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Seasonal Dynamics of Trace Metals in Marine Sediment Influenced Bioaccumulation in Giant Tiger Prawn (*Penaeus monodon*) from Rivers State, Nigeria

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Abstract

This study investigated the temporal bioaccumulation of trace metals (Cd, Pb, Cr, As, Zn, Cu, Ni) in the Giant Tiger Prawn (*Penaeus monodon*) sourced from Bille Creek, Degema LGA, Rivers State, Nigeria, over a six-month duration from December 2024 to May 2025. Monthly, three sites adjacent to oil facilities and one control site located 2 km away were utilised to collect three samples of prawns and sediments. We conducted in situ measurements of physicochemical parameters, including pH, electrical conductivity, dissolved oxygen, biological oxygen demand, temperature, and salinity. Trace metals were examined in prawn tissues and soil samples utilising Atomic Absorption Spectrophotometry (AAS). The findings suggested a distinct hierarchy of metals in prawn tissues: Zn > Cu > Pb > Ni > Cr > Cd > As. Copper (Cu) attained a maximum concentration of 10.451 ± 1.023 mg/kg in March, while zinc (Zn) reached a peak concentration of 10.67 ± 0.946 mg/kg in December. The damp season commenced in December, as lead (Pb) and cadmium (Cd) concentrations increased to elevated levels. In April, arsenic (As) exhibited the greatest Bioaccumulation Factor (BAF) of 1.222, indicating its increased availability to biota. The research demonstrated that seasonal variations in trace metals, resulting from runoff and sediment resuspension, significantly influenced bioaccumulation in *Penaeus monodon*. The analysis reemphasizes the necessity of both seasonal pollution control and rigorous basin and consumption advisory as tools for engaging in the unfortunate exposure of the environmental and human population to the dangers of heavy metal poisoning in the Niger Delta.

Keywords: *Peanaeus Monodon*; SDG 12; SDG 14 (Life Below Water); Bioaccumulation; Trace Metals; Degema

1. Introduction

Trace metal pollution in water bodies is one of the most important environmental issues, which is caused by both natural and human factors. Mining, industrial effluent, and agricultural runoff result in the introduction of metals like cadmium (Cd), lead (Pb), As, and copper (Cu) into the ecosystems, which act as persistent pollutants being added and accumulating in ecosystems, particularly in sediments. These metals are very dangerous in terms of ecology and public health because they tend to accumulate in marine life [1,2] (Yang et al., 2022; [2] Szynkowska et al., 2018). Niger Delta, which has high biodiversity, extensive fisheries and aquaculture dependence, and an extensive level of industrialization and urban sprawl, is especially vulnerable to this sort of contamination [3, 4] (Wang et al., 2014; Aransiola et al., 2024).

The Giant Tiger Prawn (*Penaeus monodon*) is one of the marine species of interest since, besides being a source of economic resources, it is also used as a bioindicator of environmental status. *P. monodon* lives in estuarine water; in coastal waters in the Niger Delta, they are vulnerable to changes in water conditions and pollution. The prawn has an advantage of being able to accumulate trace metals in the environment in which it lives, hence making it a good choice in monitoring aquatic pollution [5, 6, 7] (Chris et al., 2024; Jolaosho et al., 2024; Edo et al., 2024). This is justified by its

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twofold economic and ecological importance since it is a major source of protein among the local population as well as an important resource in aquaculture and fisheries.

Seasonal phenomena, including rainfall, tidal processes, and the resuspension of sediments, can influence the kinetics of trace metals in estuarine environments and, to some degree, the mobility and bioavailability of trace metals. Research studies indicate that the severity of trace metal pollution in water bodies is greatly influenced by seasonal changes in the environment, e.g. the wet and dry seasons caused by the monsoons in the Niger Delta [8, 9, 10] (de Almeida Rodrigues et al., 2022; Ololade et al., 2024; Oros, 2025). Such daily and seasonal fluctuations of exposure to the metals can cause massive variations in metal levels among different prawn locations, altering their bioaccumulation.

This work is aimed at examining the temporal accumulation of trace metals in *P. monodon* that are sourced in Bille Creek, Degema LGA, Rivers State, Nigeria. We found that there are major seasonal variations in concentrations of metals in prawn tissues, with levels of zinc (Zn) and copper (Cu) being the most bioaccumulative. Interestingly, in the wet season, concentrations of copper and zinc were found to reach a peak, indicating the importance of seasonal rainfall in the availability and uptake of trace metals by sea organisms. The paper further showed that arsenic (As) had the maximum bioaccumulation factor (BAF) in April, indicating the differences in bioavailability of metals over the sampling period.

The study concludes that it is beneficial to monitor trace metal contamination in different seasons, to have an understanding of temporal variation in trace metal pollution and its effect on marine life. This paper informs the field of the bioaccumulation of heavy metals in *P. monodon*, and also explains the environmental and biological data integrated to derive inferences on the potential health risks of heavy metal contamination in the Niger Delta. The study also recommends thorough policies of pollution management policies in the form of routine checkups and health alerts in order to tackle the dangers posed by the presence of traces of these metals, which have been detected in the water.

2. Materials and methods

2.1. Study area

The Bille Creek is situated in Rivers State in the Degema local government area. It is one of the major navigable waterways that links the Bille community to the Sombrero River in Rivers state, which drains to the Sombrero River. It is also a fishing community and depends heavily on the creek. Its climate is tropical, where high temperatures and humidity are experienced throughout. The average annual high temperature is 29.79ºC (85.62ºF) and the low temperature is 22.8ºC (73.04ºF). The average annual precipitation is 331.38mm (13.05in), with January being the warmest month and August being the coldest. The wet seasons are warm and overcast, while the dry seasons are hot and mostly cloudy. The creek is also known for its hydrocarbon deposits and tourism potential. The Bille community is host to oil companies such as Shell, New Cross, and Eroton. However, the region has been involved in legal disputes with Shell due to environmental damage and oil spillage.

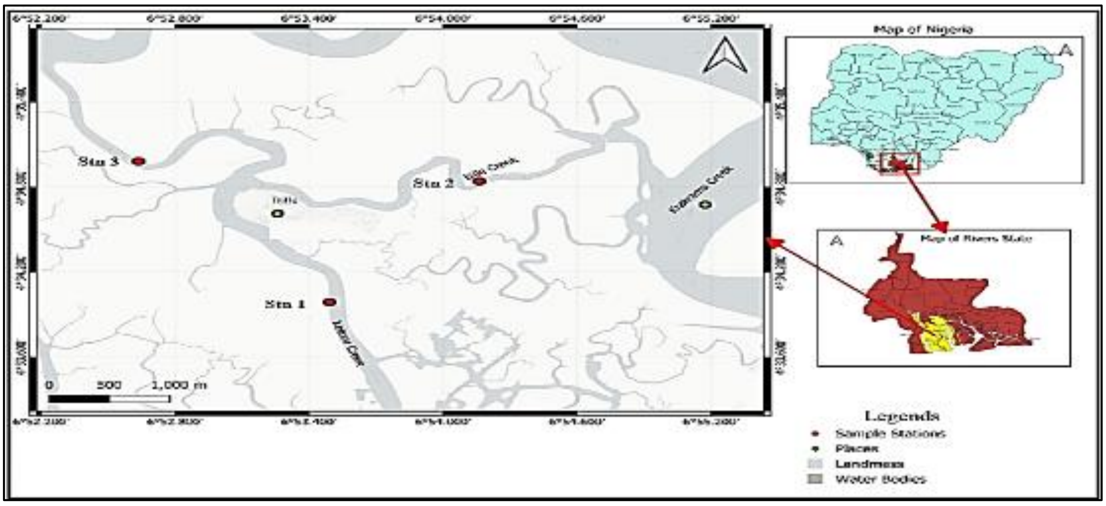

Figure 1 Map Showing the Sample Sites from the Bille Creeks

2.2. Sample and Sampling Techniques

The sampling sites from the study area were denoted with GPS coordinates. Triplicate samples of seafood and sediment were collected twelve times in both wet and dry seasons from the near facilities of the three (3) selected oil and gas companies, and within three (3) selected areas of Bille Ketoru and Krakraama. The Control samples were collected at a location at least two kilometres (2Kms) from the sampling sites. This was decided after a field visit and evaluations. The timeline for sample collection in this study was 6 calendar Months (December 2024 to May 2025). Samples were collected every first week of the month.

2.3. Determination of Physicochemical Parameters

pH, Electrical Conductivity (us/cm), Temperature ºC, Dissolved Oxygen. mg/l, Biological Oxygen Demand. mg/l, and Salinity (%) was measured using a handheld pocket-sized multi-meter (Milwaukee model pH600) as recommended by [11] Davies *et al.* (2022). For Nitrate and phosphate HACH DR/890 Colourimeter was used for the determination of nitrate in the water samples.

2.4. Shrimp (*Penaeus monodon*) Samples Collection

The Freshly caught live shrimp samples were collected from the local fisher folks in the three sampling Stations and identified using [12] Powell (1983). A total of sixty representative shrimp samples from each Station were stored in a cooler packed with ice blocks to maintain freshness and later transported to the laboratory.

2.5. Sediment Samples Collection

A total of nine sediment samples were taken at monthly intervals for six months, from December 2024 to June 2025, from three sampling stations. The sediments were collected once a month for three six in the form of a composite from three different stations from both creeks using an 'Ekman grab' sampler and kept in a plastic container which had been previously treated with 10% nitric acid for 24 hours and rinsed with de-ionised water. Muddy sediment was collected and not sandy sediment because of the low porosity of the former. The sediment samples were taken to Giolee Global Resources Limited, 18 Uyo Street, Rumuomasi, Port Harcourt. In the laboratory, samples were stored at 20°C until further treatment and analysis using the Atomic Absorption Spectrophotometric Machine (API-RP 45). The distance of sampling from the bank was to ensure that the water and sediment samples represented the actual and pronounced pollution pockets in the study area.

2.6. Determination of Trace Metals

The trace metals [Copper (Cu), Zinc (Zn), Lead (Pb), and Cadmium (Cd) concentration in the samples was determined using atomic absorption spectrophotometry (Varian AA 240 AAS) (American Public Health Association [APHA] and American Water Works Association [13] (APHA, 1992).

2.7. The Bioaccumulation Factor (BAF)

By dividing the concentration of a chemical in an organism (fish) by the concentration of that compound in its environment (sediment), the Bioaccumulation Factor (BAF) was computed. The BAF findings for each parameter at the three stations were calculated using the mean values from the tables that were supplied.

The formula for BAF is: BAF = Concentration in Fish / Concentration in Sediment.

2.8. Statistical Analysis

Descriptive statistics and Analyses of Variance (ANOVA) were conducted using SPSS version 16. Significance was determined using the Duncan Multiple Range Test at a significance level of 0.05. Mean values were used to calculate the concentrations of water, sediment, and shellfish tissue. The data presented was interpreted using Microsoft Excel software. The mean, standard deviation, and standard error of the mean were utilised as the statistical measures for data management.

2.9. Quality Assurance/Quality Control

According to the methodology of [14] Shi et al. (2018), quantitative analysis was carried out under ideal experimental conditions using an internal standard. Throughout the project, quality assurance measures were employed, and both field and laboratory procedures were altered to improve overall data quality. In the laboratory, sample vials were thoroughly cleaned with dilute hydrochloric acid before being rinsed with deionised water. The glass was properly cleaned, and all chemicals used were of analytical grade.

The quality of shellfish, water, and sediments was assessed using conventional methods for assessing trace metals and mineral components. This was done with a Perkin-Elmer atomic absorption spectrophotometer and a Flame Photometer (FP Model 140). Deionised water was often used during the experiment. Trace metal samples were obtained in Port Harcourt and analysed independently. To ensure reliability, the mussels were kept in an ice chest before being brought to the laboratory for additional testing. The soil, water, and shellfish specimens were all properly labelled.

3. Results and discussion

3.1. Temporal Distribution of Trace Metals in *Penaeus monodon* Tissue

The temporal analysis of trace metal concentrations in *Penaeus monodon* over six months, as seen in Table 1, revealed a distinct seasonal hierarchy: Zn > Cu > Ni > Pb > Cd > Cr > As. Zinc (Zn) remained the most prevalent metal throughout, peaking in December (10.67 ± 0.946 mg/kg) and declining during the dry season, consistent with reports by Abdel-Baki et al. (2011), who linked elevated Zn levels in shrimp to pre-monsoon runoff and sediment resuspension. This seasonal variation likely indicates environmental changes, including heightened runoff during the rainy season, which introduces metal-laden particulates into the water column.

Copper (Cu) exhibited statistically significant temporal variations ($p < 0.05$), with peak accumulation recorded in March (10.451 ± 1.023 mg/kg) and a minimum in May (8.267 ± 1.039 mg/kg). Fluctuations may be affected by biological factors, such as moulting and reproductive cycles, which modify the metabolic demand for copper, an essential cofactor in hemocyanin synthesis [15] (Rainbow, 2002). Seasonal variations in dietary intake and water chemistry may influence outcomes, as evidenced by similar research conducted by [16] Sarkar (2017) on Indian coastal prawns.

The nickel (Ni) content demonstrated relative stability over the months, varying between 4.069 and 4.903 mg/kg. [17] Gemaque (2024) observed stable nickel concentrations in benthic feeders throughout various seasons, suggesting a reliable exposure mechanism, likely through sediment ingestion and direct contact.

Lead (Pb), cadmium (Cd), and chromium (Cr), recognised as highly hazardous metals, exhibited notable temporal variations. Concentrations of Pb and Cd increased significantly in December, most likely due to increased anthropogenic inputs from waste discharge and agricultural runoff, which coincided with initial rainy bouts. Cr concentrations fluctuated, peaking in December.

The observed patterns demonstrate the influence of hydrological regimes on pollutant transport and availability, corroborating the seasonal trends of metal enrichment identified by [18] Otitoloju et al. (2009) in organisms from the Niger Delta estuary. The lowest overall concentrations of arsenic (As) were observed, with a range of 0.006 to 0.018 mg/kg, and significant monthly fluctuations ($p < 0.05$).

Salinity and redox conditions can be altered as a result of seasonal transitions, which may explain the temporal variations of arsenic. These elements influence its assimilation and speciation [19] (Smedley and Kinniburgh, 2002).

Table 1 Temporal Variation of Metals in *Penaeus monodon* Tissue

Months	Cd (mg/kg)	Pb (mg/kg)	Cr (mg/kg)	As (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Ni (mg/kg)
December	0.086±0.018^{a}	0.216±0.067^{a}	0.076±0.01^{a}	0.018±0.003^{a}	10.67±0.946^{a}	9.512±1.208^{b}	4.885±0.619^{a}
January	0.055±0.012^{c}	0.16±0.055^{c}	0.044±0.08^{c}	0.006±0.00^{c}	7.808±0.642^{b}	9.066±0.957^{ab}	4.559±0.473^{a}
February	0.052±0.011^{c}	0.16±0.053^{c}	0.051±0.007^{b}	0.008±0.001^{c}	7.937±0.615^{b}	9.959±0.942^{a}	4.626±0.45^{a}
March	0.055±0.012^{c}	0.165±0.054^{c}	0.055±0.007^{b}	0.007±0.001^{c}	8.358±0.659^{b}	10.451±1.023^{a}	4.903±0.5^{a}
April	0.06±0.011^{b}	0.171±0.053^{b}	0.063±0.008^{ab}	0.011±0.002^{b}	9.065±0.733^{a}	8.349±1.002^{b}	4.069±0.472^{a}
May	0.057±0.013^{bc}	0.172±0.055^{b}	0.06±0.008^{ab}	0.008±0.001^{b}	8.917±0.721^{b}	8.267±1.039^{b}	4.1±0.488^{a}

4. Temporal Distribution of Trace Metals in Sediment

The metal profile consistently exhibited a predominance of copper (Cu), zinc (Zn), and nickel (Ni) in the order Cu > Zn > Ni > Pb > Cd > Cr > As, derived from the temporal analysis of sediment samples gathered over six months. The patterns depicted in Table 2 demonstrate the impact of human activities and hydrological dynamics on environmental processes.

In December, the copper content peaked at 29.834 ± 0.363 mg/kg, followed by a notable decrease in February, with a partial recovery noted by May. The statistical validation ($p < 0.05$) suggests that this variation corresponds with patterns noted in similar tropical estuarine ecosystems, where increased urban runoff, agricultural leaching, and sediment resuspension result in elevated Cu concentrations during or immediately following the rainy season [20] (Gantayat et al., 2023). Elevated concentrations of Cu were observed in the Lagos Lagoon, corresponding with increased riverine input and hydrodynamic activity, consistent with the findings of [21] Adeniyi et al. (2011).

Zinc, the second most abundant metal, demonstrated a similar cyclical pattern, peaking in December before decreasing throughout the arid months. The observed changes align with the findings of [22] Chatterjee et al. (2007), who recorded Zn enrichment in estuary sediments following monsoonal inflow, attributing the source to both natural weathering and anthropogenic discharge from industrial and domestic activities. The slightly increasing trend toward May could be attributed to pre-rainfall buildup of surface contaminants, which become trapped in the benthic sediment.

Nickel displayed a marked decline from 15.001 ± 0.520 mg/kg in December to 10.311 ± 0.495 mg/kg in February, indicating a strong seasonal signature possibly linked to terrestrial runoff and erosion during heavy rainfall. According to [17] Gemaque (2024), similar temporal declines in Ni levels were observed in Red Sea coastal sediments and were explained by reduced input during low-precipitation months.

In contrast to Cu, Zn, and Ni, lead (Pb) and cadmium (Cd) demonstrated stable concentrations over time, showing no significant variations across months. This suggests a persistent low-level input or increased binding to sediment matrices, resulting in reduced mobility. This pattern aligns with the findings of [18] Otitoloju et al. (2009), who indicated that Pb and Cd concentrations in Nigerian estuarine sediments exhibit year-round stability, likely due to sorption onto clay and organic matter under mildly reducing conditions.

Chromium (Cr) demonstrated a decreasing trend from December to May, marked by significant monthly fluctuations. This indicates episodic input, likely stemming from tannery or metal processing industries, as well as sediment leaching or dilution effects over time. Arsenic (As) demonstrated a consistently low concentration across all months, exhibiting no significant variation, which indicates possible geogenic origins rather than anthropogenic influences [19] (Smedley and Kinniburgh, 2002).

Table 2 Temporal Variation of Metals in Sediment

Month	Cd (mg/kg)	Pb (mg/kg)	Cr (mg/kg)	As (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Ni (mg/kg)
December	$0.394±0.054^{a}$	$1.238±0.295^{a}$	$0.213±0.008^{a}$	$0.016±0.004^{a}$	$21.001±1.323^{a}$	$29.834±0.363^{a}$	$15.001±0.520^{a}$
January	$0.267±0.040^{a}$	$0.997±0.244^{a}$	$0.173±0.008^{b}$	$0.008±0.002^{a}$	$16.952±1.278^{b}$	$25.936±0.382^{bc}$	$11.311±0.495^{b}$
February	$0.249±0.036^{a}$	$0.965±0.236^{a}$	$0.167±0.008^{b}$	$0.009±0.002^{a}$	$15.954±1.279^{c}$	$24.936±0.382^{c}$	$10.311±0.495^{c}$
March	$0.259±0.038^{a}$	$0.981±0.241^{a}$	$0.171±0.008^{b}$	$0.010±0.002^{a}$	$16.668±1.244^{bc}$	$25.834±0.363^{bc}$	$11.284±0.493^{b}$
April	$0.252±0.036^{a}$	$0.969±0.237^{a}$	$0.165±0.008^{b}$	$0.009±0.002^{a}$	$16.001±1.229^{b}$	$25.334±0.363^{bc}$	$11.168±0.492^{b}$
May	$0.278±0.040^{a}$	$1.009±0.246^{a}$	$0.178±0.008^{b}$	$0.010±0.002^{a}$	$17.168±1.244^{ab}$	$26.334±0.363^{b}$	$11.568±0.488^{b}$

5. Bioaccumulation Factor of Trace Metals in *Penaeus monodon* based on the Month

The changes in Bioaccumulation Factors (BAFs) of the trace metals in *P. monodon* per month during December-May are reported in Table 3 to indicate the seasonal effect of influence on the absorption of metals in the Degema estuarine environment. BAF values, the ratio of metal concentrations in tissue to sediment, are needed to help understand the extent and the long-term pattern of the biological exposure risks and ecological health. BFs larger than 1 indicate the presence of bioaccumulation; that is, the organism is actively picking up the metals in its environment [23] (USEPA, 2000).

The arsenic (As) had the biggest value with BAF up to 1.222 and 1.125, a safety limit in April and December, respectively. The current tendency is that *P. monodon* has a strong tendency to absorb arsenic, which, therefore, should probably be estimated because it is likely to be much more available in the environment at the times of the increased organic activity and sediment mobilisation [24] (Bellante et al., 2016). The observed increase in April can be reasonably explained by the following reasons: the onset of the rainy season, which is a stage of resuspension of sediments, metal ion desorption, and redox conditions that make arsenic more mobile [25] (Maurya et al., 2024).

The levels of zinc (Zn) BAFs were also persistently elevated and stable in the course of the study, with concentrations oscillating between 0.461 in January and 0.567 in April. Zinc is an essential element that is important to most of the biological functions, especially enzymatic functions and structural parts. The continuous bioaccumulation indicates that it is a constant absorption and despite the minor seasonal changes [26] (Rainbow, 2007). The increased values in April align with arsenic trends, implying a potential shared environmental driver such as increased organic content or metal exchange rates in the sediment–water interface.

Chromium (Cr) showed a gradual rise in BAF values from 0.254 (January) to 0.382 (April). Although remaining below the threshold of 1, the steady increase suggests enhanced Cr mobilisation as estuarine systems transition from dry to wet season. Chromium's speciation, especially the proportion of bioavailable Cr (VI) versus less mobile Cr (III), may shift with changes in sediment redox potential and microbial activity, leading to differential uptake [27] (Amanatidou, 2023).

Copper (Cu) BAF values exhibited a modest upward trend from 0.319 in December to 0.405 in March, followed by a slight decline to 0.314 in May. These fluctuations may reflect seasonal changes in dietary exposure, reproductive metabolic demands, or variations in Cu binding within sediments. As Cu is both essential and potentially toxic, even small seasonal differences are ecologically significant and may influence metabolic stress in prawns [15] (Rainbow, 2002).

Nickel (Ni) showed a similar temporal pattern, rising from 0.326 (December) to a maximum of 0.449 (February), before decreasing to 0.354 (May). This pattern may result from increased Ni solubility and transport during the dry season's peak evaporation and sediment consolidation, followed by dilution effects in early rainy periods. Ni mobility in estuarine systems is known to be affected by pH fluctuations, salinity gradients, and dissolved organic carbon [28] (Pan and Wang, 2012).

Cadmium (Cd) and lead (Pb) maintained consistently low BAFs across all months. Cd ranged from 0.205 (May) to 0.238 (April), while Pb remained between 0.160 (January) and 0.177 (April). These low values suggest limited bioavailability, possibly due to the strong sediment binding of these metals to sulfides and organic matter, or physiological resistance mechanisms in prawns that restrict their uptake [29] (Wang and Rainbow, 2008). Nonetheless, even at low levels, these metals pose a long-term toxicological concern, particularly given their non-essential nature and cumulative toxicity [30] (Afzal and Mahreen, 2024).

A notable finding is the uniform peak in BAF values during April across nearly all metals. This convergence points to seasonal drivers, such as increased freshwater inflow, resuspension of fine-grained sediments, and higher microbial decomposition rates, all of which enhance trace metal mobilisation and assimilation. The early rainy season may thus serve as a critical window for metal transfer from sediment to biota, elevating potential ecological risks.

Table 3 Bioaccumulation Factor of Trace Metals in *Penaeus monodon* based on the Month

Month	Cd	Pb	Cr	As	Zn	Cu	Ni
Dec	0.218	0.174	0.357	1.125	0.508	0.319	0.326
Jan	0.206	0.160	0.254	0.750	0.461	0.350	0.403
Feb	0.209	0.166	0.305	0.889	0.497	0.399	0.449
Mar	0.212	0.168	0.322	0.700	0.501	0.405	0.435
Apr	0.238	0.177	0.382	1.222	0.567	0.330	0.364
May	0.205	0.170	0.337	0.800	0.520	0.314	0.354

5.1. Temporal Variation of Physicochemical Parameters

Table 4 presents a temporal analysis of critical physicochemical parameters [pH, electrical conductivity (EC), temperature, dissolved oxygen (DO), biological oxygen demand (BOD), and salinity] recorded monthly from December to May in the Degema estuarine ecosystem. The importance of these environmental factors is evident in their influence on the behaviour of trace metals. Their influence encompasses solubility, the diverse forms they assume, their movement patterns, and their accumulation in aquatic organisms like *Penaeus monodon* [31, 32] (Förstner and Wittmann, 2012; Chapman et al., 1996).

The pH levels demonstrated slight fluctuations, changing from 6.120 ± 0.004 in May to 6.213 ± 0.005 in January. No statistically significant differences were noted across the months. This consistent slightly acidic range supports the enhanced solubility and ionic mobility of several trace metals, including Cd, Zn, and Pb, thereby potentially increasing their bioavailability [33] (Luoma and Rainbow, 2008). The pH stability also points to minimal influence from acidifying or buffering events, such as industrial runoff or freshwater pulses with differing alkalinity.

Electrical Conductivity (EC), which serves as a proxy for total dissolved ions and salinity, remained relatively stable, showing only a slight dip in January (15.763 ± 0.001 µS/cm) and a peak in December (16.809 ± 0.002 µS/cm). Despite the numerical range, statistical analyses indicated no significant variation among months. This constancy suggests a temporally stable ionic load, reflecting minimal perturbations in salt or solute input, consistent with relatively uniform sediment-water ion exchange and negligible seasonal intrusion effects [34] (Rajeshkumar and Li, 2018).

Temperature values varied narrowly from 24.100 ± 0.041°C (February) to 24.933 ± 0.053°C (January) and, similar to pH and EC, showed no significant monthly differences. This thermal uniformity implies a climatically steady aquatic habitat, important for regulating enzyme kinetics, biogeochemical reactions, and organismal metabolism. Since metal uptake and microbial degradation processes are temperature-dependent, the observed consistency supports predictable metal behaviour across time [35] (Boyd, 2000).

Dissolved Oxygen (DO) exhibited a gentle downward trend from 4.81 ± 0.009 mg/L (December) to 4.69 ± 0.006 mg/L (May), without statistical significance. The stable and relatively high oxygen levels throughout the six months suggest a well-oxygenated environment, conducive to oxidative reactions that often immobilise metals like Fe and Mn in their oxidised forms [36] (Zhou, 2020). It also supports aerobic respiration in aquatic fauna and sediment microbial communities responsible for organic matter breakdown.

Similarly, Biological Oxygen Demand (BOD) decreased gradually over time, from 3.48 ± 0.009 mg/L in December to 3.31 ± 0.006 mg/L in May, reflecting a progressive decline in organic matter load. Although this trend is not statistically significant, it may point to seasonal flushing, reduced anthropogenic discharge, or enhanced microbial decomposition. The relatively stable BOD values suggest a balanced ecological state, free from major eutrophication or oxygen depletion events.

Salinity was the only parameter with significant temporal variation, declining from 0.943 ± 0.004‰ in December to 0.840 ± 0.006‰ in May. The statistically distinct groups (December–January, April-May) highlight a clear seasonal pattern, likely influenced by increased freshwater inflow due to the onset of the rainy season. This dilution effect may alter metal speciation, particularly for elements like arsenic and zinc, which form chloro-complexes at higher salinities [37] (Bryan and Langston, 1992). Lower salinity could therefore shift metals toward more labile or bioavailable forms, influencing uptake kinetics in resident biota.

Table 4 Temporal Distribution of Physicochemical Properties

Month	pH	Electrical Conductivity	Temperature (°C)	Dissolved Oxygen (mg/L)	Biological Oxygen Demand (mg/L)	Salinity (‰)
December	6.207 ± 0.003 a	16.809 ± 0.002 a	24.233 ± 0.033 a	4.81 ± 0.009 a	3.48 ± 0.009 a	0.943 ± 0.004 a
January	6.213 ± 0.005 a	15.763 ± 0.001 a	24.933 ± 0.053 a	4.793 ± 0.005 a	3.41 ± 0.006 a	0.94 ± 0.006 a
February	6.177 ± 0.005 a	16.759 ± 0.001 a	24.100 ± 0.041 a	4.75 ± 0.006 a	3.37 ± 0.006 a	0.90 ± 0.006 a
March	6.160 ± 0.004 a	16.756 ± 0.001 a	24.200 ± 0.041 a	4.73 ± 0.006 a	3.35 ± 0.006 a	0.88 ± 0.006 ab
April	6.140 ± 0.004 a	16.754 ± 0.001 a	24.300 ± 0.041 a	4.71 ± 0.006 a	3.33 ± 0.006 a	0.86 ± 0.006 b
May	6.120 ± 0.004 a	16.752 ± 0.001 a	24.400 ± 0.041 a	4.69 ± 0.006 a	3.31 ± 0.006 a	0.84 ± 0.006 b

6. Conclusion

This research illustrates significant temporal variability in trace metal contamination in the Degema estuary, with peak concentrations in P. monodon tissues observed during the early wet season, particularly for Zn, Pb, and Cd. Arsenic, despite low concentrations, displayed the highest bioaccumulation, underscoring its ecological and public health risk. Copper exhibited complex bioaccumulation behaviour, likely influenced by physiological regulation. The study suggests focused monitoring during the wet season (December-April) when metal bioavailability peaks and calls for further research into arsenic speciation and its uptake mechanisms. Seasonal consumption advisories and targeted pollution control, particularly for arsenic and other metals, are essential for safeguarding human health and the estuarine ecosystem.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest to be disclosed.

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