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Pertubations of Physicochemical Properties and Heavy Metal in the Soil of Coastal Areas of Akwa Ibom State, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This study aimed at assessing the concentrations and perturbations of the physicochemical properties and heavy metals in the soil of the coastal regions of Akwa Ibom State, Nigeria. Sampling was carried out across three mangrove locations (Iko Town, Okoroutip and Uta Ewa) in Eastern Obolo, Ibeno and Ikot Abasi Local Government Areas respectively. Four vegetation plots were randomly selected, and within each plot, three belt transects were established. Physicochemical properties [Sand, Clay, Silt, organic carbon (OC), total nitrogen, sulphate and chlorine content] and heavy metals (Arsenic, Silver, Chromium, Copper, Nickel, Lead, Mercury, Cadmium, Titanium, Vanadium and Zinc) were analyzed using standardized methods. Results from this study revealed considerable variations in the physicochemical properties of soil in the study area. The aforementioned heavy metals were present in both wet and dry seasons in considerable

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concentrations in the soil samples within the study areas. However, were within and below WHO limits. The variations in the physicochemical properties and the presence of these heavy metals in the samples are indicative of an impacted environment unsuitable for the growth and survival of the endemic flora and fauna species of this unique ecosystem. In view of the current knowledge of the role of mangrove ecosystems in blue-economy of the nation and mitigation of ongoing climate change, we advocate a tripartite alliance between the government, multinational companies operating within the area and the various impacted communities that leads to a concerted efforts of constant monitoring and remediation in the reduction of current and future pollutant levels.

Keywords: Perturbations; blue-economy; mangrove; crude oil; pollutants.

1. INTRODUCTION

The global coverage of mangroves spans approximately 137,760 km^2 to 152,360 km^2 (Kainuma *et al*. 2013), with over 73 distinct species of mangroves across 123 countries and territories worldwide (Spalding *et al*. 2010). The classification of mangrove vegetation encompasses two Nigeria's vegetation belt reflect a very close link between vegetation and climate (Wang *et al*., 2011b). Vegetation belts are of two main categories: true mangroves and mangrove associates (Wang *et al*., 2011b). Mangrove ecosystems exhibit distinct features such as a humid climate, elevated temperatures, significant tidal influence, a saline environment with high levels of silt and clay (Sandiyan, 2010) and also possess the ability to endure and acclimate to various environmental factors, including extreme marine and tidal conditions (Lewis *et al*., 2016). The ecosystems are susceptible to the influence of climate change variables, including temperature, rainfall, atmospheric carbon dioxide (CO_2) levels, and sea level rise (Gilman *et al*., 2008). Mangroves are found in environments characterized by nutrient-rich, hypoxic muddy substrates and varying levels of salinity (Ferreira *et al.,* 2007). The composition, structure, and plant distribution within mangroves are influenced by soil characteristics, including organic matter content, salinity levels, and nutrient availability (Otero *et al.,* 2009). The distribution of plants and animals in an ecosystem can be influenced by the quality of water (Essien *et al*., 2007).

Mangroves offer a wide range of ecosystem services, including the safeguarding of coastal regions against the negative influence of greenhouse effect, elevated sea levels, wave activity, and erosion. Additionally, they serve as a source of nutrients for various organisms (Carugati *et al.,* 2018, Anwana *et al.,* 2014). They serve as crucial locations for primary production and provide habitats for numerous species (Ribeiro *et al.,* 2019) and possess the ability to assimilate and amass diverse pollutants, owing to their inherent attributes such as elevated productivity, organic composition, fine-grained wetland soil, and oxygen-deprived conditions (Osuagwu and Otitoju, 2021). The degradation of mangrove ecosystems on a global scale, both in terms of quality and quantity, can be attributed to the escalation of anthropogenic activities (Husodo *et al.,* 2017). These activities have resulted in alterations in precipitation patterns, climate change, elevated sea levels, heightened salinity levels, and a significant risk to the growth and survival of these ecosystems (Akpabio *et al.,* 2024). Goldberg *et al.* (2020) estimated that global losses of mangrove ecosystems occurred between the year 2000 and 2016. The adverse effects of pollution, degradation, and depletion on mangrove ecosystems can result in a reduction of the ecosystem services they offer (Moonsammy, 2021). Crude oil exploitation is one of the major causes of pollution to the ecosystem (Akpabio *et al.,* 2024) which contains high concentrations of toxic heavy metals (Enujiugha and Nwanna, 2004). Heavy metals are a classification of naturally occurring elements found in the Earth's crust, characterized by an atomic density exceeding 5 gcm^{-3} and an atomic number greater than 20 (Ali and Khan, 2018; Ali *et al*., 2019).

Akwa Ibom State is part of the Niger Delta, which is widely documented for extensive environmental pollution linked to the oil industry, with heavy metals often detected at toxic levels in soil and water (Akinbile *et al.,* 2022). Such metals, including lead (Pb), cadmium (Cd), and chromium (Cr), can accumulate in the soil over time, disrupting local ecosystems and leaching into groundwater sources (Ekanem *et al.,* 2019). It necessary to assess the extent of contamination and provide baseline data for managing soil and water quality in these vulnerable areas. Coastal soils in regions impacted by industrial activities, oil extraction, urban runoff, and agricultural practices are particularly vulnerable to contamination, which can degrade soil quality, threaten biodiversity, and pose significant health risks to local communities (Otu *et al.,* 2021). The high toxicity and unsafe concentration of these heavy metals in the environment have instigated the interest and concern to ecologist to access their perturbations in mangroves species. Heavy metals are non-biodegradable and can easily enter the food chain through crops grown in contaminated soils, leading to bioaccumulation and potential health risks for local populations (WHO, 2022). Populations consuming contaminated food or water may face increased risks of chronic illnesses, including kidney damage, cancer, and neurological disorders (Adedokun *et al.,* 2021). Understanding the levels of heavy metal contamination in Akwa Ibom's soils is critical to protect public health and develop effective soil and water management practices. Soil quality is essential for agriculture, and coastal soils in Akwa Ibom are vital for local food production. Heavy metal contamination and altered physicochemical properties—such as pH, organic content, and cation exchange capacity (CEC)—can reduce soil fertility and affect crop yields (Okoye *et al.,* 2021, Anwana *et al.,* 2024). For instance, acidic soils can increase the bioavailability of metals, leading to greater uptake by crops and increased toxicity in food products (Nwankwoala and Amadi, 2022). Coastal ecosystems are highly dynamic and support a range of biodiversity. Soil contamination can harm plant and microbial diversity, destabilizing local food webs and reducing ecosystem resilience (Osuagwu and Otitoju, 2021). Heavy metals can inhibit soil microbial activity, impacting nutrient cycling and reducing soil health, which ultimately affects the broader ecosystem. Evaluating soil perturbations and metal levels is thus essential to preserve the ecological balance and support biodiversity conservation in the area (Usoro *et al.,* 2020). Therefore, this study aimed at assessing the concentrations and perturbations of the physicochemical properties and heavy metals in the soil of the coastal regions of Akwa Ibom State, Nigeria.

2. METHODOLOGY

2.1 Study Area

This study was carried out at three mangrove locations in Akwa Ibom State. These were Iko Town in Eastern Obolo Local Government Area, Okoroutip community in Ibeno Local Government Area and Uta Ewa community in Ikot Abasi Local Government Area. The coordinates of the Mangrove locations are 4° 33' N to 23^{o} 02' N and 7° 44' E to 50^{o} 60' E and 4° 33' N to 06^{o} 74' N and 7° 32' E to 48^{o} 64' E and 4° 32' N to 48^{o} 50' N and 7°32' E to 4^{o} 83' E Iko Town, Okoroutip and Uta Ewa respectively.

2.2 Vegetation Sampling and Soil Collection

Four vegetation plots were randomly selected, and within each plot, three belt transects were established. Systematic sampling was conducted in each sampling plot to collect data on vegetation and soil. This involved sampling a 10 m x 10 m quadrat at regular intervals of 20 m along the established transects. Two soil samples were collected within each quadrat using a soil auger at the respective depths of 0 – 15 cm and 15 – 30 cm, corresponding to the rooting depths. The individual samples were then placed in ziploc bags that were appropriately labeled.

2.3 Collection of Soil Sample

The soil samples were collected from each location at two different points with 10 x 12cm Eckman Grab. For better results, the samples were taken from both surface and dug area. They were further transported to the laboratory in labelled polythene bags for physicochemical and heavy metal analysis. These analyses were done separately.

2.3.1 Physicochemical and chemical analysis

The Physicochemical analysis (Particle Size Analysis – Hydrometer method) was done using standard method as described by Avery and Bascomb (1974). Determination of Soil pH, Electrical Conductivity (EC): The dip-type cell of the Jenway Pcm. A 128723-model conductivity meter was utilized in this experiment. Organic carbon, moisture, temperature and phosphate in the soil was conducted according to the APHA (1995) method. The readings were then obtained using the HACH DR 2400 spectrophotometer. The determination of total nitrogen, sulphate and chlorine content were done by Total Kjeldahl method according to Horneck and Miller (1998) and APHA (1995).

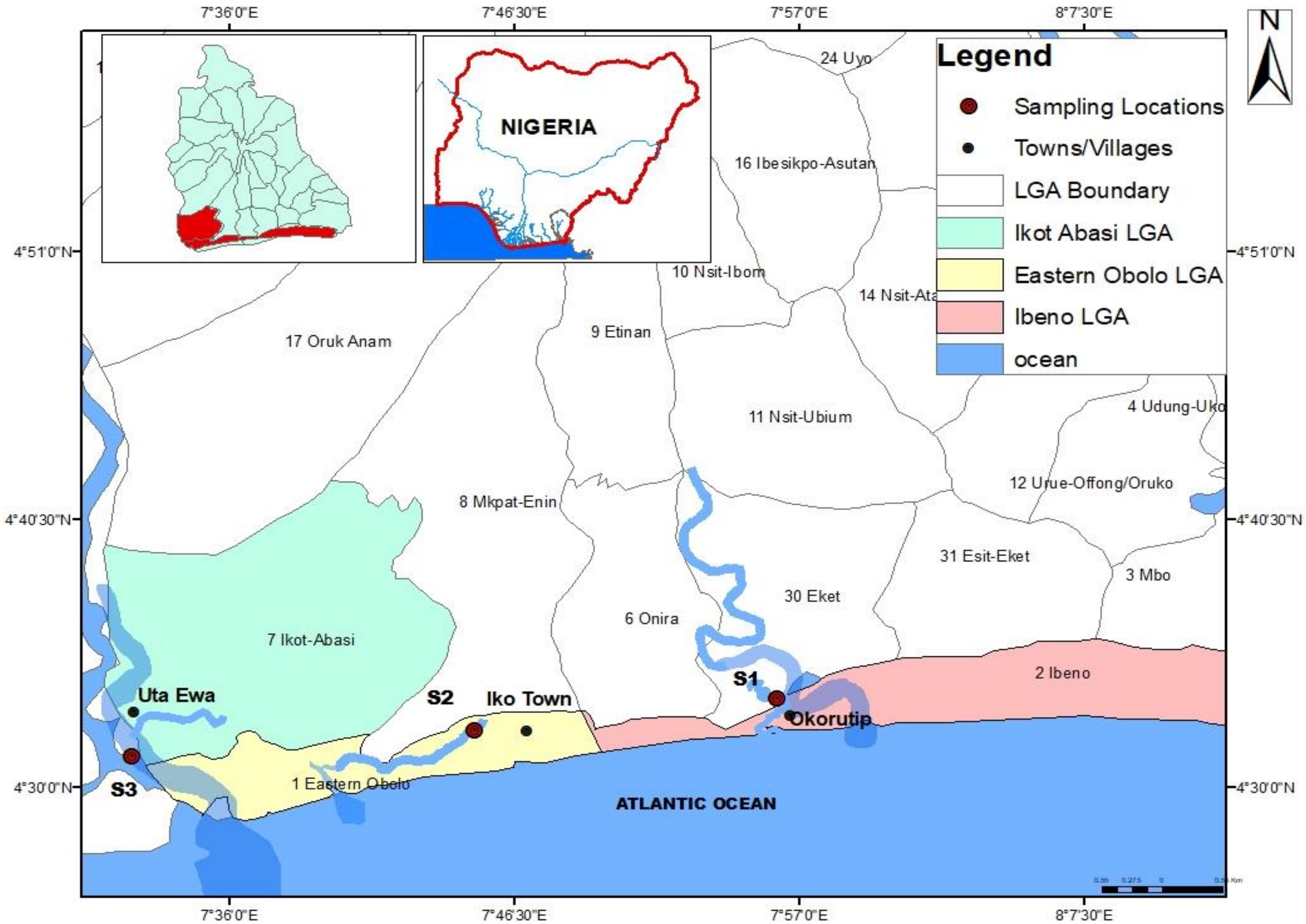

Fig. 1. Map of the study areas showing sampling location

2.3.2 Analysis of heavy metals in soil

The heavy metal analysis was done with an Acid Digestion for Inductively Coupled Plasma Optical Emission Spectrophotometry (ICP-OES) (Ibef *et al*., 2018; Ihedioha *et al.,* 2019).

2.4 Data Analysis

Data were uploaded into Microsoft Excel 2010 and were calculated and presented as mean ± standard deviation. A one-way ANOVA was used to determine significant difference (p≤0.05) in results across locations.

3. RESULTS

3.1 Physicochemical Properties of Soils Across the Mangrove Communities

3.1.1 Dry Season physicochemical properties of soils

The dry season physicochemical properties of the soil across the three mangrove communities are presented in Table 1. Okoroutip mangrove had highest values for temperature (26.57±0.24 °C) and sand content (2.02±0.01%) while Uta Ewa mangrove had highest values for chloride (640.80±0.40 mg/kg) and silt (14.77±0.02%).

3.1.2 Wet season physicochemical properties of soils

The physicochemical properties of soils across the mangrove communities for the wet season are shown in Table 2. The soil in Uta Ewa, Okoroutip and Iko Town were strongly acidic (4.82±0.01), slightly acidic (6.51±0.58) and strongly acidic (5.43±0.02) respectively. Uta Ewa mangrove had the highest value for bulk density (1.24±0.58 g/cm^3), Okoroutip mangrove had highest values for chloride (1205.00±2.89 mg/kg), moisture (62.00±1.73%), sand (4.29±0.15%) and silt (15.56±0.08%) while Iko Town mangrove had highest values for electrical conductivity (11.04±0.02 µs/cm), phosphate (30.07±2.89 mg/kg), sulphate (814.40±1.15 mg/kg), temperature (24.12±2.31 °C), salinity (4.35±0.03 ppt), organic carbon (5.20±0.12%), total nitrogen (0.72±0.58%) and clay (89.00±2.31%). Okoroutip mangrove had least values for electrical conductivity (2.01±0.58 µs/cm), phosphate (3.30±0.12 mg/kg), sulphate (340.10±2.89 mg/kg), temperature (21.75±0.58°C), salinity (2.00±0.58 ppt), bulk density (0.80±0.12 g/cm^3), organic carbon (2.80±0.12%) and clay (80.00±11.55%), Iko Town mangrove had least values for chloride (213.50±0.01 mg/kg), moisture (31.54±0.58%), sand (0.68±0.02%) and silt (10.32±0.58%) while Uta Ewa mangrove had least value for total nitrogen (0.09±0.01%). The variations in some physicochemical properties of the soil across the mangroves were significantly different ($p < 0.05$).

3.2 Heavy Metal Characterization of Soils across the Mangrove Communities

3.2.1 Dry season heavy metal characterization of soils across the mangrove communities

The dry season heavy metal characterization of soils across the mangrove communities is presented in Table 3. Ag was below detectable limits in Iko Town and Uta Ewa mangroves, Cd was below detectable limits in Iko Town mangrove while Hg was below detectable limits in Okoroutip and Iko Town mangroves. Iko Town mangrove had highest values for As (1.65±0.01 mg/kg), Cr (3.69±0.006 mg/kg), Cu (1.95±0.003 mg/kg), Ni (1.60±0.01 mg/kg), Pb (2.91±0.006 mg/kg) and V (14.89±0.006 mg/kg) while Uta Ewa mangrove had highest values for Ti (3.49±0.006 mg/kg) and Zn (3.68±0.01 mg/kg). Okoroutip mangrove had least values for As (0.83±0.01 mg/kg), Cd (0.005±0.001 mg/kg), Cr (2.79±0.006 mg/kg), Cu (1.39±0.02 mg/kg), Ti (1.65±0.006 mg/kg), V (9.86±0.02 mg/kg) and Zn (3.43±0.02 mg/kg) while Uta Ewa mangrove had least values for Ni (1.38±0.02 mg/kg) and Pb (1.92±0.01 mg/kg). The variations in some of the heavy metals across the mangrove communities were significantly different ($p < 0.05$).

3.2.2 Wet season heavy metal characterization of soils across the mangrove communities

The wet season heavy metal characterization of soils across the mangrove communities is shown in Table 4. Hg was not detected across the three mangrove ecosystems. The soil in Okoroutip mangrove ecosystem had highest values for the following heavy metals: Ag (0.05±0.01 mg/kg), As (0.08±0.01 mg/kg), Cd (0.04±0.02 mg/kg), Cr (0.32±0.01 mg/kg) and Cu (0.15±0.03 mg/kg). The soils in Okoroutip and Iko Town mangrove ecosystems jointly had highest values for Ni (0.06±0.02 and 0.06±0.006 mg/kg), Pb (0.33±0.006 and 0.33±0.02 mg/kg), Ti (0.18±0.02 and 0.18±0.01 mg/kg), V (0.31±0.006 and 0.31±0.01 mg/kg) and Zn (0.10±0.03 and 0.10±0.03 mg/kg).

Table 1. Mean values of dry season physicochemical properties of soils across the mangrove communities

Properties	Iko Town	Okoroutip	Uta Ewa
pH	5.43±0.02[a]	6.33±0.02[a]	4.26±0.05[a]
Electrical Conductivity (µs/cm)	11.37±0.32[a]	4.46±0.01[b]	6.79±0.17[b]
Phosphate (mg/kg)	30.06±0.01[a]	4.80±0.58[b]	5.61±0.58[b]
Sulphate (mg/kg)	880.00±1.15[a]	359.60±0.78[c]	723.33±6.01[b]
Temperature (°C)	26.34±0.12[a]	26.57±0.24[a]	26.43±0.15[a]
Chloride (mg/kg)	242.04±0.60[c]	360.13±0.99[b]	640.80±0.40[a]
Salinity (ppt)	5.94±0.02[a]	2.50±0.26[b]	3.57±0.02[b]
Moisture (%)	28.03±0.03[b]	27.10±0.06[b]	33.30±0.44[a]
Bulk Density (g/cm^3)	1.23±0.01[a]	0.94±0.001[a]	1.01±0.0003[a]
Organic Carbon (%)	5.87±0.02[a]	3.10±0.0[a]	4.35±0.05[a]
Total Nitrogen (%)	0.51±0.04[a]	0.08±0.001[a]	0.04±0.008[b]
Sand (%)	0.51±0.01[a]	2.02±0.01[a]	1.49±0.01[a]
Silt (%)	9.12±0.01[b]	12.14±0.02[a]	14.77±0.02[a]
Clay (%)	90.37±0.02[a]	85.84±0.02[b]	83.74±0.02[b]

Mean ± Standard error
Means with different superscripts along the same row are significantly different (p<0.05)

Table 2. Mean values of wet season physicochemical properties of soils

Parameters	Iko Town	Okoroutip	Uta Ewa
pH	5.43±0.02[a]	6.40±0.58[a]	4.82±0.01[a]
Electrical Conductivity (µs/cm)	11.04±0.02[a]	2.01±0.58[b]	6.77±0.01[b]
Phosphate (mg/kg)	30.07±2.89[a]	3.30±0.12[b]	5.60±0.03[b]
Sulphate (mg/kg)	814.40±1.15[a]	340.10±2.89[c]	687.10±0.03[b]
Temperature (°C)	24.12±2.31[a]	21.75±0.58[a]	24.00±2.31[a]
Chloride (mg/kg)	213.50±0.01[c]	1205.00±2.89[a]	619.50±0.58[b]
Salinity (ppt)	4.35±0.03[a]	2.00±0.58[a]	2.71±0.58[a]
Moisture (%)	31.54±0.58[b]	62.00±1.73[a]	37.36±1.15[b]
Bulk Density (g/cm^3)	1.10±0.01[a]	0.80±0.12[a]	1.24±0.58[a]
Organic Carbon (%)	5.20±0.12[a]	2.80±0.12[a]	3.72±0.58[a]
Total Nitrogen (%)	0.72±0.58[a]	0.17±0.12[a]	0.09±0.01[a]
Sand (%)	0.68±0.02[a]	4.29±0.15[a]	1.59±0.06[a]
Silt (%)	10.32±0.58[a]	15.56±0.08[a]	13.52±1.73[a]
Clay (%)	89.00±2.31[a]	80.00±11.55[b]	84.89±2.31[b]

± Standard error
Means with different superscripts along the same row are significantly different (P<0.05)

Table 3. Mean values of dry season heavy metal of soils across the mangrove communities

Heavy metals (mg/kg)	Iko Town	Okoroutip	Uta Ewa	WHO permissible limits of metals in soils (1996)
Ag	ND	0.29±0.006	ND	0.30
As	1.65±0.01[a]	0.83±0.01[c]	1.13±0.006[b]	0.01
Cd	ND	0.005±0.001[a]	0.01±0.0006[a]	0.80
Cr	3.69±0.006[a]	2.79±0.006[c]	3.18±0.01[b]	0.10
Cu	1.95±0.003[a]	1.39±0.02[c]	1.60±0.12[b]	0.036
Hg	ND	ND	0.006±0.0006	0.72
Ni	1.60±0.01[a]	1.14±0.01[c]	1.38±0.02[b]	0.35
Pb	2.91±0.006[a]	2.08±0.006[b]	1.92±0.01[c]	0.085
Ti	2.90±0.06[b]	1.65±0.006[c]	3.49±0.006[a]	0.056
V	14.89±0.006[b]	9.86±0.02[c]	14.79±0.006[b]	1.00
Zn	3.64±0.02[a]	3.43±0.02[b]	3.68±0.01[a]	0.03

± Standard error; ND= Not Detected; As – Arsenic, Cd – Cadmium, Cr – Chromium, Cu – Copper, Hg – Mercury, Ni – Nickel, Pb – Lead, Ti – Titanium, V – Vanadium and Zn - Zinc
Means with different superscripts along the same row are significantly different (p≤0.05)

Table 4. Mean values of wet season heavy metal of soils across the mangrove communities

Heavy metals (mg/kg)	Iko Town	Okoroutip	Uta Ewa	WHO permissible limits of metals in soils (1996)
Ag	0.01±0.003[a]	0.05±0.01[a]	0.01±0.006[a]	0.30
As	0.04±0.01[a]	0.08±0.01[a]	0.04±0.01[a]	0.01
Cd	0.01±0.003[a]	0.04±0.02[a]	0.005±0.001[a]	0.80
Cr	0.28±0.01[a]	0.32±0.01[a]	0.28±0.01[a]	0.10
Cu	0.11±0.01[a]	0.15±0.03[a]	0.10±0.06[a]	0.036
Hg	ND	ND	ND	0.72
Ni	0.06±0.006[a]	0.06±0.02[a]	0.02±0.006[a]	0.35
Pb	0.33±0.02[a]	0.33±0.006[a]	0.29±0.01[a]	0.085
Ti	0.18±0.01[a]	0.18±0.02[a]	0.14±0.01[a]	0.056
V	0.31±0.01[a]	0.31±0.006[a]	0.27±0.01[a]	1.00
Zn	0.10±0.03[a]	0.10±0.03[a]	0.06±0.003[a]	0.03

± Standard error; ND – Not Detected; As – Arsenic, Cd – Cadmium, Cr – Chromium, Cu – Copper, Hg – Mercury, Ni – Nickel, Pb – Lead, Ti – Titanium, V – Vanadium and Zn - Zinc

Means with different superscripts along the same row are significantly different (p≤0.05)

4. DISCUSSION AND CONCLUSION

4.1 Discussion

The physicochemical characteristics of the soil exhibited variability among the different mangrove sites. The observed discrepancies in soil characteristics can be attributed to the effects of groundwater seepage and the response of the parameters to tidal flushing of the uppermost layer of soil (Akpabio *et al.,* 2014). The pH values of the soil observed in the dry and wet conditions of these mangroves fall within the reported ranges of previous studies in mangrove swamps in Southeastern Nigeria (Ukpong, 1997); mangrove system in Southeast Brazil (Ferreira *et al.*, 2010), mangrove soil at Hooker Bay and San Andres Island-Colombia (Moreno and Calderon (2011). The seasonal variation in soil pH observed in the three mangrove locations suggests the presence of acidic conditions commonly found in mangrove soils (Boto and Wellington, 1984). The electrical conductivity (EC), a parameter indicating the overall salt content of the soil, exhibited greater values during the dry seasons compared to the wet seasons in several mangrove sites. This observation provides evidence for the phenomenon of rainwater dilution on the soil composition of the mangrove ecosystem. The soil in the Iko town community mangrove had higher seasonal values for electrical conductivity, whereas the soil in the Okoroutip community mangrove displayed the lowest values. This variety may have emerged as a result of varying amounts or frequencies of tidal flooding within the mangrove ecosystem. Pattanaik *et al.,* (2008) reported that mangrove soils experiencing frequent tidal inundations exhibit elevated electrical conductivity (EC) values, whereas soils subject to infrequent tidal inundations display lower EC values. The presence of different levels of phosphate within the mangroves can be attributed to various geogenetic factors, such as the spatial arrangement of wetlands in relation to freshwater supplies from higher ground (Harguinteguy *et al.,* 2014). The occurrence of lower values was seen in areas where marine influences were more pronounced compared to terrestrial factors (Duruibe *et al.,* 2007). The elevated levels of sulphate seen in these specific mangrove areas may perhaps be attributed to the acidic nature of the soil, which is a result of the decomposition of organic matter in the water-saturated soils (Abdu, 2015). The variation in chloride concentrations in the soil across different mangrove locales can be attributed to the varying frequencies of tidal waves. The salinity levels observed in the mangrove soils exhibited seasonal variations, with higher values recorded during the dry seasons as compared to the wet seasons. The wet season's low soil salinity observed in the three mangrove areas underscores the significant role of rainwater in diluting sodium within these ecosystems. The observed differences in salinity levels across the three mangroves can be attributed to their spatial positioning relative to oceanic and freshwater sources, and align with a gradual shift in vegetation composition **(**Singh *et al.,* 2017). The elevated levels of soil moisture observed in mangrove sites during the wet season, in comparison to the dry season, can be attributed to reduced evaporation rates resulting from lower temperatures, as well as more precipitation. The observed elevated soil moisture levels in the three mangrove sites could potentially be attributed to the substantial presence of clay within the soil composition. The bulk density values observed for the various mangrove areas align with the previously reported range of 0.73 g/cm^3 to 1.42 g/cm^3 (Ukpong, 1994). The observed low bulk density and high soil moisture values in the mangrove regions can be attributed to the saturation of soils by tides. This was in agreement to Singh *et al.,* (2017) that reported moderately low level of bulk density in a Wetland. Bonanno (2013) reported that the seasonal decrease in bulk densities within mangroves is likely ascribed to the increased concentrations of organic matter and clay.

The organic carbon and total nitrogen levels in the three mangrove locations were found to be relatively low, a phenomenon that can be explained by the sluggish rates of litter breakdown and mineralization in the soil (Ita, 2019). Furthermore, Reef *et al.,* (2010) have posited that a significant proportion of mangrove soil exhibit a characteristic deficiency in nutrients, mostly due to the inhibitory effects of flooded soils on nitrification and the microbial synthesis of NO^{3-}. The presence of many mangrove roots has a significant role in the reduced levels of total nitrogen observed in mangrove soils (Ita, 2019). This is due to the inability of the roots to take up nutrient for their own growth. The presence of significant amounts of organic carbon in the mangrove ecosystem of Iko town community is likely linked to the periodic influx of organic materials through tidal processes (Moorman and Pons, 1974). The observed elevated levels of organic carbon in the mangrove ecosystem of Iko town community could potentially be attributed to the peaty composition of the soil and the abundance of roots and pneumatophores. A seasonal variation in particle sizes was detected throughout the several mangrove areas, with a consistent decreasing pattern: clay > silt > sand. The observed distribution of particle size percentages in different mangrove habitats disagreed with previous literature (Moreno and Calderon, 2011). They reported varying sequences of particle size distribution, in the order - silt > sand > clay (Moreno and Calderon, 2011) and sand > silt > clay, (Ita, 2019). Nevertheless, the prevalence of clay particles in the three mangrove sites examined in this research corresponds reports from Deshmukh (2012) in a study conducted on mangrove soil in Ahmadnagar District, Maharastra, Rasayan, India. The high clay content observed in mangrove soils has been related to the frequent occurrence of flooding events (Cao *et al.,* 2017).

The phenomenon of heavy metal buildup in mangrove soils, as demonstrated in this work, has been documented in other mangroves (Ganeshkumar *et al.,* 2019). The soils of the mangrove ecosystems exhibited fluctuations in the apportionments of heavy metals, both in terms of seasonality and spatial distribution. While several heavy metals exhibited elevated levels, others demonstrated decreased concentrations. The mangrove environment with elevated anthropogenic activities and pollutants exhibited a greater concentration of heavy metals. The observed spatial heterogeneity in the concentrations of heavy metals in the soil of the studied mangroves indicates the diverse degrees of human-induced disturbances and industrial contamination resulting from activities such as oil exploration, accidental chemical releases, gas flaring, and the discharge of diesel and petrol from speed boats. In comparison, the concentrations of heavy metals exhibited higher levels during the dry season as opposed to the wet season. This was in agreement to report from a Chinese estuarine mangrove wetland (Hong *et al.,* 2021). According to Edokpayi *et al.,* (2017), the observed tendency can be attributed to the increased water volume and velocity during the rainy season, which leads to a significant dilution of heavy metals. This dilution process can potentially impact the concentration of metals in both water and soil. It has been suggested that precipitation has the potential to cause erosion of mangrove soils and dilute the concentrations of heavy metals in soil through runoff events occurring during the rainy season (Thampanya *et al.,* 2006; Hong *et al.,* 2021).

The elevated levels of heavy metals observed in the mangroves of Iko Town during the dry season, in comparison to the other two mangrove locations, can be attributed to the persistent oil exploration, drilling, and extraction activities conducted by the Sterling Oil Exploration and Energy Production Company. These activities were prevalent in the area during the time of field sampling. Liu *et al.,* (2014) added that the elevated concentrations of heavy metals found in the mangrove soils can be attributed to the discharge of effluents and occurrences of oil spillages during the process of oil transportation. The soil found in the mangrove ecosystem of Iko town exhibit elevated levels of organic matter, sulphide, and clay content. This result could likely have contributed in the enhancement capacity of the soil to retain heavy metals. Also, the retention of heavy metals in the soil is contingent upon the pH level of the soil solution. However, the Okoroutip mangrove had the highest concentration of heavy metals in the soil during the rainy season. The clarity of this pattern is somewhat ambiguous as the Iko Town mangrove exhibited elevated levels of soil heavy metals throughout the dry season, which could have been attributed to the influx of metal runoffs from diverse sources into this area during the wet season. Arsenic (As), Chromium (Cr), Copper (Cu), Lead (Pb), Titanium (Ti), Vanadium (V), and Zinc (Zn) were the heavy metals present in the soil samples collected from Iko town and Uta Ewa mangroves and are said to be beyond the acceptable threshold established for soil (WHO, 1996). The increased concentrations of heavy metals in the soil pose a significant hazard to benthic creatures (MacDonald *et al.,* 2000; Akpabio *et al.,* 2024). The presence of heavy metals in elevated concentrations can potentially lead to negative consequences for soil microbes, aquatic species, plants, and directly and indirectly to human beings, hence giving rise to public health concerns and environmental issues.

4.2 Conclusion

The variations in the physicochemical properties above WHO's limits and the presence of heavy metals in the soil of selected coastal areas of Akwa Ibom State is indicative of pollution in the areas which have been attributed to a number of anthropogenic activities. This has been ability to bio accumulate in these soils, thus affecting the flora and fauna species of the mangrove ecosystem of the study area. In view of the current knowledge of the role of mangrove ecosystems in blue-economy of the nation and mitigation of ongoing climate change, we advocate a tripartite alliance between the government, multinational companies operating within the area and the various impacted communities that leads to a concerted efforts of constant monitoring and remediation in the reduction of current and future pollutant levels.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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