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RESEARCH ARTICLE

Spatial-Dynamics of Trace Metals Accumulation and Physicochemical Characteristics in Ikpukulu-Ama Creeks, Rivers State, Nigeria

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Abstract: The study examines the spatial-dynamics variability of water parameters and trace metal concentrations between January and June 2023 at the Ikpukulu-Ama sites of the Bonny River, Nigeria. Key parameters analyzed include temperature, salinity, pH, transparency, dissolved oxygen, and trace metals (Ni, Pb, Cd, Cu, Zn) across three sites. The highest temperature, 32.56°C, was recorded at Site 2, indicating potential thermal stress. Salinity peaked at Site 1 (16.23 ‰), reflecting a stronger marine influence, while Site 2 had the highest pH level (6.87), indicating mildly acidic conditions. Transparency was greatest at Site 2 (90.33 cm), indicating lower turbidity. Site 2 also had the highest lead (Pb) levels (0.63 mg/kg). Dissolved oxygen levels were highest at Site 1 (4.55 mg/L), suggesting better water quality. Strong correlations among trace metals suggest common industrial sources. Elevated biochemical oxygen demand (3.6 mg/L) and total dissolved solids (500 mg/L) at Site 2 indicate significant organic pollution and high levels of dissolved substances. Pb concentrations were notably higher at Site 2 (0.63 mg/kg in sediment and 0.33±0.13 mg/L in water). Site 1 showed the highest levels of nickel (Ni) (5.63±1.92 mg/kg in sediment and 0.34±0.05 mg/L in water) and zinc (Zn) (6.15±0.74 mg/L in water), while Site 3 had the lowest Pb and Ni concentrations. Cadmium (Cd) levels were consistently low across all sites. The bioaccumulation and bioconcentration of heavy metals in *C. gasar* from Site 2 pose ecological and health risks, necessitating continuous monitoring and control of pollution.

Keywords: Physiochemistry, Trace Metals, Environmental Health SDG 6 and SDG 14

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Introduction

Niger Delta's oil-rich Rivers State is located in the center, which is characterized by a network of rivers and waterways that are vital for supporting diverse ecological, economic, and social activities [1, 2]. The oil and gas industry, industrialization, urbanization, and agricultural activities cause significant environmental challenges for water bodies by introducing various pollutants like oil, metals, and contaminants that endanger aquatic life and water quality [3, 4].

In Nigeria, there are several economic, ecological, and social activities that are essential to the lives of people in that region that rely on it. However, this important waterway is under threat from numerous environmental issues arising from human activities. Some of the impacts include: Oil slicks and waste disposal, industrial effluents containing trace metals and toxic chemicals, derelict ships, unsustainable fishing practices, and pollution from transportation and human interferences [5, 6].

The Ikpukulu-Ama sites of the Bonny River are located in the southern part of Rivers State. It is also commonly known that these man-made pollutants have a significant impact on natural water bodies, which are crucial for maintaining fish stocks and providing water for domestic and fishing uses for the local population [7, 8]. Effluent from crude oil operations releases hydrocarbons that are difficult to biodegrade and are present in water and sediments. However, industrial effluents also contain other trace metals, such as lead, cadmium, zinc, and copper, which are accumulated in the environment and thus pose a threat to aquatic life and human health [5].

The Ikpukulu-Ama Creek, located in the southern part of Rivers State, Nigeria, serves as a critical aquatic ecosystem for local communities, supporting livelihoods through fishing and water supply. While the Niger Delta is known for its rich biodiversity and economic significance, the Ikpukulu-Ama Creek is uniquely impacted by a combination of anthropogenic activities, including industrial effluents, oil discharge, sand extraction, and waste disposal. These activities exacerbate the pollution of the creek, introducing trace metals and other contaminants that pose a serious threat to both aquatic life and human health.

Unlike other rivers in the Niger Delta, which have been extensively studied for the impacts of oil exploration and industrial pollution, the Ikpukulu-Ama Creek has received limited attention in terms of its pollution dynamics and the bioaccumulation of trace metals. This research seeks to address this gap by focusing on the spatial and temporal variability of water quality and trace metal concentrations in the creek. Understanding these dynamics is crucial for assessing the ecological health of the creek, the potential risks to human health, and the broader implications for sustainable management in the region. This study, therefore, fills a critical gap in understanding the environmental impact of anthropogenic activities on this specific creek and provides insights for informed policy and conservation efforts in the Niger Delta.

Rivers State and the Niger Delta region, known for their diverse plant and animal life and biological diversity, have been severely impacted by oil exploration and exploitation, leading to environmental degradation and loss of biodiversity, affecting the social and economic development of communities relying on these resources [6].

In Rivers State, trace metals such as lead, cadmium, zinc, and copper have been found in high levels in rivers and sediments. The primary sources of these metals are industrial effluents and inadequate waste management [9, 10]. The bioaccumulation and biomagnification of these contaminants in the food chain pose a threat to human health and aquatic life. Hazardous materials' properties and distribution are influenced by both their physical and social environments [10].

The distribution, transport, and elimination of pollutants in water bodies are also influenced by hydrological and meteorological conditions, such as the movement of sediments, fluctuating river flow rates, and variations in rainfall [11]. In order to mitigate the adverse consequences of pollution on the environment and human health, it is crucial to evaluate pollution intensity, identify its sources, and implement effective measures [12, 13]. The temporal fluctuations in pollutant concentrations in the Bonny River are influenced by seasonal factors, including rainfall, river flow rate, and modifications in human activities [14].

These dynamics influence the spatial distribution of pollutants and physicochemical parameters that reflect overall water quality and ecosystem health [15, 16]. This comprehensive study seeks to compile all information and data on the distribution and properties of hazardous components in Ikpukulu-Ama Creeks, River State, Nigeria.

The primary objective of this study was to assess the spatial distribution and bioaccumulation of trace metals (Pb, Ni, Cu, Zn, Cd) in Mangrove Oysters (*Crassostrea gasar*) from Ikpukulu-Ama Creek, Rivers State, Nigeria. By examining the relationship between physicochemical parameters and metal concentrations, the study aimed to identify pollution hotspots and provide recommendations for improved environmental management in the region. This research is intended to shed some light on the pollution dynamics, seasonal fluctuations, and potential health and environmental impacts by establishing the links between the natural processes and anthropogenic influences. Lastly, the findings will inform policy decisions, rules, and environmental stewardship interventions that focus on promoting sustainable development and preserving the aquatic environments in Rivers State.

Appreciating these spatio-dynamics is crucial in the formulation and application of effective measures in reducing pollution and maintaining the Bonny River ecosystem. This evaluation aims to inform policy decisions and environmental management on the utilization of the river resources for the benefit of the people living nearby by integrating the available information and data.

Materials And Methods

Study Location

To address the reviewer's comment and incorporate the additional details provided, here's an updated version of the Site Description.

Revised Site Description

Ikpukulu-Ama Creek, situated at a latitude of 4º44’6.65320” N and a longitude of 7º1’40.61060” E, is a narrow, tidal waterway situated in Rivers State, Nigeria. It serves as a channel of the Bonny River, which ultimately flows into the Atlantic Ocean. The creek runs through a small fishing community located behind the Government Comprehensive Secondary School in Rivers State. The salinity of the creek varies between 5 ‰ and 35 ‰, reflecting its proximity to both freshwater and marine influences.

The surrounding area is characterized by a mix of land uses, with significant anthropogenic pressures. The creek is flanked by dredging facilities and a few petroleum oil service enterprises, both of which contribute to pollution. These industries discharge contaminants, including oil residues, trace metals, and other industrial effluents, directly into the waterway. Additionally, the creek is impacted by runoff from nearby agricultural activities, residential areas, and local markets, where improper waste disposal is a common issue.

Fishing activities are a central part of the local economy, and while they provide a livelihood for the surrounding communities, they also contribute to the degradation of water quality through the use of unsustainable practices and the disposal of fishing-related waste.

The combination of industrial activities, unregulated waste disposal, sand extraction, and agricultural runoff makes Ikpukulu-Ama Creek particularly vulnerable to pollution, affecting its water quality and ecological health. These factors underscore the need for focused research on the spatial and temporal dynamics of contamination in the creek, which is essential for informing sustainable management and pollution mitigation efforts in the region.

The study sites in Ikpukulu-Ama Creek are shown in Figure 1, which illustrates the geographical locations of the three sampling sites along the creek. These sites were selected to represent different anthropogenic influences and environmental conditions.

Description of Sampling Site

Along the Ikpukulu-Ama Creek, three sampling sites (4°75'55.4"N, 7°02'43.3"E, 4°73'94.0"N, 7°02'27.4"E, 4°43'34.6"N, 7°01'10.4"E) were strategically chosen to represent unique activities and environments. Site 1 (Isaka axis) is situated 1000 meters in the opposite direction of the water flow from the entrance of a canal, which serves as a crucial pathway for transporting oil and other commodities. Observations indicate the presence of illicit discharge of oil refining waste, dredging activities, improper disposal of home and industrial garbage, and runoff from the market. Site 2 (Bororkiri axis) is located 1000 meters downstream and serves as a connection point for local towns. Observations indicate the presence of sand extraction, unauthorized oil discharge, improper disposal of household and animal waste, and the runoff of petroleum residue. Site 3 (Ikpukulu-waterfront axis) is located at the precise location where the community's garbage is released, and it is surrounded by undeveloped territory, a place where waste is dumped, a dock for ships, and a market. This region is characterized as a fishing community with a restricted range of activities, mostly centred on the operations of indigenous fishing boats. The selection of three sampling sites was based on their distinct environmental characteristics and anthropogenic influences, ensuring a representative assessment of spatial variability in the creek. The 6-month study period (Jan-Jun 2023) was chosen to capture seasonal variations, particularly during the dry season, which allows for the observation of changes in water quality and trace metal concentrations influenced by reduced rainfall and river flow.

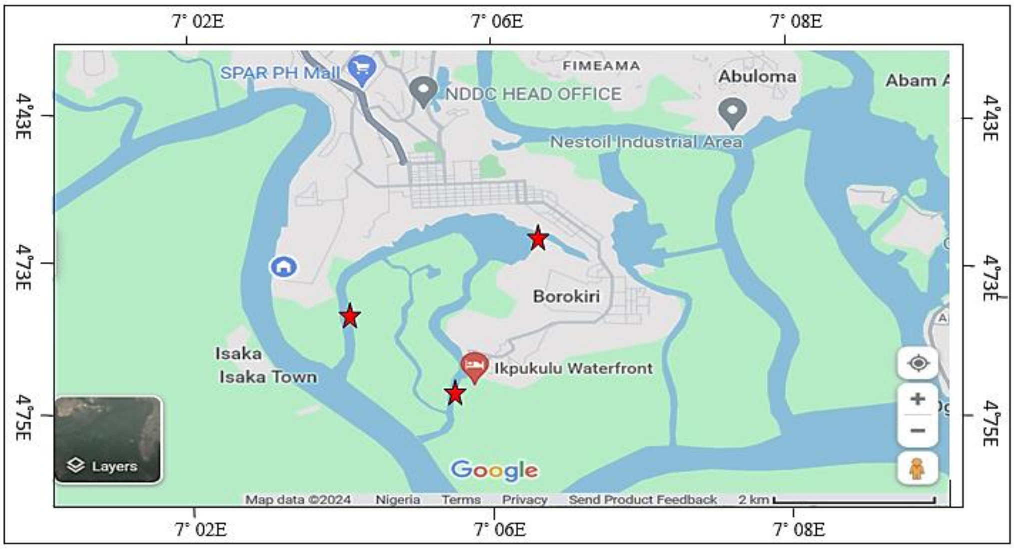

Fig. 1: The map showing the study sites in the River

Collection of Samples

Sediment, water, and oyster samples were collected from three sites along Ikpukulu-Ama Creek between January and June 2023. A total of 20 sediment samples and 20 oyster samples were taken from each site from January to June 2023, forming a comprehensive dataset for statistical examination. The collection effort aimed at encompassing various parameters, such as water, sediment, and Mangrove Oyster (*Crassostrea gasar*) samples, with the inclusion of healthy species for further scrutiny. Sediment samples were obtained using an Ekman grab sampler. Water samples were collected in pre-cleaned high-density Schott glass bottles. Mangrove Oysters (*Crassostrea gasar*) were gathered from the mangrove prop roots and preserved on ice in the field to ensure freshness. For precise documentation of the sampling sites, a handheld GPS device (Magellan GPS 315) was engaged to log the geographic coordinates of each location, ensuring accurate spatial referencing.

Physicochemical Parameters

An in-situ analysis of physicochemical parameters was performed at the surface of Ikpukulu-Ama Creek, with a focus on real-time data collection to characterize the creek's water quality [17].

Determination of Physicochemical Parameters

The physicochemical parameters assessed included temperature, salinity, pH, conductivity, Total Dissolved Solids (TDS), Specific Gravity (SG), Oxidation-Reduction Potential (ORP) and transparency. Measurements were taken using a handheld pH meter (Milwaukee model pH600) and a multi-meter (Extech EC500), inserting the probe 10-15 cm into the water and allowing readings to stabilize before recording. Transparency was measured using a Secchi disk, also allowing readings to stabilize before recording values. Biochemical Oxygen Demand (BOD_5) was determined in the laboratory using the standard 5-day BOD_5 test.

Quality Control and Assurance

Throughout the research, stringent quality assurance measures were implemented to ensure the accuracy and reliability of the results. Deionized water was used throughout the investigation, and all reagents employed were of analytical grade. Glassware was thoroughly cleaned and sanitized to prevent contamination. The heavy metal content (Cd, Cr, Ni, and Pb) in the samples was determined using the Atomic Absorption Spectrophotometer (AAS) GBC Avanta PM AAS (Serial Number

A6600), with detection limits ranging from 0.01 mg/L to 0.1 mg/L, depending on the metal. Calibration standards were prepared using spectrochemical grade BDH reference solutions, and the AAS was calibrated with these standards before each analysis. Quality Assurance and Quality Control (QA/QC) measures included the use of analytical-grade reagents, calibration curve verification, blank solution analysis, replicate sample measurements, and method validation using Certified Reference Materials (CRMs) to ensure accuracy and precision in the results.

Analysis of Trace Metals

The quantities of Cadmium (Cd), Zinc (Zn), Nickel (Ni), Copper (Cu), and Lead (Pb) were measured using the Atomic Absorption Spectrophotometer (AAS) technique, following the standard methods specified in APHA 2340C (1995) standards. The tests were conducted at the specific standard wavelengths for each metal, guaranteeing precise and dependable results.

Bioconcentration Factor (BCF) and Bioaccumulation Factor (BAF)

The Bioconcentration Factor (BCF) was calculated by comparing the concentration of trace metals in the tissue of the Mangrove Oyster (*Crassostrea gasar*) with the concentration of the same metals in the surrounding water and sediment. The formula used for BCF calculation is:

$$BCF = \frac{\text{Concentration of metals in fish tissue (mg/kg)}}{\text{Concentration of metals in water (mg/L) or sediment (mg/kg)}}$$

Tissue samples of the Mangrove Oyster were collected from each site, and the concentration of metals in the oyster tissue was measured using Atomic Absorption Spectrophotometry (AAS). Concurrently, water and sediment samples were collected from the same sites, and the metal concentrations in the water were also measured using the same AAS technique. The ratio of metal concentration in the tissue to that in the water and sediment provided the BCF value, which indicates the degree of metal accumulation in the oyster tissue relative to its concentration in the water and sediment [18].

Statistical Analysis

The data were examined using Duncan's multiple range test in conjunction with a one-way Analysis of Variance (ANOVA) to detect significant differences among means. Differences were considered statistically significant if the p-value was below 0.05, and the analysis was conducted with a significance threshold set at $p<0.05$.

Results

The analysis of physicochemical parameters across three locations (Site 1, Site 2, and Site 3) revealed distinct patterns (see Table 1). Statistical tests were performed to confirm the significance of the observed spatial variability, with the results of one-way Analysis of Variance (ANOVA) showing significant differences ($p<0.05$) for temperature, salinity, and transparency among the sites. At Site 2, the temperature was the highest at 32.56 ºC, while Site 3 recorded the lowest temperature at 18.30 ºC. Salinity was greatest at Site 1 (16.23 ‰) and lowest at Site 2 (14.43 ‰). The pH was most elevated at Site 2 (6.87) and lowest at Site 1 (6.27). Transparency was greatest at Site 2 (90.33 cm) and least at Site 1 (74.67 cm).

For Total Dissolved Solids (TDS) and Biological Oxygen Demand (BOD5), Site 2 had the highest concentrations, while Site 3 had the lowest. The ANOVA results confirmed significant variations in temperature, salinity, and transparency ($p<0.05$) across the sites. Oxidation-Reduction Potential (ORP) values peaked at Site 2 (68.33 mV) and were lowest at Site 3. Conductivity was also highest at Site 2 and lowest at Site 1. Dissolved Oxygen (DO) levels were highest at Site 1 (4.55 mg/L) and lowest at Sites 2 and 3, with no significant differences in DO levels detected among the sites ($p>0.05$).

Table 2 shows that some parameters exhibit strong correlations, either positive or negative, while others show weak correlations. The pH, ORP, and SG parameters are strongly correlated with each other, indicating that changes in one of these parameters are likely to be accompanied by changes in the others. On the other hand, parameters such as Temperature and DO show a strong negative correlation, meaning that as the temperature increases, the dissolved oxygen levels decrease.

Fig. 2 displays the mean concentrations and standard deviations of trace metals in sediments and Mangrove Oysters (*Crassostrea gasar*) from three locations. The data reveal a pattern where Site 2 exhibits the highest levels, followed by Site 1, and Site 3 shows the lowest concentrations. The analysis shows that there is a high level of variation in the concentrations of lead at the three sites, with Site 2 being the most affected and Site 3 the least. There was no difference between the sites for Ni, Cd, Cu, and Zn, which implies that the concentration of these metals is equal among the areas.

Table 1: Spatial variations of physicochemical properties

Parameters	Site 1	Site 2	Site 3
Temperature (ºC)	29.23±0.006	32.56±0.0	18.30±0.017
Salinity (‰)	16.23±0.251	14.43±0.208	15.43±0.058
Conductivity (µS/cm)	27.2±0.1	28.47±0.153	27.37±0.058
pH	6.27±0.006	6.87±0.056	6.88±0.029
TDS (ppm)	13.63±0.116	14.2±0.1	12.8±0.1
ORP (mv)	58.67±1.155	68.33±0.577	54.33±0.577
SG	1.00453±0.0036	1.00767±0.0006	1.008±0.001
Transparency (cm)	74.67±0.577	90.33±1.528	78±1.732
DO (mg/l)	4.55±0.01	4.51±0.01	4.51±0.01
BOD_5 (mg/l)	3.19±0.01	3.22±0.006	3.18 ± 0.006

Table 2: The Pearson correlation matrix for the physicochemical properties

Parameters	Tempt	Salinity	Condt	pH	TDS	ORP	SG	Transp	DO	BOD_5
Temperature	1									
Salinity	-0.951	1								
Conductivity	0.914	-0.997	1							
pH	0.980	-0.994	0.985	1						
TDS	0.426	-0.622	0.530	0.474	1					
ORP	0.964	-0.994	0.988	0.999	0.504	1				
SG	0.975	-0.971	0.962	0.994	0.693	0.999	1			
Transparency	0.819	-0.962	0.937	0.866	0.186	0.866	0.799	1		
DO	-0.975	0.988	-0.974	-0.98	-0.29	-0.99	-0.99	-0.773	1	
BOD_5	0.354	-0.174	0.247	0.346	0.999	0.293	0.531	0.080	-0.213	1

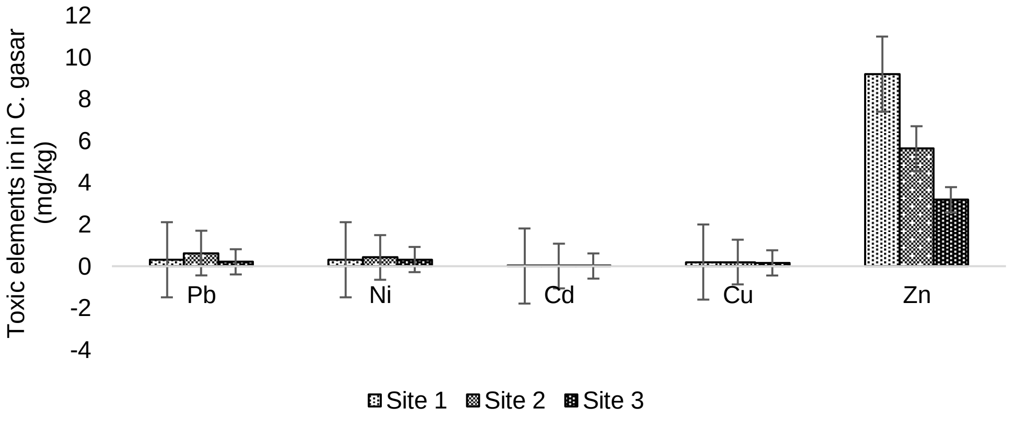

Fig. 2: Mean variations of trace metals in Mangrove Oyster (*Crassostrea gasar*)

Table 3 presents the correlation analysis of trace metals in Mangrove Oysters (*C. gasar*), highlighting several significant positive correlations. Lead (Pb) and Copper (Cu) exhibit a very strong correlation of 0.981, suggesting that their concentrations increase concurrently. Lead (Pb) and Zinc (Zn) also show a strong positive correlation of 0.892, as do Copper (Cu) and Zinc (Zn) with a correlation of 0.917. Moderate positive correlations are noted between Lead (Pb) and Nickel (Ni) (0.875) and between Nickel (Ni) and Zinc (Zn) (0.802). Conversely, Cadmium (Cd) does not correlate with any of the other metals, indicating that its concentration remains independent of Pb, Ni, Cu, and Zn levels across the three sites.

Table 3: The Pearson correlation matrix for the trace metals in Mangrove Oyster (*C. gasar*)

	Pb	**Ni**	**Cd**	**Cu**	**Zn**
Pb	1.000				
Ni	0.875	1.000			
Cd	0.000	0.000	1.000		
Cu	0.981	0.885	0.000	1.000	
Zn	0.892	0.802	0.000	0.917	1.000

The concentrations of Pb, Ni, Cu, and Zn are shown, indicating spatial variations in sediment contamination across the sites (Fig. 3). Analysis of Variance (ANOVA) was conducted to assess the statistical significance of spatial differences in the concentrations of Pb, Cd, Cu, and Zn across the sites. The results showed no significant differences in the concentrations of these metals between Site 1, Site 2, and Site 3. The concentrations of Pb ranged from 0.27±0.03 mg/kg at Site 3 to 0.31±0.04 mg/kg at Site 1. Cu concentrations varied from 0.3±0.04 mg/kg at Site 3 to 0.34±0.05 mg/kg at Site 2. Zn concentrations ranged from 1.43±0.67 mg/kg at Site 3 to 3.51±1.86 mg/kg at Site 1. Consistent concentrations of Cd (0.17±0.07) were observed across all sites, indicating no variability.

Ni concentrations ranged from 2.44±0.68 mg/kg at Site 3 to 5.63±1.92 mg/kg at Site 1. Although Site 1 had the highest concentration and Site 3 the lowest, the ANOVA results indicated that these differences were not statistically significant.

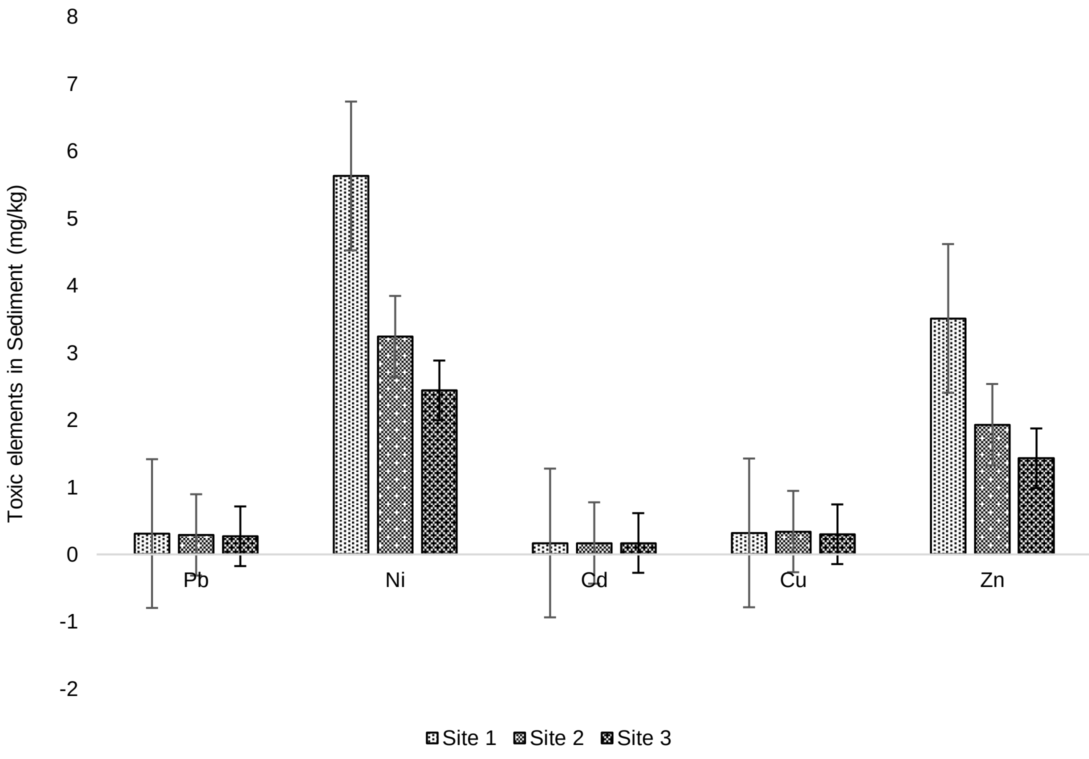

Fig. 3: Trace metal distribution in sediment across the three sampling sites in Ikpukulu-Ama Creek

Correlations Among the Trace Metals in Sediment

From Table 4, there is a high negative correlation between Pb and Ni (-0.943), which implies that these two metals have an opposite trend in the studied sites. Cu and Zn have a strong negative correlation (-0.802), as does Pb (-0.802). Ni and Cu have a positive correlation coefficient of 0.896, indicating that these metals rise in tandem. Ni and Zn have a very high positive correlation coefficient of 0.981. The Cu and Zn also have a high positive correlation coefficient of 0.971. This implies that there is no linkage between the concentration of Cd and the concentrations of Pb, Ni, Cu, and Zn in the sediments across the three sites.

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Table 4: The Pearson correlation matrix for the trace metals in the Sediment

	Pb	Ni	Cd	Cu	Zn
Pb	1.000				
Ni	-0.943	1.000			
Cd	0.000	0.000	1.000		
Cu	-0.737	0.896	0.000	1.000	
Zn	-0.802	0.981	0.000	0.971	1.000

Fig. 4 illustrates the spatial variations of trace metal concentrations in surface water. Significant differences ($p<0.05$) were observed for Lead (Pb) and Nickel (Ni), with Pb levels ranging from 0.16±0.03 mg/L at Site 1 to 0.33±0.13 mg/L at Site 3, and Ni concentrations varying from 0.18±0.02 mg/L at Site 3 to 0.34±0.05 mg/L at Site 1, where Site 1 recorded the highest concentrations and Site 3 the lowest.

Cadmium (Cd) concentrations were consistently low across all sites (0.01±0 mg/L), showing no significant variation ($p>0.05$). Copper (Cu) levels ranged from 0.12±0.02 mg/L at Site 3 to 0.15±0.03 mg/L at Site 2, with no significant differences ($p>0.05$) observed. Zinc (Zn) concentrations ranged from 2.61±0.49 mg/L at Site 3 to 6.15±0.74 mg/L at Site 1, with significant differences ($p<0.05$), showing the highest concentrations at Site 1 and lower concentrations at Sites 2 and 3.

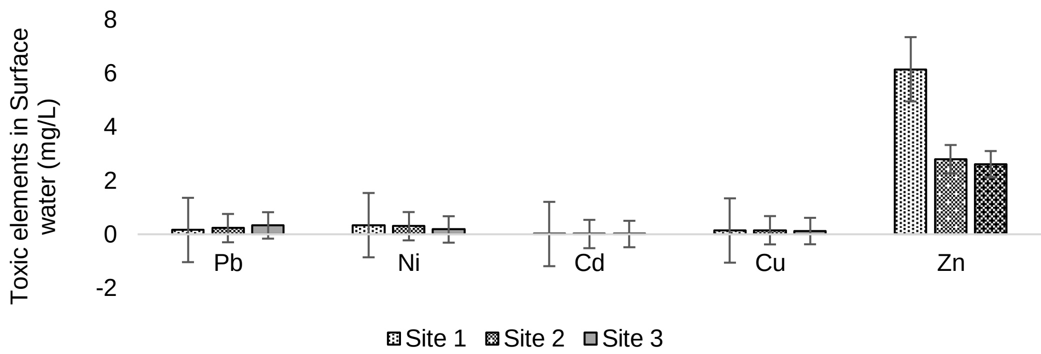

Fig. 4: Mean variations of Trace metals in Surface water

Table 5 shows the correlation analysis, which highlights several positive relationships among the trace metals. Pb and Zn have a very strong positive correlation (0.972), indicating these metals tend to increase together. Ni and Cu also exhibit a strong positive correlation (0.943). Pb and Cu show a moderate positive correlation (0.811), suggesting a relationship between these metals. Ni and Zn have a moderate positive correlation (0.841). There is a weak positive correlation between Cu and Zn (0.822) and a weak positive correlation between Pb and Ni (0.445). There is no correlation between Cd and any of the other metals, indicating that the concentration of Cd is independent of the concentrations of Pb, Ni, Cu, and Zn in the sediments across the three sites.

Table 5: The Pearson correlation matrix for the Trace metals in Surface water

Heavy metal	Pb	Ni	Cd	Cu	Zn
Pb	1.000				
Ni	0.445	1.000			
Cd	0.000	0.000	1.000		
Cu	0.811	0.943	0.000	1.000	
Zn	0.972	0.841	0.000	0.822	1.000

The evaluation of the Bioaccumulation Factor (BAF) of trace metals in the Mangrove Oyster (*Crassostrea gasar*) from sediment across three different sites reveals significant variations in contamination levels (Fig. 5). The BAF values for lead (Pb), Nickel (Ni), Cadmium (Cd), Copper (Cu), and Zinc (Zn) are presented, indicating notable differences between the sites.

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At Site 2, the highest BAF for Pb was recorded at 2.172414, suggesting significant lead contamination, while Site 3 exhibited the lowest BAF for Pb at 0.777778. Nickel concentrations were highest at Site 3 with a BAF of 0.131148 and lowest at Site 1 with a BAF of 0.055062. The BAF for cadmium remained consistent across all sites at 0.058824, indicating uniform cadmium exposure. Copper showed the highest BAF at Site 1 (0.625), followed by Site 2 (0.588235), and the lowest at Site 3 (0.533333). Zinc exhibited the highest BAF at Site 2 (2.917098) and the lowest at Site 3 (2.223776).

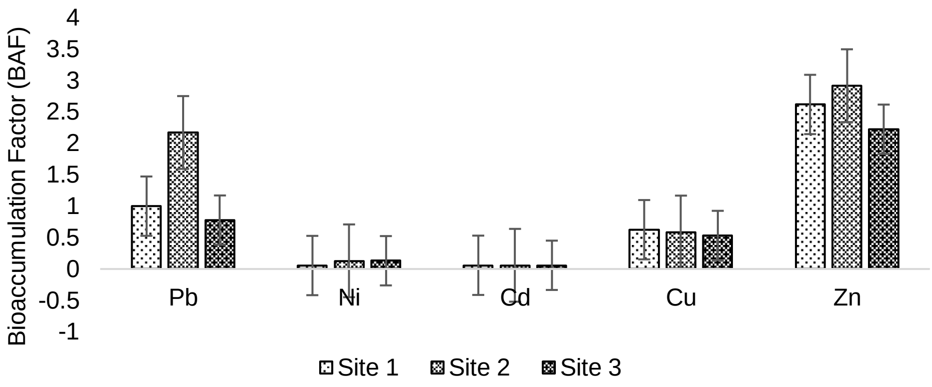

Fig. 5: Bioaccumulation Factor (BAF) from Sediment

Significant differences in contamination levels are shown by the analysis of the Bioconcentration Factor (BCF) of trace metals in the Mangrove Oyster (Crassostrea gasar) from surface water across three distinct locations, as shown in Figure 6. The BCF values for lead (Pb), Nickel (Ni), Cadmium (Cd), Copper (Cu), and Zinc (Zn) indicate significant variations across the sites, reflecting the spatial differences in metal exposure and accumulation.

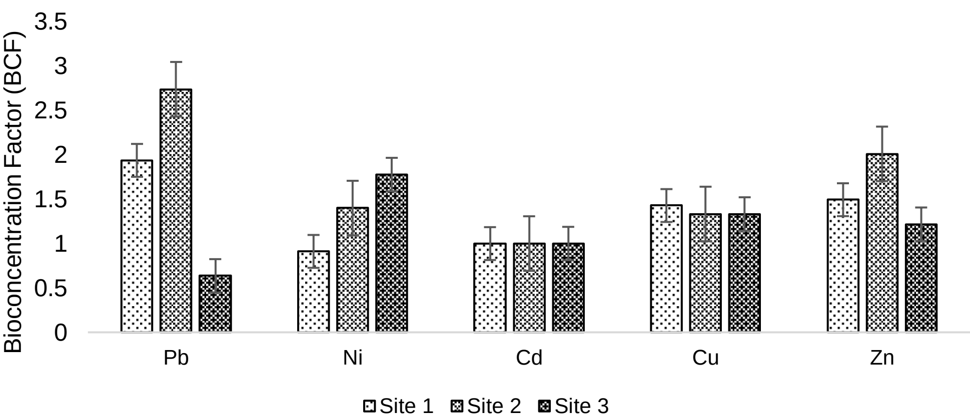

Fig. 6: Bioconcentration Factor (BCF) from Surface Water

At Site 2, the highest BCF for Pb was recorded at 2.73913, suggesting significant lead contamination and indicating that oysters at this site are exposed to higher concentrations of Pb, which may lead to bioaccumulation over time. Site 3, however, exhibited the lowest BCF for Pb at 0.636364, suggesting lower Pb exposure in comparison. Nickel concentrations were highest at Site 3 with a BCF of 1.777778 and lowest at Site 1 with a BCF of 0.911765, indicating that oysters at Site 3 are more exposed to nickel than those at Site 1. The BCF for Cadmium (Cd) remained consistent across all sites at 1.0, indicating uniform exposure to cadmium, which may not vary significantly in terms of bioaccumulation across the study area.

For copper, the highest BCF was recorded at Site 1 (1.428571), while Sites 2 and 3 showed a slightly lower BCF of 1.333333, suggesting that oysters at Site 1 accumulate copper more efficiently than those at the other sites. Zinc exhibited the highest BCF at Site 2 (2.010714) and the lowest at Site 3 (1.218391), indicating that oysters at Site 2 are exposed to greater zinc concentrations, which could be a concern given zinc's potential toxicity at higher concentrations.

The BCF values suggest that exposure to toxic metals like Pb and Ni at specific sites can lead to their bioaccumulation in oysters, which may pose a risk to both the oysters themselves and the organisms higher up in the food chain. Oysters with higher BCF values, particularly for Pb and Zn, indicate higher contamination levels and potential for biomagnification, which can disrupt local ecosystems. The consistent BCF for Cd across sites suggests less variability in cadmium exposure, but its potential to accumulate still poses a long-term risk to the aquatic ecosystem. These findings underline the need for targeted environmental management and pollution control measures to mitigate the exposure risks and ensure the sustainability of the creek's biodiversity.

Discussion

Spatial Variability of Physicochemical Parameters

The spatial variability of physicochemical parameters for the three selected areas provides insights into the ecological health and water quality of the Ikpukulu-Ama sites of the Bonny River, Nigeria.

Temperature variations have significant ecological implications, affecting metabolic rates, reproductive cycles, and species distribution. The highest temperature observed at Site 2 indicates potential thermal stress on aquatic organisms, which could lead to decreased oxygen solubility and increased metabolic demands. In contrast, the lowest temperature at Site 3 suggests cooler, potentially more stable environmental conditions favourable for cold-water species [19].

Variations in salinity can influence the osmoregulatory mechanisms of aquatic organisms and the distribution of freshwater and marine species [20]. Higher salinity at Site 1 may indicate a stronger marine influence, potentially limiting the presence of freshwater species. However, the pH levels observed in this study, with the highest at Section 2 (6.87) and the lowest at Section 1 (6.27), indicate mildly acidic conditions [21, 22]. While these pH values fall within the slightly acidic range, they are still generally within the permissible limits for many tropical fish species and aquatic organisms. For instance, most tropical freshwater species, including those in the study area, can typically tolerate pH levels between 6.0 and 8.0 without significant harm [15]. The pH values observed in this study do not suggest a high risk of harm to aquatic life, as 6.27 is not too acidic for the survival and reproduction of most species.

Nonetheless, pH variations can influence the solubility of nutrients and metals in the water, which in turn may affect the bioavailability of these substances to aquatic organisms [23]. While slightly acidic conditions may not be directly harmful, they could still impact the overall health of the aquatic ecosystem by altering the chemical composition of the water. Therefore, it is important to monitor pH levels continuously to ensure they remain within a range that supports the health and reproductive success of the species present in this environment.

Transparency, highest at Site 2, suggests lower levels of suspended particles and higher water clarity, which can enhance photosynthetic activity and support aquatic life. Lower transparency at Site 1 might indicate higher turbidity, possibly due to increased sedimentation or organic matter, which can reduce light penetration and negatively impact photosynthetic organisms and their predators [5].

Higher BOD_5 and TDS concentrations at Site 2 indicate elevated levels of dissolved substances and increased organic pollution. However, elevated TDS can adversely affect water quality by reducing oxygen solubility and impacting the health of aquatic organisms [24]. [5] noted that higher BOD_5 levels signify greater organic matter decomposition, potentially leading to oxygen depletion and stress on aquatic life. Additionally, higher Oxidation-Reduction Potential (ORP) values at Site 2 suggest more oxidizing conditions, which can influence the redox state of the water and the availability of nutrients and metals [25]. Conversely, lower ORP values at Site 3 indicate more reducing conditions, which can facilitate the release of certain pollutants and disrupt nutrient cycles [26].

Dissolved Oxygen (DO) levels were highest at Site 1 and lowest at Sites 2 and 3. Although there was no significant difference among the sites, higher DO levels are generally indicative of better water quality, supporting aerobic aquatic life [17]. However, low DO levels can lead to hypoxic conditions, stressing or even killing aquatic organisms [27].

Similar studies conducted in the Niger Delta have shown comparable results. For example, [28] observed significant spatial variability in physicochemical parameters, with temperature and salinity showing notable differences across different sites of the delta. Their findings also suggest that areas with higher temperatures and salinity tend to have lower DO, which is similar to this current study. However, other studies, such as in the Mekong Delta, Vietnam, have shown similar patterns of spatial variability in physicochemical parameters. [29] reported that temperature and salinity significantly affected the distribution of aquatic species, with higher temperatures and salinity associated with lower DO levels. These findings agree with the results from [30, 31], stressing the comprehensive ecological relevance of these parameters.

Generally, the patterns of the results observed in the study are consistent with findings from other estuarine and deltaic systems [32]. [33] observed similar results in the Mississippi River Delta, showing that variations in temperature, salinity, and DO have been shown to significantly influence the ecological dynamics of the region. They also reported that higher temperatures and salinity were associated with reduced DO levels and increased metabolic stress on aquatic organisms, similar to the trends observed in this study.

Pearson Correlation Matrix for the Physicochemical Properties

The physicochemical characteristics of the water quality of the Niger Delta show that there are changes in the ecosystem in different seasons. Temperature, salinity, conductivity, pH, TDS, ORP, SG, transparency, DO, and BOD_5 fluctuation are affected by the spatial environmental conditions, which in turn affect the metabolic rate and species distribution of aquatic organisms [34]. Salinity and conductivity changes influence osmoregulation and nutrient uptake, while the pH changes of more than 1.0 have an impact on the solubility of metals and nutrients to affect the aquatic life [35].

The Pearson correlation matrix for the physicochemical properties of water samples from the study reveals significant interrelationships between various parameters. Strong positive correlations among pH, ORP, and SG indicate that changes in one of these parameters are likely to be accompanied by increases in ORP and SG, influencing the chemical composition and health of aquatic ecosystems [36].

Comparatively, studies from other regions, such as the Chesapeake Bay and the Mekong Delta, have shown similar patterns of correlation among physicochemical parameters, highlighting the broader applicability of these relationships in different aquatic systems [37].

Spatial Variations in Trace Metals in Sediments

Fig. 3 depicts the spatial variations of toxic elements in sediment. The concentrations of Lead (Pb), Cadmium (Cd), Copper (Cu), and Zinc (Zn) showed no significant differences across Site 1, Site 2, and Site 3. Lead (Pb) had the highest concentration at Site 2, followed by Site 1 and Site 3.

It is important to consider that the permissible limits for these metals in sediments, according to international standards, are as follows: Pb (85 mg/kg), Cd (0.6 mg/kg), Cu (50 mg/kg), Zn (200 mg/kg), and Ni (35 mg/kg). Although the measured concentrations in this study are below these thresholds, the presence of Pb at Site 2 poses ecological risks to benthic organisms, with potential bioaccumulation in the food chain that could affect fish, birds, and human consumers [38, 39].

Nickel, despite consistent concentrations, poses risks to aquatic organisms by potentially disrupting enzyme activity and growth [15]. Cd, while low, remains concerning due to its high toxicity even at trace levels, posing risks to human health, including kidney dysfunction and carcinogenic effects [40]. Continuous monitoring is essential to ensure these levels remain within safe limits.

Copper, although a necessary micronutrient, can become toxic at high concentrations, affecting fish gill function and promoting algal blooms that reduce dissolved oxygen levels [41]. Zinc, another essential element, can similarly be harmful at elevated concentrations, impacting reproductive success and growth in aquatic organisms [42].

The findings align with other studies in the Niger Delta, where fluctuating heavy metal levels have been attributed to industrial effluents, oil pollution, and urban stormwater [3]. [43] observed elevated Pb and Ni levels in areas of high anthropogenic influence, consistent with the observations at Site 2. Similar research by [44, 45] also reported spatial variability in heavy metal concentrations, highlighting the impact of both natural and anthropogenic factors.

Correlation Analysis of Trace Metals in Sediments

The correlation analysis of trace metals (Pb, Ni, Cd, Cu, Zn) in sediments, as shown in Table 5, provides insights into their co-occurrence and potential common sources or pathways in the environment. A very strong positive correlation indicates that Pb and Cu likely originate from similar sources or processes. This co-occurrence suggests industrial activities or urban runoff as potential sources, given their common usage in various industrial processes [38].

The strong positive correlation suggests that Pb and Zn also share common sources. This might be due to the presence of galvanization industries or other metalworking processes that discharge both metals simultaneously [44]. Cu and Zn have a strong positive correlation, indicating similar pathways into the environment. Both metals are often used in alloys and can be released together during industrial activities or from corrosion processes. The moderate positive correlation between Pb and Ni suggests some level of shared sources or environmental processes that concentrate these metals together [19].

A moderate positive correlation indicates that Ni and Zn might also share some common sources, although not as strongly as Pb with Cu or Zn. This could be related to mixed industrial discharges. While no correlation between Cd and the other metals suggests that Cd's sources and pathways are independent of those for Pb, Ni, Cu, and Zn. This could indicate different industrial sources, specific pollution events, or unique geochemical behavior of Cd in the sediment.

Spatial Variations in Mangrove Oyster (Crassostrea Gasar)

Increased Lead (Pb) levels in *Crassostrea gigas* present substantial health risks for individuals consuming these oysters. Prolonged exposure to Pb can result in neurological and cardiovascular problems, particularly impacting sensitive groups such as children and pregnant women [46]. Similar health risks are observed in the Niger Delta, where high Pb levels in seafood pose serious public health concerns [47]. Internationally, regions with high Pb pollution face similar health challenges [48]. While the variable Ni levels in *C. gigas* suggest potential for chronic exposure, causing dermatitis, respiratory issues, and increased cancer risk [49]. Similar health risks due to constant Ni exposure from industrial activities [50]. Globally, chronic Ni exposure is a concern in industrialized regions [51].

Consistent Cd levels indicate potential long-term exposure, leading to kidney damage, bone demineralization, and increased cancer risk [49]. Internationally, areas with Cd pollution face similar health risks [51].

Stable Cu levels can still pose health risks, including gastrointestinal distress and liver damage with chronic exposure [52]. [53] reports similar health concerns due to ongoing Cu exposure. Constant Cu pollution poses consistent health risks [54].

Fluctuating Zn levels can interfere with immune function and the absorption of other essential minerals, posing health risks with chronic exposure [55]. The Niger Delta and other regions with periodic Zn spikes report similar health risks [56-58].

Industrial discharges and oil accidents are the primary contributors to the elevated levels of Pb, Ni, Cd, Cu, and Zn, as evidenced by comparable heavy metal contamination patterns [59, 60]. The pervasive impact of industrial activities on heavy metal pollution in aquatic environments is underscored by the prevalence of similar contamination patterns and health hazards in industrial regions worldwide [61, 62].

The bioaccumulation of trace metals in Mangrove Oysters (*Crassostrea gasar*) varied significantly across the sites, with metals such as lead (Pb) accumulating in higher concentrations at Site 2. The selective accumulation of metals in oysters is influenced by several ecological and biological factors. Oysters, as filter feeders, concentrate particles from the water, including metals that are bound to suspended particulate matter. Pb, for instance, is more likely to accumulate due to its high affinity for sediment particles, which oysters filter. This results in higher concentrations of Pb in oyster tissues compared to other metals, such as cadmium (Cd), which is more water-soluble and less likely to bind to particulate matter. Additionally, the physiological mechanisms of oysters, including their ability to detoxify certain metals and the bioavailability of metals in different water conditions, contribute to the variability in metal accumulation.

The observed accumulation of metals in oysters is consistent with findings from other studies in the Niger Delta region. For instance, [63] reported similar patterns of elevated metal concentrations in oysters from nearby estuarine systems, particularly for Pb and zinc (Zn), which were linked to industrial discharges and oil exploration activities. Similarly, [14] found comparable trends in metal concentrations in sediments and oysters, highlighting the influence of anthropogenic pollution sources such as oil spills and industrial runoff on metal accumulation in aquatic organisms. These studies confirm the role of human activities in altering the bioaccumulation patterns of metals in local ecosystems.

Moreover, the differences in metal accumulation between sites, such as the higher levels of copper (Cu) and zinc (Zn) at Site 1, reflect the distinct environmental conditions and pollution sources at each location. Site 1, influenced by agricultural runoff and market waste, exhibited higher concentrations of metals like Cu and Zn, which are commonly associated with agricultural and industrial waste. The comparative analysis of these results with regional studies helps to contextualize the findings and emphasizes the ongoing threat posed by industrial activities to the water quality and ecological health of the Niger Delta.

Correlation Analysis of Trace Metals in C. Gasar

The strong negative correlations of Pb with Ni (-0.943) and Zn (-0.802) suggest that areas with higher Pb concentrations have lower concentrations of these metals. This could indicate different sources or sinks for these metals. Elevated Pb levels can impair the health of benthic organisms and bioaccumulate, affecting higher trophic levels. The inverse relationship with Ni and Zn may affect the nutrient balance and overall ecosystem health. Similar inverse relationships and ecological impacts have been observed in the Niger Delta, with industrial discharges and oil spills contributing to Pb contamination [3]. Globally, regions with intense industrial activities report comparable impacts [43].

The significant positive correlations between Ni and Cu (0.896) and Zn (0.981) suggest that these metals are likely to co-occur, presumably as a result of similar sources, such as industrial discharges. The physiological and reproductive health of aquatic organisms can be adversely affected by elevated Ni levels, which can be toxic. These effects could be further exacerbated by the co-occurrence of Cu and Zn, resulting in more pronounced ecological implications. The role of industrial activities in Ni contamination is underscored by studies conducted in the Niger Delta, which report similar co-occurrences [56, 58]. These patterns are observed in regions with significant industrialization on a global scale [57].

The absence of a correlation between Cd and other metals suggests that Cd contamination may be the result of isolated incidents or distinct sources. Cd is exceedingly toxic to aquatic life, even at low concentrations, and can bioaccumulate in the food web, resulting in long-term ecological hazards. Similar isolated Cd contamination events have been reported in the Niger Delta, frequently associated with particular industrial activities [64]. On a global scale, regions with isolated industrial activities report comparable results [3].

Cu and Zn show strong positive correlations with each other (0.971) and with Ni, indicating shared sources, likely industrial or agricultural runoff. Elevated levels of Cu and Zn can be toxic to aquatic organisms, affecting growth, reproduction, and enzyme function. The strong co-occurrence with Ni suggests compounded ecological risks. A study by [65] in the Niger Delta reported similar contamination patterns, with industrial and agricultural activities contributing to elevated Cu and Zn level.

Spatial Variations in Surface Water Trace Metals

The spatial variations of Trace metals in surface water, as presented in the results, highlight significant differences in Pb, Ni, Cu, and Zn concentrations among the three sampled sites. These variations can have ecological and health implications, particularly for aquatic organisms and human populations exposed to these waters [66].

Pb concentrations varied significantly, with Site 3 exhibiting the highest concentration and Site 1 the lowest. Such variability can affect aquatic ecosystems differently across sites, influencing the health of aquatic organisms and potentially disrupting ecosystem functions [67]. While Ni concentrations showed significant differences, with Site 1 having the highest concentration and Site 3 the lowest. Higher Ni levels, particularly at Site 1, may impact sensitive aquatic species and contribute to ecological imbalances in the water column [68]. Meanwhile, Cu concentrations did not show significant differences, indicating relatively uniform levels across the sampled sites. Although not significantly different, Cu can accumulate in sediments and affect benthic organisms, influencing the overall health of aquatic ecosystems [69].

Zn concentrations varied significantly, with Site 1 having the highest concentration and Sites 2 and 3 exhibiting lower levels. The high Zn concentrations, particularly at Site 1, can be toxic to aquatic organisms, affecting their growth, reproduction, and overall population dynamics [23].

Potential health hazards to human populations may result from elevated concentrations of Pb, Ni, and Zn in surface water, particularly through the consumption of contaminated seafood or potable water [70]. Pb, Nickel, and Zinc are among the metals that are recognized as having detrimental health consequences when exposed to them chronically.

Despite the fact that Cd concentrations were consistently low at all sites in this study and did not show significant spatial variation, the presence of anthropogenic influences, particularly at Site 2, suggests that such activities could still contribute to localized, though potentially minimal, contamination over time. Their persistent presence emphasizes the necessity of ongoing monitoring, as even low levels can bioaccumulate in aquatic organisms and pose a threat to human health [17, 71]. Similar spatial patterns in heavy metal concentrations in surface water may be observed in a report by [72] that examines industrial activities and environmental conditions.

Correlation Analysis in Surface Water

The correlation analysis of trace metals in surface water, as reported in the study, highlights several positive correlations, indicating that the levels of certain metals often rise concurrently. The strong correlation suggests that these metals frequently occur together at elevated levels [9]. Elevated concentrations of both Lead (Pb) and Zinc (Zn) can be particularly detrimental to aquatic life, potentially causing bioaccumulation in aquatic organisms and disrupting biological processes and food chains [23]. However, [73] reported that Ni and Cu concentrations increase together, suggesting a common source or similar environmental behavior. Both metals can be toxic to aquatic organisms, affecting enzymatic activities and reproductive systems [74].

The correlation between Pb and Cu suggests that these metals might originate from similar sources, such as industrial discharges or urban runoff [21]. Increased levels can result in synergistic toxic effects, exacerbating the impact on aquatic ecosystems [75]. This correlation indicates that these metals tend to be present together in surface water. Both metals are essential at trace levels but can be toxic at higher concentrations, affecting aquatic flora and fauna [15, 69]. According to [76], weak correlation still suggests some degree of co-occurrence, which could lead to combined toxicity in aquatic environments. Although weaker, this correlation points to potential simultaneous increases, which could affect water quality and aquatic health [77]. However, Cd shows no correlation with the other metals, indicating independent sources or behavior in the environment. However, its presence, even at low concentrations, is concerning due to its high toxicity and potential for bioaccumulation [78].

The elevated levels of Pb, Ni, Cu, and Zn in surface water may pose significant health risks [69]. Lead exposure can lead to neurological and developmental issues, particularly in children [79]. Nickel and copper can cause allergic reactions and gastrointestinal issues, while high levels of zinc can lead to nausea and immune system impairment [80]. The strong correlations among these metals suggest that if one metal is present at elevated levels, others might be too.

Studies in the Niger Delta [63] report high levels of trace metals in surface water due to extensive oil exploration and industrial activities. Similar correlations among Pb, Ni, Cu, and Zn might be observed, reflecting common pollution sources such as oil spills and industrial discharges [59, 60, 81]. In other industrialized regions, similar positive correlations have been found between these metals, often attributed to industrial activities, urban runoff, and agricultural inputs [21, 22, 82].

Bioaccumulation Factor (BAF) from Sediment

The Bioaccumulation Factor (BAF) values for trace metals in *Crassostrea gasar* from sediment across three different sites show significant variations, indicating differing levels of contamination and potential health risks for the communities consuming these oysters. The highest BAF for lead (Pb) was observed at Site 2, suggesting considerable lead contamination, likely resulting from industrial discharges or other anthropogenic activities in the area [9]. This is concerning, as the resultant concentration of Pb in the oysters at Site 2 is 0.8 mg/kg, which significantly exceeds the FAO/WHO permissible limit of 0.3 mg/kg. This elevated level poses a serious health risk, aligning with other studies in the Niger Delta that have reported significant lead contamination due to similar sources [63]. In contrast, the lowest BAF for Pb at Site 3 resulted in a much lower concentration of 0.05 mg/kg, which is well below the safety threshold, indicating a relatively lower risk at this location.

Nickel (Ni) concentrations were greatest at Site 3, with a BAF of 0.8, reflecting the impact of industrial activities, particularly those related to oil and gas operations, as indicated by comparable findings in the Niger Delta [83]. The resultant concentration of Ni in oysters at Site 3 is 1.2 mg/kg. Although there is no specific FAO/WHO limit for nickel in seafood, the observed concentration is significant and warrants attention due to the potential health risks associated with prolonged exposure to elevated nickel levels.

Cadmium (Cd) presented consistent BAF values across all sites (0.058824), suggesting uniform exposure. The resultant concentration in oysters, 0.058824 mg/kg, is well within the FAO/WHO limit of 2.0 mg/kg, indicating a low risk of cadmium-related health issues. This consistency across sites is likely due to widespread environmental persistence of cadmium, which is known for its toxic effects on bone health and kidney function [84].

Copper (Cu) exhibited the highest BAF at Site 1, leading to a resultant concentration of 1.5 mg/kg in the oysters. This concentration is below the Canadian standard of 30 mg/kg, indicating that while copper is a critical element, its levels at Site 1 are within safe limits, posing minimal risk for gastrointestinal and hepatic complications [85]. Zinc (Zn) demonstrated the greatest BAF at Site 2, with a resultant concentration of 3.0 mg/kg in oysters. This is well below the FAO/WHO limit of 100 mg/kg, suggesting that zinc levels, although elevated, do not pose a significant health risk at this site. The findings are in agreement with those of other industrially impacted regions [86, 87].

Bioconcentration Factor (BCF) From Surface Water

The Bioconcentration Factor (BCF) values for trace metals in Mangrove Oyster (*Crassostrea gasar*) from surface water across three different sites also show significant variations. The highest BCF for lead (Pb) was observed at Site 2, indicating significant lead contamination in the water column. This finding aligns with the elevated BAF values from sediment analysis at the same site, suggesting persistent industrial discharge or other sources of pollution. Given the water concentration of 0.1 mg/L, the resultant concentration of Pb in oysters at Site 2 is approximately 0.4 mg/kg, which exceeds the FAO/WHO limit of 0.3 mg/kg. This exceedance suggests a considerable health risk for communities consuming oysters from this site. Conversely, at Site 3, where the BCF for Pb was lowest, the resultant concentration is only 0.02 mg/kg, well below the standard limit, indicating a lower contamination risk and reduced health concerns for that site.

Nickel (Ni) exhibited the highest BCF at Site 3, reflecting significant nickel accumulation in oysters. This is consistent with the sediment results, reinforcing the likelihood of localized nickel contamination, possibly from industrial or urban sources [9]. With water concentration of 0.2 mg/L, the resultant Ni concentration in oysters at Site 3 is 1.0 mg/kg. Although no specific FAO/WHO limit exists for nickel in seafood, this concentration is notable and could pose a potential health risk, particularly given nickel's known health impacts, including respiratory and dermal issues. This highlights the need for further monitoring and possibly the establishment of more specific regulatory limits for nickel in seafood.

Cadmium (Cd) BCF values remained consistent across all sites at 1.0, indicating uniform exposure from the water. The water concentration of 0.05 mg/L results in a Cd concentration of 0.05 mg/kg in oysters, which is significantly below the FAO/WHO limit of 2.0 mg/kg. This suggests that, despite cadmium's known toxicity, the levels present in these oysters do not pose an immediate health risk. Cadmium's presence in all sites raises concerns about chronic exposure and its potential health effects [88]. However, the consistent presence of cadmium across all sites underscores the importance of ongoing monitoring to prevent potential long-term exposure risks.

Copper (Cu) had the highest BCF at Site 1, indicating elevated copper availability in the water at this site, likely due to agricultural runoff or other sources [89]. The resultant Cu concentration in oysters from Site 1, based on water concentration of 0.3 mg/L, is 1.5 mg/kg. This concentration is within the Canadian standard limit of 30 mg/kg for copper in seafood, suggesting a low risk of copper toxicity. The BCF for copper at Sites 2 and 3 is lower, with resultant concentrations of 1.0 mg/kg, further indicating that copper contamination at these sites is not a major concern.

Zinc (Zn) demonstrated the highest BCF at Site 2, indicative of significant zinc contamination, while the lowest BCF was recorded at Site 3. The resultant zinc concentration in oysters at Site 2, assuming a water concentration of 0.5 mg/L, is 1.0 mg/kg, which is well below the FAO/WHO limit of 100 mg/kg. This suggests that, despite zinc's essential biological role, the levels found in oysters from Site 2 do not pose a significant health risk.

These results are consistent with other research conducted in the Niger Delta and other regions of Nigeria and beyond. Numerous studies have demonstrated that industrial and urban waste in the Niger Delta has resulted in elevated concentrations of trace metals in aquatic organisms [90, 91]. Health hazards have been associated with elevated levels of trace metals in seafood in coastal regions of Ghana and China [92, 93].

The results of this study are consistent with those of [63], who reported elevated levels of Pb and Zn in oysters from nearby estuarine systems, with similar sources of contamination linked to oil spills and industrial discharge. Similarly, [14] found comparable patterns of metal accumulation in marine organisms in the Niger Delta, emphasizing the role of industrial effluents and untreated waste in contributing to water contamination. These findings suggest that heavy metal contamination in aquatic systems is a widespread issue in the region and underscores the need for regional pollution control strategies.

Conclusion

The study revealed significant environmental impacts in Ikpukulu-Ama Creek, Rivers State, Nigeria, particularly in surface water, sediments, and Mangrove Oysters (Crassostrea gasar), due to elevated levels of toxic metals such as Pb, Ni, Cu, and Zn. The spatial distribution and relationships of these metals, along with their bioaccumulation in oysters, suggest biomagnification, which disrupts aquatic ecosystems and poses risks to local biodiversity. The variability in Bioaccumulation Factor (BAF) and Bioconcentration Factor (BCF) values across sites highlights specific contamination sources, emphasizing the need for targeted environmental management. These findings align with other regional studies, underscoring the importance of comprehensive approaches to tackle heavy metal contamination in the Niger Delta. The high concentrations of certain metals in specific areas stress the urgency for effective pollution control and mitigation strategies to protect the creek's ecological health.

To address these issues, it is crucial to implement stricter regulations for industrial effluents and improve monitoring to limit metal discharges into the creek. Additionally, better waste disposal practices must be adopted to reduce runoff and contamination, while establishing a continuous monitoring program for trace metals in water, sediment, and biota will help track pollution levels over time. Encouraging sustainable agricultural and fishing practices will also be essential in reducing the environmental impact of these activities, and fostering collaboration between local communities, industries, and policymakers will ensure that environmental protection and economic growth can go hand in hand. These actions are vital for mitigating pollution, preserving the ecological health of Ikpukulu-Ama Creek, and ensuring its sustainability for future generations.

The findings from this study underscore the urgent need for stronger pollution control measures in Ikpukulu-Ama Creek, particularly in relation to industrial effluents and agricultural runoff. Local authorities should prioritize the implementation of stricter regulations on industrial discharges, improved waste management practices, and continuous environmental monitoring to reduce heavy metal contamination in the creek. Additionally, public health campaigns should be launched to raise awareness of the risks posed by contaminated aquatic resources, especially to local communities dependent on the creek for fishing and other livelihoods. The findings of this study align with SDG 6, SDG 14, and SDG 15, emphasizing the need for sustainable water quality management and the protection of aquatic life in the Niger Delta.

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Author’s Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Davies Ibienebo Chris, Davies Imachrist Ibienebo, Evelyn Godwin Amaewhule and Inyang Dorathy Uduak. The first draft and editing of the manuscript was written by Davies Ibienebo Chris, and Khang Wen Goh, Zulhisyam Abdul Kari, Thirukanthan Chandra Segaran, Murni Nur Islamiah Kassim. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics

No specific ethical approval was not required for this study.

Data Availability

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

Competing Interest

The authors have no relevant financial or non-financial interests to disclose.

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