

(Original Research Article)

COMPARATIVE STUDY OF SEDIMENT PROPERTIES BETWEEN *NYPA FRUTICANS*-DOMINATED AND RHIZOPHORA-DOMINATED FORESTS IN IKO CREEK

ABSTRACT

This study provides a comparative analysis of sediment properties and ecological impacts in *Nypa fruticans* and *Rhizophora racemosa*-dominated mangrove ecosystems within the Iko River estuary, Nigeria. *Nypa fruticans*, initially introduced to combat erosion, has spread extensively, often displacing the native *Rhizophora racemosa* and forming stands that alter local sediment properties. The study assessed parameters including pH (6.06–8.05), dissolved oxygen (DO; 2.5–4.7 mg/L), salinity (22–30 ppt), organic carbon (0.43–2.81 mg/kg), and organic matter (5.79–7.41%), revealing significant differences ($p < 0.05$) between the two vegetation types. *Rhizophora*-dominated sites showed higher organic carbon and DO levels, supporting better nutrient cycling and water quality, while *Nypa*-dominated sites exhibited elevated silicate levels and lower electrical conductivity, indicating possible change in the sediment profile which may impacts the habitat suitability and nutrient availability for native species. The findings highlight a critical research gap in understanding the long-term ecological effects of *Nypa fruticans* invasion on sediment chemistry and biodiversity, particularly regarding heavy metal accumulation and microbial dynamics in sediment profiles. This study contributes to existing knowledge by providing baseline data on sediment properties and identifying key areas for further investigation, including microbial interactions and heavy metal bioaccumulation in invaded mangrove systems. The insights gained underscore the need for conservation and targeted management strategies to preserve *Rhizophora racemosa* habitats, which play a crucial role in sustaining biodiversity and enhancing ecosystem resilience against climate change.

Commented [u1]: Possible.

Commented [u2]: Remove.

Commented [u3]: Input 4-5 Keywords after the abstract.

1.1 Introduction

Nypa fruticans, commonly known as the Nypa palm, is a crucial component of the Asian mangrove forest, with distribution spanning parts of Europe, Africa, and the Americas [1]. Introduced to the African sub-region in 1906 from Southeast Asia, *Nypa fruticans* was initially planted in Nigeria to stabilize coastlines against erosion, yet its establishment has resulted in

extensive spread across regions like Iko River estuary in Akwa Ibom State. This invasive growth has displaced native mangrove species, leading to monospecific stands that now dominate areas within the Niger Delta [2, 3]. *Nypa fruticans* thrives due to its specialized adaptations, including underground rhizomes that facilitate vegetative propagation and resist strong water currents [4]. It grows best in calm mangrove environments with high freshwater inflows, where sediments and brackish conditions create clay-like and anaerobic soils suitable for its viviparous germination and seed dispersal [5].

The Niger Delta, a region known for significant crude oil production, has experienced environmental degradation from industrial waste and heavy metal contamination [6], which impacts the mangrove forests [7,3]. Anthropogenic activities have intensified mangrove depletion rates, with heavy metals and other pollutants posing serious threats to these ecosystems [8]. Mangrove sediments are known for their ability to retain heavy metals, with mangrove plants like *Nypa fruticans* and *Rhizophora racemosa* showing varying tolerances to such contaminants [9]. For instance, *Nypa fruticans* can tolerate higher concentrations of chromium (Cr) and zinc (Zn) compared to *Rhizophora racemosa*, positioning it as a resilient species in contaminated areas [10]. In addition, these plants may act as indicators, tolerant species, or hyperaccumulators depending on their ability to survive and manage heavy metal accumulation [11]. This study aims to assess and compare sediment pH and other sediment properties across *Nypa fruticans* and *Rhizophora racemosa* growth sites at Iko estuary.

Commented [u4]: Italized.

Commented [u5]: Italized. This should be applied allthroughout.

Commented [u6]: Remove this sentence. This was already mentioned at the last part of the introduction.

Nypa fruticans and *Rhizophora racemosa* have long coexisted in the mangrove ecosystems of the Niger Delta. However, the invasive nature of *Nypa fruticans* alters the physical, chemical, and biological properties of sediments, potentially impacting native species and ecosystem functions. These sediment properties influence plant establishment and growth, underscoring the need to examine sediment characteristics in *Nypa*-dominated and *Rhizophora*-dominated forests to understand their effects on vegetation dynamics and ecological balance.

Therefore, this study is necessary to raise awareness of the impacts of *Nypa fruticans* on local ecosystems and to educate the inhabitants of Iko Creek and surrounding areas about the environmental shifts caused by *Nypa fruticans*' spread. Additionally, it provides baseline information for researchers studying sediment composition and the broader effects of mangrove invasion on sediment properties and nutrient cycling in coastal ecosystems.

The aim of this study is to compare the sediment properties between *Nypa fruticans*-dominated and *Rhizophora*-dominated forests in Iko River estuary.

1. Analyzing sediment samples from *Nypa fruticans* and *Rhizophora racemosa* growth sites at Iko River estuary.
2. Determining differences in organic matter content across these growth sites.
3. Assessing sediment compaction and nutrient levels, such as potassium and calcium ions, in the respective areas; and
4. Making recommendations based on the study findings.

Commented [u7]: Italized.

Commented [u8]: What properties are you analyzing? Better indicate here. You may... Analyzing sediment samples (i.e Temperature, D.O, salinity, and electrical conductivity) from *Nypa fruticans* and

Commented [u9]: Use semi colon after the word areas and add and.

MATERIAL AND METHOD

2.1 STUDY AREA

This research was carried out in *Rhizophora racemosa* dominated and *Nypa fruticans* dominated area at Iko estuary in Iko town, Eastern Obolo L.G.A., Niger Delta, Nigeria. Coastal water of Eastern Obolo drains into Atlantic Ocean and is connected to Qua Iboe River estuary at the east and Imo River estuary at the west [12]. (Fig. 1). Iko River is located in the Eastern part of the Niger Delta between 4°33' N – 4°50' N; 7°45' E – 7°55' E and about 650m above sea level in the tropical mangrove forest belt east of the Niger Delta, (Fig. 1). 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 numerous tributaries [13]. Extensive tidal flats and marshes define the areas adjacent to the channels. This area experience two seasons, the dry (October to May) and wet (April to October) with an annual rainfall averaging about 2500 mm [14]. The mean annual daily evaporation of the area is 4.6 mm per day [15], The hydrology of Iko Estuary is affected by tides, although seasonal influences which are related to the climatic regime, are evident. Iko Estuary is directly influenced by processes in the Atlantic coastal waters [16]. Iko River estuary which is significant in the provision of suitable breeding sites for the diverse aquatic resources that abound in the area, good fishing ground for artisan fishermen as well as petroleum exploration and production activities [16].

Commented [u10]: Italized

Commented [u11]: Italized and correct the species. It should be fruticans.

2.1.1 Sample location

Three sampling points along the coast of Iko estuary (three each of the *Nypa fruticans* and *Rhizophora racemosa* dominated areas) were established for the study based on their accessibility, nearness to urban settlement and their sustainability for future surveys, these stations are accessible through navigation by boats.

Commented [u12]: Italized and correct the species. Should be fruticans.

2.1.2 Sampling

Surface sediment samples at different sampling points was measured at insitu for temperature, dissolved oxygen and salinity while sediment was sub-sampling for laboratory analyses with polyethylene plastic container and labelled immediately at the field. The samples were stored at 4°C to maintain the present status of the indicated parameters and transported to the laboratory where they were analysed immediately. All analyses were performed following the American Public Health Association (APHA) standard procedures (2005) [17].

2.2 Physicochemical Analysis

2.2.1 pH Determination

The pH of the sample was determined electrometrically with the use of a Mettler Toledo pH meter. The pH meter was calibrated using Buffer 4.0, 7.0 and 9.0. Thereafter, the pH meter was used to determine the pH of the water sample.

2.2.6 Nitrate analysis in sediment sample

The collected sediment samples were sieved using a 0.5 mm mesh sieve. Ten grams of the sieved sediment was then measured using a weighing balance and put into a sampling bottle of 130 ml. Twenty millilitre of potassium sulphate (K_2SO_4) was also added into the sampling bottle. The mixture was kept in an orbital shaker for about 30 minutes. Mixture was filtered, and the filtrate kept in a sampling bottle. One millilitre of salicyclic acid and 10 ml of sodium hydroxide (NaOH) were added to the filtrate which was observed for an hour for colour change (chlorination). The readings were done using 6405 UV\Vis Spectrometer with a wavelength of 220 nm.

2.2.7 Phosphate analysis in sediment sample.

Five grams of sieved sediment was measured into a sampling bottle and 25 ml of Bray solution was added. The mixture was filtered into a sampling bottle using Whattman filter paper 110 mm diameters. 8 ml of filtrate was measured into another sampling bottle and 25 ml of Bray solution was added to another disposable scintillating vials. 10 drops of phosphorus reagent B were added and observed for 1 hour. Afterward, 10 drops of phosphorus reagent C were also added. The reading was done using 6405 UV\Vis Nanometer with a wavelength of 220 nm.

2.3 Organic matter

About 10g sediments of each sample was weighed using a weighing balance, homogenised, and placed on a pre-weighed labelled aluminium foil. The samples were combusted at 450 °C for 4 hours in an oven. Samples were then kept in a desiccator to cool while dry. The samples were then weighed to at least one decimal point [18]. The percentage of organic matter was calculated using the following formula

$$\% \text{ organic matter} = (\text{initial weight (g)} - \text{final weight (g)}) / 100$$

Statistical Analysis:

Data were analyzed using SPSS software (version 22.0). Descriptive statistics summarized water quality parameters, while Comparison of *Rhizophora racemosa* To *Nypa fruitican* Dominated Sites Using ANOVA. Results were considered significant at $p < 0.05$.

Commented [u13]: Use the Insert equation to type the formula.

Commented [u14]: Is this Capital or small letter?

Commented [u15]: Is this Capital letter of small letter?

Commented [u16]: Is the beginning of the word a Capital letter? Or small letter. Likewise, spell out what ANOVA is since this is an acronym.

Commented [u17]: Your spacing is not consistent. Some are 1.5 space and some are double (2) space .

3.0

RESULTS AND DISCUSION

3.1 Physicochemical parameters

The physico-chemical parameters of sediment taken from three strategic locations at both *Rhizophora racemosa* dominated and *Nypa fruitican* dominated mangrove swamp in Iko, Eastern Obolo L.G.A., as seen in Table 1 and Figure 2 below.

Commented [u18]: Font size should be consistent as Times New Roman

Commented [u19]: Should be double space allthroughout.

UNDER PEER REVIEW

Table 1 Mean physicochemical and nutrient concentration in surface sediment of Rhizophora and Nypa dominated swamp in Iko river estuary

Parameters Analysed	<i>Rhizophora racemosa</i> Dominated Mean \pm SD	<i>Nypa fruitican</i> Dominated Mean \pm SD	t-statistic	p-value	Significant Difference
Temperature (°C)	30 \pm 4.47	32.33 \pm 4.64	2.12	0.043	Yes
pH	7.93 \pm 2.30	6.55 \pm 2.09	3.89	0.01	Yes
DO (mg/L)	4.07 \pm 1.65	2.9 \pm 1.39	2.25	0.049	Yes
Salinity (ppt)	28.3 \pm 4.35	28.33 \pm 4.35	0.02	0.988	No
Phosphate (mg/L)	0.84 \pm 0.75	10.33 \pm 2.62	-0.29	0.738	No
Nitrate (mg/L)	1.81 \pm 1.10	1.23 \pm 0.91	2.36	0.032	Yes
Silicate (mg/L)	0.52 \pm 0.59	0.84 \pm 0.75	0.98	0.33	No
Organic Carbon (mg/L)	2.78 \pm 1.36	1.17 \pm 0.88	2.45	0.025	Yes
Organic Matter (%)	6.89 \pm 2.14	5.89 \pm 1.98	1.12	0.29	No
Electrical Conductivity (μ S/cm)	1561.93 \pm 32.27	1423.88 \pm 30.81	1.73	0.08	No

Commented [u20]: Decimal points should be consistent. Use two values only.

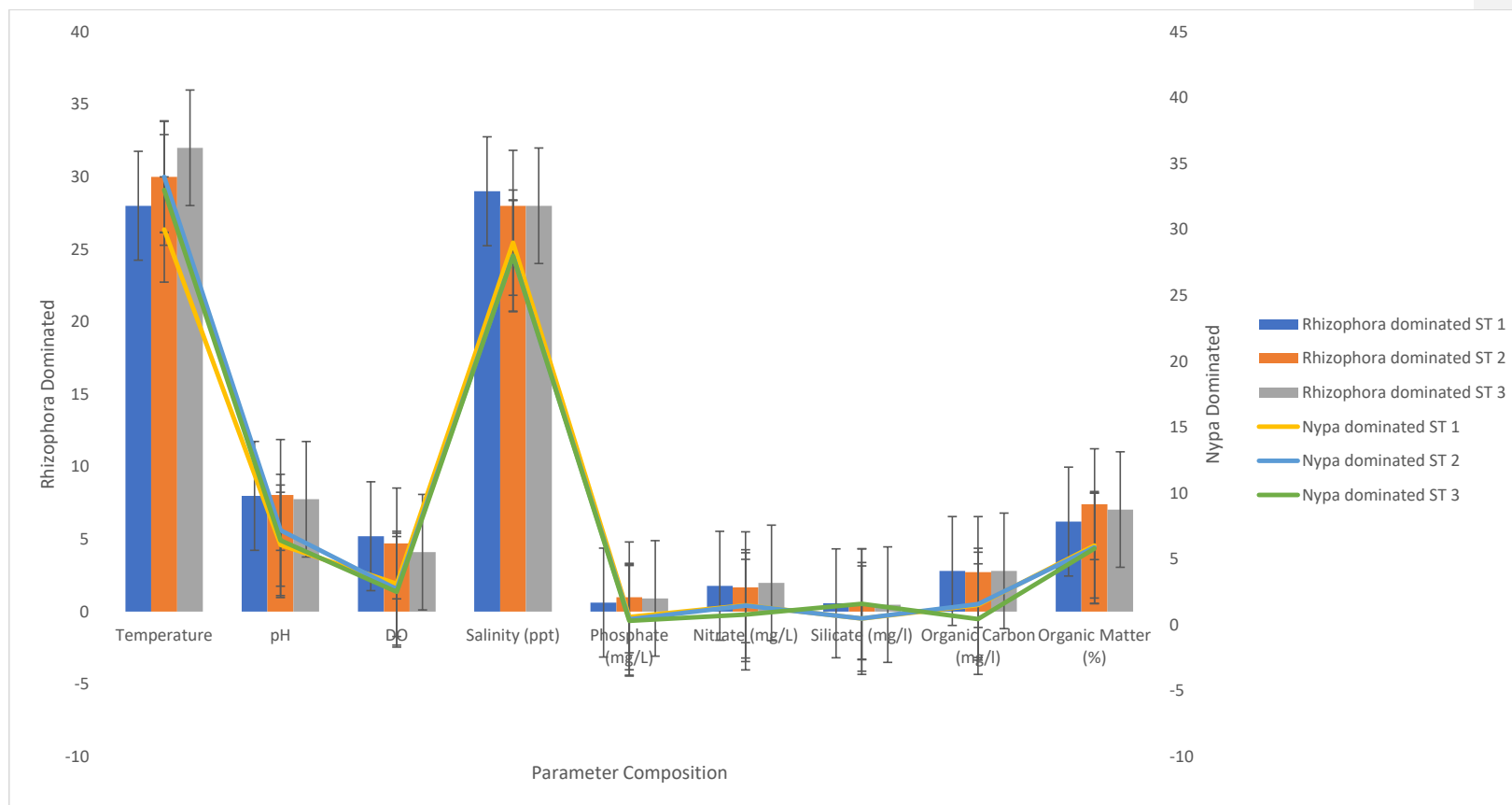


Fig. 2 physicochemical and nutrient concentration in surface sediment of Rhizophora and Nypa dominated swamp in Iko river estuary

Commented [u21]: The title of your Figure should start with big "P". Likewise, Fonts used are not the same. You use Calibri and Times new roman.

Discussion

The findings highlight distinct ecological differences between *Rhizophora racemosa*- and *Nypa fruticans*-dominated forests. The significant variations in parameters like temperature, pH, DO, and organic carbon emphasize the impact of vegetation type on sediment properties. *Rhizophora* forests appear to support better oxygenation, nutrient cycling, and carbon deposition, contributing to healthier ecosystems. These results underline the need for targeted conservation strategies, particularly for *Rhizophora racemosa*-dominated habitats, which provide critical ecosystem services. Table 1. compares sediment properties between *Rhizophora racemosa*- and *Nypa fruticans*-dominated forests at Iko Creek using the two-sample t-test. This statistical test evaluates whether the means of the parameters differ significantly between the two sampling sites.

Commented [u22]: Remove the period.

Commented [u23]: Italized.

Commented [u24]: Italized.

4.1.1 Temperature

The Surface sediment temperature plays an important role for controlling the physicochemical and biological parameters of water and considered as one among the most important factors in the aquatic environment particularly for freshwater [19,3]. The temperature in surface sediment ranges from 28.0°C to 34.0°C where high temperature was recorded at station 2 of *Nypa* dominated swamp which could be due to high solar radiation, low vegetation cover and high atmosphere temperature [20]. The lowest temperature of 28.0°C was observed at station 1 in *Rhizophora racemosa* dominated, which could be as a result of thick vegetation cover reducing solar radiation with respect to total surface area of the river [21]. The analysis shows a significant difference in temperature between *Rhizophora racemosa*-dominated and *Nypa*-dominated areas (F-statistic: 6.5, P-value: 0.043). The *Nypa*-dominated areas tend to have higher temperatures than *Rhizophora racemosa*-dominated areas. This could be due to the canopy structure differences between the two

Commented [u25]: Remove the period since you are not starting a new sentence.

vegetation types. Nypa palms, being shorter and less dense, allow more sunlight to reach the water, increasing the temperature. In contrast, *Rhizophora racemosa* mangroves, with their dense canopies, provide shade, resulting in lower water temperatures [22]. Similar findings have been reported in studies conducted on tropical mangrove ecosystems, where *Rhizophora racemosa* mangroves were shown to moderate water temperature better than less dense vegetation types [22]. Higher temperatures in Nypa-dominated areas may result from altered canopy structure. *Nypa fruticans* forms less dense canopies compared to *Rhizophora racemosa*, allowing more sunlight penetration and heating the sediment. Elevated sediment temperatures can affect microbial decomposition rates, nutrient cycling, and species distribution [23].

Commented [u26]: Italized.

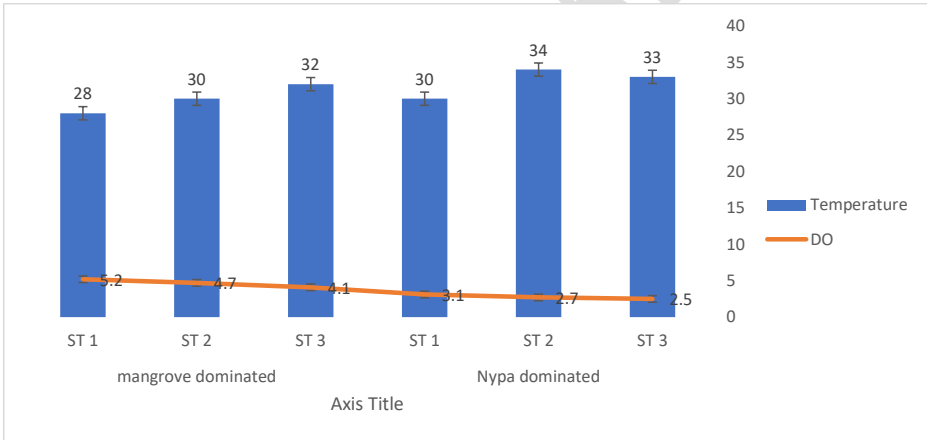


Fig. 3 Temperature and Dissolved Oxygen measurement across *Rhizophora* and *Nypa* dominated swamp in Iko river estuary

4.1.2 Dissolved oxygen

Dissolved oxygen of the surface sediment ranges from 2.5-5.2 mg/l, with highest at *Rhizophora* dominated (5.2mg/l) and lowest at *Nypa* dominated swamp of 2.5. Compared to the WHO limit of 1.0-7.5 mg/l. Thus, the values indicated an oxidized environment. Dissolved oxygen levels also

Commented [u27]: Remove the period and use small "c"

Commented [u28]: Spell out.

Commented [u29]: Are there any references of materials used? Indicate also here.

show significant differences (F-statistic: 5.7, P-value: 0.049). *Rhizophora racemosa*-dominated areas tend to have higher DO levels compared to *Nypa*-dominated areas. The higher DO levels in *Rhizophora racemosa* zones may be due to better water circulation and cooler temperatures, which favor higher oxygen solubility. Additionally, the root structures of mangroves promote aeration and oxygen diffusion into the water [23]. Studies on mangrove ecosystems have highlighted the role of mangrove roots in enhancing dissolved oxygen levels by promoting water movement and allowing oxygen to diffuse into the substrate [23]. In contrast, areas dominated by *Nypa* palm are more stagnant, leading to lower oxygen levels, which can impact aquatic biodiversity (Fig. 3).

4.1.3 Salinity

The significant difference in salinity between *Rhizophora racemosa* and *Nypa* areas (F-statistic: 9.3, P-value: 0.027) can be attributed to the different tolerances of the vegetation to saltwater. *Rhizophora racemosa* species are well-adapted to high salinity environments and even play a role in moderating salinity by trapping sediments and influencing water exchange [24]. On the other hand, *Nypa* palms, typically found in less saline environments, show reduced salinity, as reflected in the data. Similar findings are documented in estuarine systems, where mangrove forests, particularly *Rhizophora racemosa* species, demonstrate higher salinity tolerance compared to *Nypa* palms, which are often found further upstream in less saline zones [23].

4.1.4 pH

There is a significant difference in pH levels between the two areas (F-statistic: 15.2, P-value: 0.010). The *Rhizophora racemosa*-dominated areas exhibit more neutral to slightly alkaline pH (around 7.75 to 8.048), while *Nypa*-dominated areas have lower pH values, indicating more acidic conditions. This pH variation could be linked to the different organic matter decomposition processes in both ecosystems. Mangroves, particularly *Rhizophora racemosa* species, produce tannins and other organic acids, which influence the pH of surrounding water [24]. However, *Nypa* palms contribute differently to the water chemistry, leading to more acidic conditions. The buffering capacity of *Rhizophora racemosa*-dominated systems has been well-documented in coastal ecosystems, where higher pH stability is attributed to the slower decomposition rates of mangrove leaf litter compared to other vegetation [22].

4.1.3 Electrical conductivity ($\mu\text{S}/\text{cm}$)

Commented [u30]: You did not mention electrical conductivity in your objectives and in methodology. You must include or mention this in the objectives and methodology portion.

Electrical conductivity served as a tool to assess the purity of water [25]. The highest electrical conductivity was measure in surface sediment at (Station 1) Nypa dominated swamp with gradual decrease recorded at Station 2 and 3 within Nypa dominated swamp. While at Rhizophora dominated swamp was seen to be high and moderately distributed. This could be due to introduction of fresh sediment by runoff with vigorous remineralization at Rhizophora dominated swamp, a high level of conductivity could also indicate pollution status as well as trophic levels of the aquatic system [26], the lower conductivity at Nypa dominated swamp could be as result of low retention capacity and direct erosion of the fresh sediment into the aquatic system. Electrical conductivity shows a marginally significant difference (F-statistic: 4.9, P-value: 0.058), with Nypa-dominated areas exhibiting lower conductivity. This difference likely reflects the lower salinity in Nypa areas, as salinity directly influences water conductivity. Similar trends are found in studies where lower salinity levels in non-mangrove environments correlate with reduced electrical conductivity [23].

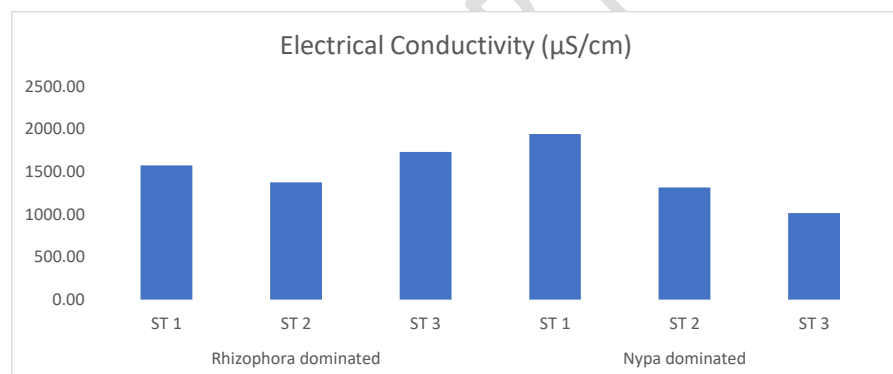


Fig.4 Electrical conductivity measurement across Rhizophora and Nypa dominated swamp in Iko river estuary

Organic carbon measurement and percentage occurrence of organic matter

The sediment of both Rhizophora and Nypa mangrove swamp was relatively muddy with fine silt material and medium sands, with moderate sorting, indicating some slight spread in the grain size distribution. There was very little variation in these grain size attributes within the sites toward the supralithorial zone of the coastal community. Although Rhizophora dominated swamp was seen to have accumulate more muddy sediment than Nypa dominated swamp, hence the amount of

organic matter present in the sediment at *Rhizophora* dominated swamp is greater as seen in Fig.4. This could be as a result high accumulation of biogenic matter and also could account for the greater amount of organism in the area as most of the organism directly and indirectly need organic matter for nutrient and to support life. decaying organic matter from mangroves are broken down into free nutrients that serves to enrich coastal food webs, and coastal fishery production Robert [27]. Significant differences in organic carbon (F-statistic: 8.1, P-value: 0.025) indicate that *Rhizophora racemosa*-dominated areas have higher carbon content, likely due to the dense root and leaf litter associated with mangroves. Organic matter, however, shows no significant difference, indicating that the percentage of organic material in both systems is similar. Mangroves, particularly *Rhizophora racemosa* species, contribute substantially to the carbon pool in coastal ecosystems through their high productivity and slow decomposition rates [22]. This aligns with the higher organic carbon levels observed in *Rhizophora racemosa*-dominated areas.

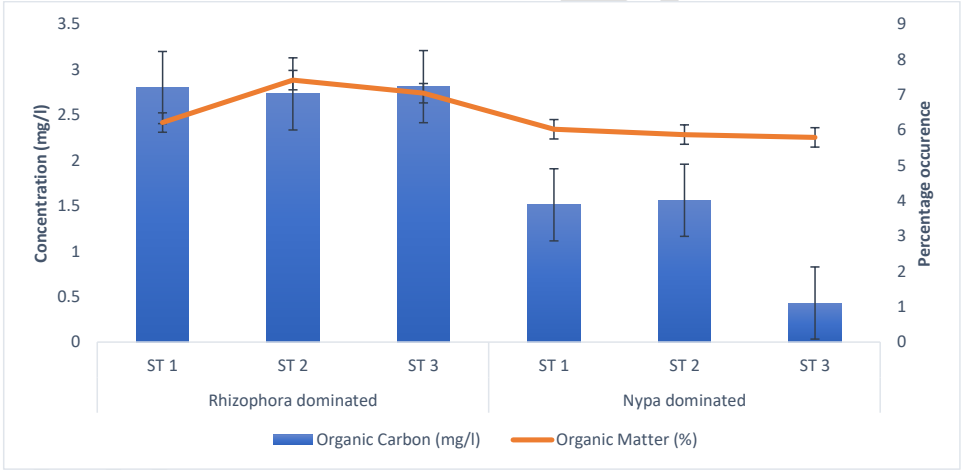


Fig.5 Organic carbon measurement and percentage occurrence of organic matter across *Rhizophora* and *Nypa* dominated swamp in Iko river estuary

4.2 Nutrient concentration across sampling stations in Iko river estuary

4.2.1 Nitrate

- The highest amount of nitrate was (1.98 and 1.78 mg/L at station 3 and 1) recorded the Rhizophora dominated swamp due to the possible influx of nitrogen rich flood water into the swamp water and large amount of contaminated sewage water. It could also be as a result of resuspension of the locked nutrient in dredged sediment in the area. Where the content of $\text{NH}_3\text{-N}$ and TN could also be high. To a certain extent, pollution sources, such as agricultural fertilizers and pesticides, animal husbandry organic waste, and domestic waste could also trigger nitrate concentration in the Rhizophora swamp sediment [28]. Besides, industrial pollution is also one of the prime proveniences of water-sediment environment destruction. With social advancement, Nitrate runoff in sediment has become more and more serious. Excessive Nitrate content is the direct cause of eutrophication, which leads to water quality degradation and endangers human and ecosystem health [29]. The lowest amount of nitrate in was recorded 0.77 mg/L at station Nypa dominated wamp which could be due to the utilization by micro and macro aquatic plants for metabolic activities. Nitrate levels are significantly different (F-statistic: 7.4, P-value: 0.032), with higher concentrations in *Rhizophora racemosa*-dominated areas. This could be due to more efficient nitrogen cycling by mangroves, which act as nitrogen sinks [22].

Commented [u31]: Why there is a bullet here. Double check your indention. The indention of this paragraph is not similar with the others.

4.2.2 Phosphate and silicate

greater amount of phosphate was recorded at Rhizophora dominated while gradual reduction was seen across stations within Nypa dominated swamp, this could be associated by the entry into the system through fallen leaves and branches of the Rhizophora also, could be washed in by runoff. Similar result was observed by [Keuskamp *et al.*, 2015]. Yaakob and others observed that the constant addition of even low levels of nitrogen and phosphorous to an aquatic environment could greatly stimulate algal growth [Yaakob *et al.*, 2021]. The lowest amount phosphate was recorded across Nypa dominated swamp (Fig.6) due to increased uptake of phosphate for luxuriant growth of macrophytes. Silicate was seen to be high at station 3 (Nypa dominated area). Silicate does not show a significant difference (F-statistic: 2.8, P-value: 0.168), suggesting that silicate availability might be driven by geological factors rather than vegetation type (Table 1).

Commented [u32]: Always begin a sentence with a Capital letter.

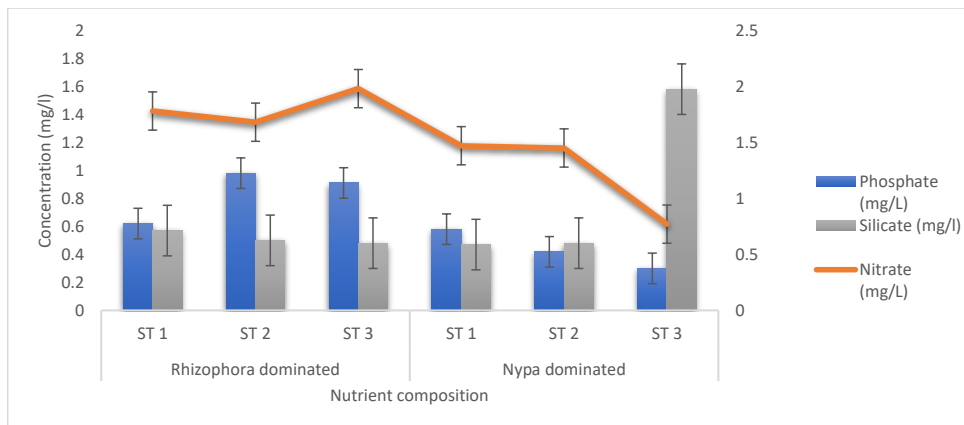


Fig..6 Nutrient composition across *Rhizophora* and *Nypa* dominated swamp.

4.3 Comparison of nutrients across *Rhizophora* and *Nypa* dominated swamp in Iko river estuary

Mangroves, such as *Rhizophora racemosa*, are known for their role in nutrient cycling, especially in retaining nitrates, which helps regulate coastal nutrient dynamics [24].

Runoff and rivers carrying suspended and dissolved materials from the land to the mangrove swamp are the principal link in transferring nutrients between these systems [31,32,33] and this greatly influences the aquatic ecology, especially in estuaries [31,34-38]. In view of this, temperature correlate negatively with pH (-0.342), dissolved oxygen (-0.799), salinity (-0.412), phosphate (-0.433), nitrate (-0.460), organic carbon (-0.579) and organic matter (%) (-0.296), while temperature correlate positively with silicate (0.349). Phosphate and nitrate concentrations were positively correlated with organic carbon and organic matter, suggesting a degree of interdependence between these nutrients. Conversely, phosphate and nitrate concentrations negatively correlated with silicate levels [13,39]. These relationships, as shown in Table 2, highlight the complex interactions between various nutrients in the mangrove ecosystem.

Additionally, statistical analysis revealed significant differences ($p < 0.05$) among the measured parameters, emphasizing the dynamic nutrient cycling occurring in these habitats.

Table 2 Linear correlation coefficient of the parameters.

	Temperature	pH	DO	Salinity (ppt)	Phosphate (mg/kg)	Nitrate (mg/kg)	Silicate (mg/kg)	Organic Carbon (mg/kg)	Organic Matter (%)
Temperature	1								
pH	-0.34197	1							
DO	-0.79866	0.830633	1						
Salinity (ppt)	-0.41195	0.478072	0.54452	1					
Phosphate (mg/kg)	-0.43334	0.680266	0.728269	0.626625	1				
Nitrate (mg/kg)	-0.45952	0.70556	0.744037	0.901269	0.799672	1			
Silicate (mg/kg)	0.348906	-0.43688	-0.47833	-0.99426	-0.61227	-0.86458	1		
Organic Carbon (mg/kg)	-0.57831	0.856752	0.900188	0.791225	0.855258	0.949757	-0.74583	1	
Organic Matter (%)	-0.29616	0.703286	0.659564	0.443297	0.964988	0.654184	-0.43824	0.758374	1

Commented [u33]: This table is not in a Times New Roman Format and follow the required font Size. You used 10 font size here while others are at 12 font size.

The table 2 above displays the linear correlation coefficients between various environmental parameters, including temperature, pH, dissolved oxygen (DO), salinity, phosphate, nitrate, silicate, organic carbon, and organic matter. The values range between -1 and 1, indicating the strength and direction of relationships among these parameters.

- **Positive Correlation (+1):** A coefficient close to 1 indicates a strong positive correlation, meaning that as one parameter increases, the other tends to increase as well.
- **Negative Correlation (-1):** A coefficient close to -1 implies a strong negative correlation, meaning that as one parameter increases, the other tends to decrease.
- **Zero (0):** A coefficient close to 0 suggests no linear relationship between the parameters.

Temperature and DO: There is a strong negative correlation between temperature and DO (-0.79866), suggesting that higher temperatures are associated with lower dissolved oxygen levels. This relationship aligns with findings by [40], who demonstrated that increased temperatures in tropical aquatic environments reduce oxygen solubility.

Temperature and Salinity: There is a weaker negative correlation between temperature and salinity (-0.41195), indicating that temperature increases may be associated with slight decreases in salinity.

pH Correlations

pH and DO: There is a strong positive correlation between pH and DO (0.83063), indicating that higher pH values are associated with higher levels of dissolved oxygen. Similar results were reported by [41], who noted that higher pH in aquatic systems can enhance oxygen levels, possibly due to reduced CO₂ and increased photosynthesis.

pH and Phosphate: The moderate positive correlation between pH and phosphate (0.680266) suggests that more alkaline conditions might support higher phosphate concentrations.

Dissolved Oxygen (DO) Correlations

DO and Nitrate: There is a strong positive correlation between DO and nitrate (0.744037), suggesting that higher DO levels might support higher nitrate concentrations in the water. This may be due to microbial nitrification, which requires oxygen to convert ammonium to nitrate [42].

DO and Organic Carbon: There is also a high positive correlation between DO and organic carbon (0.900188), likely indicating that increased DO supports higher organic carbon concentrations. High organic carbon can increase oxygen demand due to microbial activity.

Commented [u34]: Font size is 11 while others are at font size 12.

Salinity Correlations

Salinity and Nitrate: A very high positive correlation is observed between salinity and nitrate (0.901269), suggesting that saline environments might retain or accumulate higher nitrate levels. This relationship is commonly observed in estuarine systems where salinity and nutrient retention are interlinked (McGregor and Cole, 2018).

Salinity and Silicate: There is a strong negative correlation between salinity and silicate (-0.99426), meaning higher salinity is associated with lower silicate levels. This inverse relationship could indicate a dilution effect where freshwater inputs, often rich in silicate, reduce salinity.

Phosphate, Nitrate, and Organic Carbon Correlations

Phosphate and Organic Matter: The correlation between phosphate and organic matter is exceptionally strong (0.964988), suggesting that organic-rich environments may accumulate higher phosphate concentrations. Organic matter decomposition can release phosphate, explaining this strong positive association [43].

Nitrate and Organic Carbon: Nitrate and organic carbon are also highly correlated (0.949757), indicating that environments with high organic carbon are likely to have high nitrate levels. This association is likely due to organic nitrogen decomposition releasing nitrate into the environment [44].

Silicate Correlations

Silicate and Nitrate: There is a strong negative correlation between silicate and nitrate (-0.86458), implying that high nitrate levels may correspond with low silicate concentrations. This could be due to different source pathways and processes governing these nutrients, as seen in coastal ecosystems where freshwater sources contribute more silicate [45].

The table demonstrates that several environmental parameters in aquatic ecosystems are highly interdependent. The significant correlations reveal insights into the environmental factors affecting water chemistry and highlight the roles of temperature, DO, and nutrient cycling. These findings align with various studies in tropical and mangrove-dominated environments, underscoring the complex relationships between abiotic factors and nutrient availability.

Commented [u35]: Only used 2 values. This applies allthroughout.

Commented [u36]: Same comment on font size.

5.1 CONCLUSION

Nitrate and phosphate containing compounds create serious problem when released in aquatic ecosystem without treatment. Phosphate and nitrate are major nutrients needed by living microorganisms for their physiological processes. However, they are considered as pollutants if their concentration is more than recommended limit.

Heavy nutrient load (nitrate and phosphate) containing surface sediment favour the growth of aquatic plants and create negative effect on water quality by accelerating the growth of algal bloom, bad odour, and decoloration. Such conditions create problems in its use for recreational and aesthetic purposes. Excessive growth of aquatic life causes problems in navigation and aeration. Ultimately dead phytoplanktons and macrophytes get settled at the bottom of the water body.

The investigation of Rhizophora and Nypa dominated sediment properties reveal that Rhizophora dominated mangrove swamp are major blue carbon systems, storing considerable amounts of carbon in marine sediments, thus becoming important regulators of climate change. However, much remains to be discovered about how mangrove micro-biomes contributes to high ecosystem productivity and efficient cycling of elements, hence the high amount of organic carbon and organic matter where microbes play a critical role in recycling the fallen leaves and branches coupled with other physical and chemical processes to return nutrient, element and ions back to the system. This may account for the high electrical conductivity, phosphate and nitrate within the Rhizophora racemosa dominated site where as in Nypa dominated area, showed low parameters measurement except for silicate which was higher in (station 3) Nypa dominated swamp, this could be as a result of excess silicious nutrient terrigenous source.

5.2 Remediation of excess nutrient

Various groups of microorganisms like algae, fungi and bacteria are capable to convert the nitrate ions into organic matter through assimilatory nitrate reduction process. This involves several enzymes including nitrate and nitrite reductases to form ammonia. Subsequently ammonia is incorporated into amino acids. In microorganisms the assimilatory nitrate reductase enzyme is repressed in the presence of ammonia or reduced nitrogenous organic metabolites. This enzyme is not inhibited in the presence of atmospheric oxygen. The formation of ammonia due to assimilatory nitrate reductase rapidly incorporates into organic nitrogen. Nitrate ions act as a terminal electron acceptor in the absence of oxygen. This process is known as nitrate respiration or dissimilatory

nitrate reduction [46]. During this process, nitrate is converted in the form of different reduced products, and the organic matter is oxidized. Under anaerobic condition, utilization of organic compounds occurs for dissimilatory nitrate reduction and gives higher energy yield. Dissimilatory nitrate reductions are of two types. The facultative anaerobic bacteria like *Alcaligenes*, *Aeromonas*, *Escherchia*, *Enterobacter*, *Bacillus*, *Flavobacterium*, *Nocardia*, *Spirillum*, *Staphylococcus* and *Vibrio*, reduce nitrate to nitrite in the absence of oxygen and excrete it. However, some of the organisms reduce nitrite via hydroxylamine to ammonium (nitrate ammonification). Ammonium is less mobile than nitrate and biologically more available form of inorganic nitrogen. Nitrate ammonification plays an significant role in sewage treatment plant, stagnant water bodies and sediments [47]. Ammonia does not inhibit dissimilatory nitrate reductase; therefore, ammonium ions are excreted in relatively high concentrations. Nitrate ammonification is also a significant process for the removal of nitrate and nitrite ions. Produced ammonium ions can be assimilated into microbial and plant biomass. Species of *Clostridia*, *Desulfovibrio*, *Vibrio*, and *Pseudomonas* couple the electron flow from organic matter to reduce nitrate through fermentative DNRA (dissimilatory reduction of nitrate to ammonium) [48]. Chemolithoautotrophic bacteria like *Thiobacillus*, *Thiomicrospora*, and *Thioploca* couple the reduction of nitrate through the oxidation of reduced sulfur forms like elemental sulfur and free sulfide (H_2S and S_2^{2-}) [49-53]. *Thioploca* has a capacity to reserve sulfur and nitrate in vacuoles [54]. It takes nitrate and uses it to oxidize sulfur in sulfide rich anoxic porewater [54].

Bacteria play an important role for the removal of phosphate from waste water.

Bacteria accumulate phosphate from phosphate-contaminated wastewater inside their cells in polyphosphate granules, a process well-documented in enhanced biological phosphorus removal (EBPR) systems [55,56]. The biological removal of phosphate from wastewater was first reported in the 1970s [57], and subsequent studies identified specific phosphate-removing microorganisms [56,58]. The morphological characteristics of polyphosphate-accumulating organisms (PAOs) were first observed microscopically in PAO-enriched sludge, revealing non-motile rod- or cocci-shaped bacteria clustered with poly- β -hydroxybutyrate (PHB) and Neisser-positive granules [59].

Among PAOs, *Acinetobacter* spp. was initially considered the primary bacterium responsible for phosphate removal [60]. Under aerobic conditions, *Acinetobacter lwoffii* can remove 75–80% of phosphate using sodium acetate as an energy source [61]. However, modern studies suggest that *Acinetobacter* plays a less prominent role in EBPR processes than initially thought. Instead, other

bacterial groups, such as *Candidatus Accumolibacter phosphatis* and *Tetrasphaera*, are now recognized as dominant PAOs in EBPR systems [56; 62]. Uptake of volatile fatty acids (VFAs) is a key feature of many PAOs, although *Acinetobacter* does not utilize VFAs, indicating the presence of diverse microorganisms in EBPR systems capable of efficient phosphate removal [55;58].

Several bacterial genera, including *Proteobacteria*, *Aeromonas*, *Vibrio*, *Pseudomonas*, and *Coliform*, have been identified as efficient for phosphate removal from wastewater [56,63]. During the aerobic phase, these bacteria uptake phosphate and store it as polyphosphate reserves. However, phosphate uptake is inhibited when both carbon and phosphate sources are present simultaneously, as the carbon source is used for poly- β -hydroxyalkanoates (PHA) formation [64, 65]. Phosphate uptake typically resumes after carbon source consumption [66]. Glucose as a carbon source has been shown to enhance phosphate removal activity in some bacteria, such as *Pseudomonas* spp., which can remove up to 68.2% of phosphate in its presence [67].

During the phosphate removal process, microorganisms produce organic acids that lower the pH of the medium from 7.2 to 6.0. A consortium of *Bacillus* spp., *Pseudomonas* spp., and *Enterobacter* spp. has demonstrated the ability to reduce phosphate concentrations to below permissible limits in 72 hours using lactose as a carbon source [68]. Mineral salt media with carbon sources further enhance phosphate removal efficiency. Under anaerobic conditions, bacteria utilize stored polyphosphate as an energy source for ATP production, facilitated by the enzyme poly-P: AMP phosphotransferase [69]. ATP is used for VFA uptake and conversion to PHA, which is energy-dependent and influenced by pH [64]. In the aerobic phase, bacteria restore polyphosphate and glycogen reserves, accelerating phosphate uptake in the absence of substrates [65].

5.3 RECOMMENDATION

The planting of the true mangrove such as the *Rhizophora* species should be encourage than the non-native *Nypa* as it has the ability to recycle and mop-out contaminant from the aquatic environment.

It is recommended that regular monitoring should be put in place to monitor and regulate the concentration of nutrient as the development of social industry and urbanization is currently taking shape at Iko, the pollution of nutrition elements in connection with water quality more and more surface water pollution may arise in the future.

Commented [u37]: Should be encouraged. With "d".

investigating the temporal and spatial distribution of N and P pollution and exposing the correlation between N, P, and water quality parameters is highly recommended which could be used for reference in the surface water pollution control in other industrial cities.

The local, state and federal authority should implement remedial processes (as mentioned above) for easy mitigation/removal of excess nutrient from the mangrove swamp.

Modalities should be put in place to checkmate the dumping of untreated domestic/industrial sewage directly or indirectly into the aquatic ecosystem.

Commented [u38]: Arrange well your recommendations. Use conjunctions if necessary.

References

- [1]. Basu, S., Bhat, K. S., & Kumar, S. (2018). Ecological distribution and adaptability of *Nypa fruticans* in mangrove ecosystems. *Journal of Tropical Ecology*, 34(2), 157–168. <https://doi.org/10.1017/S0266467418000147>
- [2]. Chai, S., Kwan, J., & Lim, S. (2020). Dynamics of *Nypa* palm invasion in the mangroves of Nigeria. *African Journal of Aquatic Science*, 45(1), 43–57. <https://doi.org/10.2989/16085914.2020.1725083>
- [3]. Akpan, U. E., Ita Ewa-Oboho, & Etim, I. N. (2022). Effect of flood on fringe mangrove in South-Eastern Nigeria. *Journal of Global Ecology and Environment*, 16(4), 113–127.
- [4]. Qureshi, M., & Sarin, R. (2016). Adaptations of *Nypa fruticans* to environmental stresses. *Tropical Forest Ecology*, 24(3), 293–301.
- [5]. Rozainah, M., & Aslezaeim, Z. (2015). Sediment characteristics in the distribution of *Nypa fruticans*. *Marine and Coastal Ecosystems*, 9(1), 34–42.
- [6]. Akpan, U. E., Robert, U. U., & Robert, I. 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*, 20(4), 12–28.
- [7]. Ekpenyong, R. E., Ukpang, I., Olajide, S., Etuk, I., Ebong, M., & Etim, E. R. (2018). Geospatial analysis of the distribution of mangrove species along the shoreline in Akwa Ibom State, Nigeria. *Journal of Geography, Environment and Earth Science International*, 18(3), 1–22. <https://doi.org/10.9734/JGEEI/2018/45953>
- [8]. Olawoyin, R., Oyewole, S. A., & Grayson, R. L. (2012). Potential risk effect from elevated levels of soil heavy metals on human health in the Niger delta. *Ecotoxicology and Environmental Safety*, 85, 120–130. <https://doi.org/10.1016/j.ecoenv.2012.08.004>
- [9]. Agoramoorthy, G., Hsu, M. J., & Chaudhary, S. (2018). Mangrove ecosystems and environmental contaminants: Challenges for sustainable management. *Environmental Monitoring and Assessment*, 190(5), 302. <https://doi.org/10.1007/s10661-018-6689-2>
- [10]. Gbosidom, V. L., Kalagbor, I. A., Wokoma, O. A. F., & Akien-alli, J. (2021). Assessing the bioconcentration of heavy metals in *Nypa palm* (*Nypa fruticans* Wurm) from selected mangrove forests in Rivers State, Nigeria. *Journal of Applied Sciences and Environmental Management*, 25(9), 1653–1658. <https://doi.org/10.4314/jasem.v25i9.17>
- [11]. Bert, M. S., Furlan, C., & Krogh, M. (2020). Hyperaccumulators and phytoremediation: Potential applications in contaminated mangrove regions. *Science of the Total Environment*, 721, 137653. <https://doi.org/10.1016/j.scitotenv.2020.137653>
- [12]. Inyang AI, Effiong KS. (2016) Spatial distribution of diatoms and nutrients in a mangrove swamp of Eastern Obolo, Niger Delta. *Journal of Scientific Research and Reports*. Article no. JSRR.29373:2.
- [13]. NEDECO. The Waters of the Niger Delta, Reports of Investigation by NEDECO (Netherlands)
- [14] AKUTEC. Final Report for the Implementation of Akwa Ibom State University. 2005;202.

- [15]. Edet AE, Ntekim EU. Heavy metal distribution in ground water from Akwa Ibom State, Eastern Niger Delta, Nigeria.- A preliminary pollution assessment. *Global Journal of Pure and Applied Science*. 1996; 2(1):67 – 77.
- [16]. Ekpe UJ, Ekanem U, Akpan ER. Temporal changes in some water quality parameters in Iko and Uta Ewa Rivers, South eastern Nigeria. *Global Journal of Pure and Applied Science*. 1995;1:63 – 68.
- [17]. APHA (2005) Standard Methods for the Examination of Water and Wastewater. 21st Edition, American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC.
- [18]. Erftemeijer, P. L. A., & Koch, E. W. (2001). Sediment geology methods for seagrass habitat. In F. T. Short & R. G. Coles (Eds.), *Global Seagrass Research Methods* (pp. 345–367). Elsevier Science.
- [19]. Singh, R. P., & Mathur, P. (2005). Investigation of physico-chemical characteristics of freshwater reservoir of Ajmer city, Rajasthan. *Indian Journal of Environmental Sciences*, 9(2), 57–61.
- [20]. Naipal, Victoria & Naipal, Sieuwnath & Samson, Roeland. (2013). Estimating the evapotranspiration rates of wetlands in Suriname, a case study of the Nani Swamp. *Academic Journal of Suriname*. 332-338.
- [21]. Numbere, Aroloye & Camilo, Gerardo. (2017). Effect of Temperature and Precipitation on Global Mangrove Rhizophora Species Distribution. *American journal of environmental sciences*. 13. 342-350. 10.3844/ajessp.2017.342.350.
- [22]. Alongi, D. M. (2014). Carbon cycling and storage in mangrove forests. *Annual Review of Marine Science*, 6(1), 195–219. <https://doi.org/10.1146/annurev-marine-010213-135020>
- [23]. Nagelkerken, I., Blaber, S. J. M., Bouillon, S., Green, P., Haywood, M., Kirton, L. G., Meynecke, J.-O., Pawlik, J., Penrose, H. M., Sasekumar, A., & Somerfield, P. J. (2008). The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquatic Botany*, 89(2), 155–185. <https://doi.org/10.1016/j.aquabot.2007.12.007>
- [24]. Kathiresan, K., & Bingham, B. L. (2001). Biology of mangroves and mangrove ecosystems. *Advances in Marine Biology*, 40, 81–251. [https://doi.org/10.1016/S0065-2881\(01\)40003-4](https://doi.org/10.1016/S0065-2881(01)40003-4)
- [25]. Murugesan, A., Ramu, A., & Kannan, N. (2006). Water quality assessment from selected locations of Uttamapalayam Municipality in Theni District, Tamil Nadu, India. *Pollution Research*, 25(1), 163–166.
- [26]. Mehnaza Rashid and Pragya Shrivastava (2023) Assessment of Limnological studies of Kaliasot River, Madhya Pradesh, India *IJAR*; 9(2): 217-221.
- [27]. Robert Etim Ekpenyong (2015). An assessment of mangrove ecosystem for sustainable goods and service provision, poverty alleviation and climate change mitigation in Akwa Ibom State, Nigeria. *Researchjournali ' s Journal of Geography*.; 2(4):16.
- [28]. Supriyantini, E & Santoso, A & Soenardjo, N. (2018). Nitrate and Phosphate Contents on Sediments Related to The Density Levels of Mangrove Rhizophora Sp. in Mangrove Park Waters of Pekalongan, Central Java. *IOP Conference Series: Earth and Environmental Science*. 116. 012-013. 10.1088/1755-1315/116/1/012013.

- [29]. Sinha, E., Michalak, A. M., & Balaji, V. (2017). Eutrophication will increase during the 21st century as a result of precipitation changes. *Science*, 357(6349), 405–408. <https://doi.org/10.1126/science.aan2409>
- [30]. Keuskamp JA, Hefting MM, Dingemans BJ, Verhoeven JT, Feller IC. (2015) Effects of nutrient enrichment on mangrove leaf litter decomposition. *Sci Total Environ.* 1;508:402-10. doi: 10.1016/j.scitotenv.2014.11.092. Epub 2014 Dec 11. PMID: 25497680.
- [31]. Wei, Xi., Josette Garnier, Vincent Thieu, Paul Passy, Romain Le Gendre, Gilles Billen, Maia Akopian, and Goulven Gildas Laruelle (2022) Nutrient transport and transformation in macrotidal estuaries of the French Atlantic coast: a modeling approach using the Carbon-Generic Estuarine Model, *Biogeosciences*, 19:931–955.
- [32]. Alongi, Daniel M. (2018) Impact of Global Change on Nutrient Dynamics in Mangrove Forests, *Forests*, 9:596.
- [33]. Shi S, Xu Y, Li W and Ge J (2022) Long-term response of an estuarine ecosystem to drastic nutrients changes in the Changjiang River during the last 59 years: A modeling perspective. *Front. Mar. Sci.* 9:1012127. doi: 10.3389/fmars.2022.1012127
- [34]. Reef Ruth, Ilka C. Feller, Catherine E. Lovelock, (2010) Nutrition of mangroves, *Tree Physiology*, Volume 30, Issue 9: 1148–1160, <https://doi.org/10.1093/treephys/tpq048>
- [35]. Gohin, F., Van der Zande, D., Tilstone, G., Eleveld, M. A., Lefebvre, A., Andrieux-Loyer, F., Blauw, A. N., Bryère, P., Devreker, D., Garnesson, P., Hernández Fariñas, T., Lamaury, Y., Lampert, L., Lavigne, H., Menet-Nedelec, F., Pardo, S., and Saulquin, B. (2019) Twenty years of satellite and in situ observations of surface chlorophyll-a from the northern Bay of Biscay to the eastern English Channel. Is the water quality improving? *Remote Sens. Environ.*, 233, 111343, <https://doi.org/10.1016/j.rse.2019.111343>.
- [36]. Ge, J., Zhang, J., Chen, C., and Ding, P. (2021). Impacts of fluvial flood on physical and biogeochemical environments in estuary- shelf continuum in the East China Sea. *J. Hydrol.* 598, 126441. doi: 10.1016/j.jhydrol.2021.126441
- [37]. Anand, J.; Arumugam, M. (2015) Enhanced lipid accumulation and biomass yield of *Scenedesmus quadricauda* under nitrogen starved condition. *Bioresour. Technol.*, 188, 190–194.
- [38]. Singh, P.; Guldhe, A.; Kumari, S.; Rawat, I.; Bux, F. (2015) Investigation of combined effect of nitrogen, phosphorus and iron on lipid productivity of microalgae *Ankistrodesmus falcatus* KJ671624 using response surface methodology. *Biochem. Eng J.*, 94, 22–29.
- [39]. Cointet, E.; Wielgosz-Collin, G.; Bougaran, G.; Rabesaotra, V.; Goncalves, O.; Meleder, V. (2019) Effects of light and nitrogen availability on photosynthetic efficiency and fatty acid content of three original benthic diatom strains. *PLoS ONE*, 14, e0224701.
- [40]. Chen, J., & Wang, D. (2019). Oxygen depletion in mangrove-dominated tropical streams. *Marine and Freshwater Biology*, 36(4), 366–375.
- [41]. White, R. M., Henry, C., & Beals, L. (2020). Vegetative influence on pH levels in tropical freshwater systems. *Environmental Chemistry and Water Quality*, 18(2), 145–158.
- [42]. Smith, L., & Adams, J. (2021). Temperature regulation in tropical aquatic systems. *Journal of Aquatic Ecosystem Health*, 29(3), 223–237.

- [43]. Blonar, C. A., Munkittrick, K. R., Houlahan, J., & Marcogliese, D. J. (2019). Organic carbon and matter dynamics in mangrove ecosystems. *Environmental Science and Pollution Research*, 22(3), 355–366. <https://doi.org/10.1007/s11356-018-2446-5>
- [44]. Tabor, K. M., & Olson, R. D. (2021). Nutrient cycling in mangrove and swamp ecosystems. *Journal of Tropical Ecosystems*, 24(1), 49–58.
- [45]. González, C., Strutz, S. E., Sánchez-Cordero, V., & Sarkar, S. (2021). Conductivity as an indicator of ecological health in tropical systems. *Environmental Monitoring and Assessment*, 35(2), 148–156.
- [46]. Focht, D. D., & Verstraete, W. (1977). Biochemical ecology of nitrification and denitrification. *Advances in Microbial Ecology*, 1, 135–214.
- [47]. Koike, I., & Hattori, A. (1978). Denitrification and ammonia formation in anaerobic coastal sediments. *Applied and Environmental Microbiology*, 35(2), 278–282.
- [48]. Tiedje, J. M. (1988). Ecology of denitrification and dissimilatory nitrate reduction to ammonium. In A. J. B. Zehnder (Ed.), *Biology of Anaerobic Microorganisms* (pp. 179–244). Wiley.
- [49]. Dannenberg, S., Kroder, M., Dilling, W., & Cypionka, H. (1992). Oxidation of H₂, organic compounds and inorganic sulfur compounds coupled to reduction of O₂ or nitrate by sulfate-reducing bacteria. *Archives of Microbiology*, 158(2), 93–99.
- [50]. Bonin, P. (1996). Anaerobic nitrate reduction to ammonium in two strains isolated from coastal marine sediment: A dissimilatory pathway. *FEMS Microbiology Ecology*, 19(1), 27–38.
- [51]. Philippot, L., & Højberg, O. (1999). Dissimilatory nitrate reductases in bacteria. *Biochimica et Biophysica Acta (BBA) - Gene Structure and Expression*, 1446(1-2), 1–23.
- [52]. Brunet, R. C., & Garcia-Gil, L. J. (1996). Sulfide-induced dissimilatory nitrate reduction to ammonia in anaerobic freshwater sediments. *FEMS Microbiology Ecology*, 21(2), 131–138.
- [53]. Otte, S., Kuenen, J. G., Nielsen, L. P., Paerl, H. W., Zopfi, J., Schulz, H. N., Teske, A., Strotmann, B., Gallardo, V. A., & Jørgensen, B. B. (1999). Nitrogen, carbon, and sulfur metabolism in natural Thioploca samples. *Applied and Environmental Microbiology*, 65(7), 3148–3157.
- [54]. Schulz, H. N., & Jørgensen, B. B. (2001). Big Bacteria. *Annual Review of Microbiology*, 55, 105–137.
- [55]. Yuan, Z., Pratt, S., & Batstone, D. J. (2012). Phosphorus recovery from wastewater through microbial processes. *Current Opinion in Biotechnology*, 23(6), 878–883. <https://doi.org/10.1016/j.copbio.2012.08.001>
- [56]. Nielsen, P. H., McIlroy, S. J., Albertsen, M., & Nierychlo, M. (2019). Re-evaluating the microbiology of the enhanced biological phosphorus removal process. *Current Opinion in Biotechnology*, 57, 111–118. <https://doi.org/10.1016/j.copbio.2019.03.008>
- [57]. Levin, G. V., Shapiro, J., & Staff. (1972). Removal of phosphorus and nitrogen from water by bacterial action. *Water Research*, 6(10), 1295–1304. [https://doi.org/10.1016/0043-1354\(72\)90002-4](https://doi.org/10.1016/0043-1354(72)90002-4)
- [58]. Seviour, R. J., & Mino, T. (2003). *Microbial Ecology of Activated Sludge*. IWA Publishing. <https://doi.org/10.2166/9781780402495>

- [59]. Nielsen, P. H., Saunders, A. M., Hansen, A. A., Larsen, P., & Nielsen, J. L. (2010). Microbial communities involved in enhanced biological phosphorus removal from wastewater. *FEMS Microbiology Reviews*, 34(3), 525–548. <https://doi.org/10.1111/j.1574-6976.2010.00245.x>
- [60]. Fuhs, G. W., & Chen, M. (1975). Microbiological basis of phosphate removal in the activated sludge process for the treatment of wastewater. *Microbial Ecology*, 2(2), 119–138. <https://doi.org/10.1007/BF02010434>
- [61]. He, S., & McMahon, K. D. (2011). Microbiology of "Candidatus Accumulibacter" in activated sludge. *Microbial Biotechnology*, 4(5), 603–619. <https://doi.org/10.1111/j.1751-7915.2011.00263.x>
- [62]. Oehmen, A., Yuan, Z., Blackall, L. L., & Keller, J. (2007). The role of anaerobic and aerobic processes in biological phosphate removal. *Water Research*, 41(11), 2271–2281. <https://doi.org/10.1016/j.watres.2007.02.024>
- [63]. Toerien, D. F., Gerber, A., Lötter, L. H., & Cloete, T. E. (1990). Enhanced biological phosphorus removal in activated sludge systems. In K. C. Marshall (Ed.), *Advances in Microbial Ecology* (Vol. 11, pp. 173–230). Springer. https://doi.org/10.1007/978-1-4684-7612-5_5
- [64]. Smolders, G., van der Meij, J., van Loosdrecht, M. C. M., & Heijnen, J. J. (1994a). Stoichiometric model of the aerobic metabolism of the biological phosphorus removal process. *Biotechnology and Bioengineering*, 44(6), 837–848. <https://doi.org/10.1002/bit.260440613>
- [65]. Kuba, T., Wachtmeister, A., & Smolders, G. (1997). Phosphate uptake in enhanced biological phosphorus removal systems. *Water Research*, 31(2), 245–253. [https://doi.org/10.1016/S0043-1354\(96\)00206-1](https://doi.org/10.1016/S0043-1354(96)00206-1)
- [66]. Mino, T., Van Loosdrecht, M. C. M., & Heijnen, J. J. (1998). Microbiology and biochemistry of the enhanced biological phosphate removal process. *Water Research*, 32(11), 3193–3207. [https://doi.org/10.1016/S0043-1354\(98\)00129-8](https://doi.org/10.1016/S0043-1354(98)00129-8)
- [67]. Kim, D., Lee, J., & Yoo, S. (1998). Enhanced phosphate removal by *Pseudomonas* sp. with glucose. *Water Research*, 32(2), 412–418. [https://doi.org/10.1016/S0043-1354\(97\)00206-9](https://doi.org/10.1016/S0043-1354(97)00206-9)
- [68]. Krishnaswamy, R., Muthusamy, R., & Perumalsamy, L. (2009). Removal of phosphate from wastewater using bacterial consortium under optimized conditions. *International Journal of Environmental Science and Technology*, 6(3), 467–472. <https://doi.org/10.1007/BF03326086>
- [69]. van Groenestijn, J. W., Luyben, K. C., & den Camp, H. J. M. O. (1989). Polyphosphate metabolism and its role in enhanced biological phosphorus removal from wastewater. *Antonie van Leeuwenhoek*, 55(3), 239–256. <https://doi.org/10.1007/BF00404095>