



Spatiotemporal patterns of trace element bioaccumulation in the mangrove oyster (*Crassostrea gasar*) from the Bundu-Ama Waterfront, Bonny River System, Nigeria

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Abstract: This study assessed the spatiotemporal variation of trace elements in mangrove oysters (*Crassostrea gasar*) from the Bundu-Ama shoreline, Rivers State, between February and July 2024. Monthly water and oyster samples were analysed for Cr, Zn, Pb, Cd, and Ni using a UNICAM Solaar 969 AAS. Cd ranged from 0.007 to 0.012 mg/kg and Cr from 0.015 to 0.032 mg/kg, below DPR limits; however, Ni exceeded the 3.5 mg/kg limit, reaching 8.142 ± 0.456 mg/kg. Higher concentrations occurred during the wet season. Significant spatial-temporal differences ($p < 0.05$) and strong correlations (Cd - Cr $r = 0.840$; Cd - Zn $r = 0.855$) highlight ongoing contamination risks, requiring continuous monitoring and management.

Keywords: trace metals, environmental monitoring, public health

1. Introduction

Important coastal habitats and mangrove systems are the source of biodiversity, shoreline stabilization, and carbon sequestration among other ecological functions [1]. The mangrove swamp in the upper reaches of the Bonny Estuary, Isaka-Bundu, is a highly significant habitat in Rivers State, Nigeria, and is under ever-increasing threat from human activities. Heavy pollution from the extremely active industrial activities, urban growth, and agricultural runoff has facilitated trace element accumulation in an aquatic environment, with variables that have far-reaching implications [2–3].

This is an important insight into the dynamics of pollutants concerning the ecological status as well as the animals inhabiting the mangrove ecosystems. Discharging domestic and industrial wastes into the Isaka-Bundu mangrove swamp poses a massive threat to aquatic life, and particularly to the filtration-feeding organisms of the mangrove oyster (*Crassostrea gasar*).

These oysters are amongst the crucial sources of nutrition for natives and also hold an important place in the coastal food chain. However, the susceptibility of oysters to heavy metal pollution brings up serious problems related to human health and food safety, especially in areas where oysters make up a large part of the diet [4–5]. As such, studying the temporal and spatial variations of trace elements in oysters is of the essence in order to gain valuable insight into the overall impacts of pollution on ecological and human health. The conditions in the Isaka-Bundu mangrove swamp range from wet to dry, with a significant impact on bioavailability and trace element accumulation.

Increased rainfall during the wet seasons would increase runoff, which actually enhances the concentration in the water column and sediments. On the other hand, the dry season can decrease the levels of water and increase the concentration of these pollutants, hence increasing the risk from such exposures to aquatic species. Along this line of reasoning, a study by [6] was conducted with an emphasis on understanding how trace element concentrations are influenced by seasonal dynamics in *C. gasar* while identifying possible sources of contamination contributing towards the observed fluctuations.

In this regard, the research focuses on the three sample sites located in the Isaka-Bundu mangrove swamp, having different gradients of pollution. In particular, it is focused on a specific affected area, with a nearby heap of sediments and an abandoned bunkering plant, where visible oil slicks and trash show high human impact. While the second site is located near a densely populated area with substantial discharges of domestic and industrial waste yielding high levels of trace elements, the third site, at the local market, is polluted by maintenance fluids and large quantities of commercial wastes [7]. The presence of these many pollution sources offers an ideal setting for studying the spatial and temporal distribution of trace elements in mangrove oysters.

The understanding of trace element interactions and their ecological repercussions is highly essential for the development of successful pollution reduction strategies in the Niger Delta.

The current research offers a critical analysis of the health hazards of a seafood chain and adds to the broader discussion on the environmental sustainability of the mangrove ecosystem in the form of an analysis of the patterns of trace element concentrations at various locations and in different seasons [8–9].

The outcomes of this project will contribute to scientific knowledge about the dynamics of pollution in the Isaka-Bundu mangrove swamp and to the policy recommendations based on local settings.

Studies like this highlight the importance of intensive monitoring of pollution problems with a regulatory framework that will protect human health and ensure the resilience of mangrove ecosystems in the face of continued environmental changes [10]. Finally, our research hopes to contribute to the international effort towards mangrove habitat maintenance and its many benefits for the ecosystem and the human population.

2. Materials and methods

Study area and the sampling stations

The Isaka-Bundu mangrove swamp, which is in the upper reaches of the Bonny Estuary, has been under pollution pressure. Waste entering it consists of residential and industrial refuse from companies along its banks, such as the Nigerian Ports Authority, OandO Oil & Gas, Conoil, the Ibeto cement factory, dredging firms, etc., from adjacent creeks and the heavily populated coastal communities on its banks. The region is characterized by distinct wet and dry seasons. The three sample sites were chosen based on the human activity, each located about 500 meters apart (*Figure 1*).

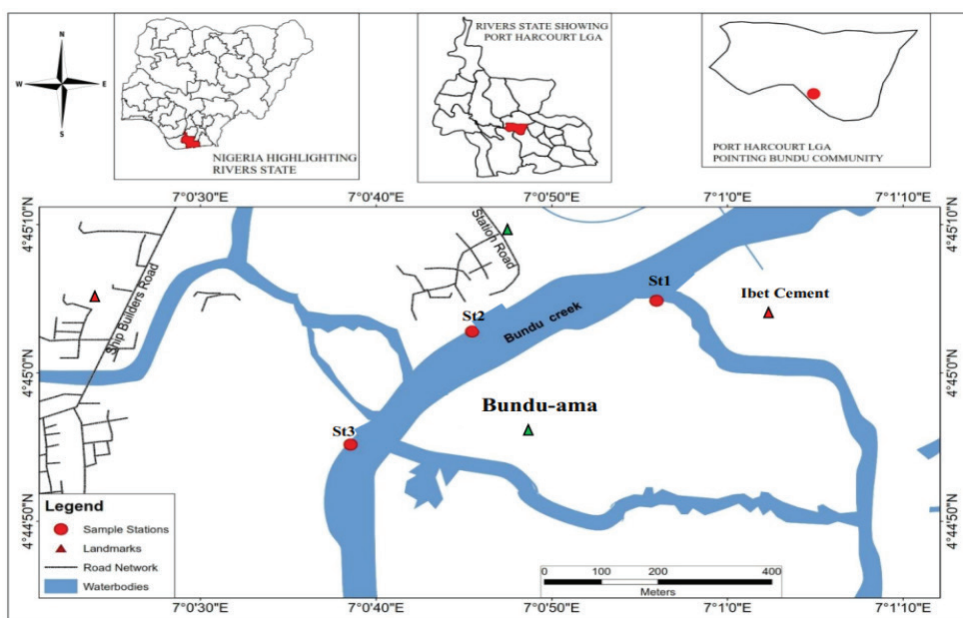


Figure 1. Map of Port Harcourt, Rivers State, Nigeria, showing the study area

Station 1 (latitude 04°45'03.05" N, longitude 007°00' 45.51" E) was a dumpsite destroyed by an oil slick, with tidal currents carrying garbage and other particulate matter. An abandoned bunkering installation was discovered within the station.

Station 2 (latitude 04°44' 55.35" N, longitude 007°00' 38.40" E) was in a highly populated hamlet in the mangrove marsh that had been swept by the tide. The station recorded a significant release of human, animal, and domestic waste and runoff from the shoreline.

Station 3 (latitude 04°45' 03.58" N, longitude 007°00'57.75" E) is next to the famous Creek Road Market. Maintenance fluid and other associated liquid and solid wastes are discharged from the dockyard, while sewage, rubbish, and other massive amounts of commercial waste from the market are dumped around the station.

2.1. Sample collection and analyses

Freshly acquired live mangrove oyster (*Crassostrea gasar*) samples were collected from the catch of local fishermen at three sampling locations and identified as *Crassostrea gasar* following Powell (1983). The study included sixty typical oyster samples (mean length: 6.03 ± 0.62 cm, mean weight: 8.22 ± 0.18 g) from each site.

The dissected dry tissues (about 0.5g each) were weighed and digested in concentrated nitric acid (AnalaR grade, BDH 69%). The sample was digested by heating the nitric-acid-treated samples at 40 °C for 1 hour before increasing to 140 °C for at least 3 hours to ensure full digestion. After digestion, the samples were filled to 40 ml with DDW before being filtered through Whatman No. 1 (filter speed: medium) filter sheets and placed in acid-washed polypropylene containers. The quantities of hazardous elements such as chromium (Cr), zinc (Zn), lead (Pb), and cadmium (Cd) in water were determined using a UNICAM Solaar 969 atomic absorption spectrometer (AAS) with an acetylene/air flame.

2.2. Quality control and assurance

Procedural blanks were analysed once in every 5 samples and all the glassware and equipment were acid-cleaned to achieve consistency of data collection in the investigation. Standard solutions for all five metals were developed and tested sporadically during the investigation aimed at heavy metal recovery. Recovery rates for heavy metals were good and ranged between 90% and 110%. The analytical techniques adopted for the oyster samples were verified using CRM for Dogfish Liver (DOLT-3, National Research Council Canada). CRM recoveries were excellent, ranging from 80% to 120%.

2.3. Statistical analysis

The findings were summarized with the help of Microsoft Excel, and one-way ANOVA was performed to determine if there were significant differences in the levels of metals in water and oysters across the locations. The Tukey pairwise post-hoc test was used to determine the reason underlying significant differences ($p < 0.05$). Pearson's correlation coefficient was used to determine whether there was a significant ($p < 0.05$) association between heavy metal levels in the water and oysters.

3. Results and discussion

Spatial distribution of toxic elements in mangrove oysters (Crassostrea gasar)

The spatial distribution of hazardous components in mangrove oysters (*Crassostrea gasar*) over several stations was analysed, and heavy metal concentrations were found to vary dramatically. *Table 1* reveals that the amounts of Cadmium (Cd), Chromium (Cr), Zinc (Zn), and Nickel (Ni) differed substantially throughout the three portions.

Station 3 showed the highest Cd concentration of 0.012 mg/kg, much higher than that of other parts ($p < 0.05$). Station 2 had the lowest Cd value, at 0.007 mg/kg.

All the stations fall below the authorized limit of the Department of Petroleum Resources (DPR), 0.8 mg/kg for Cd, indicating very low levels of contamination. Station 3 contained the largest concentration of Cr at 0.032 mg/kg, which varied greatly from stations 1 and 2 ($p < 0.05$), which indicated lower Cr levels of 0.015 mg/kg and 0.017 mg/kg, respectively, with no significant difference between them. Cr values in each part are significantly lower than the DPR limit of 100 mg/kg, indicating a minimal contamination of Cr.

Station 1 had the largest Zn concentration at 9.965 mg/kg, which was notably different from Station 2 ($p < 0.05$), which had the lowest Zn level, measuring 6.545 mg/kg. Zn levels fall below the DPR limit of 140 mg/kg, suggesting that Zn contamination is safe in all stations.

At Station 1, the Ni level was higher, with 8.142 mg/kg, which is significantly higher than in the other stations ($p < 0.05$). Although Station 2 demonstrated the lowest level of Ni at 3.702 mg/kg, staying below the DPR limit of 3.5 mg/kg, it indicated potential issues with Ni contamination. Ni concentration at Station 1 was higher than the limit under DPR, which indicates a significant pollution concern that has to be addressed promptly, and appropriate mitigation measures have to be implemented.

The wide geographical distribution of the hazardous elements in mangrove oysters (*C. gasar*) in the Bundu-Ama community of Rivers State can offer valuable information on the subject of human health and environment management. Station 3 had the highest cadmium concentration (0.012mg/kg), which is much higher than stations 1 and 2, with 0.009 mg/kg and 0.007 mg/kg respectively. All these results are far below the Department of Petroleum Resources' (DPR) approved limit of 0.8 mg/kg, showing insignificant contamination levels [11]. However, the low levels of Cd signal that contemporary environmental circumstances and regulatory frameworks may be effective in lowering Cd pollution in the area.

Station 3 exhibited the highest chromium (Cr) concentration of 0.032mg/kg, which is significantly different compared to the values at stations 1 (0.015 mg/kg) and 2 (0.017 mg/kg). These values are considerably lower than the maximum limit of DPR, 100 mg/kg, and therefore they have low levels of Cr contamination [12–13]. This minimal Cr contamination indicates good environmental management and probably a low industrial emission of Cr within the region. Maintaining such levels would involve regular monitoring of the industrial activities as well as putting in place an appropriate waste management process to prevent additional contamination [9]. Station 1 presented a maximum value for Zn, equal to 9.965 mg/kg, which is significantly greater than that of Station 2 with the lowest value reading of 6.545 mg/kg. All the values obtained for Zn are well below the limit set by the DPR at 140 mg/kg, indicating an acceptable value in all studied stations [5–14].

The permitted limits of Zn demonstrate that the local environment is not significantly affected by sources of Zn pollution such as industrial waste. Nonetheless, its high concentrations in some locations require continuous check-up to keep the levels within the acceptable range and not to become harmful to the local aquatic fauna [15].

It has been reported that Station 1 had the largest amount of nickel (Ni) at 8.142 mg/kg, which is higher than the DPR limit of 3.5 mg/kg, indicating significant pollution issues [11]. Station 2 exhibited the lowest Ni level at 3.702 mg/kg. Ni levels exceeding the permissible limit at Station 1 indicates a potential health issue affecting the local people. This, therefore, calls for mitigation measures that set limits for Ni levels to protect public health, as high concentrations have severe health outcomes upon exposure, such as respiratory problems and skin irritation [16–17].

Various studies carried out across Nigeria showed different levels of heavy metal contamination in aquatic environments that are mostly related to industrial activities and the absence of suitable waste disposal practices. In that respect, a research by [18], carried out in the Lagos Lagoon, found a high concentration of heavy metals, such as Cd and Cr, caused by the discharge of industrial waste and urbanization. The levels registered in Bundu-Ama are lower compared to

other, more industrialized areas like Lagos, providing a case of relatively lower industrial activity with very good regulatory enforcement in Rivers State. The Niger Delta is an oil and gas region and is usually characterized by high heavy metal concentrations caused by oil spills and industrial wastes [11].

Indicatively, research works have been documented in Warri and Port Harcourt with high concentrations of Ni and Cr in aquatic life. The levels of Ni also show an upward tendency at Station 1, therefore corroborating the results obtained in other parts of the Niger Delta to further affirm that strict environmental management is required in mitigating pollution within the area resulting from oil exploration and production activities [9]. In fact, studies carried out in the coastal areas of countries like Ghana and Brazil have demonstrated variable heavy metal concentrations in marine organisms that are often related to local industrial activities and waste disposal strategies [19].

For example, there are higher levels of Cd and Ni in the coastal waters of Ghana due to mining activities and industrialization. Levels of Cd and Cr in Bundu-Ama are relatively lower when compared to recorded levels from other parts of the world that are more industrialized, which is indicative of good environmental management. However, the higher levels of Ni are in line with data from areas with heavy industrial activities and hence call for special measures in mitigating this problem of pollution [11].

Table 1. Spatial distribution of toxic elements
in mangrove oysters (*Crassostrea gasar*)

Heavy metals	Station 1	Station 2	Station 3	DPR
Cd (mg/kg)	0.009 ± 0.001 ^{ab}	0.007 ± 0.001 ^b	0.012 ± 0.001 ^a	0.8
Cr (mg/kg)	0.015 ± 0.001 ^b	0.017 ± 0.001 ^b	0.032 ± 0.002 ^a	100
Zn (mg/kg)	9.965 ± 0.623 ^a	6.545 ± 0.628 ^b	8.42 ± 0.492 ^{a^b}	140
Ni (mg/kg)	8.142 ± 0.456 ^a	3.702 ± 0.456 ^b	4.023 ± 0.456 ^b	3.5

Note: ^{abcd} means that different superscripts across rows are significantly different ($p < 0.05$).

Temporal distribution of toxic elements in mangrove oysters (C. gasar)

The temporal distribution of toxic elements in mangrove oysters (*Crassostrea gasar*) from February to July indicates considerable changes in the amounts of heavy metals (Table 2). These findings are essential in determining the seasonal variation and environmental meanings. July yielded the greatest concentration of Cd at 0.021 mg/kg; however, this is not substantially different from the other months ($p < 0.05$). On the other hand, February reported the lowest Cd value at 0.005 mg/kg. All monthly Cd values fall far below the allowed DPR value of 0.8 mg/

kg, and this shows that Cd concentration was maintained at low levels throughout the research period. July had the highest Cr content at 0.034 mg/kg, which is substantially different from the other months ($p < 0.05$), whereas February exhibited the lowest Cr levels at 0.015 mg/kg. With the DPR limit for Cr set at 100 mg/kg, the concentration of Cr remained below this limit throughout the studied months, showing no seasonal fluctuations and posing an insignificant risk of Cr pollution.

Compared to other months ($p < 0.05$), the highest Zn content of 13.468 mg/kg was reported in July, and the lowest content of 6.157 was recorded in the month of February. Zn values were constantly below the DPR limit of 140 mg/kg, showing no major danger of Zn contamination during the months under study. Similarly, July exhibited the greatest concentration of Ni at 9.205 mg/kg, which is substantially different from the other months ($p < 0.05$), whereas February had the lowest Ni level at 3.205 mg/kg.

Ni values in the studied months are higher than the DPR limit of 3.5 mg/kg, with July registering the highest significant exceedance, which implies potential environmental and health hazards related to Ni pollution.

The regular exceedance of nickel (Ni) levels set by the Department of Petroleum Resources (DPR), i.e. 3.5 mg/kg, creates severe health issues to the Bundu-Ama people. High levels of Ni can have many adverse health-related consequences such as rashes, respiratory problems, and even cancer [5, 14, 15]. The repeated observation of high levels of Ni with large temporal variations indicates possible sources of environmental pollution, which requires further studies. This, therefore, calls for continued monitoring and regulatory efforts as effective approaches to eliminating the sources of pollution [16–17].

The seasonal variations observed and the relatively high concentrations of heavy metals recorded for the month of July suggest that environmental factors such as rainfall, a variety of industrial activities, and tidal movements may have increased influence on metal accumulation in oysters. In this respect, reference may be made to [20] and [21]. The temporal pattern thus defined is highly significant in developing an effective environmental management plan adapted to the dynamics of pollution within the region. For instance, rainfall in increasing magnitudes may increase the amount of runoff from industrial facilities and enhance the transport of heavy metals to the aquatic ecosystem [9].

In the Niger Delta, for example, [22] recorded various levels of heavy metals in different oysters; Ni and zinc (Zn), for the most part, surpassed admissible limits. This also supports the observation of a more serious regional Ni pollution problem in aquatic organisms found in the present study. [1] also confirmed similar seasonal trends of heavy metals in aquatic organisms, pointing out that only a time-specific monitoring could capture all the dynamics of pollution.

On the other hand, [23] performed an elaborate investigation of heavy metals within marine bivalves and identified that Cd and Cr were frequently below the

permissible limits in that regard, corroborating the occurrence of those elements in the current study. However, Ni pollution issues did emerge and become a common factor in developed coastal areas, which evidences its continuance as an environmental threat. Research into heavy metal accumulation in oysters in Malaysia by [24] stated that the levels of Zn were within permissible limits at all times, which also agrees with this study's findings for the region of the Niger Delta.

Indeed, in their study on heavy metals in oysters of the Ghanaian coastal origin, [25] showed relatively lower concentrations of Ni compared to the level found in this study concerning the Niger Delta, which might suggest a limited number of contamination sources in Nigeria. Indeed, [26] recorded a parallel trend in seasonal changes in oysters from Ivory Coast, with higher levels during the wet season, which agrees with the current findings.

This study shows that there are acute health and environmental problems associated with Ni pollution in the Bundu-Ama community. This is in agreement with the works done nationally and internationally, especially within the Niger Delta region and other West African coastal areas [16–17].

Table 2. Temporal distribution of toxic elements in mangrove oysters (*C. gasar*)

Heavy metal	February	March	April	May	June	July	DPR
Cd (mg/kg)	0.005 ± 0.001 ^a	0.006 ± 0.001 ^a	0.008 ± 0.001 ^a	0.007 ± 0.001 ^a	0.008 ± 0.001 ^a	0.021 ± 0.001 ^a	0.8
Cr (mg/kg)	0.015 ± 0.002 ^b	0.018 ± 0.003 ^b	0.02 ± 0.003 ^b	0.019 ± 0.003 ^b	0.02 ± 0.003 ^b	0.034 ± 0.003 ^a	100
Zn (mg/kg)	6.157 ± 0.533 ^b	7.157 ± 0.533 ^b	8.024 ± 0.48 ^b	7.251 ± 0.49 ^b	7.801 ± 0.497 ^b	13.468 ± 0.53 ^a	140
Ni (mg/kg)	3.205 ± 0.715 ^a	4.205 ± 0.715 ^a	5.205 ± 0.715 ^a	4.705 ± 0.715 ^a	5.205 ± 0.715 ^a	9.205 ± 0.715 ^a	3.5

Note: ^{abcd} means that different superscripts across rows are significantly different ($p < 0.05$).

Correlations between the different elements in mangrove oysters (C. gasar)

Table 3 presents a correlation investigation of toxic element concentrations in mangrove oysters (*Crassostrea gasar*), which reveals significant relationships between metals. Cd and Cr show a strong positive correlation ($r = 0.840$), which is significant at the 0.01 level. This shows that Cd is most probably related to Cr perhaps because they have a common origin or because they are accumulated together in oysters. There is a strong positive correlation between Cd and Zn (0.855) with the value being significant at the 0.01 level. This is a clear indication that Cd and Zn share the same rising trend, indicating that they are of the same origin or are affected by the same environmental conditions.

Cd has a somewhat positive correlation with Ni ($r = 0.594$), which is significant at the 0.01 level. This correlation demonstrates that although there is a link between the presence of Cd and Ni, it is weaker than the links to Cr and Zn. However, Cr has a slight positive correlation with Zn ($r = 0.521$), which is significant at the 0.01 level, indicating that the two metals are likely to coexist, maybe due to similar environmental conditions or sources.

Cr shows no significant relationship with Ni ($r = 0.128$), which implies that these two metals are not likely to have a shared origin and pathway in oysters. However, Zn has a strong positive correlation with Ni ($r = 0.897$), which is statistically significant at the 0.01 level. Such a wide array of correlations demonstrates that Zn and Ni must have similar sources or be affected by similar environments.

Table 3 presents a correlation study of toxic elements' levels in mangrove oysters (*Crassostrea gasar*), showing high-order relationships within metals. These would give indications of common sources of contaminants and as to how they interact with the aquatic environment.

Cd and Cr are positively correlated at 0.840, being significant at the 0.01 level. This hints at the fact that Cd is most probably related to Cr through similar sources or mechanisms of concentration in oysters. Cd and Zn also show a strong positive correlation, 0.855, which is statistically significant at 0.01. This clearly shows that the Cd and Zn concentrations build up together; it could also point to a common source or similar environmental factors affecting their presence.

The value of the correlation between Cd and Ni is fairly positive and is significant at 0.01. That is, the occurrence of Cd is related – though not as strongly as with Cr and Zn – to that of Ni. However, Cr shows a slight positive correlation with Zn ($r = 0.521$), significant at the 0.01 level, which can be taken to mean that both metals may coexist, probably due to similar environmental conditions or sources. Cr does not vary considerably with Ni ($r = 0.128$), showing that the oyster metals have no common source or pathway. However, Zn shows a very strong positive correlation with Ni ($r = 0.897$), which is statistically significant at the 0.01 level. The fact that the correlation between the considered aspects is stronger also indicates that the factors could have a common origin or be affected by the same environmental factors.

The correlation analysis of heavy metal concentrations in mangrove oysters, *Crassostrea gasar*, provides important information on the relationship that exists between the different elements and their possible sources of pollution in the aquatic environment of the Bundu-Ama community in Rivers State. This kind of link is important for identifying common sources of pollution and the interactions across ecosystems of the metals.

Cd and Cr were found to exhibit a close relationship with $r = 0.840$, $p < 0.01$; meaning that both metals could have a similar origin or be accumulated in oysters by a similar mechanism. This finding indicates that such metals must have accumulated as a result of similar human practices, including industrial discharge

or urban runoff, which are the sources of water contamination [20–21]. Cadmium and zinc are highly positively correlated, with the increase in one leading to an increase in the other ($r = 0.855$, significant at $p < 0.01$).

This correlation indicates the same cause, and it could be connected with agricultural runoff or industrial processes releasing these metals into the water [13–38]. It highlights the comparable environmental situations of the bioavailability and accumulation of the two metals in oysters [11].

Cd and Ni show a relatively weak positive correlation ($r = 0.594$, $p < 0.01$), which does not show the same relationship as observed among other metals. Although Cd and Ni might have certain similar effects on the environment, it is likely that they are sources or accumulation pathways [16].

On the same note, the moderate positive relationship of Cr with Zn ($r = 0.521$, $p < 0.01$) indicates the possibility of mutual occurrence, perhaps due to identical environmental conditions or sources, e.g. deposition of sediments or other localized pollution processes. Nevertheless, Cr and Ni have a low correlation ($r = 0.128$), which means that these metals do not have a common source or route in oysters. It implies that factors impacting their survival in the aquatic habitat may have no relationship with one another [2]. The strong positive correlation of Zn and Ni ($r = 0.897$, $p < 0.01$) confirms that they originate from similar sources or are influenced by similar environmental factors.

The extent of association is high, which makes it possible to consider that pollutants may be combined, possibly, with effluents of metal processing facilities or urban waste [5–14]. These high levels in the interaction between the heavy metals indicate potential health hazards in the consumption of mangrove oysters by the Bundu-Ama community, through the accumulation. When a number of metals are deposited by various common sources, they may have cumulative or synergistic negative effects, and this may be dangerous to human health.

Table 3. Correlations between the different elements
in mangrove oysters (*C. gasar*)

Heavy metals	Cd (mg/kg)	Cr (mg/kg)	Zn (mg/kg)	Ni (mg/kg)
Cd (mg/kg)	1			
Cr (mg/kg)	0.840	1		
Zn (mg/kg)	0.855	0.521	1	
Ni (mg/kg)	0.594	0.128	0.897	1

Notes: Correlation is significant at the 0.05 level (2-tailed). Correlation is significant at the 0.01 level (2-tailed).

Spatiotemporal variations of physical and chemical properties of surface water

The temperature values of Station 1 (27.62 ± 0.71 °C), Station 2 (31.59 ± 1.27 °C), and Station 3 (33.55 ± 1.28 °C) demonstrate a significant difference between the temperature at Station 1 and Station 3. This is in line with the results obtained in Rivers State, where increased temperatures during the wet season are associated with an increase in aquatic metabolism and possibly high pollution levels [27]. The same trends have been noted in other areas of the Nile Delta whereby the changes in temperature determine the biological and chemical functions of water bodies [28]. Station 3 (96.78 ± 4.68 mv) and Station 2 (92.78 ± 4.68 mv) have the highest and lowest oxidation-reduction potential (ORP) values respectively. Increased ORP means that the water has a higher quality with lower organic pollution. This finding is consistent with the data found in the Niger Delta where elevated values of ORP are a sign of better aquatic ecosystems [29]. However, reduced ORP at Station 2 can be indicative of increased organic content or contamination.

Station 3 (89.44 ± 10.13 cm) has the highest level of transparency, which means cleaner water. The same can be compared with research in the Niger Delta where increased transparency is accompanied by a decrease in turbidity and sedimentation [30]. The high score of transparency is usually found in cleaner or more stable water environments. pH values across the locations (6.52 ± 0.01 to 6.62 ± 0.01) are within the optimal range for aquatic life. The consistency of pH levels are in line with data from Rivers State and other Niger Delta studies where pH variations are restricted [31]. The same stability has been established in other sites, implying that there is a good buffering ability in the regions studied.

Station 1 has the largest values of TDS (29.23 ± 0.06 ppt), and Station 3 has the largest values of conductivity (37.30 ± 0.10 uS/cm). High TDS and conductivity usually indicate growing amounts of dissolved ions and probable sources of pollution [32]. Similar results have been documented in the Niger Delta where agricultural runoff and industrial activity have been linked to high levels of TDS and conductivity. However, the specific gravity (SG) and salt levels were the highest at Station 3, which proves the presence of higher mineral content and higher salinity. The trends identified are in line with the research in similar conditions, where an increase in salinity was accompanied by the increase in mineral concentration caused by evaporation and pollution [33].

Variation in the levels of nitrate and nitrite was observed, with higher degrees of nitrates at Station 3 (1.47 ± 0.06 mg/L) and nitrites at Station 2 (0.18 ± 0.01 mg/L). The high nitrate rates usually accompany agricultural runoff, which is emphasized in the research on the Niger Delta [34]. Nitrite levels, though not frequently studied, are essential in evaluating the health impact of water contamination. However, the dissolved oxygen (DO) content is higher at Station 1 (5.30 ± 0.10 mg/L) than

at stations 2 and 3, suggesting better water quality at Station 1. Station 1 (5.50 ± 0.10 mg/L) has also high values in BOD, which implies the presence of organic materials. Indeed, similar patterns in the Niger Delta have recorded increased values of BOD, showing increasing levels of organic pollution [35].

Table 4. Spatiotemporal variations of physical and chemical properties of surface water

	Station 1	Station 2	Station 3
Temperature (°C)	27.62 ± 0.71^b	31.59 ± 1.27^{ab}	33.55 ± 1.28^a
ORP (mv)	93.89 ± 4.43^b	92.78 ± 4.68^b	96.78 ± 4.68^a
Transparency (cm)	53.56 ± 5.0^b	86.44 ± 10.13^a	89.44 ± 10.13^a
pH	6.62 ± 0.01^a	6.52 ± 0.01^a	6.62 ± 0.01^a
TDS (ppt)	29.23 ± 0.06^a	25.30 ± 0.10^b	27.30 ± 0.10^{ab}
Conductivity ($\mu\text{S}/\text{cm}$)	49.30 ± 0.10^a	35.30 ± 0.10^b	37.30 ± 0.10^b
SG	1.017 ± 0.001^a	1.021 ± 0.001^a	1.022 ± 0.001^a
Salinity (ppt)	15.60 ± 0.10^b	20.53 ± 0.06^a	22.53 ± 0.06^a
Nitrate (mg/L)	1.20 ± 0.10^c	1.37 ± 0.06^{ab}	1.47 ± 0.06^a
Nitrites (mg/L)	0.80 ± 0.10^c	0.18 ± 0.01^a	1.10 ± 0.10^b
DO (mg/L)	5.30 ± 0.10^a	4.63 ± 0.06^{ab}	4.47 ± 0.06^b
BOD (mg/L)	5.50 ± 0.10^a	5.23 ± 0.06^{ab}	5.10 ± 0.00^b

Correlations between the different physicochemical parameters

Temperature showed a strong positive correlation with both conductivity (0.897) and DO (0.800). High temperatures usually enhance conductivity due to the elevated ion mobility and reduce DO due to the low oxygen solubility [36]. The trend here is similar to research works on Rivers State showing increasing temperatures in relation to alterations in water chemistry and reduction in oxygen levels [29]. On the other hand, ORP displays considerable relationships with transparency (0.521) and pH (0.128).

The better the ORP, the better the water quality and the more significant the transparency, which means that organic contamination will be minimal [30]. Similar relations have also been found, suggesting that ORP is a useful indicator of water quality. Also, pH is strongly correlated with transparency (0.897) and conductivity (0.625), which proves that pH stability is typically preceded by the clear water and ionic strength variation [37]. Similar conclusions are made based on the research conducted in the Niger Delta and Southeast Asia, where the pH balance is vital in preserving the health of the ecosystem.

Table 5. Correlations between the different physicochemical parameters

Parameters	Temp (°C)	ORP (mv)	Transparency (cm)	pH	TDS (ppt)	Conductivity (µS/cm)	SG (ppt)	Salinity (ppt)	Nitrate (mg/L)	Nitrite (mg/L)	DO (mg/L)	BOD (mg/L)
Temperature (°C)	1											
ORP (mv)	0.840	1										
Transparency (cm)	0.855	0.521	1									
pH	0.594	0.128	0.897	1								
TDS (ppt)	0.128	0.321	0.540	0.380	1							
Conductivity (µS/cm)	0.897	0.703	0.750	0.625	0.590	1						
SG	0.560	0.490	0.560	0.540	0.500	0.520	1					
Salinity (ppt)	0.350	0.280	0.320	0.290	0.290	0.340	0.330	1				
Nitrate (mg/L)	0.600	0.440	0.460	0.530	0.470	0.530	0.490	0.410	1			
Nitrite (mg/L)	0.470	0.560	0.610	0.450	0.310	0.620	0.480	0.370	0.450	1		
DO (mg/L)	0.800	0.670	0.680	0.620	0.460	0.720	0.590	0.470	0.620	0.560	1	
BOD (mg/L)	0.650	0.550	0.630	0.550	0.430	0.680	0.540	0.420	0.580	0.500	0.670	1

Notes: Correlation is significant at the 0.05 level (2-tailed). Correlation is significant at the 0.01 level (2-tailed).

TDS has significant correlations with conductivity (0.590) and salinity (0.290). This indicates that an increase in TDS leads to an increase in conductivity and salinity as per literature investigations into different aquatic settings [34]. The same patterns have been recorded elsewhere around the world, which shows that TDS is a major parameter when assessing the quality of water. DO, however, correlates with temperature (0.800) as well as BOD (0.670). With an increase in temperature, DO levels are expected to decrease, and the increase in the values of BOD means that there is an increase in the organic matter as well [36]. These correlations are proven by research on the Niger Delta, where temperature and organic load affect the DO levels [35].

Temporal distribution of physicochemical parameters

The temperature ranges between 27.0 ± 0.08 °C in February and 33.3 ± 0.06 °C in June. This seasonal change is in line with the climate trends in the Niger Delta, where an increase in temperature during the dry season is typical [27]. The global patterns of climate have been reported in Southeast Asia as well [37]. Nevertheless, the values of ORP increase between 91.0 ± 0.29 mV in February and 113.0 ± 0.45 mV in July, which implies the increase of oxidative conditions. The given seasonal variation is consistent with the evidence provided in Rivers State, where ORP levels reflect the seasonal trends in water quality [29].

These ORP increases have also been noted across other temperate and tropical parts of the world. The level of transparency increases to 79.0 ± 0.33 cm in July as compared to 54.7 ± 0.22 cm in February. This increment represents reduced turbidity and sedimentation, similar to the Niger Delta, where the level of transparency is higher with less amounts of runoff and sedimentation [30]. The same trends have been observed in other aquatic systems in terms of seasonal variations [37]. The pH value was 6.62 ± 0.01 in February and 7.12 ± 0.01 in July, therefore showing a tendency towards alkalinity.

This agrees with observations in Rivers State, where seasonal changes in pH depend on several factors, one of which is biological activity [31]. Because the pH fluctuations are mostly concurrent with seasons and environmental changes, very similar patterns are present throughout the globe [35].

TDS and conductivity are both rising throughout the studied months, with TDS increasing from 28.2 ± 0.10 ppt in February to 39.2 ± 0.10 ppt in July, whereas conductivity changes by ranges between 49.3 ± 0.10 μ S/cm and 69.3 ± 0.18 μ S/cm. These increases are seasonal changes that occur due to the increased water temperature and reduction in rainfall, which increases ion concentrations [32].

Table 6. Temporal distribution of physicochemical parameters

Parameters	February	March	April	May	June	July
Temperature (°C)	27.0 ± 0.08 ^b	30.2 ± 0.05 ^b	32.2 ± 0.09 ^a	31.5 ± 0.10 ^{ab}	33.3 ± 0.06 ^a	25.5 ± 0.07 ^b
ORP (mv)	91.0 ± 0.29 ^b	93.0 ± 0.65 ^b	97.0 ± 0.57 ^{ab}	104.0 ± 0.77 ^a	110.0 ± 0.52 ^a	113.0 ± 0.45 ^a
Transparency (cm)	54.7 ± 0.22 ^b	74.0 ± 0.40 ^a	78.0 ± 0.40 ^a	65.0 ± 0.28 ^{ab}	69.0 ± 0.42 ^{ab}	79.0 ± 0.33 ^a
pH	6.62 ± 0.01 ^b	6.60 ± 0.02 ^b	6.64 ± 0.02 ^b	6.88 ± 0.02 ^a	7.05 ± 0.01 ^a	7.12 ± 0.01 ^a
TDS (ppt)	28.2 ± 0.10 ^b	25.3 ± 0.11 ^b	27.3 ± 0.11 ^b	33.2 ± 0.19 ^a	36.2 ± 0.08 ^a	39.2 ± 0.10 ^a
Conductivity (µS/cm)	49.3 ± 0.10 ^{ab}	35.3 ± 0.20 ^b	36.2 ± 0.22 ^b	37.3 ± 0.18 ^b	63.3 ± 0.25 ^a	69.3 ± 0.18 ^a
SG	1.02 ± 0.001 ^a	1.02 ± 0.001 ^a	1.02 ± 0.001 ^a	1.03 ± 0.001 ^a	1.03 ± 0.001 ^a	1.03 ± 0.001 ^a
Salinity (ppt)	15.6 ± 0.07 ^c	20.5 ± 0.07 ^b	22.6 ± 0.07 ^b	21.4 ± 0.10 ^b	24.2 ± 0.09 ^{ab}	27.3 ± 0.08 ^a
Nitrate (mg/L)	1.20 ± 0.07 ^b	1.38 ± 0.05 ^a	1.44 ± 0.07 ^a	1.42 ± 0.03 ^a	1.36 ± 0.06 ^a	0.30 ± 0.09 ^c
Nitrites (mg/L)	0.8 ± 0.05 ^c	0.19 ± 0.02 ^a	1.10 ± 0.10 ^b	0.03 ± 0.01 ^c	0.11 ± 0.03 ^b	0.10 ± 0.01 ^b
DO (mg/L)	5.30 ± 0.05 ^a	4.67 ± 0.05 ^b	5.15 ± 0.07 ^{ab}	5.30 ± 0.06 ^a	5.34 ± 0.07 ^a	4.67 ± 0.06 ^b
BOD (mg/L)	5.50 ± 0.07 ^a	5.20 ± 0.04 ^b	5.12 ± 0.08 ^b	5.80 ± 0.04 ^a	5.85 ± 0.06 ^a	5.16 ± 0.07 ^b

Further, the specific gravity and salinity show gradual increases over time and hence changes in water density and mineral composition. The observed trend corroborates previous works elsewhere indicating that variation in salinity levels is in relation with seasonal climatic changes [39]. The levels of nitrates and nitrites show seasonal variation, with higher amounts recorded in the months under study [34]. These changes correspond with trends as reported in the Niger Delta regarding nutrient levels, which are subject to variation depending on agricultural runoff and other causes. DO values exhibit a cyclic pattern, with the highest level of 5.30 ± 0.05 mg/L in February and the lowest of 4.67 ± 0.06 mg/L in July, while BOD values also increase, which indicates changes in the organic load and the rate of degradation [35]. These trends are similar to observation results in the Niger Delta where DO and BOD fluctuations are determined by seasons and pollution loads.

Conclusions

The mangrove oysters of the Bundu-Ama community in Rivers State were analysed in terms of toxic element distribution. Results indicate extensive changes in heavy metal levels, such as cadmium, Cr, zinc, and Ni, at the stations studied and also seasonally. While levels of Cd and Cr remain within permitted limits, the values of Ni are very high and thus constitute serious health risks to the inhabitants. This calls for urgent consideration of possible sources of Ni contamination, including industrial release and urban runoff. The investigation into physico-chemical parameters revealed certain visible trends, with the maximum count being at Station 3, which agrees with the data on Rivers State.

It was observed that Station 3 had the highest oxidation-reduction potential values, indicating better water quality and reduced organic pollution. The healthy aquatic conditions were also indicated by the levels of transparency, pH, TDS, and conductivity. The correlations of trace elements provide evidence of a common source of pollution, and so adequate management strategies should be implemented. Changes in trace elements depending on the season also serve to emphasize the influence of environmental conditions such as rainfall in terms of contamination. The paper has highlighted the need to continuously monitor the levels of heavy metal and the relevant physicochemical parameters to assess the health of aquatic systems and guarantee food security within the Bundu-Ama community.

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