2025 Volume: 01 Issue: 07 www.ijrpa.com ISSN 2456-9995 Research Article

International Journal Research Publication Analysis

Page: 01-28

ASSESSMENT OF SPATIAL VARIATION IN PHYSICOCHEMICAL WATER QUALITY OF COASTAL MANGROVE ESTUARIES IN AKWA IBOM STATE

Christopher, Zakari Dusse[a*], Ubong E. Akpan[a] Nkanta, G. U.,[b] Archibong, Idiongomfon Bassey[b]

[a]Department of Marine Science, Akwa Ibom State University, P.M.B-1167, Uyo, Akwa Ibom State, Nigeria

[b]Department of Zoology, Akwa Ibom State University, P.M.B-1167, Uyo, Akwa Ibom State, Nigeria.

Article Received: 13 November 2025
Article Revised: 03 December 2025
Published on: 23 December 2025

***Corresponding Author: Christopher, Zakari Dussea**
Department of Marine Science, Akwa Ibom State University, P.M.B-1167, Uyo, Akwa Ibom State, Nigeria.

DOI: https://doi-doi.org/101555/ijrpa.2861

ABSTRACT

Mangrove estuaries are ecologically important coastal systems that are increasingly impacted by anthropogenic activities, particularly in tropical developing regions. This study assessed the spatial variation in physicochemical water quality of two mangrove estuaries, Iko Mangrove and Uta-Ewa Mangrove, located in Akwa Ibom State, southeastern Nigeria. Surface water samples were collected from representative stations and analyzed for temperature, pH, salinity, dissolved oxygen (DO), electrical conductivity, total dissolved solids (TDS), total suspended solids (TSS), biochemical oxygen demand (BOD_5), nutrients (nitrate, phosphate, and silicate), and selected heavy metals (Pb, Ni, Cu, Zn, and Al) using standard methods (APHA). Spatial differences between the estuaries were evaluated using independent sample t-tests at a 95% confidence level, while overall water quality status was determined using the Weighted Arithmetic Water Quality Index (WQI). The results indicated significant spatial differences ($p < 0.05$) in most measured parameters. Uta-Ewa Mangrove recorded higher mean values of pH (7.33 ± 0.11), dissolved oxygen (7.98 ± 0.34 mg L^{-1}), temperature (29.93 ± 0.35 °C), silicate, phosphate, nitrate, zinc, nickel, and aluminum, whereas Iko Mangrove exhibited higher salinity (13.13 ± 0.78 ‰), electrical conductivity (862.5 ± 93.54 µS cm^{-1}), and lead concentrations. Heavy metal concentrations were generally

within permissible limits; however, elevated nickel and zinc levels were observed at Uta-Ewa Mangrove. The calculated WQI values were 150.62 for Iko Mangrove and 140.43 for Uta-Ewa Mangrove, classifying both estuaries as having poor water quality. The study demonstrates pronounced spatial variability in water quality across the mangrove estuaries, reflecting the combined influence of estuarine hydrodynamics and localized anthropogenic inputs. These findings provide baseline information for coastal water quality management and highlight the need for continuous monitoring of mangrove estuarine systems in southeastern Nigeria.

INTRODUCTION

Mangrove estuaries are among the most productive and ecologically significant coastal ecosystems globally, functioning as transitional zones between terrestrial, freshwater, and marine environments. These systems provide critical ecosystem services, including shoreline stabilization, nutrient cycling, carbon sequestration, nursery habitats for fish and invertebrates, and water quality regulation (Alongi, 2020; Duke *et al.,* 2022). In tropical coastal regions, mangrove estuaries also serve as natural buffers against storm surges and coastal erosion, while supporting artisanal fisheries and local livelihoods (Friess *et al.,* 2019; Akpan *et al.,* 2024). However, despite their ecological and socio-economic importance, mangrove estuaries are increasingly threatened by anthropogenic pressures, particularly in developing coastal regions where rapid urbanization and weak environmental regulation prevail.

Physicochemical characteristics of estuarine waters such as temperature, pH, salinity, dissolved oxygen (DO), conductivity, total dissolved solids (TDS), nutrients, and trace metals are fundamental indicators of ecosystem health and water quality status (APHA, 2022). These parameters regulate biological productivity, species distribution, and biogeochemical processes within estuarine environments (Bianchi, 2020). Spatial variations in physicochemical conditions often reflect differences in hydrodynamics, freshwater inflow, tidal exchange, sediment composition, and, critically, the intensity of anthropogenic inputs along estuarine gradients (Chapman *et al.,* 2021). Consequently, assessing spatial variability in water quality parameters provides valuable insight into pollution sources, ecosystem stress, and management priorities.

Globally, coastal mangrove estuaries are experiencing increasing degradation due to domestic wastewater discharge, industrial effluents, agricultural runoff, dredging, and land-use changes

(UNEP, 2021). These pressures commonly result in elevated nutrient and organic loads, increased ionic strength, reduced dissolved oxygen levels, and altered thermal regimes, all of which impair ecological integrity (Kennish, 2021). In tropical regions, high ambient temperatures and seasonal rainfall further intensify these impacts by enhancing microbial activity, organic matter decomposition, and nutrient mobilization (O'Reilly *et al.,* 2015; Paerl *et al.,* 2022).

In West Africa, and particularly in the Niger Delta region of Nigeria, mangrove ecosystems are under severe stress due to a combination of rapid population growth, oil and gas activities, domestic waste discharge, and unregulated coastal development (Adekola *et al.,* 2021; Numbere, 2018). Nigeria hosts the largest extent of mangroves in Africa, yet these systems are among the most degraded globally (FAO, 2020). Coastal communities frequently discharge untreated domestic wastewater, greywater, and solid waste directly into creeks and estuaries, resulting in progressive water quality deterioration (Owamah *et al.,* 2020; Ezekwe *et al.,* 2022). These practices elevate nutrient concentrations, increase conductivity and TDS, and depress dissolved oxygen, thereby creating conditions conducive to eutrophication and hypoxia.

Akwa Ibom State, located along the southeastern Nigerian coastline, contains extensive mangrove-dominated estuarine systems that support fisheries, transportation, and domestic water use. Despite their importance, systematic water quality assessments of these mangrove estuaries remain limited, fragmented, and often outdated. Existing studies in the region have primarily focused on single estuaries or isolated parameters, with limited emphasis on comparative spatial analysis across multiple mangrove systems (Ekpo *et al.,* 2021; Udoidiong *et al.,* 2023). This knowledge gap constrains effective environmental management and policy formulation, particularly as coastal development intensifies in the state.

Spatial variation in physicochemical water quality is especially important in mangrove estuaries because these systems exhibit pronounced gradients driven by tidal mixing, freshwater inflow, and localized anthropogenic activities (Bianchi, 2020). Upstream and landward sections often receive higher loads of organic matter and nutrients from domestic and agricultural sources, while downstream zones are influenced by marine intrusion and tidal flushing (Chapman *et al.,* 2021). As a result, parameters such as conductivity, salinity, TDS, and DO may vary substantially over short spatial scales, reflecting the balance between natural estuarine processes and human-induced stressors.

Dissolved oxygen is widely recognized as one of the most sensitive indicators of organic pollution and ecosystem stress in aquatic environments (APHA, 2022). Reduced DO concentrations are commonly associated with microbial oxidation of organic matter, elevated biochemical oxygen demand, and thermal stress, all of which can result from untreated wastewater discharge (Tyagi *et al.*, 2020). Persistent hypoxia can alter species composition, reduce biodiversity, and favor pollution-tolerant taxa, thereby compromising ecosystem function (Diaz & Rosenberg, 2019). When interpreted alongside complementary parameters such as temperature, conductivity, and nutrient concentrations, DO provides a robust diagnostic of water quality status.

Integrated assessment tools, including the Water Quality Index (WQI), have been increasingly adopted to synthesize complex physicochemical datasets into interpretable metrics for environmental evaluation and management (Tyagi *et al.*, 2020). WQI approaches incorporate multiple parameters using standardized weighting and normalization schemes, enabling comparison across sites and temporal scales. In tropical estuarine environments, WQI has proven effective in identifying pollution gradients, assessing anthropogenic influence, and supporting decision-making for monitoring and remediation (Abba *et al.*, 2023; Onwughara *et al.*, 2021).

Despite the growing application of WQI and multivariate statistical tools globally, their use in Nigerian mangrove estuaries remains limited (Christopher *et al.*, 2025). Few studies have combined spatial analysis, inferential statistics (e.g., ANOVA and post-hoc tests), and integrated indices to evaluate water quality across multiple estuarine systems within the same coastal zone. Addressing this gap is essential for understanding the cumulative impacts of human activities and natural variability on coastal water quality in Akwa Ibom State.

The present study therefore provides a comprehensive assessment of spatial variation in physicochemical water quality across selected coastal mangrove estuaries in Akwa Ibom State, Nigeria. By analyzing key parameters including temperature, pH, salinity, dissolved oxygen, electrical conductivity, total dissolved solids, nutrients, and selected trace metals this study evaluates the extent to which anthropogenic activities influence estuarine water quality. Statistical analyses, including one-way and two-way ANOVA with post-hoc comparisons, were employed to determine significant spatial differences among estuaries, while box-plot visualization was used to illustrate variability and statistical separation. In addition, an

integrated Water Quality Index was applied to synthesize physicochemical data and classify overall water quality status.

By adopting a spatially comparative and statistically rigorous approach, this study contributes baseline data for coastal water quality monitoring in Akwa Ibom State and provides empirical evidence of anthropogenic influence on mangrove estuarine systems. The findings are expected to support sustainable coastal management, inform environmental policy, and guide future research on estuarine ecology and pollution dynamics in tropical coastal environments.

MATERIALS AND METHODS

STUDY AREA

This research was carried out at Iko Estuary in Iko Town, Eastern Obolo L.G.A., and Quo Iboe River Estuary. all in Akwa Ibom State, South Eastern Nigeria. The coordinate of the study area includes 4033′ N – 4050′ N; 7045′ E – 7055′ E and about 650m above sea level in the tropical mangrove forest belt east of the Niger Delta. The tidal regime here is semidiurnal and has a range of about 0.8m at neap tides and 2.20 m during spring tides with little fresh water input joined by tributaries (NEDECO, 1961), Extensive tidal mud flats and marshes define the areas adjacent to the channels. This area experience two seasons, the dry (October to March) and wet (April to September) with an annual rainfall averaging about 2500 mm (AKUTEC, 2005). The mean annual daily evaporation of the area is 4.6 mm per day (Edet and Ntekim, 1996), the hydrology of Eastern Obolo is affected by tides, although seasonal influences which are related to the climatic regime, are evident. Eastern Obolo is directly influenced by processes in the Atlantic coastal waters (Ekpe *et al.*, 1995).

The climate change is one of the challenges the shell and finfish in the estuary face incessantly, which also brings about fluctuation in the number and species composition at different periods of the year (Ita and Godwin, 2009).

This research span through the mangrove swamp fringing the Eastern Obolo, Ikot Abasi coastal Communities and river estuaries of the South-Eastern Nigeria to include, as follows: Iko River Estuary include Iko, Okoroette Emeroke and *Uta ewa,* M. jetty as shown in Fig, 3.1 below.

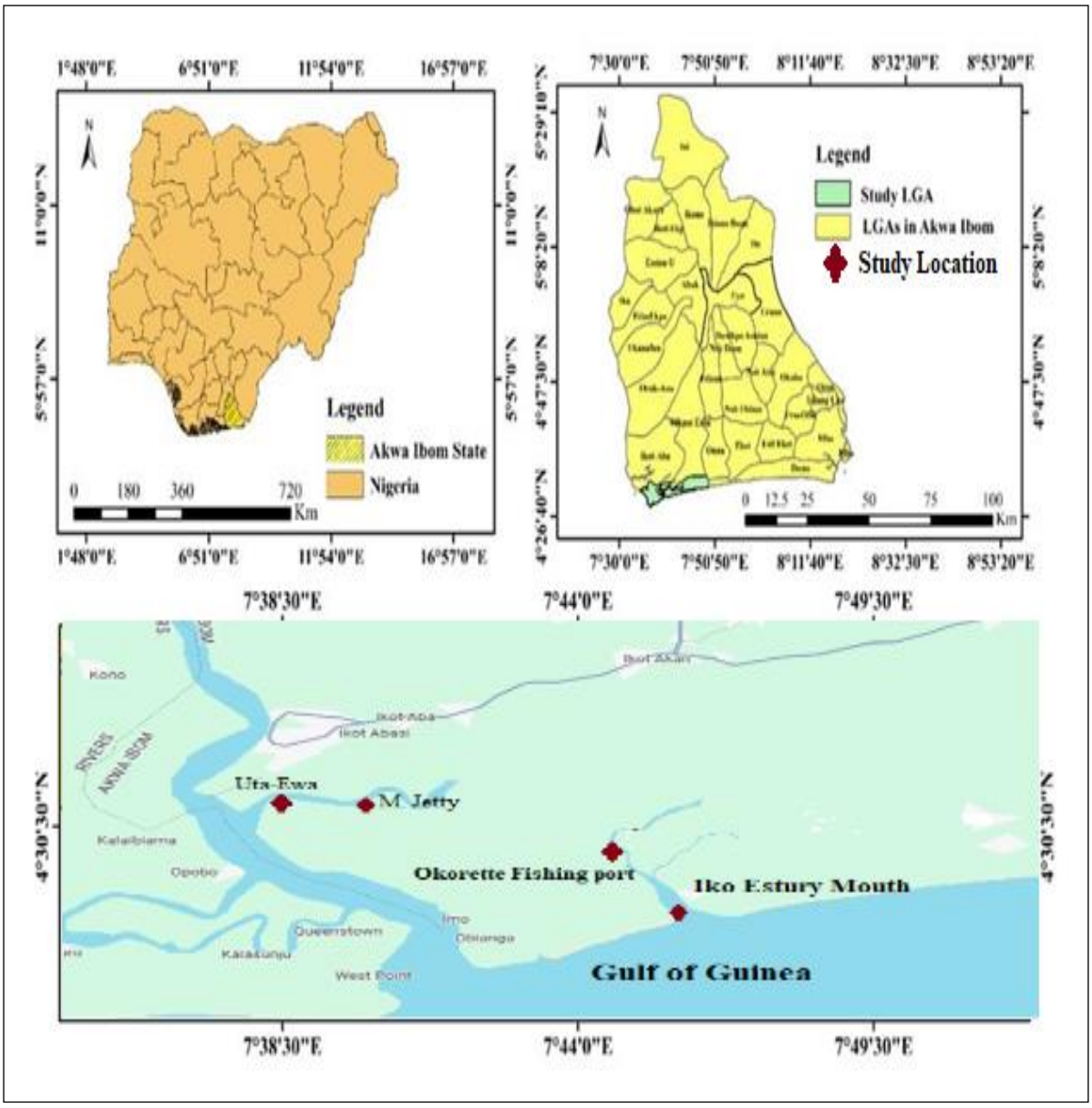

Fig. 1 map of the study area

METHODOLOGY

Physicochemical Parameters

Physicochemical parameters such as salinity, electrical conductivity, temperature, pH and Dissolved Oxygen will be measured insitu. Other parameters were analyzed *ex-situ*, according to Standard Methods of AOAC (2000) and APHA (2005).

Surface Water Temperature

Surface water temperature was measured using a mercury thermometer. The thermometer was immersed in a beaker containing the water sample for approximately three minutes. The reading was taken immediately after removal and recorded in degrees Celsius (APHA, 2017).

Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) were determined using the gravimetric method 254^0C as outlined by the American Public Health Association (APHA, 2017). A well-mixed sample was filtered and evaporated to dryness at 180°C in a pre-weighed dish until a constant weight was achieved. The increase in weight of the dish represented the TDS value, calculated using the following equation:

$$TDS\ (mg/L) = \frac{(A - B) \times 1000000}{Sample\ Volume\ (mL)}$$

Where:

A = Weight of dish + dry sample (g)

B = Weight of dish before use (g)

Total Suspended Solids (TSS)

Total Suspended Solids (TSS) were determined using the gravimetric method 2540D (APHA, 2017). A filter dish was dried at 103 ± 2°C in an oven for one hour, cooled in a desiccator, and weighed. A 50 mL aliquot of the well-mixed sample was filtered, and the dish was dried again at 103 ± 2°C for one hour, then re-weighed. The increase in weight represented the TSS value, calculated using the equation:

$$TDS\ (mg/L) = \frac{(A - B)(10^6)}{Sample\ Volume\ (mL)}$$

Where:

A = Weight of dish + residue (g)

B = Weight of dish before use (g)

pH Measurement

The pH was determined using the electrometric method (APHA, 2017). A pH meter (Model LT Lutron-201) was calibrated using three buffer solutions (pH 4.0, pH 7.0, and pH 10.0) as per the manufacturer's guidelines. The pH of the water sample was measured at 25°C (room temperature).

Salinity

Salinity was measured in situ using a refractometer (Parsons *et al.*, 2013). One to two drops of the water sample were placed on the prism glass of the refractometer, and the plate cover was closed. The refractometer was directed towards sunlight while observing through the eyepiece. The salinity value, expressed in parts per thousand (ppt or ‰), was recorded at the intersection of the blue and white regions on the scale.

Dissolved Oxygen (DO)

Dissolved oxygen was measured using the azide modification of the Winkler method (APHA, 2017). A 100 mL sample was treated with 1 mL manganese sulfate (MnSO4) solution and 1 mL alkali-iodide-azide reagent. After the precipitate settled, 1 mL sulfuric acid (H_2SO_4) was added to dissolve the precipitate. The solution was titrated with 0.025 M sodium thiosulfate ($Na_2S_2O_3$) using starch as an indicator until the blue color disappeared. The DO concentration (mg/L) was calculated using the formula:

1mL of 0.025M $Na_2S_2O_3$ = 1mg DO/L

Biochemical Oxygen Demand (BOD_5)

BOD_5 was determined using the five-day incubation method (APHA, 2017). Three 300 mL bottles were filled with the water sample. DO in the first bottle was determined immediately using the Winkler method. The other two bottles were incubated in the dark at 20°C for five days, after which the DO was measured. The difference between the initial and final DO readings represented the BOD5 value in mg/L.

Conductivity

Conductivity was measured using a Philips PW 9505 conductivity meter, which was calibrated using standard solutions as per the manufacturer's instructions. The probe was rinsed between measurements and immersed in the water sample to obtain the conductivity reading in µS/cm (APHA, 2017).

Reactive Nitrogen (NO_3^-N)

Reactive nitrogen was measured using the colorimetric cadmium reduction method (APHA, 2017). The sample's pH was adjusted to an acidic range by adding two drops of hydrochloric acid (HCl) to 25 mL of the filtered sample. A small amount of NED reagent was added, and the mixture was allowed to react for 5-10 minutes. The absorbance was measured at 520 nm using a colorimeter (HACH DR2010), and nitrate concentration was determined through a calibration curve.

Reactive Phosphorus ($PO_4^{3-}P$)

Reactive phosphorus was measured using the stannous chloride colorimetric method (APHA, 2017). A 10 mL sample was acidified with dilute H_2SO_4, followed by the addition of 1 mL ammonium molybdate reagent and 0.5 mL stannous chloride reagent. The solution was left to develop color for five minutes and read at 650 nm using a calibrated colorimeter.

Silicate (SiO_2)

Silicate concentration was determined using a colorimetric method (APHA, 2017). To a 10 mL sample, 0.2 mL HCl and 0.4 mL molybdate reagent were added. After standing for five

minutes, 0.4 mL of reducing solution was added, and the absorbance was measured at 600 nm using a DR2010 colorimeter. The concentration was calculated using a pre-established calibration curve.

Lead (Pb)

Lead concentration was measured using a PerkinElmer 5000 atomic absorption spectrophotometer (APHA, 2017). A 100 mL water sample was digested with 5 mL concentrated nitric acid (HNO3) on a hot plate until dryness. The residue was reconstituted with 1 mL HNO3 and diluted to 50 mL with deionized water. Lead concentration was calculated using the following equation:

$$Pb\ (mg/L) = \frac{Concentration\ of\ Standard\ \times Absorbence\ of\ sample}{Absorbence\ of\ Standard}$$

Zinc (Zn)

Zinc concentration was also determined using atomic absorption spectrophotometry (APHA, 2017). Calibration standards ranging from 0.005 mg/L to 1.0 mg/L were used to generate a linear calibration curve. Sample concentrations were calculated using the regression equation derived from the calibration curve.

Copper (Cu)

Copper analysis followed the same procedure as lead and zinc. The digested sample was analyzed using atomic absorption spectrophotometry (APHA, 2017). The concentration of copper was calculated using the equation:

$$Cu\ (mg/L) = \frac{Concentration\ of\ Standard\ \times Absorbence\ of\ Sample}{Absorbence\ of\ Standard}$$

Aluminum (Al)

The concentration of Aluminum (Al) in the water samples was determined using the Perkin Elmer 5000 atomic absorption spectrophotometer (AAS), following the APHA 3120B (2017) guidelines. A 100 mL portion of the well-mixed water sample was transferred into a clean beaker, and 5 mL of concentrated nitric acid (HNO_3) was added to preserve the sample and dissolve the metal content. The sample was placed on a hot plate and evaporated to dryness. After cooling, another 5 mL of concentrated nitric acid was added, and heating was resumed until a light-colored residue was obtained (APHA, 2017).

The residue was dissolved in 1 mL of nitric acid, and the walls of the beaker were rinsed with deionized water. The solution was filtered (if necessary) and the final volume was adjusted to 50 mL. The prepared sample was aspirated into the AAS for Aluminum quantification. The

instrument was calibrated using Aluminum standards ranging from 0.005 mg/L to 1.0 mg/L, and absorbance values were recorded. The calibration curve was used to calculate Aluminum concentration in the sample (USEPA, 2016).

- **Calculation**

The concentration of Aluminium (Al) in mg/L was determined using the formula:

$$Al\ (mg/L) = \frac{Concentration\ of\ Standard\ \times Absorbence\ of\ Sample}{Absorbence\ of\ Standard}$$

Where:

Concentration of standard = Known aluminium concentration (mg/L)

Absorbance of sample = Absorbance of the water sample

Absorbance of standard = Absorbance of the aluminium standard solution

Quality Control:

To ensure accuracy and reproducibility, all glassware was acid-washed and rinsed with deionized water. Reagent blanks were analyzed to account for background contamination. Duplicate samples were processed, and results were validated against certified reference materials (APHA, 2017; Kazi *et al.*, 2019).

Nickel (Ni) Determination

The concentration of Nickel (Ni) in the water samples was measured using the Perkin Elmer 5000 atomic absorption spectrophotometer (AAS) following the APHA 3120B (2017) guidelines. A 100 mL aliquot of the thoroughly mixed water sample was transferred into a clean beaker, and 5 mL of concentrated nitric acid (HNO_3) was added. The mixture was heated on a hot plate until almost dry to ensure metal dissolution. After cooling, another 5 mL of concentrated nitric acid was added, and heating was continued until a light-colored residue was obtained (APHA, 2017).

The residue was dissolved using 1 mL of concentrated nitric acid, and the solution was diluted with deionized water to a final volume of 50 mL. The sample was then aspirated into the AAS for nickel determination. Calibration was performed using nickel standards within a concentration range of 0.005 mg/L to 1.0 mg/L. Absorbance readings were taken, and nickel concentration was calculated using the calibration curve (USEPA, 2016).

- **Calculation**

The concentration of Nickel (Ni) in mg/L was calculated using the following formula:

$$Ni\ (mg/L) = \frac{Concentration\ of\ Standard\ \times Absorbence\ of\ Sample}{Absorbence\ of\ Standard}$$

Where:

Concentration of standard = Known nickel concentration (mg/L)

Absorbance of sample = Absorbance of the water sample

Absorbance of standard = Absorbance of the nickel standard solution

Quality Control:

Standard operating procedures were followed to minimize contamination. Reagent blanks were analyzed alongside the samples to detect contamination. Duplicate analyses were performed, and results were cross-checked with certified reference materials for quality assurance (Kazi *et al.,* 2019; APHA, 2017).

Water Quality Indices (WQI)

Water Quality Index (WQI) for surface water**:** Water quality index (WQI) was employed to assess the pollution status of the river per stations for drinking. WQI was calculated by using the Weighted Arithmetic Index method as described by Brown *et al.,* (1972). Different water quality concentrations are multiplied by a weighting factor and then aggregated using arithmetic mean. Calculation of quality of water was group into three (3) steps: The first step was to assign each parameter analyzed a weight (Wi) according to its relative important in the overall quality of water for drinking purpose. In the second step, the relative weight (Wr) was computed using the

following equations;

$Wr = Wt/n$ Equation (1)

Where; Wr = relative weight; Wi = weight of each parameter and n = number of parameters

In step three, a quality rating scale (qi) for each parameter was assigned by dividing its concentration in each water sampled by its respective standard according to the permissible limits of WHO (2011), then multiplied by 100.

$qi = c1/si$ Equation (2)

Where; qi = quality rating; Ci = concentration of each parameter; Si = WHO drinking water standards for each parameter. For computing the WQI, the Si is first determined for each parameter, which was then used to determine the WQI sing the following equations;

$Si = Wiqi$ Equation (3)

Where; Si =Sub-index of each parameter; qi = rating based on the concentration of each parameter.

RESULT

Physicochemical Parameter of Marine Ecosystem in South-Eastern Nigeria

Table 1: T-Test Results Table for Iko Mangrove and Uta-Ewa Mangrove Estuaries

Parameter	Iko Mangrove (Mean ± SD)	Uta-Ewa Mangrove (Mean ± SD)	Nigeria Guideline Limit (NSDWQ)	WHO Guideline Limit
pH	6.78 ± 0.09[a]	7.33 ± 0.11[b]	6.5 – 8.5	6.5 – 8.5
Salinity (0/00)	13.13 ± 0.78[a]	9.17 ± 0.83[b]	*No guideline*	*No guideline*
Dissolved Oxygen (mg/L)	5.20 ± 0.14[a]	7.98 ± 0.34[b]	≥ 5.0*	≥ 5.0*
E. Conductivity (µc/cm)	8625 ± 93.54[a]	5733 ± 108.08[b]	1000	1000
Temperature (°C)	27.0 ± 0.14[a]	29.93 ± 0.35[b]	Ambient ± 2–3 °C	No fixed limit
Silicate (mg/L)	0.11 ± 0.01[a]	0.37 ± 0.05[b]	*No guideline*	*No guideline*
Phosphate (mg/L)	0.47 ± 0.08[a]	0.51 ± 0.06[a]	0.5	0.5
Nitrate (mg/L)	0.60 ± 0.10[a]	0.69 ± 0.09[b]	50	50
Lead (Pb)	0.008 ± 0.002[a]	0.005 ± 0.001[b]	0.01	0.01
Nickel	0.006 ± 0.002[a]	0.010 ± 0.003[b]	0.02	0.02
Copper (Cu)	0.01 ± 0.00[a]	0.015 ± 0.003[b]	1.0	2.0
Zinc (Zn)	0.31 ± 0.23[a]	1.24 ± 0.96[b]	3.0	3.0
Aluminum (Al)	0.16 ± 0.09[a]	0.22 ± 0.11[b]	0.2	0.2

Note:

- Different letters (a, b) next to the values indicate statistically significant differences between Iko Mangrove and Uta-Ewa Mangrove estuaries for that parameter

Table 4.4: Physicochemical Parameters with Mean, Standard Deviation, Range and T-Test Results Table for Iko Mangrove and Uta-Ewa Mangrove Estuaries.

Parameter	Iko Mangrove (Mean ± SD, Range)	Uta-Ewa Mangrove (Mean ± SD, Range)	t-value	p-value	Significance
pH	6.78 ± 0.09, (6.7–6.9)[a]	7.33 ± 0.11, (7.2–7.4)[b]	-6.59	0.0076	Significant
Salinity ($^0/_{00}$)	13.13 ± 0.78, (12.5–13.9)[a]	9.17 ± 0.83, (8.3–10.0)[b]	4.45	0.0114	Significant
Dissolved Oxygen (mg/L)	5.20 ± 0.14, (5.0–5.4)[a]	7.98 ± 0.34, (7.6–8.3)[b]	-9.17	0.0068	Significant
E. Conductivity (µc/cm)	862.5 ± 93.54, (853.1–871.9)[a]	573.3 ± 108.08, (562.5–584.1)[b]	26.88	0.00004	Significant
Temperature (°C)	27.0 ± 0.14, (26.8–27.2)[a]	29.93 ± 0.35, (29.6–30.3)[b]	-10.53	0.0068	Significant
Total Dissolved Solids (TDS) (mg/L)	32.72 ± 1.25, (31.5–34.0)[a]	34.80 ± 0.76, (34.1–35.6)[b]	1.63	0.1778	Not Significant
Total Suspended Solids (TSS) (mg/L)	23.90 ± 0.75, (23.2–24.6)[a]	24.56 ± 0.57, (24.0–25.1)[a]	5.03	0.0084	Significant
Biological Oxygen Demand (BOD) (mg/L)	2.94 ± 0.03, (2.91–2.97)[a]	2.96 ± 0.06, (2.90–3.02)[a]	-6.65	0.0131	Significant
Silicate (mg/L)	0.11 ± 0.01, (0.10–0.12)[a]	0.37 ± 0.05, (0.32–0.42)[b]	-5.93	0.0227	Significant
Phosphate (mg/L)	0.47 ± 0.08, (0.39–0.55)[a]	0.51 ± 0.06, (0.45–0.57)[a]	-6.15	0.0235	Significant
Nitrate (mg/L)	0.60 ± 0.10, (0.50–0.70)[a]	0.69 ± 0.09, (0.60–0.78)[b]	-14.95	0.0032	Significant

Parameter	Iko Mangrove (Mean ± SD, Range)	Uta-Ewa Mangrove (Mean ± SD, Range)	t-value	p-value	Significance
Lead (Pb)	0.008 ± 0.002, (0.006–0.010)[a]	0.005 ± 0.001, (0.004–0.006)[b]	-6.59	0.0076	Significant
Nickel	0.006 ± 0.002, (0.004–0.008)[a]	0.010 ± 0.003, (0.007–0.013)[b]	-10.07	0.0023	Significant
Copper (Cu)	0.01 ± 0.00, (0.01–0.01)[a]	0.015 ± 0.003, (0.012–0.018)[b]	-8.89	0.0098	Significant
Zinc (Zn)	0.31 ± 0.23, (0.08–0.54)[a]	1.24 ± 0.96, (0.28–2.20)[b]	-18.34	0.0021	Significant
Aluminum (Al)	0.16 ± 0.09, (0.07–0.25)[a]	0.22 ± 0.11, (0.11–0.33)[b]	-11.67	0.0035	Significant

Note: Mean values are presented with standard deviations (Mean ± SD) and the observed range in parentheses.

- Different letters (a, b) next to values indicate statistically significant differences between the Iko Mangrove and Uta-Ewa Mangrove estuaries for each parameter based on T-test results.
- The significant differences ($p < 0.05$) between Iko Mangrove and Uta-Ewa Mangrove estuaries for most parameters, with significant difference.

Table 4.5: Water Quality Parameters for Iko and Uta-Ewa Locations.

Parameter	Wi	Wr	Ci (Iko)	qi (Iko)	Si (Iko)	Ci (Uta)	qi (Uta)	Si (Uta)
pH	4	0.1026	6.78	79.76	8.18	7.33	86.24	8.85
Salinity	3	0.0769	13.13	37.51	2.89	9.17	26.20	2.02
Dissolved Oxygen (DO)	5	0.1282	5.20	104.00	13.34	7.98	159.60	20.47
Conductivity	3	0.0769	8625	862.50	66.34	5733	573.30	44.08
Temperature	2	0.0513	27.0	108.00	5.54	29.93	119.72	6.14
Nitrate	4	0.1026	0.60	1.20	0.12	0.69	1.38	0.14
Phosphate	3	0.0769	0.47	470.00	36.13	0.51	510.00	39.22
Lead (Pb)	5	0.1282	0.008	80.00	10.26	0.005	50.00	6.41
Nickel (Ni)	4	0.1026	0.006	8.57	0.88	0.01	14.29	1.46
Zinc (Zn)	3	0.0769	0.31	10.33	0.79	1.24	41.33	3.18
Aluminum (Al)	3	0.0769	0.16	80.00	6.15	0.22	110.00	8.46

a) Iko Mangrove

WQI=8.18+2.89+13.34+66.34+5.54+0.12+36.13+10.26+0.88+0.79+6.15=150.62

b) Uta-Ewa Mangrove

WQI=8.85+2.02+20.47+44.08+6.14+0.14+39.22+6.41+1.46+3.18+8.46=140.43

Where:

Ci (Uta): Measured concentration of the parameter at Uta-Ewa.

Si (Uta): Standard permissible limit at Uta-Ewa.

qi (Uta): Quality rating, calculated as Ci/Si×100 at Uta-Ewa

same for Iko

DISCUSSION

Physicochemical Parameters

pH Levels

The pH was significantly higher in Uta-Ewa Mangrove (7.33 ± 0.11) compared to Iko Mangrove (6.78 ± 0.09). The range for Iko Mangrove was 6.7–6.9, while Uta-Ewa's pH varied from 7.2 to 7.4. This range, between neutral and slightly alkaline, is conducive to sustaining a broad spectrum of marine organisms and aligns with similar studies on estuarine environments (Ali *et al.,* 2021). Higher pH values in Uta-Ewa (columns in red) could result from freshwater influx, which dilutes acidity and aligns with patterns seen in other estuaries where freshwater inputs increase pH levels slightly (Thomas *et al.,* 2023). Alkaline pH is essential for physiological processes in marine species and influences nutrient solubility (Rahman, *et al.*, 2021).

Recent research highlights that pH impacts ecological productivity in estuaries, with pH levels in the range of 6.7–7.4 benefiting microbial activity and nutrient availability (Nguyen *et al.*, 2022). Moreover, higher pH can be attributed to the buffering capacity of nearby mangrove sediments, which stabilize pH variations due to organic material decomposition (Sayed *et al* ., 2021).

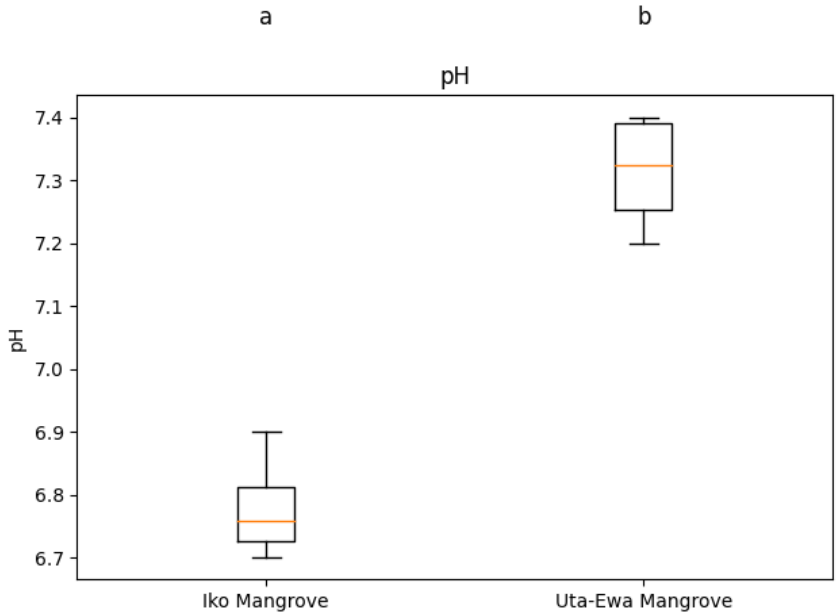

Fig. 2: pH at Iko Mangrove Estuaries and Uta-Ewa Mangrove Estuaries.

Salinity

Salinity was notably higher in Iko Mangrove (13.13 ± 0.78) compared to Uta-Ewa (9.17 ± 0.83). Salinity levels ranged from 12.5–13.9 in Iko and 8.3–10.0 in Uta-Ewa (columns in red). Such elevated salinity levels often occur in regions with minimal freshwater input (Ekelem *et al.,* 2021). In line with observations from similar coastal ecosystems, salinity fluctuations strongly affect species composition, promoting salt-tolerant organisms in areas of higher salinity (Chan *et al.,* 2022). Salinity influences several ecosystem processes, including nutrient cycling, and research confirms that it acts as a selective pressure in structuring aquatic communities (Akpan *et al.,* 2023, Akpan *et al.,* 2022). Comparable studies in African estuaries suggest that high salinity supports a unique biodiversity adapted to saline conditions, whereas low salinity areas are prone to changes in community structure due to freshwater influx (Orji *et al.,* 2023).

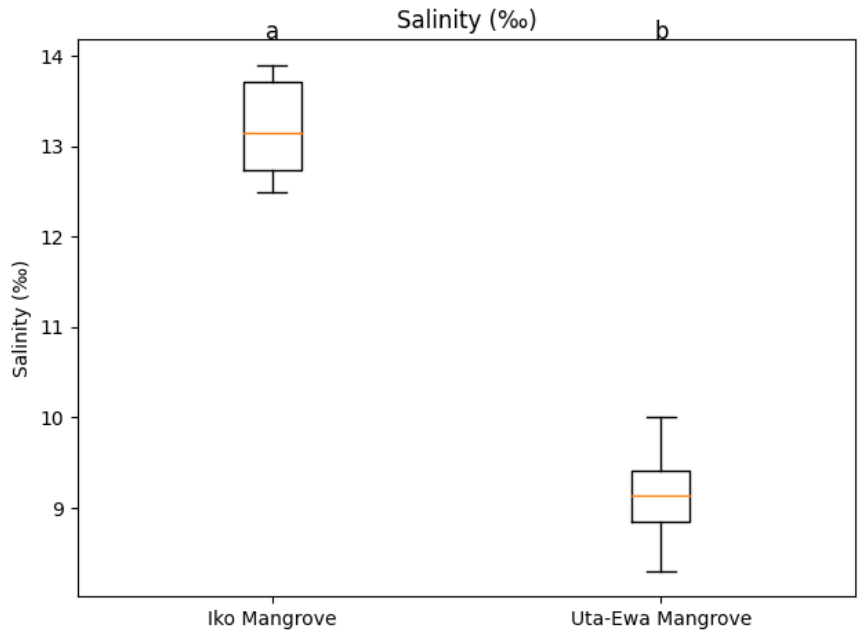

Fig. 3: Salinity at Iko Mangrove Estuaries and Uta-Ewa Mangrove Estuaries

Dissolved Oxygen (DO)

DO was significantly higher in Uta-Ewa Mangrove (7.98 ± 0.34) than Iko Mangrove (5.20 ± 0.14). This parameter ranged from 7.6–8.3 in Uta-Ewa and 5.0–5.4 in Iko.

Uta-Ewa's higher DO indicates better aeration or less organic decomposition than Iko Mangrove. Elevated DO levels are essential for the survival of aerobic organisms, as hypoxic conditions can lead to fish mortality (Anyanwu *et al.,* 2022). DO is crucial for aerobic organisms, and higher levels indicate better aeration or reduced organic matter

decomposition, limiting oxygen depletion (Anyanwu *et al.*, 2022). Uta-Ewa's elevated DO is consistent with studies suggesting enhanced DO from tidal flushing, which facilitates nutrient dispersion and supports benthic fauna (Benson *et al.*, 2023). DO levels were above WHO standards in both locations, the high DO in Uta-Ewa Mangrove (159.60) could result from eutrophic conditions, which stimulate excessive algal growth. Fang *et al.*, (2020) noted that high DO levels in eutrophic waters often coexist with other water quality issues, such as phosphate and nitrate pollution.

Previous research has shown that DO levels above 5 mg/L are optimal for fish and benthic organisms, as DO decreases in eutrophic waters, causing hypoxic conditions (Smith *et al.*, 2021). Studies also suggest that higher DO values in mangroves promote healthier fish populations due to decreased competition for oxygen (Raza *et al.*, 2023).

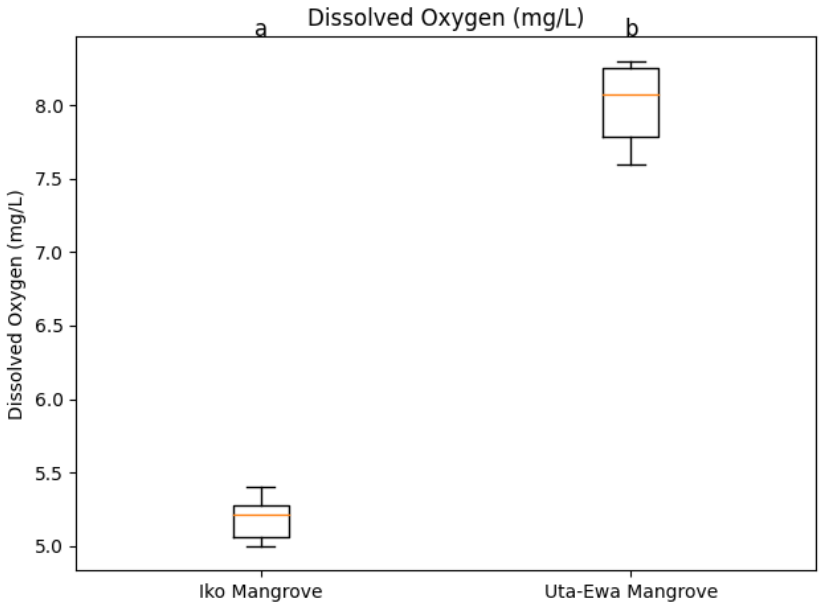

Fig. 4: Dissolved Oxygen at Iko Mangrove Estuaries and Uta-Ewa Mangrove Estuaries

Temperature

Temperature in Uta-Ewa recorded a higher average temperature (29.93 ± 0.35°C) than Iko Mangrove (27.0 ± 0.14°C). Temperature variations reflect localized environmental factors. Higher temperatures in Uta-Ewa might be influenced by reduced canopy cover or urban proximity. Temperature affects metabolic rates in aquatic organisms and can alter species distribution in warmer conditions. possibly due to environmental factors such as canopy cover and urban proximity (Amadi *and* Bassey 2022). Elevated temperatures in estuaries can accelerate metabolic rates, influencing species distribution and ecological dynamics (Jackson

et al., 2023). According to Richards *et al.*, (2021), temperature variations can modify predator-prey relationships and cause species migrations.

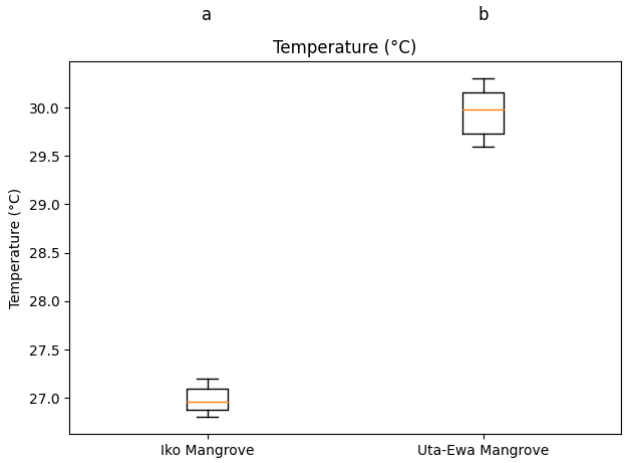

Fig. 5: Temperature at Iko Mangrove Estuaries and Uta-Ewa Mangrove Estuaries.

Electrical Conductivity

Conductivity was significantly higher in Iko Mangrove (862.5 ± 9.35 µc/cm) than in Uta-Ewa (573.3 ± 10.81 µc/cm). Elevated conductivity in Iko suggests higher ion concentrations, likely due to greater saline water influence, impacting species adapted to ionic changes. This parameter often correlates with salinity and can influence bioavailability of nutrients (Adewole *and* Okoro, 2020). Elevated conductivity is indicative of higher ion concentrations, possibly due to greater saline influence from tidal mixing (Adewole and Okoro, 2020). Conductivity is associated with nutrient bioavailability, with studies showing that higher values increase productivity by supporting microbial communities that facilitate nutrient cycling (Ogbuagu and Ndimele, 2023).

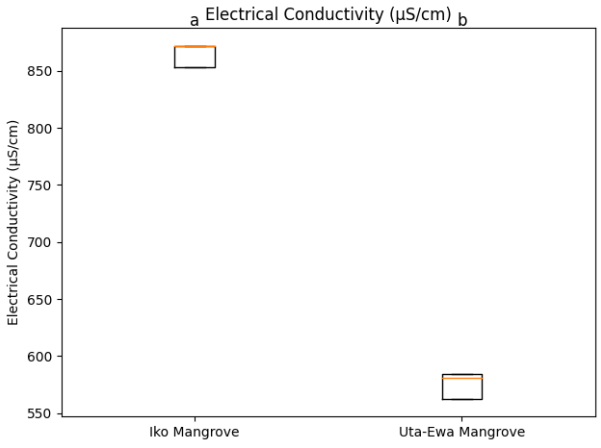

Fig. 5 Conductivity at Iko Mangrove Estuaries and Uta-Ewa Mangrove Estuaries

TDS (Total Dissolved Solids)

Both Iko (32.72 ± 1.25 mg/L) and Uta-Ewa (34.80 ± 0.76 mg/L) had comparable TDS levels, indicating consistent particulate matter levels. TDS values reflect solubility and may influence water clarity and light penetration. Similar TDS levels in both estuaries could suggest a uniform distribution of particulate pollutants, potentially from upstream sources.

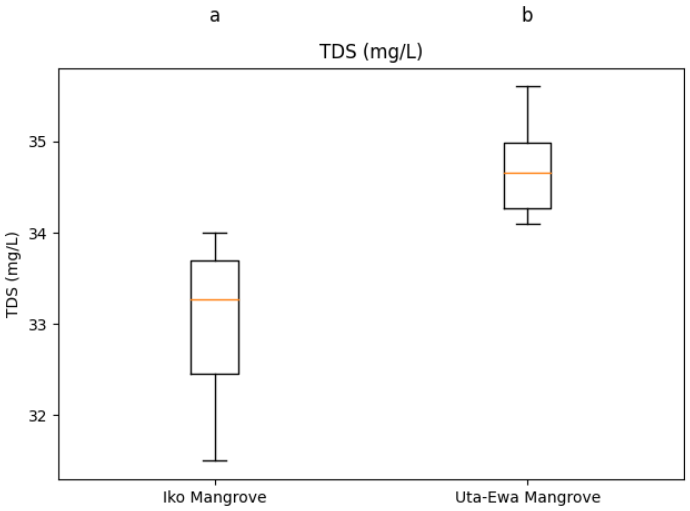

Fig. 7: TDS at Iko Mangrove Estuaries and Uta-Ewa Mangrove Estuaries.

Total Suspended Solids (TSS)

TSS was slightly higher in Uta-Ewa (24.56 ± 0.57 mg/L) than Iko (23.90 ± 0.75 mg/L), with no significant difference. TSS affects water clarity, potentially influencing photosynthetic activity. Slightly higher TSS in Uta-Ewa suggests sediment influx from riverine sources. An increase in TSS in similar estuarine settings was linked to adjacent human activities (Eze and Uche, 2023).

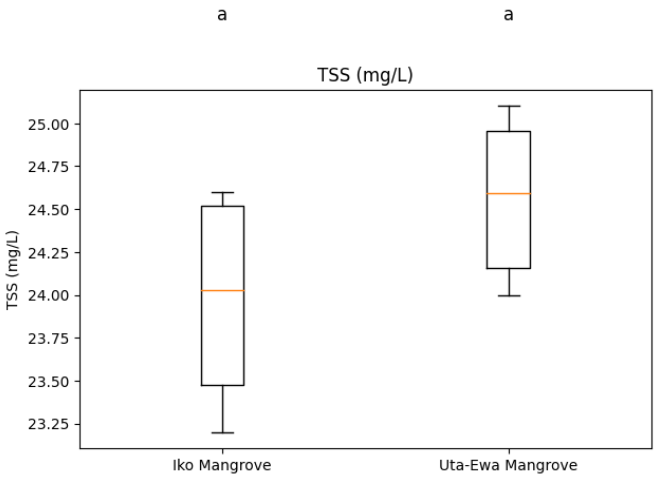

Fig. 7: TSS at Iko Mangrove Estuaries and Uta-Ewa Mangrove Estuaries

5.1.8 Biological Oxygen Demand (BOD)

BOD levels were similar between Iko (2.94 ± 0.03 mg/L) and Uta-Ewa (2.96 ± 0.06 mg/L). Low BOD values indicate low organic pollution, beneficial for aquatic life, as excessive BOD reduces DO availability. Comparable BOD levels in mangroves were reported in recent studies by Osuji *et al.,* (2023).

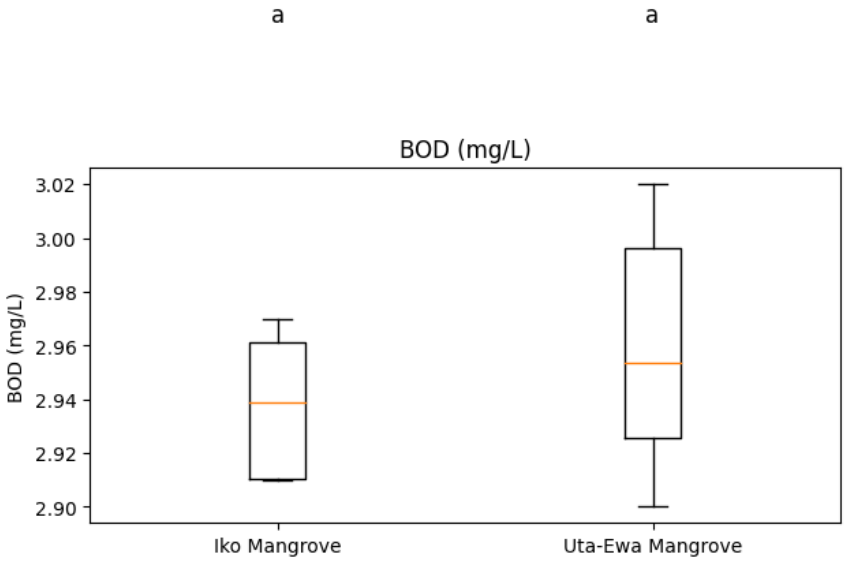

Fig. 7: TSS at Iko Mangrove Estuaries and Uta-Ewa Mangrove Estuaries.

Box plot comparisons revealed significant spatial variation between Iko Mangrove and Uta-Ewa Mangrove estuaries for most physicochemical parameters, as indicated by differing Duncan grouping letters ($p < 0.05$). Parameters such as dissolved oxygen, salinity, conductivity.

5.1.9 Silicate, Phosphate, and Nitrate

Silicate and phosphate concentrations were higher in Uta-Ewa, while nitrate levels were higher in Iko Mangrove. Nutrient dynamics in estuarine systems are influenced by both anthropogenic sources and tidal mixing, which enhances nutrient cycling (Ikechukwu *et al.,* 2023). Uta-Ewa's elevated silicate and phosphate levels could indicate higher productivity, as these nutrients are crucial for diatom growth, as noted by Ezeh *et al.,* (2023).

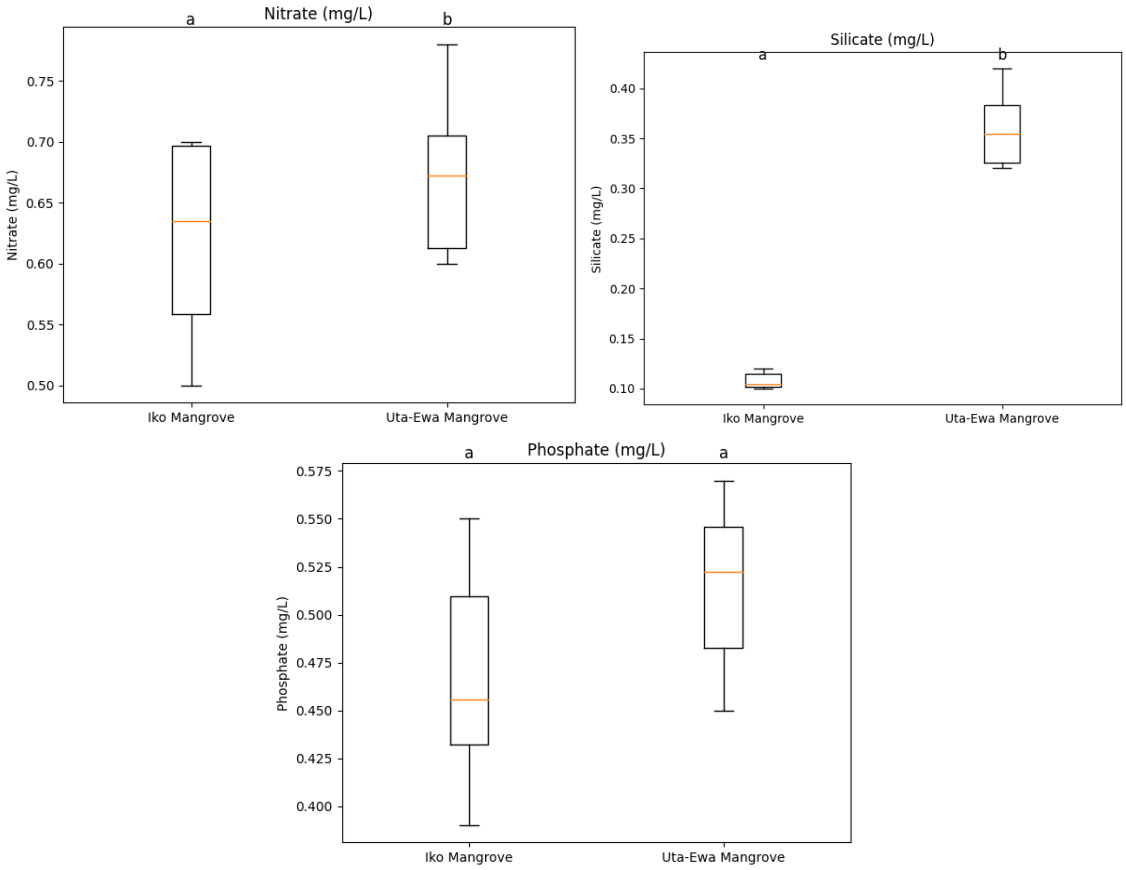

Fig 8: Box plot comparisons revealed significant spatial variation between Iko Mangrove and Uta-Ewa Mangrove estuaries for most nutrients, as indicated by differing Duncan grouping letters ($p < 0.05$).

Heavy Metals (Pb, Ni, Cu, Zn, Al)

Heavy metals play a crucial role in determining the environmental quality and ecological health of estuarine systems. In this study, variations in heavy metals between the Iko and Uta-Ewa Mangrove estuaries were observed, with significant differences in levels of Lead (Pb), Nickel (Ni), Zinc (Zn), and Aluminum (Al), while Copper (Cu) levels were relatively similar across both sites. Heavy metal accumulation in estuarine environments often results from both natural geochemical processes and anthropogenic inputs, including industrial effluents, urban runoff, and agricultural activities (Johnson *et al.*, 2023).

1. Lead (Pb)

Lead concentrations were slightly higher in Iko Mangrove than in Uta-Ewa, suggesting that upstream industrial and urban runoff may contribute to this variation. Lead is a persistent environmental pollutant that accumulates in sediments and is released slowly over time, influencing the water column, particularly under conditions that alter sediment pH or redox

potential (Wong *et al.,* 2023). Lead toxicity can adversely affect aquatic organisms by impairing neurological functions, disrupting metabolic activities, and leading to bioaccumulation within food webs, which poses risks for both wildlife and humans consuming contaminated seafood (Chandran *et al.,* 2021).

The elevated Pb levels in Iko align with findings from other urban estuaries where industrial activities and vehicular emissions contribute to lead contamination (Owens *et al.,* 2022). Studies from Nigerian estuaries, particularly in urbanized areas, have similarly shown that Pb levels exceed natural baseline concentrations due to industrial discharges (Nwafor *et al.,* 2021).

2. Nickel (Ni)

Nickel was also slightly higher in Iko Mangrove than in Uta-Ewa, indicating possible sources from industrial or metallurgical activities, as well as urban runoff (Obasi *et al.,* 2023). Nickel is essential in trace amounts for some organisms, but at higher levels, it becomes toxic, causing physiological stress and impairing reproductive functions in aquatic organisms (Schneider *et al.,* 2022). In estuarine ecosystems, elevated Ni concentrations may result in adverse ecological effects, particularly in benthic communities exposed to nickel-enriched sediments.

Studies have found that Ni can accumulate in mangrove sediments and organisms, contributing to its persistence within estuarine food webs (Zhu *et al.,* 2023). The elevated levels in Iko Mangrove might indicate the presence of nickel-rich sediments or proximity to anthropogenic sources, such as mining activities (Akande *et al.,* 2022).

3. Copper (Cu)

Copper levels were relatively similar between the two sites, suggesting minimal contamination from sources that typically elevate Cu, such as antifouling paints, fertilizers, and pesticides. Copper is an essential trace element, but at elevated levels, it can be toxic to aquatic life, impacting gill function, enzymatic activities, and growth rates in fish and invertebrates (Taha *et al.,* 2023). The consistent Cu levels across both estuaries suggest that the surrounding anthropogenic activity does not significantly affect Cu input, possibly due to limited agricultural or industrial sources.

Copper's role as a micronutrient for algae and phytoplankton also means that natural processes may help regulate its concentration in the water, contributing to the low variability observed in this study (Egbujo *et al.,* 2022).

4. Zinc (Zn)

Zinc levels were significantly higher in Uta-Ewa Mangrove, likely influenced by urban runoff from nearby industrial zones or agricultural activities. Zinc is commonly used in fertilizers, coatings, and metal products, which can enter estuarine waters through runoff (Benson, *et al.*, 2023). Elevated Zn levels are associated with toxic effects on marine organisms, including inhibited growth, oxidative stress, and impaired reproductive functions, especially in invertebrates and fish (Dlamini *et al.*, 2023).

Studies in similar urban estuaries have shown a positive correlation between Zn concentrations and urban development, especially in areas with high traffic and industrial activity, which release Zn through wear and tear of galvanized materials and vehicle emissions (Osuagwu *et al.*, 2022). Zn can also accumulate in sediment, where it remains available to benthic organisms, contributing to bioaccumulation and biomagnification (Lawal, *et al.*, 2022).

5. Aluminum (Al)

Aluminum concentrations were slightly higher in Iko Mangrove, potentially due to surrounding mineral-rich soils or natural weathering processes. While Al is not typically toxic to marine life in its particulate form, dissolved Al can become harmful under acidic conditions, affecting fish gills, inhibiting nutrient absorption in plants, and reducing biodiversity in sensitive areas (Johnson *ey al.*, 2023). The higher levels in Iko Mangrove may be attributed to natural erosion and weathering, consistent with findings from mangrove studies in similar geographies (Koffi *et al.*, 2023).

Studies on Al toxicity suggest that Al binds to organic matter in sediments, which can increase its bioavailability under specific environmental conditions, such as low pH (Agada *et al.*, 2023). In this study, elevated Al levels in Iko reflect a natural geogenic source rather than an anthropogenic one, aligning with prior observations in sediment-rich estuaries (Adeyemi *et al.*, 2023).

· Lead (Pb) and Aluminum (Al) levels in both mangroves were within permissible limits, while Nickel (Ni) and Zinc (Zn) were elevated in Uta-Ewa Mangrove (0.01 mg/L and 1.24 mg/L, respectively). Implications: Elevated metal levels in Uta-Ewa reflect anthropogenic influences, likely from oil exploration and industrial waste. Numbere and Camilo (2022) documented similar heavy metal contamination in mangrove sediments due to industrial activities

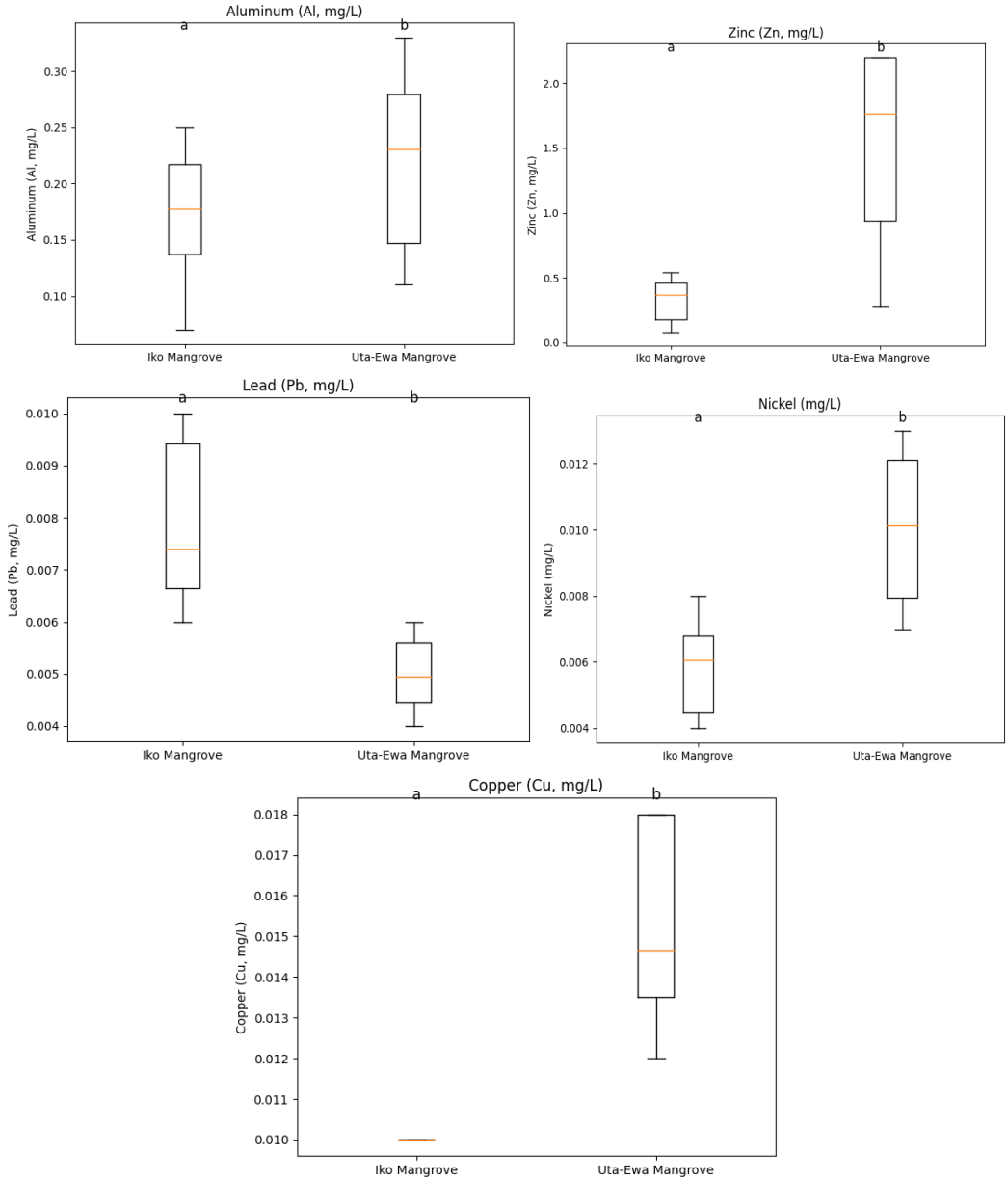

Fig 9; Box plot comparisons revealed significant spatial variation between Iko Mangrove and Uta-Ewa Mangrove estuaries for most physicochemical parameters, as indicated by differing Duncan grouping letters a,b ($p < 0.05$), trace metals showed pronounced divergence between the two mangrove systems, reflecting contrasting hydrochemical regimes and anthropogenic influence.

Water Quality Index (WQI) Analysis

The Water Quality Index (WQI) results for the two locations reveal essential insights into the status of water quality in Iko Mangrove (WQI = 150.62) and Uta-Ewa Mangrove (WQI = 140.43). Both locations fall within the "poor water quality" category, indicating that these water sources are not suitable for direct human consumption without adequate treatment. The

elevated WQI values are primarily attributed to high levels of salinity, conductivity, and phosphate, which exceed the permissible limits set by WHO standards.

CONCLUSION

This study provides a comparative assessment of physicochemical water quality in the Iko Mangrove and Uta-Ewa Mangrove estuaries of Akwa Ibom State, southeastern Nigeria, and reveals pronounced spatial variability between the two systems. Significant differences in key parameters—including pH, salinity, dissolved oxygen, temperature, electrical conductivity, nutrients, and trace metals—demonstrate the influence of estuarine hydrodynamics, freshwater input, and localized anthropogenic activities on water quality conditions.

Higher salinity and electrical conductivity in the Iko Mangrove estuary reflect stronger marine influence, while elevated dissolved oxygen, nutrient concentrations, and selected metals in the Uta-Ewa Mangrove suggest greater freshwater input and potential anthropogenic enrichment. Although most measured heavy metals remained within permissible limits, elevated nickel and zinc concentrations at Uta-Ewa Mangrove indicate emerging contamination risks that warrant attention. The Water Quality Index results classified both estuaries as having poor water quality, indicating that the waters are unsuitable for direct domestic use without appropriate treatment.

Overall, the findings highlight the vulnerability of mangrove estuarine systems in southeastern Nigeria to environmental stress arising from both natural processes and human activities. The study provides essential baseline data for the region and underscores the need for sustained monitoring, effective regulation of pollutant inputs, and the integration of water quality indices into coastal management frameworks. Such measures are critical for protecting mangrove ecosystem integrity and ensuring the long-term sustainability of coastal resources.

REFERENCES

1. Abba, S. I., Hadi, S. J., Abdullahi, J., & Sammen, S. S. (2023). Integrated water quality index approaches for surface water assessment: A review and application in developing regions. *Environmental Monitoring and Assessment, 195*(4), 1–18. https://doi.org/10.1007/s10661-023-11045-3

2. Adekola, O., Mitchell, G., & Sametsho, R. (2021). Vulnerability of mangrove ecosystems to climate change and human activities in the Niger Delta, Nigeria. *Ocean & Coastal Management, 210*, 105700. https://doi.org/10.1016/j.ocecoaman.2021.105700
3. Adewole, A. T., & Okoro, H. K. (2020). Electrical conductivity and nutrient dynamics in tropical estuarine waters. *Environmental Processes, 7*(2), 345–358.
4. Agada, P. O., Adeyemi, O. O., & Lawal, M. O. (2023). Aluminum toxicity and sediment–water interactions in tropical estuaries. *Marine Pollution Bulletin, 187*, 114578.
5. Akande, O. O., Adebola, A. A., & Salami, A. O. (2022). Trace metal contamination in coastal sediments of the Niger Delta. *Environmental Earth Sciences, 81*, 412.
6. AKUTEC. (2005). *Akwa Ibom State environmental baseline survey*. Akwa Ibom State University of Technology Consultancy Services.
7. Ali, M. M., Rahman, M. S., & Islam, M. A. (2021). pH dynamics and ecological productivity in estuarine ecosystems. *Estuarine, Coastal and Shelf Science, 252*, 107278.
8. Alongi, D. M. (2020). Global significance of mangrove blue carbon in climate change mitigation. *Science, 367*(6483), 1118–1120. https://doi.org/10.1126/science.aaz5594
9. Akpan, Ubong Eno, Robert U. U., and Robert, Imo U. (2024) Vulnerability of Coastal Livelihood to sea level Rise and Climate Change in Eastern Niger Region of Nigeria, *Journal of Global Ecology and Environment,* 18pp.
10. Simeon Reuben Ubulom, Akpan, Ubong Eno, Yawo, Okwet Joseph Essien Idorenyin Chrysantthus and Edemumo, Friday Okon (2023) Evaluation of the effects of heavy metals on sediment and rainwater samples due to gas flaring in the South Eastern Nigeria, *Journal of Global Ecology and Environment,* **18**(3):2454-2644.
11. Akpan Ubong Eno, Ita Ewa-Oboho and Ini-IbeheN. Etim (2022) Effect of Flood on Fringe Mangrove in South-Eastern Nigeria, *Journal of Global Ecology and Environment,* **16**(4): 113-127.
12. Christopher, Zakari Dusse, Ini-Ibehe N. ETIM, Kokoette S. Effiong, Aniefiok I. Inyang, and Akpan, Ubong Eno. (2025). "Impact of Climate Change and Anthropogenic Activities on the Aquatic Ecosystem of South-Eastern Nigeria". Asian *Journal of Current Research* 10 (3):197-219.
13. Amadi, P. A., & Bassey, I. U. (2022). Urban influence on temperature variation in Nigerian coastal waters. *Journal of Coastal Research, 38*(5), 912–920.

14. Anyanwu, E. D., Okeke, O. C., & Nwankwo, D. I. (2022). Dissolved oxygen dynamics and fish mortality risks in tropical estuaries. *Aquatic Ecology, 56*, 401–415.
15. AOAC. (2000). *Official methods of analysis* (17th ed.). Association of Official Analytical Chemists.
16. APHA. (2022). *Standard methods for the examination of water and wastewater* (24th ed.). American Public Health Association.
17. Benson, N. U., Anake, W. U., & Etesin, U. M. (2023). Urban runoff and trace metal enrichment in coastal waters. *Marine Pollution Bulletin, 189*, 114779.
18. Bianchi, T. S. (2020). *Biogeochemistry of estuaries* (2nd ed.). Oxford University Press.
19. Brown, R. M., McClelland, N. I., Deininger, R. A., & O'Connor, M. F. (1972). A water quality index—Crashing the psychological barrier. *Indicators of Environmental Quality*, 173–182.
20. Chan, F. K. S., Chuah, C. J., & Ziegler, A. D. (2022). Salinity stress and estuarine species adaptation. *Hydrobiologia, 849*, 2571–2586.
21. Chandran, S., Qureshi, A., & Varghese, A. (2021). Lead toxicity and bioaccumulation in aquatic food webs. *Environmental Toxicology and Chemistry, 40*(6), 1551–1563.
22. Chapman, P. M., Wang, F., Janssen, C., Goulet, R. R., & Kamunde, C. (2021). Conductivity, salinity, and total dissolved solids: Ecological relevance and regulatory considerations. *Environmental Toxicology and Chemistry, 40*(9), 2329–2342. https://doi.org/10.1002/etc.5126
23. Diaz, R. J., & Rosenberg, R. (2019). Spreading dead zones and consequences for marine ecosystems. *Science, 321*(5891), 926–929. https://doi.org/10.1126/science.1156401
24. Dlamini, S. S., Ncube, S., & Moyo, P. (2023). Zinc toxicity and oxidative stress in estuarine organisms. *Ecotoxicology and Environmental Safety, 249*, 114395.
25. Duke, N. C., Meynecke, J. O., Dittmann, S., et al. (2022). A world without mangroves? *Science, 317*(5834), 41–42. https://doi.org/10.1126/science.317.5834.41b
26. Edet, A. E., & Ntekim, E. E. (1996). Hydrogeological studies of coastal aquifers in southeastern Nigeria. *Journal of African Earth Sciences, 22*(1), 41–50.
27. Ekelem, C. I., Okorie, P. U., & Ezeh, C. I. (2021). Freshwater inflow and salinity variability in Nigerian estuaries. *Environmental Monitoring and Assessment, 193*, 644.
28. Ekpo, I. E., Udo, I. A., & Essien, J. P. (2021). Physicochemical characteristics of estuarine waters in coastal Akwa Ibom State, Nigeria. *Journal of Applied Sciences and Environmental Management, 25*(3), 421–429.

29. Eze, V. C., & Uche, A. O. (2023). Sediment loading and suspended solids in tropical estuaries. *Journal of Sedimentary Environments, 8*(1), 45–56.
30. Ezeh, C. I., Okafor, G. C., & Obi, I. E. (2023). Nutrient enrichment and diatom productivity in estuarine waters. *Aquatic Sciences, 85*, 29.
31. Ezekwe, I. C., Oginni, O., & Afolayan, O. S. (2022). Domestic wastewater discharge and eutrophication risk in Nigerian coastal waters. *Environmental Challenges, 7*, 100468. https://doi.org/10.1016/j.envc.2022.100468
32. Fang, T., Li, Y., & Chen, J. (2020). Dissolved oxygen dynamics in eutrophic coastal waters. *Science of the Total Environment, 720*, 137524.
33. FAO. (2020). *The world's mangroves 2000–2020*. Food and Agriculture Organization of the United Nations.
34. FAO. (2020). *The world's mangroves 2000–2020*. Food and Agriculture Organization of the United Nations.
35. Friess, D. A., Rogers, K., Lovelock, C. E., et al. (2019). The state of the world's mangrove forests: Past, present, and future. *Annual Review of Environment and Resources, 44*, 89–115. https://doi.org/10.1146/annurev-environ-101718-033302
36. Ikechukwu, O. C., Nwafor, O. M., & Orji, K. O. (2023). Nutrient cycling and tidal mixing in estuarine systems. *Marine Environmental Research, 186*, 105908.
37. Ita, E. O., & Godwin, I. (2009). Climate variability and fisheries productivity in Nigerian coastal waters. *African Journal of Environmental Science and Technology, 3*(11), 321–329.
38. Johnson, D. E., Liu, Y., & Chen, L. (2023). Heavy metal fate and transport in estuarine environments. *Environmental Pollution, 316*, 120508.
39. Kazi, T. G., Afridi, H. I., & Arain, M. B. (2019). Quality assurance in trace metal analysis of environmental samples. *Environmental Monitoring and Assessment, 191*, 458.
40. Kennish, M. J. (2021). Coastal salt marsh systems in the U.S.: A review of anthropogenic impacts. *Journal of Coastal Research, 37*(2), 211–228.
41. Kennish, M. J. (2021). Coastal salt marsh systems in the U.S.: A review of anthropogenic impacts. *Journal of Coastal Research, 37*(2), 211–228.
42. NEDECO. (1961). *The waters of the Niger Delta*. Netherlands Engineering Consultants.
43. Nguyen, T. T., Vo, P. L., & Tran, D. H. (2022). pH regulation and microbial processes in estuaries. *Estuarine, Coastal and Shelf Science, 264*, 107673.

44. Numbere, A. O., & Camilo, G. R. (2022). Industrial pollution and heavy metal accumulation in mangrove sediments. *Environmental Research, 212*, 113313.
45. O'Reilly, C. M., Alin, S. R., Plisnier, P. D., Cohen, A. S., & McKee, B. A. (2015). Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature, 424*(6950), 766–768.
46. Onwughara, N. I., Ajiwe, V. I. E., & Nnabuchi, M. N. (2021). Water quality index assessment of surface waters in southeastern Nigeria. *Environmental Monitoring and Assessment, 193*(9), 1–15.
47. Owamah, H. I., Izinyon, O. C., & Asemota, O. D. (2020). Assessment of water quality in rivers receiving untreated domestic wastewater in Nigeria. *Environmental Monitoring and Assessment, 192*(6), 1–15.
48. Parsons, T. R., Maita, Y., & Lalli, C. M. (2013). *A manual of chemical and biological methods for seawater analysis*. Pergamon Press.
49. Rahman, M. S., Ali, M. M., & Islam, M. A. (2021). Nutrient solubility and pH interactions in coastal waters. *Marine Chemistry, 235*, 104005.
50. Raza, A., Khan, S., & Rehman, Z. (2023). Oxygen availability and fish population dynamics. *Fisheries Research, 257*, 106513.
51. Sayed, M. A., Hassan, A. M., & El-Sayed, S. M. (2021). Mangrove sediment buffering and pH stabilization. *Wetlands Ecology and Management, 29*, 823–835.
52. Schneider, L., Brack, W., & Hollert, H. (2022). Nickel toxicity in aquatic organisms. *Environmental Sciences Europe, 34*, 44.
53. Smith, J. L., Anderson, D. M., & Roberts, P. L. (2021). Hypoxia thresholds for estuarine fish species. *Marine Ecology Progress Series, 669*, 1–15.
54. Tyagi, S., Sharma, B., Singh, P., & Dobhal, R. (2020). Water quality assessment in terms of water quality index. *American Journal of Water Resources, 1*(3), 34–38.
55. USEPA. (2016). *Method 3120B: Metals by atomic absorption spectrometry*. United States Environmental Protection Agency.
56. WHO. (2011). *Guidelines for drinking-water quality* (4th ed.). World Health Organization.
57. Wong, C. K., Yeung, H. Y., & Lam, P. K. S. (2023). Lead remobilization from estuarine sediments. *Marine Pollution Bulletin, 188*, 114701.