*, 2019; Igbemi *et al.*, 2019).

Eastern Obolo area has two main seasons; the wet or rainy (April - October), and the dry (November - March) seasons each year. It has average temperature of 26 °C to 28 °C (Igbemi *et al.*, 2019). Some slight variations in the climatic conditions, duration of the seasons, temperature and rainfall have been reported for the area due to the global climate change phenomenon (Bassey *et al.*, 2019).

### 2.3 Sampling Locations

Five sampling sites were selected and marked out for the present study (Table 1). The geographic coordinates of each of the sites were obtained with a GPS system (Garmin GPS Map 785).



**Fig. 1 : Map of Study Area showing Sampling Locations**

## 2.4 *Crassostrea*

The fresh *Crassostrea gasar* meat (tissue) was then scrapped from the shells (Fig. 2) and placed in a pre-rinsed, sterile plastic beaker and dried in the electric drying oven (Model: DHG-9070A) at 105 °C to a steady weight after about 48 hours (Benson *et al.*, 2016; Maher *et al.*, 2016; Santhanam, 2018; Tuo *et al.*, 2019). The

dry composite oyster meat or tissues were ground with porcelain mortar and pestle, sieved to less than 2.0 mm size powdered tissue samples (US EPA, 2007; 2023). Precisely, 2.0 g size of each sieved oyster meat was put into a digestion flask for acid digestion (Benson *et al.*, 2016; Tuo *et al.*, 2019; APHA, AWCF, APHA., 2005).

**Table 1:** The sampling locations and their geographic coordinates.

Location No	Name of Location	Coordinates	
		Latitude	Longitude
L 1	Atlantic Ocean beach	04°30.405'N	07°43.663'E
L 2	Iko river mud flat	04°30.734'N	07°45.199'E
L 3	Obolo river mud flat	04°32.227'N	07°42.159'E
L 4	Amadaka river beach	04°32.227'N	07°42.159'E
L 5	Emeremen river mud flat	04°31.154'N	07°39.808'E



**Fig. 2:** Collection of oyster samples



## 2.5 ICP-OES Analyses of heavy metals

Inductively coupled plasma-optical emission spectrometer (Model: Agilent 720 ICP-OES) was used to analyze the total metal contents in each 100 cm<sup>3</sup> digest of the Oyster samples. The instrumental procedure used for the ICP-OES analysis is presented in detail in Appendix A.

## 2.6 Data Analysis

Microsoft Excel was used for graphical representation of data among stations and Statistical Package for Social Sciences (SPSS) version 25 was employed to compute Mean, Variance and Standard deviation in the data. Also, the student's t – distribution and F- test

distribution were used in the analysis of locational and seasonal variations of heavy metal levels in *Crassostrea gasar* at the probability level of  $p \leq 0.05$ .

## 3.0 Results and Discussion

### 3.1 Results of heavy metals in Oysters during the rainy season.

The results of the levels of heavy metals in Oysters from Iko river marine ecosystems at different locations (L1 – L5) during the dry season are presented in Table 2. The results of the levels of heavy metals in oysters from Iko river marine ecosystems at different locations (L1 – L5) during the rainy season are presented in Table 3.

**Table 2:** Levels of heavy metals in oysters during the dry season (mg/kg)

Metals	L1	L2	L3	L4	L5
V	94.83 ± 1.25	131.6 ± 2.57	3.03 ± 0.05	< 0.001	< 0.001
Cr	0.001	0.84 ± 0.007	< 0.001	< 0.001	< 0.001
Mn	26.62 ± 0.15	17.88 ± 0.11	107.9 ± 2.54	120.8 ± 3.05	224.9 ± 4.65
Fe	368.9 ± 3.49	294.5 ± 4.71	945.7 ± 10.75	3144 ± 21.17	2527 ± 30.09
Co	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Ni	0.53 ± 0.02	2.72 ± 0.04	< 0.001	< 0.001	< 0.001
Cu	50.65 ± 3.08	64.59 ± 3.04	9.012 ± 0.51	6.97 ± 0.09	< 0.001
Zn	912.9 ± 12.98	1189 ± 21.93	1256 ± 19.23	2143 ± 32.08	8534 ± 27.97
Cd	0.001	0.001	< 0.001	< 0.001	< 0.001
Pb	2.35 ± 0.19	24.72 ± 24.72	< 0.001	< 0.001	< 0.001

During the dry season (Fig. 3), Zn has the highest level (8534 ± 27.97 mg/kg) at L5, Fe has the highest (3144 ± 21.17 mg/kg) at L4, Mn has the highest level (224.9 ± 4.65 mg/kg) at L5, V has the highest level (131.6 ± 2.57 mg/kg) at L2, Ni has the highest level (2.72 ± 0.04 mg/kg) at L2, Cu has the highest level (64.59 ± 3.04 mg/kg) at L2, Pb has the highest level (24.72 ± 0.25 mg/kg) at L2, Cr has the highest level (0.84 ± 0.007 mg/kg) at L2 whilst Co, Cd were below the detection limit (BDL).

During the rainy season (Fig. 4), Zn has the highest level (8788 ± 29.16 mg/kg) at L5, Fe has the highest (4413 ± 41.11 mg/kg) at L5, Mn has the highest level (362.2 ± 10.75 mg/kg) at L5, V has the highest level (902.6 ± 22.78 mg/kg) at

L2, Ni has the highest level (1.99 ± 0.06 mg/kg) at L2, Cu has the highest level (52.11 ± 2.05 mg/kg) at L2, Pb has the highest level (21.66 ± 1.05 mg/kg) at L2, Cr has the highest level (0.96 ± 0.006 mg/kg) at L2 whilst Co, Cd were below the detection limit (BDL). The levels of heavy metals in both seasons in Fig. 5 indicated Zn and Fe having values that exceeded WHO limits (WHO, 2010; USEPA, 2023), however the values were lower than the levels obtained in other studies by Inyang and Effiong (2017); Kiin-kabari *et al.* (2017); Botta *et al.* (2020) and Tuo *et al.* (2019) in Ebrie lagoon, Cote d'Ivoire. Bioaccumulation factor of heavy metals in Oysters during both seasons from Iko river marine ecosystem is presented in Fig. 6.

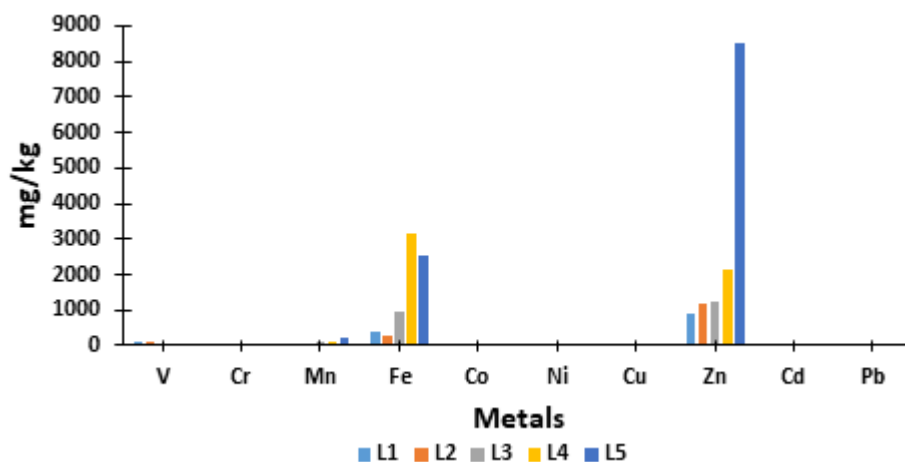
**Table 3:** Levels of heavy metals in oysters during the rainy season (mg/kg)

Metals	L1	L2	L3	L4	L5
V	133.4 ± 11.15	902.6±22.78	< 0.001	< 0.001	< 0.001
Cr	0.96± 0.07	< 0.001	< 0.001	< 0.001	< 0.001
Mn	110.2±8.36	44.31±2.97	113.3±8.14	170.5± 21.07	362.2± 11.74
Fe	1331±29.07	749.4± 24.38	1552± 36.17	2224±33.16	4413± 33.25
Co	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Ni	0.46±0.05	1.99±0.03	< 0.001	< 0.001	< 0.001
Cu	39.06±1.67	52.11± 2.62	6.09± 0.15	4.94± 0.21	< 0.001
Zn	816.5± 7.09	1175± 10.75	1287± 16.23	2167± 17.26	8788± 22.19
Cd	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Pb	1.97± 0.15	21.66± 0.11	< 0.001	< 0.001	< 0.001

**Table 4:** Results of heavy metals in oysters in both seasons

	L1		L2		L3		L4		L5	
	D	R	D	R	D	R	D	R	D	R
V	94.83	193	131.6	902.6	3.03	< 001	< 0.001	< 0.001	< 0.001	< 0.001
Cr	0.001	0.96	0.84	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Mn	26.62	1102	17.88	44.31	107.9	113.3	120.8	170.5	224.9	362.2
Fe	368.9	1331	294.5	749.4	945.7	1552	3144	2224	2527	4413
Co	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Ni	0.53	0.46	2.72	1.99	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cu	50.65	39.06	64.59	52.11	9.012	6.09	6.97	4.94	< 0.001	< 0.001
Zn	912.9	816.5	1189	1175	1256	1287	2143	2167	8534	8788
Cd	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Pb	2.35	1.97	24.72	21.66	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

D = dry season, R = rainy season

**Fig. 3:** Results of heavy metals in oyster during dry season

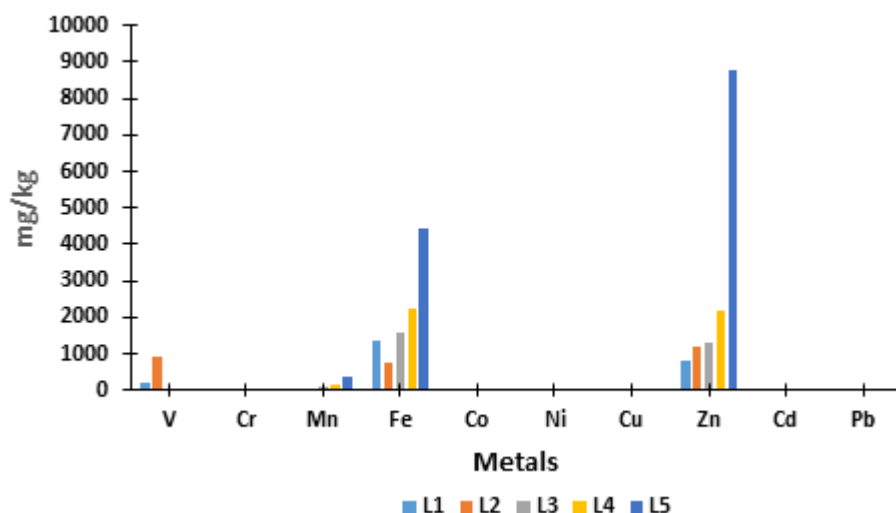


Fig. 4: Results of heavy metals in oyster during rainy season

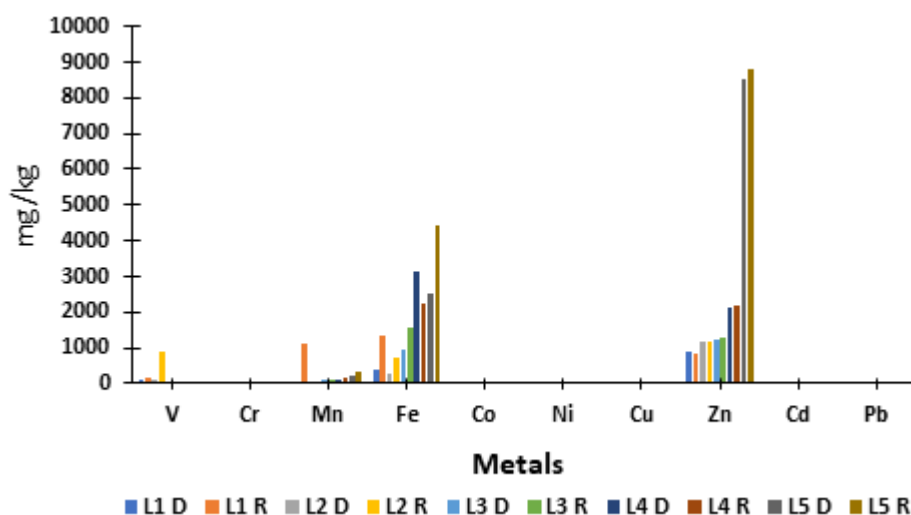


Fig. 5: Heavy metals during the dry (D) and rainy (R) seasons

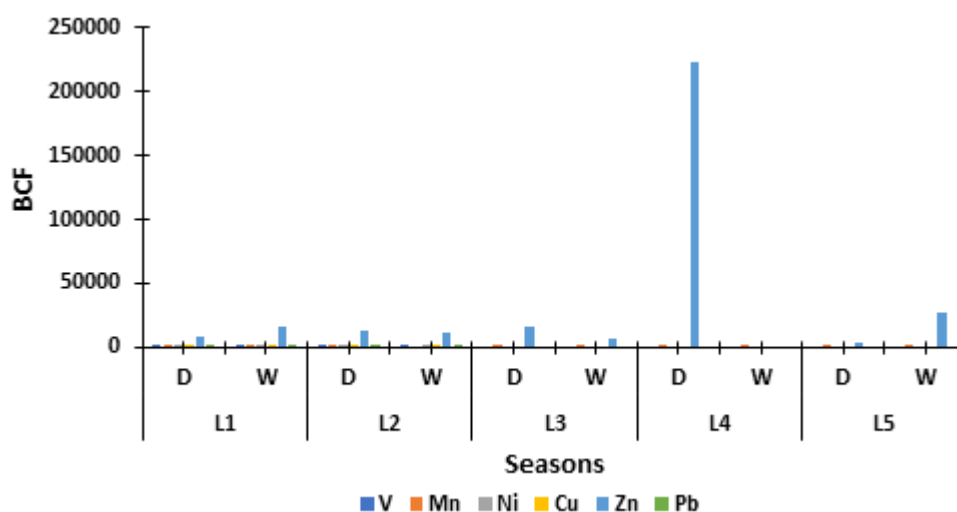


Fig. 6: Bioaccumulation factor of heavy metals in oysters during both seasons

Zinc metal has the highest bioaccumulation at location L4 in both dry and rainy seasons. The order of bioaccumulation is as follows in both

seasons:  $Zn > Mn > Pb > Ni > Cd$ . In a similar study conducted by Claudia et al (2022) in Yellowknife, Northwest Territories, Canada, the

average total arsenic concentration in fish muscle tissue was  $2.30 \pm 1.72 \mu\text{g/g}$  dry weight, and that in burbot liver tissue was  $3.16 \pm 2.49 \mu\text{g/g}$  dry weight.

The order of magnitude of the metals' bioaccumulation in this study is not reflecting the general outlook observed in the sediments and waters in previous communication (Etesin *et al.*, 2025), is suggestive of the influence of some factors in the bioaccumulation process in the oysters. As established by other studies, such factors may include the ambient physiochemical conditions, the type and concentration of metals, water salinity, pH, temperature, oyster uptake process and excretion (Isotuk *et al.*, 2024).

This trend has confirmed some earlier studies which found that oysters and other bivalve mollusks can accumulate high concentrations of Zn and Cu, etc. and still function effectively (exhibit high tolerance) by storing the metals in sub-cellular, non-toxic forms, while leaving only very small amount of the metal in metal-sensitive cell components (Ansari *et al.*, 2004; Maher *et al.*, 2016; Juhl, 2018).

The BCF data obtained were interpreted based on the established ecological risk assessment criteria for BCF and BSAF, which are (USEPA, 2023):

BCF or BSAF:

< 250, indicate low concern;

≥ 250, medium concern;

≥ 1000, considered as high concern;

≥ 5000, indicate contaminants that are of high-risk concern.

Using these quality guidelines ranking scheme, the present study has indicated that Zn, Mn, Cd, Pb, Ni, have low concerns at the five sampling sites (BCF < 250). The BCF data predicts the contamination status of the ecosystem with respect to the heavy metals measured, but do not necessarily indicate their toxicity to the oysters due to high tolerance capacity of oysters (US EPA, 2007, 2023; Maher *et al.*, 2016; Etesin *et al.*, 2025).

Many impaired oysters (evidenced by dead and empty shells on substrates) were found at L5 during sample collection. However, the specific contribution of the metals studied to the observed oysters' impairment is not exactly clear as the sampling site is in the drain basin of an abandoned artisanal crude oil refining site (L5). Notwithstanding, Garcia *et al.* (2009) had reported among others the development of histopathological lesions in oysters in Mandinga Lagoon, Mexico due to heavy metals (Cr, Cd, Pb, etc.) contamination.

### 3.2 Human Health Risk Evaluation of Heavy Metal Contents of Oysters

The human health risk evaluation/assessment approaches developed by the US EPA (2013) were used for this assessment as reported by several researchers (Abubakar *et al.*, 2015; Benson *et al.*, 2016; Zheng *et al.*, 2016; Weissmannova *et al.*, 2019; Kortei *et al.*, 2020; Plum *et al.*, 2020). Only exposure pathway through ingestion of the oysters were considered for this risk evaluation since oysters are only ingested as food by adults and children.

The daily intake of each metal (DIM) from oral ingestion of the oysters in this study was estimated using equation 1:

$$\text{DIM} = (C_m \times \text{DNI} \times C_f) / B_w \quad (1)$$

where

- DIM (mg/kg-day) is the estimated daily intake rate of the metal through ingestion of the seafood/food item concerned (in this case oysters).
- $C_m$  is the measured metal concentrations in the oysters/seafood tissue(s) consumed (mg/kg dw).
- DNI is the estimated average rate of daily nutritional intake of seafood (in this case oysters) (g/day), which was estimated in 2011 by the United Nations Food and Agriculture Organization (FAO) as being 62.62 and 60.0 g capita<sup>-1</sup> day<sup>-1</sup> for adults and children, respectively, for Nigeria (Abubakar *et al.*, 2015; Benson *et al.*, 2016).



- $C_f$  is the conversion factor of fresh food item (seafood/oyster) to dry constant weight. This is estimated as reported by Abubakar *et al.* (2015) and Benson *et al.* (2016).

$$C_f = IR_{ww} - IR_{dw} \quad (2)$$

$$IR_{ww} = IR_{dw} (100 - W) / 100 \quad (3)$$

where  $IR_{ww}$  and  $IR_{dw}$  are the wet weight intake rate and dry weight intake rate of the food (oyster) respectively and  $W$  is the per cent moisture (water) content of the food concerned

In this study, the average moisture content of the oyster tissues was 80.62 per cent (%), which gives a  $C_f$  value of 0.1938.  $B_w$  is the average body weight of a person. The average body weight of adults (> 18 years) and children (6-18 years) in Nigeria is 70 kg and 48kg, respectively, as reported by Benson *et al.* (2016). Also, the FAO estimated daily ingestion rate (DNI) of seafood  $g \text{ capita}^{-1} \text{ day}^{-1}$  for Nigeria. Table 5 presents the DIM for the metals studied based on their concentrations in the oyster tissues.

**Table 5:** Estimated daily intake of the heavy metals (DIM) in the oysters

Metal (mg/kg-day)		L1	L2	L3	L4	L5	Cumulative Average
Pb	Adult	0.21	3.13	-	-	-	0.67
	Children	0.51	4.56	-	-	-	0.98
Zn	Adult	149.31	168.77	1872.08	20797.31	2333.56	5064.20
	Children	208.69	235.90	2616.73	29069.72	3261.77	7078.56
Cu	Adult	4.48	6.09	87.73	36.37	-	26.96
	Children	6.26	8.51	122.62	50.84	-	37.65
Ni	Adult	0.14	0.57	-	-	-	0.14
	Children	0.19	0.80	-	-	-	0.20
Cr	Adult	0.17	0.14	-	-	-	0.06
	Children	0.23	0.19	-	-	-	0.09
V	Adult	19.78	89.62	0.53	-	-	21.98
	Children	27.64	125.27	0.73	-	-	30.73

### 3.3 The Health Index (HI)

Based on the DIM results obtained (Table 5), the health index (HI) was used to estimate the possible human health risk associated with consumption of oysters from the study sites (Khan *et al.*, 2009; Abubakar *et al.*, 2015; Benson, *et al.*, 2016; Weissmannova *et al.*, 2019).

$$HI = DIM / R_{fD} \quad (4)$$

where  $R_{fD}$  = recommended daily reference intake dose (mg/kg-day) of each metal through ingestion which are: Pb (0.0035), Zn (0.3), Ni (0.02), Cr (1.5), Cd (0.001), Cu (0.04), and V (0.005) based on the US EPA estimates (Khan *et al.*, 2009; Zheng *et al.*, 2015; Kormoker *et al.*, 2020).

The following assessment criteria were adopted (USEPA, 2023; IARC, 2010):

$HI \leq 1$ , indicates there are no potential risks associated with the DIM from the food (oyster).  $HI > 1$ , indicates significant risk associated with the intake of the metal through daily ingestion of the food (oyster). From the results obtained (Table 5), all the metals analyzed for this assessment (Pb, Zn, Cu, Ni, and V), have DIM for the oysters at all the study sites above their  $R_{fD}$  limits for adults and children, except Cr, Co and Cd. It follows that adults and children intake of the metals through ingestion of oysters from the study sites would possibly pose considerable health risk to the individual consumers. The present results are in close agreement with that of the study by Benson *et*

al. (2016) which reported similar health risk for all metals studied (except Cr which had DIM below the R<sub>f</sub>D) in crabs from Douglas creek, Ibeno, Nigeria.

#### 4.0 Conclusion

This study determined the concentrations, distribution and bioaccumulation, as well as ecological and health risks of some heavy metals (V, Cr, Mn, Fe, Ni, Cu, Pb, Co, Cd, Zn, Ag) in Oysters (*Crassostrea gasar*) from five sampling sites (Atlantic coastline, Iko river, Obolo river, Amadaka river and Emeremen river) along Eastern Obolo marine coastline, Nigeria. Except Cd, Ag and Co which were not detected in any of the sample locations, the heavy metals have varied distribution levels in oysters. The study demonstrates that oysters in Iko River significantly bioaccumulate heavy metals, with zinc showing the highest levels across seasons. Although Cd and Co were not detected, several metals exceeded recommended dietary limits, posing health risks to consumers. The findings highlight oysters as effective bioindicators and underscore the urgent need for regular monitoring and remediation strategies in Eastern Obolo coastal ecosystems.

The intake of the detected metals by ingestion of the oyster may have a high potential for carcinogenic and non-carcinogenic adverse effects on the oyster consumers from the sites studied. The bioconcentration of the detected heavy metals in the oysters indicated low, moderate and high-risk (especially Zn) concerns for the ecosystems and humans. The outcome of this study buttresses the fact that Atlantic and inland coastlines of Eastern Obolo needs regulatory interventions and cleanup remediation.

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#### Conflict of interest

The authors in the course of the study express no conflict of interest.

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