UMT PRESS

Planetary Sustainability
Journal Homepage: https://journal.umt.edu.my/index.php/planetsust/
eISSN: 3009-0105
DOI: http://doi.org/10.46754/ps.2024.07.001

DISTRIBUTION OF HADROCHEMICAL PARAMETERS, TOXICOLOGY AND BIOACCUMULATION OF HAZARDOUS ELEMENTS IN PERIWINKLE (*Tympanotonus fuscatus*) AND OTHER SAMPLES FROM THE NIGER DELTA IN NIGERIA

DAVIES IBIENEBO CHRIS[1]*, OKECHUKWU KENNETH WOKEH[2], MOHAMAD NOR AZRA[3,4], FATHURRAHMAN LANANAN[5], MURNI NUR ISLAMIAH KASSIM[3] AND LEE SEONG WEI[6]

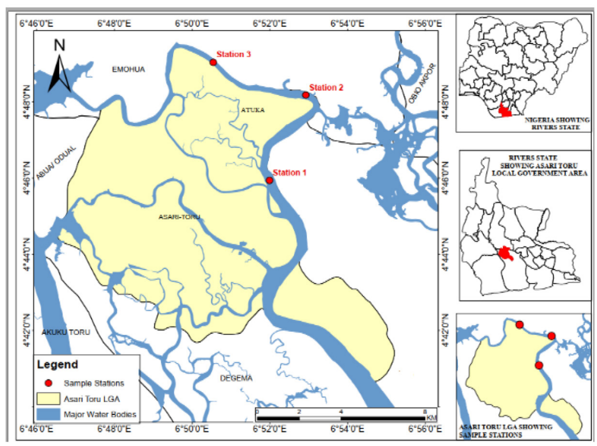
[1]Department of Fisheries, University of Port Harcourt, Rivers State, 53233 P.M.B., Nigeria. [2]Department of Animal and Environmental Biology, University of Port Harcourt, Rivers State, Nigeria. [3]Institute of Climate Adaptation and Marine Biotechnology, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia. [4]Research Center for Marine and Land Bioindustry, Earth Sciences and Maritime Organisation, National Research and Innovation Agency (BRIN), 83352 Pemenang, Indonesia. [5]East Coast Environmental Research Institute, Universiti Sultan Zainal Abidin, Gong Badak Campus, 21300 Kuala Nerus, Terengganu, Malaysia. [6]Advanced Livestock and Aquaculture Research Group, Department of Agricultural Sciences, Faculty of Agro-Based Industry, Universiti Malaysia Kelantan, Jeli Campus, 17600 Jeli, Kelantan, Malaysia.

**Corresponding author: davies.chris@uniport.edu.ng*

HIGHLIGHTS

- This study examines the distribution of physicochemical parameters and toxic metals from three sampling locations in the Niger Delta coast of Nigeria.
- The findings reveal considerable variability in levels of heavy metals and physicochemical features between stations.
- Higher metal bioaccumulation in these areas may lead to potential environmental and health implications in local communities.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article History:
Received: 5 June 2024
Accepted: 25 June 2024
Published: 31 July 2024

Keywords:
Physicochemical parameters, hazardous elements, Niger Delta, bioaccumulation.

ABSTRACT

The study examined the distribution of physicochemical parameters and toxic metals in the Niger Delta coast of Nigeria. The physicochemical data of the shellfish *Tympanotonus fuscatus*, water, and sediments were collected from three sampling stations over six months. The findings revealed considerable variability in levels of heavy metals and physicochemical features between stations. Station 2 had higher temperature and salinity levels, but lower total dissolved solids, pH, biological oxygen demand, and dissolved oxygen. Station 1 had the highest concentrations of Fe, Zn, Cd, Pb, Cu, and As in water and sediment samples, whereas Station 2 consistently had the lowest concentrations. Station 3 had the highest Fe levels while Station 2 had the lowest Zn values in terms of sediment bioaccumulation.

The study found no significant differences ($p > 0.05$) in the level of all metals in water, *T. fuscatus* and sediments between Stations 1 and 2, except for Cu, which showed slight variation ($p < 0.05$). In shellfish, Cu showed slight variation ($p < 0.05$) between Stations 1 and 2, and in sediments, Fe and Cu showed significant differences ($p < 0.05$) between the two stations. In As bioaccumulation, Station 3 had the greatest concentration, measuring 0.00000123 mg/kg while both Stations 1 and 2 shared the lowest value at 0.00000058 mg/kg. Station 3 also had the highest Fe bioaccumulation, possibly due to local conditions or iron sources. Higher metal bioaccumulation in these areas might lead to potential environmental and health implications. This study results suggested that constant assessment and remedial measures were needed to safeguard the aquatic ecosystems in the area.

Introduction

The Niger Delta is an enormous region of ecological significance in Nigeria. Spanning over a large part of the country's southern coast, it is characterised by a rich biodiversity and abundant aquatic ecosystems (Onyena *et al*., 2021). However, rapid industrialisation, urbanisation, and oil exploration have sparked concern about the potential impact of these anthropogenic activities on the coastal environment. Currently, the hydrological distribution of physicochemical parameters and bioaccumulation of heavy metals stand out as critical issues among the environmental challenges in the Niger Delta (Lv *et al*., 2020). Understanding the hydrological distribution of physicochemical parameters is essential to comprehend the overall health and function of aquatic ecosystems.

The physicochemical features such as temperature, salinity, pH, biological oxygen demand (BOD), dissolved oxygen (DO), and nutrient levels significantly influence habitat conditions and aquatic species (Chris *et al.*, 2023a). According to Sih *et al.* (2012), variations in these parameters can alter the distribution, abundance and behaviour of aquatic inhabitants, affecting the ecological dynamics of the Niger Delta coast. Heavy metals, including lead (Pb), copper (Cu), iron (Fe), cadmium (Cd), zinc (Zn), and arsenic (As), among others are persistent pollutants released by industrial activities (Davies & Ekperusi, 2021). These metals have toxic effects on aquatic organisms and the capacity for biological accumulation in the food chain poses a risk to aquatic life and human health.

The periwinkle or West African mud creeper (*Tympanotonus fuscatus*) is an edible brackish water snail that is native to the Niger Delta. It is a local delicacy with high economic value. The assessment of heavy metal bioaccumulation in the periwinkle will provide serious data that reflects the level of pollution in the local ecosystem and its potential effects on resident biota (Davies *et al.*, 2022).

The current study seeks to examine the hadrochemical distribution of physicochemical parameters along the Niger Delta coast and assess the ecotoxicology of hazardous heavy metal bioaccumulation in this shellfish from brackish coastal ecosystems. By examining the variations in physicochemical parameters, insights into total water quality can be obtained and various areas of concern may be identified for conservation and management (Chris *et al.*, 2023a). Furthermore, the study will explore the level of hazardous metals in different aquatic organisms and sediments to understand the potential pathways and sources of metal contamination (Sarker *et al.*, 2022).

The current research seeks to enhance our knowledge in the ecotoxicity of hazardous element bioaccumulation along the Niger Delta. As a result, effective strategies can be developed for the conservation and sustainable management of this ecologically significant region. It also provides essential data to formulate policies and practices aimed at mitigating heavy metal pollution and preserving the integrity of coastal ecosystems in Nigeria.

Materials and Methods

Sampling Stations

The study employed a quantitative approach, with data taken from three sampling stations located near artisanal crude oil refining operations, waste disposal sites, and dredging and fishing zones. The stations were selected based on their closeness to polluted areas, waste effluent and human waste disposal. Station 1 is located between Latitude E 06°86'64.71" and Longitude N 4°76'55.91"; Station 2 is located between Latitude E 06°88'19.09" and Longitude N 4°80'34.85". Station 3 is located between E 06°84'22.57" and Longitude N 4°81'74.11" (Figure 1).

Study Area

The Atuka Creek is a fishing village in Rivers State, Nigeria, located along the Buguma axis. The area, which includes the main channel and feeder creeks, is located southeast of the Niger Delta, which connects several riparian towns. The region is home to numerous abandoned artisanal crude oil installations, exposing it to the risk of oil leaks.

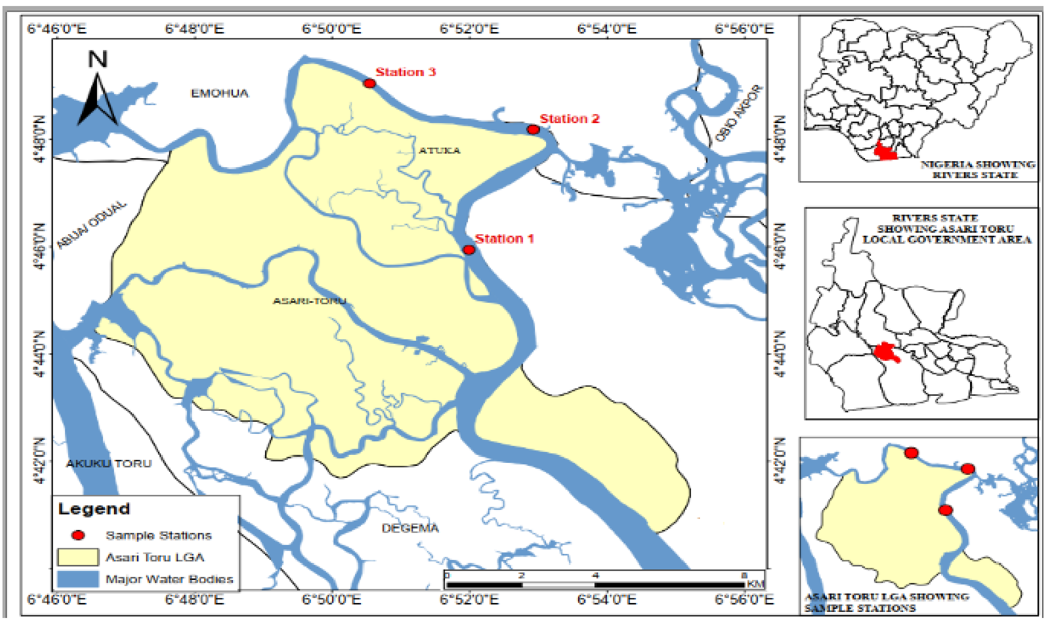


Figure 1: Map showing the location of sampling stations in Rivers State, Nigeria

Samples and Sampling Procedures

The three sampling sites were selected in local communities based on the characteristics of streams in the research region, with stations being at least 1,000 metres apart. The heavy metals (Pb, Cu, Fe, Cd, Zn, and As) were chosen due to their high content in industrial and household effluents. Sediment, water, and *T. fuscatus* (biota) samples were taken for analysis and geographic coordinates were determined using a portable Magellan GPS 315 unit (Magellan Navigation, San Dimas, CA, USA). Sampling was conducted once a month from April to September 2023, during the first week of each month.

Collection of Samples

Periwinkles

Freshly caught live periwinkles were obtained from local fishermen operating near the three sampling sites at 21-day intervals. A total of 60 shellfish were collected, with a mean length of 5.50.65 cm and weight of 5.30.87 g. A total of 15 shellfish per station were collected at each sampling community during the six-month period (April to September 2023) to allow for statistical fluctuations. The periwinkle was chosen because it is intimately associated with mangroves and neighbouring soft-bottom peritidal environments. Some fishes in the area are particularly well adapted to an amphibious lifestyle. The sampling distance from the river banks was chosen to guarantee that the water and sediment samples represented the actual and visible pollution pockets in the study region. To preserve the integrity of the materials, all samples were clearly labelled and transported to the laboratory in an ice chest on the same day. The samples were then refrigerated until they were analysed. Heavy metal content was determined using conventional procedures (WEF, 1992).

Sediments

Sediments were collected in the form of a composite with an "Ekman grab" picker at three independent locations in the creeks, and stored in a plastic bag that had previously been treated with 10% nitric acid for 24 hours and washed with deionised water. Following that, the frozen samples were transported to the laboratory. The samples were kept at 20°C until they were processed using atomic absorption spectrophotometry according to standard (API-RP 45). The sampling distance from the river banks was selected to guarantee that the water and sediment samples represented the actual and visible pollution pockets in the study region.

Water

Samples of interstitial water were collected using clean, high-density Schott glass tubing (Schott AG, Mainz, Germany). Before sampling, these bottles were rigorously cleaned with detergent before rinsing with tap water and finally, soaking for 24 hours in 50% hydrochloric acid (HCl). Prior to sampling, the vessels were cleaned with tap water and triple-distilled water after acid treatment. This thorough cleaning procedure would prevent the contamination of samples with metal residues. It also prevented metal residues from adhering to glazed surfaces, as the acid would dissolve the metals.

The glass tubes with water samples were carefully wrapped and sent to the laboratory in frozen packs. Each sample was meticulously labelled and they were promptly conveyed to the laboratory on the same day in an ice chest. The samples were subsequently measured and kept in refrigeration for analysis. The analysis of heavy metal content was conducted according to standard methods (APHA, 1998). The selection of sampling locations near the river banks were selected to ensure that both water and sediment samples accurately represented the evident pollution areas within the study zone.

Procedures for Measuring Physicochemical Parameters of Surface Water

Three pits were dug at random on each sampling station's intertidal flat to allow for the accumulation of interstitial water. The interstitial water was tested using an in situ hand-held Milwaukee pH600 multimeter (Milwaukee Instruments, Rocky Mount, NC, USA) for 15 minutes. Using the same portable multimeter and a laboratory benchtop metre (860033-model), the following parameters of the water were measured in situ: pH, temperature, salinity, conductivity, total suspended solids (TSS), and total dissolved solids (TDS). The instruments had been calibrated using a standard buffer and it was restarted to allow for self-calibration before being cleaned with distilled water. The parameters were then measured by placing the probe into the river, allowing the readings to stabilise before recording the values.

Winkle's five-day BOD test technique (APHA, 1998) was used to determine the level of DO. A 250 ml reagent amber BOD container was filled with interstitial water collected from the intertidal flat's dogged pit. The bottle was filled with the sampled water mixture and distilled water was used to dilute a 5 ml sample to 100 ml. This was poured into two 50 ml DO bottles and sealed. The initial DO was determined using the Milwaukee MW600 DO meter (Milwaukee Instruments, Rocky Mount, NC, USA) in one of the two test samples. The other test sample was incubated for five days at 200°C before being analysed for DO. The BOD was calculated using Equation 1:

BOD (mg/l) = Initial DO – Final DO (Eq. 1)

Determination of Heavy Metals

AAS was used to determine the amounts of Pb, Cu, Fe, Cd, Zn, and As (APHA, 1998). The device was set up and used in accordance with the manufacturer's instructions.

Procedure for Heavy Metal Analyses

Sample Preparation

A blender was used to granulate periwinkle samples, whereas sediment samples were air dried, and water samples were digested with 20 ml concentrated sulphuric acid (H_2SO_4). Results were typically reported in mg/L.

Total Digestion for Heavy Metals

Complete digesting technique of extraction utilising nitric, perchloric, and sulphuric acids were performed according to standard (APHA, 3030I modified): One gramme of silt and granulated flesh of shellfish samples were weighed in a 250 ml Pyrex conical flask before adding 20 ml of digestive solution. In order to ensure complete digestion, the samples were heated in the fume hood using an electrical mantle at 250°C until the colour of the granules changed from dark to grey. The heat-digested solution was then allowed to cool. While cooling down, the mixture was added with 20 ml of distilled water. The digested solution was filtered into a 100 ml glass volumetric flask using the ashless Whatman 42 paper. The digested filtrate was produced in the volumetric flask up to the 100 ml mark. This was then put onto a brand-new 100 ml plastic bottle and labelled. Pb, Cu, Fe, Cd, Zn, and As levels were quantified using the AAS machine.

Quality Assurance and Control

Atomic absorption spectrophotometry was performed using the using the Buck 210VGP spectrophotometer (Buck Scientific, Norwalk, CT, USA). The apparatus was set up using atomic absorption standards for several heavy metals that were buck certified to produce a calibration curve. For every 10 samples, a reagent blank was run to prevent equipment drifting. Recovery rates varied between 82% and 110%. The method description and wavelength (nm) were consistent with the work of Davies and Ekperusi (2021). All samples were analysed in duplicates, and the reported values were the means of these measurements.

Bioaccumulation Factor

The Bioaccumulation Factor (BAF) was computed using Equation 2 to estimate the level of heavy metal accumulation in shellfish tissue (mg/kg):

BAF = Metal concentration *T.fuscatus*/Metal concentration in sediment (Eq. 2)

Statistical Analysis

The results were tabulated in Microsoft Excel 2010 and statistical analysis was performed using IBM SPSS Version 20. The differences in heavy metal concentrations in the water, sediment and *T. fuscatus* were examined using a one-way analysis of variance (ANOVA) with a significant level of < 0.05.

Results

Spatial Variation of Physico-chemical Parameters

Table 1 displays the variance in physicochemical properties of samples obtained between stations. Temperature, pH, DO, salinity, BOD, and TDS readings were significantly different ($p < 0.05$) between Station 2 and sites 3 and 1. Temperature was significantly higher at Station

2 (29.500.74°C) than at Station 1 (25.750.57°C), whereas pH was higher at Station 1 (6.720.14) than at Station 2 (5.680.18). Station 1 had the highest DO concentration (3.350.11 mg/l), followed by Station 3 (3.270.21 mg/l) and Station 2 (2.920.20 mg/l). Salinity was highest at Station 2 (15,280.71 ppm), followed by Station 3 (12,780.81 ppm) and Station 1 (11,440.45 ppm). However, Station 2 documented the highest BOD (3.600.79 mg/l) and Station 1 reported the lowest (2.460.42 mg/l). In addition, the highest value of electrical conductivity (EC) was recorded at Station 2 (34.073.62 S/cm), followed by Station 3 (28.782.610 S/cm) and Station 1 (25.760.47 S/cm). Station 2 had the highest TDS (28,173.77 mg L-1), whereas Station 1 had the lowest (19,202.29 mg L-1). There were no significant differences between the tested parameters at Stations 1 and 3.

Table 1: Summary of distinctions in physicochemical parameters

Stations	Temperature (^{o}C)	pH	DO (mg/l)	Salinity (ppm)	BOD (mg/l)	Conductivity (µS/cm)	TDS (Mg L^{-1})
1	25.75 ± 0.57^{b}	6.72 ± 0.14^{b}	3.35 ± 0.11^{a}	11.44 ± 0.45 ^{b}	2.46 ± 0.42^{b}	25.8 ± 0.50^{b}	19.2 ± 2.30^{b}
2	29.50 ± 0.74^{a}	5.68 ± 0.18^{a}	2.92 ± 0.20^{b}	15.28 ± 0.71 ^{a}	3.60 ± 0.79^{a}	34.1 ± 3.60^{a}	28.2 ± 3.80^{a}
3	27.40 ± 0.75^{ab}	6.45 ± 0.18^{b}	3.27 ± 0.21^{a}	12.78 ± 0.81^{b}	2.78 ± 0.47^{b}	28.8 ± 2.60^{b}	21.9 ± 2.50^{b}
WHO 2011	30	6.6-8.5	6	120	10	600	500

*WHO: World Health Organisation

Correlation between Physicochemical Parameters

Table 2 depicts the relationship between physicochemical characteristics in the research area. There was evidence of a positive correlation between temperature and salinity (0.630), DO (0.246), conductivity (0.501), and TDS (0.695). The pH level and DO (0.092) were also positively correlated, although salinity (-0.500) was inversely correlated with DO (-0.917), conductivity (-0.901), and TDS (-0.688). There were no positive associations between DO and other parameters. Salinity was shown to be related to DO (0.675), conductivity (0.645), and TDS (0.350). EC and biological oxygen demand had a significant and overwhelmingly favourable connection (0.924), which was likewise linked to TDS (0.546). The relationship between EC and TDS was found to be positive (0.802).

Table 2: Correlation between physicochemical parameters in the study area

	Temperature	pH	DO	Salinity	BOD	Conductivity	TDS
Temperature (^{o}C)	1						
PH	-0.199	1					
DO (mg/l)	-0.567	0.092	1				
Salinity (ppm)	0.630	-0.500	-0.789	1			
BOD (mg/l)	0.246	-0.917*	-0.203	0.675	1		
Conductivity (µS/cm)	0.501	-0.901*	-0.263	0.645	0.924**	1	
TDS (ppt)	0.695	-0.688	-0.114	0.350	0.546	0.802	1

** Correlation is significant at the 2-tailed level of 0.01
* Correlation is significant at the 2-tailed level of 0.05

Table 3: Spatial variation of heavy metals in water

	Heavy Metals (mg/L)					
Stations	Fe	Zn	Cd	Pb	Cu	As
1	37.65 ± 3.03 [a]	10.9 ± 1.62 [a]	0.07 ± 0.09 [a]	0.08 ± 0.1 [a]	149.19 ± 154.9[a]	0.003 ± 0.001 [a]
2	35.41 ± 3.88 [a]	10.7 ± 1.71 [a]	0.05 ± 0.01 [a]	0.10 ± 0.01 [a]	146.58 ± 4.7 [b]	0.005 ± 0.001 [a]
3	37.00 ± 3.99 [a]	10.04 ± 1.13 [a]	0.06 ± 0.01 [a]	0.09 ± 0.02 [a]	146.0 ± 9.5 [b]	0.005 ± 0.001 [a]

Spatial Variation of Heavy Metals in T. fuscatus

Table 4 shows information about how the levels of heavy metals changed over time in *T. fuscatus* samples taken from Stations 1, 2, and 3. These values were expressed in mg/kg. In the case of Fe, Station 1 had the greatest average concentration (12.20 mg/kg), whereas Station 2 had the lowest (11.32 mg/kg). Station 1 had the greatest average content of Zn, equivalent to 104.8 mg/kg, whereas Station 3 recorded the lowest average concentration, measuring 101.8 mg/kg. Cd concentrations across all three stations registered very low averages of approximately 0.001 mg/kg, with minimal fluctuations. For Pb, Stations 1 and 2 exhibited identical average concentrations, both at 0.004 mg/kg, which was slightly higher than the average concentration at Station 3, rated at 0.004 mg/kg. Station 1 reported the highest average concentration of Cu at 0.73 mg/kg while Station 2 had the lowest value of 0.69 mg/kg. In contrast, the greatest concentration of As, quantifying at 0.002 mg/kg was documented at Station 3. Stations 1 and 2 displayed equivalent average As concentrations of 0.001 mg/kg. No significant differences ($p > 0.05$) were observed in all metals in *T. fuscatus*, except for Cu, which recorded slight variation ($p < 0.05$) between Station 1 and the other two stations.

Table 4: Spatial variation of heavy metals in *T. fuscatus*

	Heavy Metals (mg/kg)					
Stations	Fe	Zn	Cd	Pb	Cu	As
1	12.20 ± 4.19[a]	104.8 ± 1.37[a]	0.001 ± 0.01[a]	0.005 ± 0.02[a]	0.73 ± 4.0 [a]	0.001 ± 0.001[a]
2	11.32 ± 0.39[a]	102.9 ± 4.13[a]	0.001 ± 0.00[a]	0.004 ± 0.001[a]	0.69 ± 0.0 [ab]	0.001 ± 0.001[a]
3	11.74 ± 0.44[a]	101.8 ± 4.28[a]	0.001 ± 0.00[a]	0.004 ± 0.001[a]	0.67 ± 0.03 [b]	0.002 ± 0.001[a]

Spatial Variation of Heavy Metals in Sediments

Table 5 gives a comprehensive look at the heavy metal concentrations discovered in sediment samples. Station 1 had the greatest average concentration of Fe, measuring 1729.15 mg/kg while Station 2 had the lowest, measuring 1615.61 mg/kg. Moving on to Zn, Station 1 had the greatest concentration, averaging 220.8 mg/kg while Station 3 had the lowest, averaging 212.9 mg/kg. Cd concentrations were highest at Station 1, with an average of 2.95 mg/kg and lowest in Station 3, with an average of 2.33 mg/kg. Pb had the highest mean concentration at Station 1 (9.47 mg/kg), whereas Station 2 had the lowest mean value (7.55 mg/kg). Station 1 had the greatest mean concentration of Cu, measuring 541.22 mg/kg while Station 3 had the lowest, measuring 481.14 mg/kg. In As concentrations, they reached their highest level in Station 1, with an average of 0.017 mg/kg while both Station 2 and Station 3 displayed lower concentrations, averaging 0.015 mg/kg. No significant variations ($p > 0.05$) were observed in all metals in the sediments except for Fe and Cu, which were significantly different ($p < \pm 0.05$) between the Station 1 and the other two stations.

Table 5: Spatial variation of heavy metals in sediment

	Heavy Metals (mg/kg)					
Stations	**Fe**	**Zn**	**Cd**	**Pb**	**Cu**	**As**
1	1729.15 ± 0.51[a]	220.8 ± 6.62[a]	2.95 ± 0.00[a]	9.47 ± 0.00[a]	541.22 ± 0.0[a]	0.017 ± 0.001[a]
2	1615.61 ± 86.[b]	219.3 ± 7.50[a]	2.75 ± 0.34[a]	7.55 ± 0.92[a]	496.51 ± 22.7[b]	0.015 ± 0.001[a]
3	1625.16 ± 79.54[b]	212.9 ± 7.89[a]	2.33 ± 0.34[a]	8.27 ± 1.35[a]	481.14 ± 22.9[b]	0.017 ± 0.001[a]

Bioaccumulation Sedimentation

There is a clear picture of how metal concentrations build up over time in sediment samples from different locations in Table 6. Station 3 demonstrated the highest bioaccumulation of Fe at 0.007223904 mg/kg while Station 2 exhibited the lowest, measuring 0.007006641 mg/kg. Moving on to Zn, Station 2 displayed the highest bioaccumulation at 0.063691114 mg/kg, with the lowest recorded in Station 1, standing at 0.060607813 mg/kg. Cd showed the highest bioaccumulation in both Stations 2 and 3, with both registering 0.00000062 mg/kg while Station 1 had the lowest at 0.00000058 mg/kg. Station 1 had the greatest degree of Pb bioaccumulation, at 0.0000029 mg/kg, whereas Station 3 indicated the least, measuring 0.00000246 mg/kg. Cu demonstrated its highest bioaccumulation in Station 2 at 0.000427083 mg/kg while Station 3 reported the lowest reading, measuring 0.000412267 mg/kg. For As bioaccumulation, Station 3 had the greatest concentration, measuring 0.00000123 mg/kg while both Stations 1 and 2 shared the lowest at 0.00000058 mg/kg.

Table 6: Bioaccumulation sedimentation

	Heavy Metals (mg/kg)					
Stations	**Fe**	**Zn**	**Cd**	**Pb**	**Cu**	**As**
1	0.00705549	0.060607813	0.00000058	0.0000029	0.000422173	0.00000058
2	0.007006641	0.063691114	0.00000062	0.0000025	0.000427083	0.00000062
3	0.007223904	0.062639986	0.00000062	0.00000246	0.000412267	0.00000123

Discussion

Spatial Variation of Physicochemical Parameters

This study suggested the presence of spatial variations in physicochemical features of surface water between the three stations. The examined physicochemical attributes encompassed salinity, pH, BOD, DO, TDS, and temperature.

Temperature

Temperature plays a crucial role in influencing the metabolic rates of marine organisms (Fitzgibbon *et al.*, 2017). The temperature in Station 2 was significantly higher compared with Station 1 and Station 3. According to Davies and Efekemo (2022), changes in temperature within the aquatic environment could lead to varying effects on its lifeforms. While some may experience an increase in metabolic activity, others may be subjected to stress, particularly those adapted to colder conditions. Therefore, the higher temperature in Station 2 might indicate that certain temperature-sensitive species could be affected, potentially leading to changes in the ecological community (Chris *et al.*, 2023a).

pH

pH is a crucial physicochemical factor that impacts the solubility of different substances and plays a role in the viability and reproductive success of aquatic organisms, as noted by Akankali *et al.* (2023). The pH values observed in Station 1 were notably elevated than those in

Station 2 and Station 3. According to Bhateria and Jain (2016), variations in the optimal pH range for a particular ecosystem could be harmful to aquatic life. Therefore, the lower pH value in Station 2 might indicate that the increased acidity could negatively impact pH-sensitive species (Zhu & Bratlie, 2018). This finding aligned with the observations of Dong *et al.* (2020), which documented alterations in the community structure and morphological adaptations of benthic foraminifera in a microcosm experiment in response to pH fluctuations.

Dissolved Oxygen

The DO levels were highest in Station 1, followed by Station 3, and Station 2 had the lowest concentration. DO is vital for the viability of aquatic organisms, particularly fish, as emphasised by Emeka *et al.* (2020). According to Jaiswal and Pandey (2019), low DO levels could lead to hypoxia, where oxygen-demanding processes exceeded the available oxygen. This could stress or result in the mortality of oxygen-dependent species (Gibbs *et al.*, 2022). The lower DO levels in Station 2 might raise concerns about potential oxygen stress for aquatic organisms in that area.

Electrical Conductivity

EC is a measurement of water's ability to conduct an electrical current and is usually used to evaluate the concentration of dissolved ions or salts (Igwe *et al.*, 2021). Higher EC values typically indicate higher salinity levels. Aquatic organisms have varying degrees of salinity tolerance (Davies *et al.*, 2022) and some species are adapted to thrive in saline environments. High EC can favour the growth of salt-tolerant species.

According to Onyena *et al.* (2021), high salinity could lead to habitat fragmentation, as it restricted the distribution of species that could adapt to lower salinity conditions. The moderate EC value at Station 3 suggested intermediate salinity levels. Aquatic communities in this EC range might include both freshwater and salt-tolerant species, potentially enhancing biodiversity.

Some sensitive species might experience stress due to moderately elevated salinity (Akankali *et al.*, 2023). Station 1 recorded the lowest EC value which signified a relatively low salinity environment and this had distinct ecological implications. However, Chris *et al.* (2023a) suggested that low salinity often indicated better hydrological connectivity with freshwater sources, allowing for species migration and exchange.

Salinity

Station 2 recorded the highest salinity values, followed by Station 3 while Station 1 had the lowest salinity levels. Salinity stands as a significant parameter in aquatic ecosystems, particularly in estuaries and coastal regions, as highlighted by Tian *et al.* (2020). It holds the capacity to influence the distribution and population density of aquatic organisms, as some are better suited to freshwater environments while others thrive in brackish or marine settings, as noted by Lesiv *et al.* (2020). The higher salinity in Station 2 might be attributed to a more brackish environment, affecting the composition of aquatic communities in that area.

Biological Oxygen Demand

According to Abdullahi *et al.* (2021), BOD estimates the amount of oxygen required by bacteria to break down organic compounds in water. Station 2 had the greatest levels of BOD while Station 1 displayed the lowest. Elevated BOD levels are indicative of organic pollution, often stemming from sources like sewage or agricultural run-off, as noted by Akankali *et al.* (2023). According to Davies and Efekemo (2022), elevated BOD levels could deplete the amount of dissolved oxygen in the water, leading to adverse effects on aquatic organisms. The higher BOD in Station 2 suggested a higher organic pollution load, which might pose ecological risks for the aquatic ecosystem (Chris & Anyanwu, 2022).

Total Dissolved Solids

TDS measures all dissolved solids in water, which includes salts and minerals (Butler *et* *al.*, 2018). Station 2 had the greatest TDS while Station 1 had the lowest. Elevated TDS in Station 2 could indicate more minerals or pollution sources, affecting aquatic life (Ustaoğlu, 2021). High TDS levels could have an influence on water quality and vulnerable aquatic species (Agwu *et al.*, 2023). The significant variation in physicochemical parameters between Station 2 and the other two stations suggested that Station 2 might have different ecological conditions and potential risks for aquatic organisms compared to the other two stations (Chris & Anyanwu, 2023). These differences highlighted the importance of careful monitoring and management of the aquatic environment to mitigate potential ecological risks and preserve the health of the ecosystem.

Correlation in Physicochemical Parameters

Analysis of physicochemical parameters revealed correlations in the study area. Temperature and salinity were possibly influenced by evaporation, water circulation patterns or proximity to marine sources (Davies & Ekperusi, 2021). There was a positive relationship between DO and EC, which indicated that a higher EC value could result in more DO (Igwe *et al.,* 2021). Wu *et al.* (2022) suggested that ions and dissolved substances might influence this relationship.

However, the study showed a negative correlation between DO and pH, potentially linked to rising pH values. Davies and Oghenetekevwe (2023) noted that lower DO could impact the aquatic ecosystem's health. DO, salinity, and TDS all had negative associations. This meant that there was less DO in the water that was salty or polluted (Chis *et al.*, 2023a).

Positive correlations were observed between salinity, DO, EC, and TDS, meaning these parameters tended to rise together. High salinity levels, as per Onyena *et al.* (2021) could influence water properties and impact aquatic ecosystems. There was a strong positive relationship between BOD and EC. According to BOD data, this implied that areas with higher conductivity might also have higher levels of organic pollution (Etteieb *et al.*, 2017). According to Igwe *et al.* (2021), this suggested that higher EC might be associated with increased pollution.

TDS and EC were related in a good way, which meant that waters with more TDS might also feature more EC and higher salinity. TDS represented dissolved substance concentrations and could indicate mineral content or the level of pollution in the water.

Spatial Variation of Heavy Metals in Water

Heavy metal concentrations differ among the three sampling stations, indicating spatial flashpoints with varying metal levels. Station 1, which showed consistently higher concentrations of most metals, might be considered a flashpoint for heavy metal contamination (Table 3). However, the variations in metal concentrations between the three stations could offer valuable information about potential sources of pollution. The higher metal concentrations at certain stations could indicate point sources of pollution nearby such as industrial discharge, wastewater outfalls or run-off from contaminated sites (Chris *et al.*, 2023a). As noted by Davies and Ekperusi (2021), even at relatively low concentrations, heavy metals could exert detrimental impacts on aquatic ecosystems and human health. However, stations with elevated metal levels might require closer monitoring and mitigation strategies to protect the environment and public health (Ahmed *et al.*, 2015). Moreover, Akankali *et al.* (2023) stated that variations might also be due to random fluctuations, which could have genuinely meaningful differences.

Spatial Variation of Heavy Metals in Shellfish (T. fuscatus)

The results highlighted the spatial distinction of trace metal levels in *T. fuscatus* samples collected from three different stations. In the study area, heavy metal concentrations varied between the three stations, indicating flashpoints of metal accumulation. Station 1, with consistently higher concentrations of most metals, appeared to be a hotspot for heavy metal accumulation in the sampled shellfish. This result suggested that Station 1 might be subject to higher pollution levels or closer proximity to pollution sources.

The variance in heavy metal levels in fish across different locations could be ascribed to the process of bioaccumulation and trophic transfer. According to Ahmed *et al.* (2019), fish were known to accumulate heavy metals from their environment and these concentrations could increase as they moved up the food chain. Chris *et al.* (2023a) concurred that the higher metal concentrations in fish at specific locations might be related to the availability of contaminated prey or exposure to polluted habitats.

Chris *et al.* (2023b) reported that heavy metals could pose significant health risks to both aquatic organisms and humans. Therefore, the elevated levels of heavy metals detected in *T. fuscatus* might lead to adverse health effects, especially in this region where shellfish is a major part of the local diet. The researchers also stated that the elevated concentrations of metals such as arsenic and lead, in certain fish samples warranted further investigation and risk assessment to ensure public safety.

Heavy metal contamination in fish could entail ecological consequences. It might impair their reproductive success, growth, and overall fitness (Ustaoğlu, 2021). However, Ahmed *et al.* (2019) reported that predatory birds and mammals that feed on these fish could also be affected by the bioaccumulation of heavy metals, expanding the adverse effects beyond the aquatic ecosystem. Furthermore, stations exhibiting elevated metal concentrations might signal the existence of proximate pollution point sources or regions marked by substantial anthropogenic activities (Dan *et al.*, 2022). Analysing discrepancies in heavy metal concentrations across stations might help identify probable pollution sources in the study region.

Spatial Variation of Heavy Metals in Sediment

The study's findings have important implications for monitoring environmental contamination and its potential consequences through the spatial variation in heavy metal concentrations in sediments. Station 1 consistently exhibited the highest levels of Zn, Fe, Cd, Cu, Pb, and As in its sediments, suggesting elevated pollution levels or close proximity to pollution sources. This observation aligned with Ustaoğlu (2021).

Elevated metal concentrations at Station 1 might point to the presence of anthropogenic activities that release heavy metals into the environment as mentioned by Akankali *et al.* (2023). Dan *et al.* (2022) underscored that heightened heavy metal concentrations in sediments could pose environmental risks. As these metals entered the food chain through sediment-dwelling organisms, there was potential for bioaccumulation and biomagnification effects in the aquatic ecosystem and beyond, with adverse repercussions on the overall ecological balance, in line with the observations of Odekina *et al.* (2021).

Station 1, with higher concentrations of various heavy metals, might be considered to have poorer sediment quality compared with Stations 2 and 3. However, Simpson and Batley (2016) confirmed that poor sediment quality could affect benthic communities, sediment-dwelling organisms and overall sediment stability. According to Wu *et al.* (2022), sediments served as a reservoir for heavy metals, and their release into the water column could be influenced by environmental conditions. However, Etteieb *et al.* (2017) stated that heavy metal remobilisation and its influence on water quality should be evaluated by considering the geographical variance of heavy metals in sediments.

Davies *et al.* (2022) further demonstrated the hazardous effects of high levels of copper, cadmium, and lead on benthic creatures and aquatic life. Organisms living in or near sediments with high metal content might experience adverse health effects, reduced reproduction rate and altered community structure (Ahmed *et al.*, 2019). Moreover, Razzak *et al.* (2022) stated that sediment contamination could also affect human health, especially in areas where the sediments had been disturbed or resuspended (e.g., in dredging or construction). According to Ahmed *et al.* (2015), excessive levels of As, Pb, and other heavy metals in sediments could endanger human health if they were discharged into the water and ingested through fish or direct contact.

Bioaccumulation Sedimentation

The results of the investigation into heavy metal concentrations in soil samples from various sites revealed that Fe bioaccumulation values had surpassed 1.0 for all three stations. This suggested that organisms living in the sediment were accumulating iron at a higher rate than eliminating it (Davies & Ekperusi, 2021). Odekina *et al.* (2021) stated that Fe was an important nutrient for many species and that bioaccumulation happens spontaneously. However, extremely high levels of iron bioaccumulation could indicate potential environmental changes or presence of pollution sources (Olayinka-Olagunju *et al.*, 2021).

The bioaccumulation values for Zn were greater than 1.00 in Stations 1 and 2, but less than 1.00 in Station 3. This implied that organisms in Stations 1 and 2 were accumulating more Zn than they were eliminating while in Station 3, Zn was being efficiently eliminated. Elevated bioaccumulation of Zn in Stations 1 and 2 might indicate higher pollution or different environmental conditions affecting its uptake (Chris *et al.*, 2023a). However, the bioaccumulation values for Cd were less than one for all three stations. This suggested that organisms were efficiently eliminating cadmium from their bodies and it was not significantly accumulating in their tissues (Wu *et al.*, 2022). According to Davies and Ekperusi (2021), excessive cadmium bioaccumulation could be toxic to organisms.

The bioaccumulation values for Pb were greater than 1.0 in Station 1 but less than 1.0 in Stations 2 and 3. This indicated that organisms in Station 1 were accumulating lead at a higher rate than they were eliminating it (Razzak *et al.*, 2022) while in Stations 2 and 3, lead was being efficiently eliminated. The higher bioaccumulation in Station 1 might be due to higher lead pollution levels or other environmental factors (Odekina *et al., 2021)*.

For Cu, the bioaccumulation values were greater than one (BCF > 1) in Station 2 but less than one (BCF < 1) in Station 3. This suggested that organisms in Station 2 were accumulating more copper than they were eliminating while in Station 3, copper was being efficiently eliminated. The higher copper bioaccumulation in Station 2 might be related to local copper sources or specific environmental conditions. However, the bioaccumulation values for As were greater than 1.0 in Station 3, but less than one in Stations 1 and 2. This implied that organisms in Station 3 could be accumulating more arsenic than they were eliminating while in Stations 1 and 2, As was being efficiently eliminated. The higher bioaccumulation in Station 3 could be attributed to localised pollution sources or unique ecological conditions (Collin *et al.*, 2022).

The values greater than 1.0 suggested that certain metals might be accumulating in the food web and raising concerns for ecological health and potential risks to human health, especially if these organisms are part of the human diet (Wu *et al.*, 2022). On the other hand, Razzak *et al.* (2022) stated that bioaccumulation values of less than 1.0 indicated efficient elimination of metals, which was generally favourable from an environmental and human health perspective (Odekina *et al.,* 2021*)*. This suggested that the differences in bioaccumulation values among stations could help identify potential pollution hotspots and guide management efforts to mitigate heavy metal contamination.

The study showed that Station 3 consistently exhibited the highest bioaccumulation of the studied metals (Pb, Fe, Cd, Cu, Zn, and As). This was an indication that the area around Station 3 might be a critical location for further investigation, as it appeared s to be particularly susceptible to heavy metal bioaccumulation.

Conclusions

The investigation of heavy metal concentrations in water, soil, fish, and bioaccumulation values in Atuka Creek in the Niger Delta in Nigeria has unveiled possible environmental health concerns and their potential repercussions on aquatic ecosystems and human well-being. These results underscored the necessity for ongoing monitoring and implementation of effective management tactics to tackle pollution, diminish pollutant inputs, enhance treatment methodologies, and rehabilitate the affected regions.

Acknowledgement

The study was supported by the Department of Higher Education, Ministry of Higher Education Malaysia, under the LRGS programme (LRGS/1/2020/UMT/01/1; LRGS UMT Vot No. 56040) entitled "Charting the effects of climate change and acidification through marine organisms' physiological response".

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References

Agwu, E. J., Odanwu, S. E., Ezewudo, B. I., Odo, G. E., Nzei, J. I., Iheanacho, S. C., & Islam, M. S. (2023). Assessment of water quality status using heavy metal pollution indices: A case from Eha-Amufu catchment area of Ebonyi River, Nigeria. *Acta Ecologica Sinica*, *43*(6), 989-1000. https://doi.org/10.1016/j.chnaes.2023.02.003

Ahmed, A. S., Sultana, S., Habib, A., Ullah, H., Musa, N., Hossain, M. B. & Sarker, M. S. I. (2019). Bioaccumulation of heavy metals in some commercially important fishes from a tropical river estuary suggests higher potential health risks in children than adults. PLOS ONE*, 14*(10), e0219336. https://doi.org/10.1371/journal.pone.0219336

Ahmed, M. K., Baki, M. A., Islam, M. S., Kundu, G. K., Habibullah-Al-Mamun, M., Sarkar, S. K., & Hossain, M. M. (2015). Human health risk assessment of heavy metals in tropical fish and shellfish collected from the river Buriganga, Bangladesh. *Environmental Science and Pollution Research International, 22*(20), 15880-15890. https://doi.org/10.1007/s11356-015-4813-z

Akankali J.A., Davies I. C., and Akurokeokiya N.D. (2023). Assessment of the influence of anthropogenic activities on the water quality of Borokiri Section of Bonny River Estuary, Niger Delta, Nigeria. *Journal of Wetland and Waste Management*, *5*(1), 12-17. https://www.researchgate.net/publication/370897671_Assessment_of_the_Influence_of_Anthropogenic_Activities_on_the_Water_Quality_of_the_Borokiri_Section_of_the_Bonny_River_Estuary_Niger_Delta

APHA. (1998). *Standard methods for the examination of water and wastewater* (20th ed.). Washington DC: American Public Health Association.

Bhateria, R., & Jain, D. (2016). Water quality assessment of lake water: A review. *Sustainable Water Resources Management*, *2*(2), 161-173. https://doi.org/10.1007/s40899-015-0014-7

Chris, D. I., & Anyanwu, B. O. (2022). Pollution and potential ecological risk evaluation associated with toxic metals in an impacted mangrove swamp in Niger Delta, Nigeria. *Toxics*, *11*(1), 6. https://doi.org/10.3390/toxics11010006

Chris, D. I., & Anyanwu, E. D. (2023). Biological assessment of anthropogenic impacts in Buguma Creek, Rivers State, Nigeria. *Omni-Akuatika*, *19*(1), 47-60. http://dx.doi.org/10.20884/1.oa.2023.19.1.1004

Chris, D. I., & Ogehenetekevwe, E. (2023). Impact of artisanal crude oil refining effluents on interstitial water at a mangrove wetland, Asari-Toru axis of Sombreiro River, Rivers State. *International Journal of Environment and Geoinformatics*, *10*(2), 12-23. https://doi.org/10.30897/ijegeo.1132992

Chris, D. I., Wokeh, O. K., Lananan, F., & Azra, M. N. (2023a). 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. https://doi.org/10.15244/pjoes/166594

Chris, D. I., Onyena, A. P., & Sam, K. (2023b). 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 International, 30*(33), 80055-80069. https://doi.org/10.1007/s11356-023-27932-z

Collin, S., Baskar, A., Geevarghese, D. M., Ali, M. N. V. S., Bahubali, P., Choudhary, R., Lvov, V., Tovar, G. I., Senatov, F., Koppala, S., & Swamiappan, S. (2022). Bioaccumulation of lead (Pb) and its effects in plants: A review. *Journal of Hazardous Materials Letters*, *3*, 100064. https://doi.org/10.1016/j.hazl.2022.100064

Dan, S. F., Udoh, E. C., & Wang, Q. (2022). Contamination and ecological risk assessment of heavy metals, and relationship with organic matter sources in surface sediments of the Cross River Estuary and nearshore areas. *Journal of Hazardous Materials*, *438*, 129531. https://doi.org/10.1016/j.jhazmat.2022.129531

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. https://doi.org/10.17216/LimnoFish. 816030

Davies, I. C., Odekina, U. M., & Akoko, S. (2022). Distribution of toxic metals in biota, sediments and water from a polluted mangrove swamp in Rivers State. *Journal of Geography, Environment and Earth Science International*, *26*(4), 1-14. https://doi.org/10.9734/jgeesi/2022/v26i430343

Dodds, W. K., Bruckerhoff, L., Batzer, D., Schechner, A., Pennock, C., Renner, E., Tromboni, F., Bigham, K., & Grieger, S. (2019). The freshwater biome gradient framework: Predicting macroscale properties based on latitude, altitude, and precipitation. *Ecosphere*, *10*(7), e02786. https://doi.org/10.1002/ecs2.2786

Dong, S., Lei, Y., Li, T., & Jian, Z. (2020). Response of benthic foraminifera to pH changes: Community structure and morphological transformation studies from a microcosm experiment. *Marine Micropaleontology*, *156*, 101819. https://doi.org/10.1016/j.marmicro.2019.101819

Emeka, C., Nweke, B., Osere, J., & Ihunwo, C. K. (2020). Water Quality Index for the Assessment of Selected Borehole Water Quality in Rivers State. *European Journal of Environment and Earth Sciences*, *1*(6), 1-4. https://www.ej-geo.org/index.php/ejgeo/article/view/101/53

Etteieb, S., Cherif, S., & Tarhouni, J. (2017). Hydrochemical assessment of water quality for irrigation: A case study of the Medjerda River in Tunisia. *Applied Water Science*, *7*, 469-480. https://doi.org/10.1007/s13201-015-0265-3

Fitzgibbon, Q. P., Simon, C. J., Smith, G. G., Carter, C. G., & Battaglene, S. C. (2017). Temperature dependent growth, feeding, nutritional condition and aerobic metabolism of juvenile spiny lobster, Sagmariasus verreauxi. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *207*, 13-20. https://doi.org/10.1016/j.cbpa.2017.02.003

Franklin, P. A. (2014). Dissolved oxygen criteria for freshwater fish in New Zealand: A revised approach. *New Zealand Journal of Marine and Freshwater Research, 48*(1), 112-126. https://doi.org/10.1080/00288330.2013.827123

Gibbs, M. S., Wallace, T., & Mosley, L. M. (2022). Constraining organic matter composition and dynamics as a dominant driver of hypoxic blackwater risk during river Murray floodplain inundation. *Hydrological Processes*, *36*(3), e14529. https://doi.org/10.1002/hyp.14529

Greenberg, A. E. (1992). *Standard methods for the examination of water and wastewater* (18th ed.). Amer Public Health Association.

Ibekwe, A. M., Ors, S., Ferreira, J. F., Liu, X., & Suarez, D. L. (2017). Seasonal induced changes in spinach rhizosphere microbial community structure with varying salinity and drought. *Science of the Total Environment*, *579*, 1485-1495. https://doi.org/10.1016/j.scitotenv.2016.11.151

Ighariemu, V., Wegwu, M. O., & Chuku, L. C. (2023). Evaluation of heavy metals and health risk assessment of shellfish contaminated in Santa Barbara River, Niger Delta, Nigeria. *Current Research in Interdisciplinary Studies*, *2*(1), 1-20. https://www.jpub.org/journal-admin/uploads/articles/cris211.pdf

Igwe, O., Ngwoke, M., Ukah, B. U., & Ubido, O. E. (2021). Assessment of the physicochemical qualities of groundwater and soils around oil-producing communities in Afam, area of Port Harcourt, Niger Delta Nigeria. *Applied Water Science*, *11*(4), 1-13. https://doi.org/10.1007/s13201-021-01393-6

Jaiswal, D., & Pandey, J. (2019). Anthropogenically enhanced sediment oxygen demand creates mosaic of oxygen deficient zones in the Ganga River: Implications for river health. *Ecotoxicology and Environmental Safety*, *171*, 709-720. https://doi.org/10.1016/j.ecoenv.2019.01.039

Lesiv, M. S., Polishchuk, A. I., & Antonyak, H. L. (2020). Aquatic macrophytes: Ecological features and functions. *Studia Biologica*, *14*(2), 79-94. https://doi.org/10.30970/sbi.1402.619

Lv, M., Luan, X., Liao, C., Wang, D., Liu, D., Zhang, G., Jiang, G., & Chen, L. (2020). Human impacts on polycyclic aromatic hydrocarbon distribution in Chinese intertidal zones. *Nature Sustainability*, *3*(10), 878-884. https://doi.org/10.1038/s41893-020-0565-y

Odekina, M. U., Davies, I. C., Akoko S., & Vincent-Akpu I. F. (2021). Bioaccumulation of heavy metals in *Periophthalmus papillio*, sediment and interstitial water from Isaka-Bundu Waterfront in Rivers State. *Academic Journal of Current Research, 8*(11), 19-38. https://www.cirdjournal.com/index.php/ajcr/article/view/604

Olayinka-Olagunju, J. O., Dosumu, A. A., & Olatunji-Ojo, A. M. (2021). Bioaccumulation of heavy metals in pelagic and benthic fishes of Ogbese River, Ondo State, South-Western Nigeria. *Water, Air, & Soil Pollution*, *232*, 1-19. https://doi.org/10.1007/s11270-021-04987-7

Ondrasek, G., & Rengel, Z. (2021). Environmental salinization processes: Detection, implications & solutions. *Science of the Total Environment*, *754*, 142432. https://doi.org/10.1016/j.scitotenv.2020.142432

Onyena, A. P., Nkwoji, J. A., & Chukwu, L. O. (2021). Evaluation of hydrochemistry and benthic macroinvertebrates in Chanomi Creek, Niger Delta Nigeria. *Regional Studies in Marine Science*, *46*, 101907. https://doi.org/10.1016/j.rsma.2021.101907

Rahman, M., Penny, G., Mondal, Zaman, M., Kryston, A., Salehin, M., Nahar, Q., Islam, Bolster, D., Tank, J., & Müller, M. (2019). Salinization in large river deltas: Drivers, impacts and socio-hydrological feedbacks. *Water Security*, *6*, 100024. https://doi.org/10.1016/j.wasec.2019.100024

Razzak, S. A., Farooque, M. O., Alsheikh, Z., Alsheikhmohamad, L., Alkuroud, D., Alfayez, A., Hossain, S. M. Z., & Hossain, M. M. (2022). A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater. *Environmental Advances*, *7*, 100168. https://doi.org/10.1016/j.envadv.2022.100168

Sarker, A., Kim, J., Islam, A. R. M. T., Bilal, M., Rakib, M. R. J., Nandi, R., Rahman, M. M., & Islam, T. (2022). Heavy metals contamination and associated health risks in food webs—A review focuses on food safety and environmental sustainability in Bangladesh. *Environmental Science and Pollution Research*, *29*(3), 3230-3245. https://doi.org/10.1007/s11356-021-17153-7

Sih, A., Cote, J., Evans, M., Fogarty, S., & Pruitt, J. (2012). Ecological implications of behavioural syndromes. *Ecology Letters*, *15*(3), 278-289. https://doi.org/10.1111/j.1461-0248.2011.01731.x

Simpson, S., & Batley, G. (2016). *Sediment quality assessment: A practical guide* (2nd ed.). Clayton, Australia: CSIRO Publishing.

Tian, K., Wu, Q., Liu, P., Hu, W., Huang, B., Shi, B., Zhou, Y., Kwon, B., Choi, K., Ryu, J., Khim, J. S., & Wang, T. (2020). Ecological risk assessment of heavy metals in sediments and water from the coastal areas of the Bohai Sea and the Yellow Sea. *Environment International*, *136*, 105512. https://doi.org/10.1016/j.envint.2020.105512

Ustaoğlu, F. (2021). Ecotoxicological risk assessment and source identification of heavy metals in the surface sediments of Çömlekci stream, Giresun, Turkey. *Environmental Forensics*, *22*(1-2), 130-142. https://doi.org/10.1080/15275922.2020.1806148

Wu, G., Zhuang, D., Chew, K. W., Ling, T. C., Khoo, K. S., Van Quyen, D., Feng, S., & Show, P. L. (2022). Current status and future trends in removal, control, and mitigation of algae food safety risks for human consumption. *Molecules*, *27*(19), 6633. https://doi.org/10.3390/molecules27196633

Zhu, L., & Bratlie, K. M. (2018). pH sensitive methacrylated chitosan hydrogels with tunable physical and chemical properties. *Biochemical Engineering Journal, 132,* 38-46. https://doi.org/10.1016/j.bej.2017.12.012