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Spatial and temporal variations in physicochemical properties and specific trace metals in soils of oil exploration and production host communities in Southern Nigeria.

Biose E[1*]., Ogwo, P. A[2]., Ogbonna P. C[2]., Agbate A. E[3]., Akinlagun, O. H[1]., Imasuen J. E[1]., Osagie, C. O[1] and Enabulele, C. O[3].

[1]Department of Environmental Management and Toxicology, Faculty of Life Sciences, University of Benin, Benin City, Nigeria.
[2]Department of Environmental Management and Toxicology, College of Natural Resources and Environmental Management, Michael Okpara University of Agriculture, Umudike. Abia State, Nigeria
[3]Department of Animal and Environmental Biology, Faculty of Life Sciences, University of Benin, Benin City, Nigeria.
*Corresponding Author: ekene.biose@uniben.edu

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Abstract

The release of certain chemicals into the environment, especially into soil can pose significant and potentially dangerous threats to human health and ecosystems. This research investigates the spatial and temporal variations in the physicochemical characteristics and concentrations of selected heavy metals in soil. Composite soil samples, collected from a depth of 0–20 cm, were obtained from a consistent quadrant across five coastal wetland communities in Delta State. A total of 25 samples were gathered from some communities in Delta State. Heavy metal concentrations were determined using Atomic Absorption Spectroscopy (AAS), specifically the Solar 969 Unicam Series Model. The results revealed statistically significant differences ($p<0.01$) in several soil properties, including electrical conductivity (EC), organic carbon (OC), moisture content, available phosphorus (P), sodium (Na), calcium (Ca), magnesium (Mg), potassium (K), cation exchange capacity (CEC), sand, silt, and clay content. However, soil pH and total nitrogen (N) did not show significant differences ($p>0.05$). The average concentrations of heavy metals and total hydrocarbon content (THC) in the coastal wetland soils were as follows: iron (Fe) at 217.741±130.42, chromium (Cr) at 5.997±6.33, cadmium (Cd) at 0.275±0.13, copper (Cu) at 4.732±3.00, zinc (Zn) at 34.729±33.37, manganese (Mn) at 23.298±19.19, lead (Pb) at 10.856±2.90, and THC at 17694.98±47114.37. The concentration order of these metals was: Fe > Zn > Mn > Pb > Cr > Cu > Cd. Cluster analysis indicated notable differences between the sampled locations, suggesting variations in soil physicochemical properties and heavy metal levels. The trend in soil property dissimilarity followed the sequence: Emevor > Kwale > Effurun > Olomoro > Sapele (control). Principal component analysis (PCA) extracted six components, explaining a total variance of 82.217% in the dataset. A strong, positive correlation was found between heavy metal concentrations and total petroleum hydrocarbons, implying a shared or related source of contamination. Deviations of these soil parameters from established guideline levels could lead to negative environmental and health impacts, limit the potential use of the soil, and compromise the ecological support systems crucial to the local people

1. Introduction

Nigeria has been extracting and utilizing crude oil for decades, resulting in significant issues in both onshore and offshore production and processing regions [1]. The detrimental and ecologically adverse pollution effects of waste from these explorations necessitate the implementation of optimal technology in the conversion processes for extracting petroleum and petrochemical products from crude oil, which produce various forms of waste [1, 2, 3]. These wastes can be broadly categorized as oily substances, exhausted catalysts, depleted chemicals, and various residuals that have entered the environment due to continuous discharge [1].

The escalation of oil operations has led to significant environmental contamination due to oil spills caused by blowouts, leaks from tanks or tanker trucks, and the disposal of waste petroleum products into the environment [1]. The consequences of these actions have been recorded [4, 5]. Refined crude oil comprises several constituents, including hydrocarbons, heavy metals, color additives, antioxidants, corrosion inhibitors, and polycyclic aromatic hydrocarbons, all of which are very hazardous and detrimental to human health [6, 7]. The processed products exhibit greater toxicity than crude oil due to alterations in metal speciation and the introduction of additional metals into the matrix during refining processes [2, 8]. The waste produced from these operations may include wasted catalysts, which are typically not recovered and instead released into soil and water bodies, where they accumulate in surface waters, river sediments, and eventually groundwater [1].

Although many countries encounter natural hazards, Nigeria contends with many technological and anthropogenic risks, with oil spills being predominant and causing significant short- and long-term cumulative effects on the affected population [9]. For example, a European nation encountered 10 oil leak incidents over 40 years, whereas Nigeria faced 9,343 incidents within a decade [10, 11]. Research indicates that the volume of oil discharged into the Nigerian environment during five decades was no less than 9-13 million barrels, comparable to fifty Exxon Valdez oil disasters of 1989 (260,000 barrels) [12,13]. This established the region as one of the five most severely petroleum-damaged environments globally [14, 15]. As a result, these calamities have impacted the ecology, agricultural lands, water resources, and livelihood frameworks of the oil-producing communities in Nigeria [14]. The consequences exacerbate poverty, crises, and unrest in crude oil-producing regions [16], resulting in the emergence of various agitation organizations advocating for environmental justice and livelihood assistance measures [9].

Soil pollution caused by natural and anthropogenic human activities might endanger human health if not addressed appropriately. The knowledge of soil characteristics and other pollutants levels is important for safety policy formulation and awareness [17]. A report commissioned by the NEST/Ford Foundation, the Niger Delta Environmental Survey [18], highlighted the growing problem of soil fertility loss and declining agricultural productivity in the Niger Delta. These issues were identified as indirect but significant pressures on both natural resources and the socio-economic fabric of local communities, with the most profound impact on economically disadvantaged populations. The socio-economic effects of oil contamination in affected areas and the potential risks in communities vulnerable to oil spills have remained a persistent concern in the region [17]. Decades of oil exploration and extraction—spanning over forty years—have inflicted substantial ecological damage across the Niger Delta, with the most severe impacts observed in the often-overlooked communities within the coastal marshlands of Delta State. The unregulated release of oil and its derivatives, including chemicals and trash, primarily resulting from equipment malfunctions, operational mistakes, or intentional harm, has been recognized as the principal cause of environmental degradation in the region over time [19]. Following numerous years of neglect

regarding these deleterious impacts, recent initiatives have been undertaken by environmentalists, non-governmental organizations (NGOs), and oil multinationals to address the issue [20]. The environmental repercussions outlined are among the effects of oil spills noted in the coastal wetlands of Nigeria's Niger Delta region, while other effects may exist [20, 21]. Consequently, it is essential to implement measures to monitor, prevent, and mitigate oil spills in the coastal wetlands of Delta State.

2. Materials and Methods

2.1. Study Area and its Geology

This research was carried out in Delta State, located in the South-South geopolitical zone of Nigeria, at coordinates 5° 30' 0.00"N latitude and 6° 00' 0.00"E longitude. Sampling sites were strategically chosen based on factors such as human population density, traffic volume, roadway characteristics, and areas previously impacted by oil spills. Soil samples were collected from five distinct and accessible locations within Delta State: the control site (Sapele), along with Kwale, Emevor, Effurun, and Olomoro. Delta State spans an area of approximately 16,842 square kilometers [22] and lies within the tropical rainforest zone. It hosts rich and complex ecosystems that support a wide range of terrestrial and aquatic plant and animal life. The state is also recognized as one of Nigeria's most environmentally sensitive regions [18, 23, 24].

Geologically, Delta State falls within the Niger Delta Structural Basin, which has experienced three major sedimentary depositional cycles dating back to the early Cretaceous era. These cycles correspond to three main subsurface geological formations: the Benin, Agbada, and Akata Formations. Surface rocks in the region are predominantly from the Ogwashi-Uku Formation. The Benin Formation, about 1,800 meters thick, consists primarily of unconsolidated sand deposits and has minimal hydrocarbon presence. Lying beneath it is the Agbada Formation, composed of alternating layers of sandstone and shale, which is a significant reservoir for hydrocarbons. The deepest unit, the Akata Formation, can be found at depths reaching up to 3,000 meters. In the northeastern part of the state, the Ogwashi-Asaba Formation characterized by clay and lignite seams is the dominant geological feature [25].

2.2. Sample Collection

Soil samples were collected from multiple accessible locations, with their geographic coordinates documented using a Global Positioning System (GPS) device. To provide a basis for comparison, additional samples were taken from a designated control site within the study area. The sampling locations included the following sites:

Site 1: Control (Sapele)	N 05º 48. 502' E 005º 44. 041'
Site 2: Kwale	N 05º 41. 989' E 006º 27. 832'
Site 3: Emevor	N 05º 29. 411' E 006º 05. 680'
Site 4: Effurun	N 05º 34. 795' E 005º 46. 964'
Site 5: Olomoro	N 05º 27. 461' E 006º 10. 413'

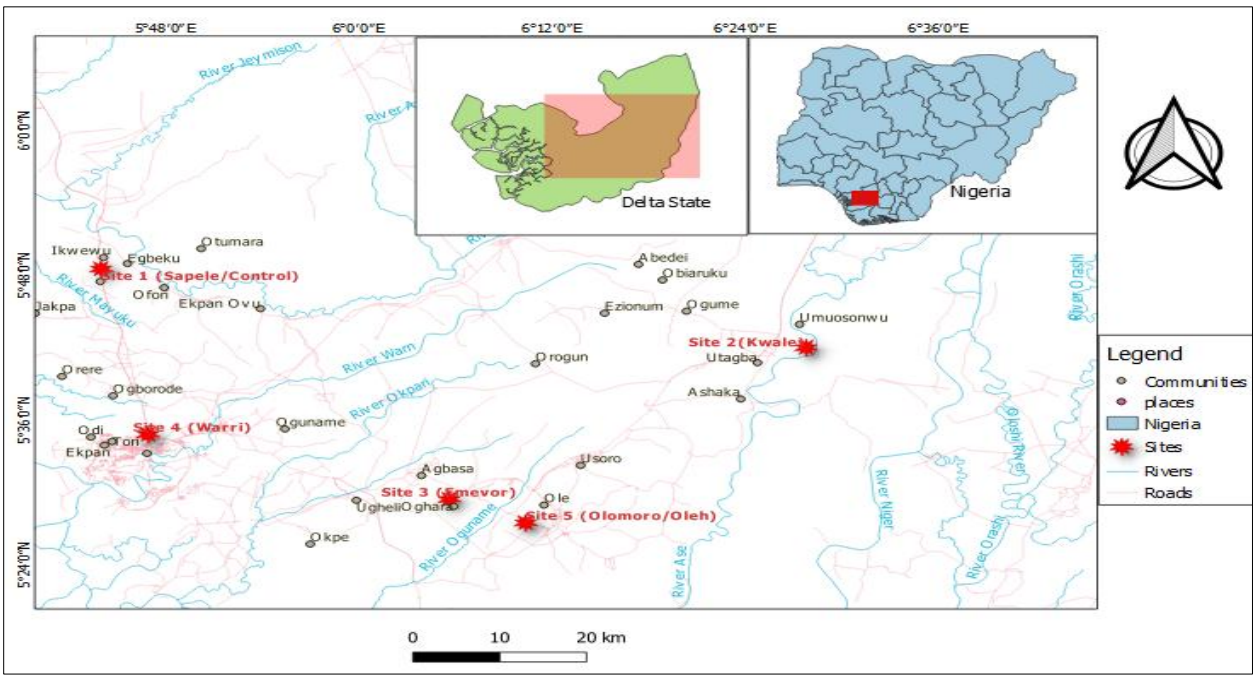

Figure 1: Map showing soil sampling sites

2.3. Collection of Soil Samples

Soil samples were collected from a depth of 0–20 cm using a manually operated stainless steel auger. Approximately 100 grams of soil were taken from each site, placed in labeled polyethylene bags, and immediately transported to the laboratory for analysis [26, 27]. In each location, multiple sub-samples were combined to form a composite sample. These were further subdivided into three sections to produce a single representative composite for each site.

2.4. Preparation of soil samples

The collected soil samples were conveyed to the laboratory by vehicle. Upon arrival, they were air-dried at room temperature (ranging from 25°C to 27°C) over a period of two to three days. After drying, the samples were finely ground, passed through a 2 mm mesh sieve, and stored in clearly labeled containers in preparation for laboratory testing. Physical and chemical parameters of the soils were subsequently analyzed. Throughout the sample handling and preparation process, strict quality assurance protocols were followed to minimize the risk of contamination.

2.5. Laboratory Analysis for Soil Samples

The soil pH was assessed using the methodology established by [28]. The method of APHA [29] was employed to ascertain electrical conductivity. The soil's organic matter percentage was ascertained using the method outlined by Walkey and Black [30]. The moisture content was assessed following the methodology outlined by Page *et al.* [31]. Available phosphorus and exchangeable cations were assessed using the methodology established by Onyeonwu [32]. The total soil nitrogen was quantified using the Kjeldahl method as per Bremmer [33]. The soil particle size distribution was assessed utilizing the enhanced Hydrometer Method as outlined by Ibitoye [34]. The total hydrocarbon content in the soil samples was determined using a HACH DR spectrophotometer, following the standard procedure outlined by the American Public Health Association [35].

2.6. Soil Digestion and Heavy Metal Analysis

For heavy metal analysis, 0.5 grams of air-dried soil were digested using concentrated nitric acid (10 cm^3, specific gravity 1.42). The mixture was heated under reflux for 45 minutes in a Kjeldahl

flask, then evaporated to dryness. Subsequently, 5 cm^3 of aqua regia was added and the solution was again heated until nearly dry. To complete the digestion process, 10 cm^3 of distilled water was introduced, and the resulting mixture was filtered through Whatman No. 42 filter paper into a 25 ml volumetric flask. The filtrate was then quantitatively transferred into a 50 ml volumetric flask and diluted up to the calibration mark [36].

Following digestion, concentrations of heavy metals specifically Iron (Fe), Chromium (Cr), Cadmium (Cd), Copper (Cu), Zinc (Zn), Manganese (Mn), and Lead (Pb) were measured using an Atomic Absorption Spectrophotometer (AAS), model Solaar 969 Unicam Series. Calibration curves were generated using certified atomic absorption standards for each element. To maintain analytical precision and account for potential instrument drift, reagent blanks were analyzed after every ten samples. To mitigate equipment drift, reagent blanks were conducted at intervals of ten samples. All samples were examined in duplicate to guarantee reproducibility, accuracy, and precision. Heavy metals in soil were analyzed in the laboratory using the method established by the Association of Analytical Chemists [37].

2.7. Multivariate Analysis

2.7.1. Cluster analysis

Cluster analysis was conducted utilizing Euclidean distance based on the compositional ratios of each heavy metal. Cluster analysis is an unsupervised pattern recognition method that reveals the inherent structure or underlying behavior of a dataset without prior assumptions, aiming to categorize system objects into clusters based on proximity or similarity [38].

2.7.2 Principal component analysis (PCA)

Principal Component Analysis (PCA) is a multivariate statistical method used to reduce the dimensionality of a dataset by converting a large number of correlated variables into a smaller set of uncorrelated variables, known as principal components. These components are linear combinations of the original variables and are designed to retain the maximum amount of variation present in the dataset [39, 40].

2.7.2 Statistical Analysis

Data analysis was carried out using a combination of statistical software tools: Microsoft Excel (2016), SPSS version 20.00, PAST3, and R-Stats. Descriptive statistics including measures of central tendency and dispersion were applied to summarize the physical and chemical characteristics of the soil samples. To determine statistically significant differences among the sampled regions, a one-way Analysis of Variance (ANOVA) was conducted. Multivariate techniques were also employed. Cluster Analysis (CA) was performed using PAST3 software to group similar sampling sites based on their physicochemical profiles. Principal Component Analysis (PCA), incorporating varimax rotation to enhance interpretability, was executed using R version 4.0.2 (R Development Core Team, 2020). Additionally, correlation analysis was applied to identify relationships among the various soil parameters.

3. Results and Discussion

3.1. Physico-chemical properties and heavy metal content of soil

Tables 1 and 2 display the results of the analysis of physicochemical characteristics and heavy metal concentrations in soils collected from five study locations. As highlighted by Saro-Wiwa [[41, 42], the release of certain chemical substances into the environment particularly into soil can have significant and detrimental impacts on human health [43]. Without a healthy and secure

environment, the realization of basic social, political, and economic rights becomes unattainable [44]. Therefore, consistent and periodic assessment of various ecological components is crucial to ensure environmental safety and public well-being.

The pH values in the study regions of control, Kwale, Emevor, Effurun, and Olomoro were comparable and somewhat acidic, with averages of 5.83, 5.76, 5.95, 5.79, and 5.51, respectively. Lower pH range values were recorded at the control environment (4.80-6.62) and Olomoro (4.10-6.40) respectively and were extremely acidic to slightly acidic when compared to other study areas which were strongly acidic to slightly acidic. Idibie and Idibie [45] obtained a different pH value range of 4.9 - 6.7. Research indicates that soil pH influences plant growth not only indirectly through nutrient availability but also by influencing toxin presence and the proliferation of soil microbes [46, 47]. Soil pH is crucial for assessing the availability of several soil nutrients and influences the behavior, degradation, and potential migration of various soil contaminants [47]. Consequently, pH values between 4.9 and 5.1 may influence nutrient availability in oil-contaminated soils. The soil pH findings in this study align with prior research [48, 49, 46], indicating that crude oil contamination elevates soil acidity. Nwankwo et al. [47] reported a comparable value of 5.81 mg/kg for pH in their investigation of soil contamination indicators resulting from oil spillage in Akinima, Rivers State. Osuji and Nwoye [17] examined the pH of oil-contaminated soils at two depths and found significantly lower values compared to background soils; however, the differences between the two depths were not significant. The result obtained is this study were similar with the results of Osuji and Nwoye [17], however Emevor had a higher pH in this study than other study areas.

Electrical conductivity (EC) readings in soil were found to be higher in the control site compared to the other study areas, a pattern consistent with the observations reported by Osuji and Nwoye [17]. The average EC values recorded were 15.68, 17.63, 39.54, and 29.81 µS/cm at Kwale, Emevor, Effurun, and Olomoro, respectively. These results suggest a lower level of anthropogenic influence at the control site. Given that crude oil, being an organic compound, has inherently low electrical conductivity, it is unlikely to have directly contributed to changes in EC values [50]. Notably, a statistically significant difference ($P<0.01$) was observed when comparing EC values across the study sites, with the control location exhibiting the highest EC at 91.66 µS/cm. In comparison, Idibie and Idibie [45] documented much higher EC levels ranging from 1023 to 5868 µS/cm in oil-contaminated soils in Okpare-Olomu Community, Ughelli South LGA, Delta State. It is possible that anaerobic degradation of hydrocarbons through dehydrogenation in the presence of electron acceptors like nitrate ions contributed to the observed EC variations [17, 45].

Organic carbon (OC) content in soil serves as a quantifiable indicator of soil organic matter and reflects the intensity of human-induced activities in a given area [51]. Higher OC levels contribute to better soil structure and tilth, enhancing its physical resilience. This, in turn, supports improved aeration, moisture retention, and water infiltration, while reducing the likelihood of erosion and nutrient loss [51]. The concentration of OC throughout all studied regions (control, Kwale, Emevor, Effurun, and Olomoro) varied from low to medium levels. Nonetheless, a substantial difference ($p<0.01$) was seen in comparison to the control environment, which exhibited lower values at 1.16% for OC. This study's difference is ascribed to the pronounced anthropogenic activity in the examined areas, which elevates the organic content of the coastal wetland soils, alongside rapid mineralization and depletion resulting from the substantial nutrient demands of macrofauna and flora, compounded by leaching effects during heavy rainfall in the control environment. The organic carbon percentages recorded from Kwale, Emevor, Effurun, and Olomoro were 3.68, 3.20, 2.89, and 2.74, respectively.

Various investigations indicated that polluted soils possessed a higher concentration of organic matter compared to uncontaminated soils [52]. This may result from the accumulation of substantial amounts of trash and other organic materials [52, 53]. Nevertheless, the outcome diverges from the values reported by Osuji and Nwoye [17] in their controlled environment, where they observed higher organic carbon levels in the control sites compared to the oil-impacted locations. They posited that the spilled oil may have hindered the metabolic processes necessary for the agronomic incorporation of organic carbon from petroleum hydrocarbons by diminishing the carbon-mineralizing capacity of the microflora [51, 54]. Accordingly, two principal decomposition processes are relevant to this study: the breakdown of native soil organic matter and the degradation of petroleum hydrocarbons introduced through contamination. Both processes are carried out by heterotrophic microorganisms. Although the presence of spilled crude oil may have initially triggered microbial activity, the microbial population may not have expanded sufficiently to fully process the excess carbon-rich material. This limitation could be due to several factors, such as adverse weather conditions, climatic influences, or the soil's inherent physicochemical characteristics [55].

Table 1: Physicochemical characteristics of soil at different locations

Parameters	Site 1 Control (Sapele) $\bar{x}$±SD (Min-Max)	Site 2 Kwale $\bar{x}$±SD (Min-Max)	Site 3 Emevor $\bar{x}$±SD (Min-Max)	Site 4 Effurun $\bar{x}$±SD (Min-Max)	Site 5 Olomoro $\bar{x}$±SD (Min-Max)	p-value
pH	5.83±0.65 (4.80-6.62)	5.76±0.44 (5.40-6.50)	5.95±0.41 (5.67-6.63)	5.79±0.50 (5.34-6.52)	5.51±0.85 (4.10-6.40)	p>0.05
EC (µs/cm)	91.66 ^{a} ±10.48 (75.88-100.00)	15.68 ^{b} ±5.89 (5.75-20.90)	17.63 ^{b} ±6.87 (8.42-24.00)	39.54 ^{b} ±29.20 (11.98-83.00)	29.81 ^{b} ±38.87 (3.57-93.00)	p<0.01
Organic carbon (%)	1.16 ^{b} ±1.08 (0.41-3.02)	3.68 ^{a} ±0.56 (3.07-4.14)	3.20 ^{a} ±0.90 (2.22-4.06)	2.89 ^{a} ±1.24 (1.63-4.48)	2.74 ^{a} ±1.08 (1.70-3.86)	p<0.01
Moisture content	8.13^{b} ±4.84 (0.96-14.52)	11.94^{b} ±5.86 (2.95-18.06)	14.99 ^{b} ±7.89 (1.54-20.17)	14.86 ^{b} ±7.51 (1.65-19.00)	33.91^{a} ±27.53 (4.72-63.01)	p<0.01
Available Phosphorus (mg/kg)	16.30 ^{a} ±1.83 (13.93-18.15)	6.69 ^{c} ±1.07 (5.52-7.51)	3.61 ^{d} ±2.52 (1.18-6.21)	19.34 ^{a} ±4.40 (14.56-23.47)	11.24 ^{b} ±5.93 (8.43-21.85)	p<0.01
Total nitrogen (%)	0.35±0.52 (0.10-1.29)	0.61±0.41 (0.19-1.20)	0.44±0.45 (0.23-1.24)	1.00±0.75 (0.16-1.68)	0.70±0.45 (0.18-1.19)	p>0.05
Na (meq/100g)	1.16 ^{a} ±0.05 (1.10-1.20)	0.96 ^{b} ±0.11 (0.80-1.10)	0.77 ^{c} ±0.19 (0.43-0.90)	0.79 ^{c} ±0.07 (0.70-0.90)	1.08 ^{a} ±0.15 (0.90-1.30)	p<0.01
Ca (meq/100g)	1.24 ^{a} ±0.08 (1.10-1.28)	0.61 ^{c} ±0.06 (0.50-0.64)	0.46 ^{b} ±0.04 (0.39-0.48)	1.49 ^{a} ±0.92 (0.50-2.89)	0.68 ^{b} ±0.27 (0.20-0.80)	p<0.01
Mg (meq/100g)	0.76 ^{a} ±0.25 (0.65-1.20)	0.54 ^{b} ±0.24 (0.11-0.65)	0.44 ^{c} ±0.26 (0.32-0.90)	0.85 ^{a} ±0.08 (0.81-1.00)	0.87 ^{a} ±0.13 (0.81-1.10)	p<0.01
K (meq/100g)	0.89 ^{a} ±0.41 (0.60-1.60)	1.33 ^{a} ±0.35 (1.03-1.80)	0.76 ^{a} ±0.41 (0.30-1.30)	0.81 ^{a} ±0.37 (0.42-1.20)	0.54 ^{b} ±0.46 (0.03-0.92)	p<0.05
CEC (meq/100g)	4.05 ^{a} ±0.40 (3.73-4.51)	3.45 ^{ab} ±0.23 (3.29-3.85)	2.42 ^{c} ±0.19 (2.10-2.58)	3.94 ^{a} ±1.09 (3.10-5.60)	3.16 ^{b} ±0.51 (2.68-3.90)	p<0.01
Sand (%)	92.08 ^{a} ±0.41 (91.56-92.64)	79.68 ^{d} ±1.29 (78.45-81.42)	93.01 ^{a} ±2.43 (90.90-95.64)	85.79 ^{b} ±0.92 (84.64-87.01)	81.85 ^{c} ±0.66 (81.26-82.67)	p<0.01
Silt (%)	4.17 ^{d} ±0.87 (3.06-5.06)	13.71 ^{a} ±1.98 (10.73-15.50)	3.05 ^{d} ±1.81 (0.78-4.41)	8.60 ^{c} ±1.10 (7.72-9.83)	10.44 ^{b} ±0.45 (9.76-10.78)	p<0.01
Clay (%)	3.75 ^{d} ±0.98 (3.00-5.38)	6.61 ^{b} ±0.74 (6.05-7.85)	3.94 ^{d} ±0.74 (3.01-4.69)	5.62 ^{c} ±0.49 (5.01-6.11)	7.71 ^{a} ±0.38 (7.11-8.01)	p<0.01

The moisture content in the coastal wetland soils of Delta State varied in response to the rainfall distribution during the study period, which spanned from January to December. Rainfall was scarce between January and March, while moderate to significant precipitation occurred between April and September, when most sampling activities were conducted. Although the wetlands exhibited comparable moisture levels, a notable statistical difference ($P<0.01$) was observed when these values were compared with the control site at Sapele, which recorded a lower moisture content of 8.13%. For comparison, Idibie and Idibie [45] reported considerably higher moisture levels ranging from 24.7% to 40% in crude oil-polluted soils within the Okpare-Olomu area of Ughelli South, Delta State. The application of hydrophobic hydrocarbons on soil surfaces may reduce water retention capacity due to a significant loss of clay binding capabilities. Typically, such partial coatings result in the degradation of soil structure and the dispersion of soil particles, hence diminishing water percolation and retention [17, 45].

Other research locations, including Kwale, Emevor, and Effurun, had similar values and demonstrated no significant differences among themselves and the control environment; nevertheless, they displayed a very significant difference ($p<0.01$) from Olomoro, which recorded higher moisture content. Osuji and Nwoye [17] documented elevated values of 30.8% and 30.0% in oiled surface and subsurface soils, respectively, attributing this phenomenon to inadequate soil aeration, maybe resulting from air displacement within the soils; this likely facilitated waterlogging and diminished the evaporation rate. The mean moisture content readings at Kwale, Emevor, Effurun, and Olomoro were 11.94%, 14.99%, 14.86%, and 33.91%, respectively. Soils exhibit significant and enduring water repellency after being contaminated with crude oil [55]. Elevated moisture levels may impede microbial activity not due to the water itself, but because it obstructs air circulation, hence diminishing oxygen availability [17].

The average concentrations of available phosphorus across the study areas Sapele (control), Kwale, Emevor, Effurun, and Olomoro showed statistically significant differences ($p<0.01$). The mean values recorded were 16.30, 6.69, 3.61, 19.34, and 11.24 mg/kg, respectively. The observed low phosphorus levels in most locations may be linked to the uptake or immobilization of nutrients by native soil microorganisms, as well as nutrient loss processes such as leaching or volatilization [56]. The relatively higher phosphorus concentrations at the Effurun and Olomoro sites, compared to Kwale and Emevor, might be attributed to an elevation in soil pH, potentially caused by the decomposition of plant residues in polluted areas. This observation is consistent with earlier findings that suggest an increase in soil pH enhances mineral weathering and nutrient release [57]. As a result, phosphorus becomes more bioavailable around a pH range of 5.5 to 6.0, while its availability tends to decline in less contaminated regions like Kwale and Emevor, possibly due to limited phosphorus input.

Nitrogen, a vital nutrient for all living organisms, is a key element in amino acids and proteins and is often the most deficient nutrient in crop production ([56, 58]. The average nitrogen levels across the research sites including the control area did not display any statistically significant differences ($p>0.05$). The relatively lower nitrogen content in the control site may indicate enhanced nitrogen losses from processes like volatilization or leaching. Given nitrogen's high mobility in soil systems, these losses could also reflect inadequate soil conservation or poor management practices

[56, 58]. Typically, soil organic matter serves as the main reservoir of nitrogen that supports plant growth [59].

The Na, Ca, Mg and K content of soils of coastal wetlands of Delta State were relatively similar in all the study areas. However, the Na (1.16 meq/100g) and Ca (1.24 meq/100g) content of the control environment was higher than the Na and Ca content of other coastal wetlands sampled in this study except for Ca (1.49 meq/100g) content which was higher at Effurun. The findings of this study align with those of Ikhajiagbe et al. [57]. Other studies observed divergent results, asserting that there is an augmentation in exchangeable Ca^{2+} levels due to crude oil, which they ascribed to the accelerated decomposition and mineralization of organic and mineral substances in the soils [57]. The research identified a substantial disparity ($p<0.01$) in the concentrations of Na, Ca, Mg, and K relative to the control environment. Cation exchange capacity (CEC) serves as a valuable indicator of soil fertility, since it reflects the soil's capability to supply critical nutrients to plants. The diversity of cation exchange capacity (CEC) in the soils of coastal wetlands in Delta State indicates the extent to which cations can be maintained on soil particle surfaces.

The variation in cation exchange capacity (CEC) observed in the soils of Delta State's coastal wetlands reflects the soils' ability to retain positively charged ions on their surfaces. The average CEC values recorded at the various study locations were 3.45, 2.42, 3.94, and 3.16 meq/100g for Kwale, Emevor, Effurun, and Olomoro, respectively. The control site (Sapele) displayed a higher CEC value of 4.05 meq/100g, indicating a statistically significant difference ($p<0.01$) across the sampled wetland regions. CEC is critical for soil fertility as it influences the retention and availability of essential nutrients. For healthy plant growth, 16 essential nutrients are required, with 13 derived from the soil among which nitrogen (N), phosphorus (P), and potassium (K) serve as primary macronutrients. However, the observed levels of these macronutrients in both the study and control sites were notably lower than the standard acceptable limits for agricultural soils, which are 15,000 mg/kg for nitrogen, 2,000 mg/kg for phosphorus, and 10,000 mg/kg for potassium, according to HSEENV [60]. In the oil-contaminated zones, the extractable nutrient levels were significantly reduced compared to the control site. This may be attributed either to microbial uptake or the chemical binding of nutrients, although interference from residual hydrocarbons during analysis cannot be completely ruled out. It is uncertain whether oil contamination alone is responsible for nutrient loss. The pronounced differences in nutrient levels between the control and impacted sites might also be explained by microbial denitrification, in which nitrate is used as an alternative electron acceptor. Given the macronutrient levels fall well below recommended agricultural thresholds, soil remediation or enrichment would be necessary to restore fertility.

The mechanical composition of soil is a crucial element influencing the degree of contamination by inorganic pollutants and their concentrations within the soil [61]. In general, the soil of the coastal wetlands in this study was dominated by sand, followed by silt, and then clay, with the exception of Emevor, where the clay content was higher than the silt content, indicating that the control environment and the study locations have similar geochemical associations or parent material. The sandy composition of the soils in the research sites demonstrates considerable porosity, facilitating substantial leachate infiltration, which may adversely affect the adjacent

groundwater. Sandy soils, characterized by low sorption capacity and acidity, exhibit minimal absorption of heavy metals, resulting in their migration to surface water and groundwater [61].

3.2. Heavy Metals and Total Hydrocarbon Content in Soil

The levels of certain heavy metals namely iron (Fe), cadmium (Cd), copper (Cu), zinc (Zn), manganese (Mn), and lead (Pb) as well as total hydrocarbon content (THC), varied significantly across the different sampling sites ($p<0.01$). However, chromium (Cr) did not show any statistically significant difference ($p>0.05$) when comparing the research areas to the control location. The overall concentration trend of heavy metals in the soils from the coastal wetlands of Delta State followed this descending order: Fe > Zn > Mn > Pb > Cr > Cu > Cd.

Iron (Fe) is one of the most commonly occurring elements in the natural environment, and its sources include environmental debris, vehicular emissions, discarded household items, brake pad dust, gas flaring residues, and oil-contaminated zones. Due to these various sources, iron tends to accumulate extensively in impacted areas and is often found in higher concentrations than other metals [13, 62, 63, 64]. The mean concentrations of iron in the soil samples were recorded as 299.51 mg/kg in Kwale, 243.44 mg/kg in Emevor, 196.40 mg/kg in Effurun, and 131.62 mg/kg in Olomoro. In contrast, the control site exhibited a substantially lower iron concentration of 26.30 mg/kg. Statistical evaluation confirmed that the differences in iron levels between the control and the impacted sites were highly significant ($p<0.01$). The mean concentrations of Cr at Kwale, Emevor, Effurun, and Olomoro were 7.52, 2.87, 4.35, and 9.25 mg/kg, respectively. Olomoro exhibited the highest concentrations, succeeded by Kwale, whereas the control environment recorded the lowest at 0.95 mg/kg. The soils in the research area exhibited considerably elevated

Cr concentrations ($p<0.05$) compared to the control environment. Nwankwo et al. [47] reported a higher concentration of chromium (7.663 mg/kg) in their study, which evaluated the variation of certain soil pollution indicators resulting from oil spillage in Akinima, Rivers State. The value acquired in this investigation was below the maximum acceptable limits (MAL) of 100 mg/kg in soil for EGASPIN [65]. Despite the infrequency of Chromium (Cr) toxicity in the environment, it poses certain risks to human health due to its accumulation in the skin, lungs, muscle tissue, and fat, as well as in the liver, dorsal spine, hair, nails, and placenta, correlating with various health conditions [47, 66].

The mean concentrations of cadmium (Cd) in the soil samples from Kwale, Emevor, Effurun, and Olomoro were recorded as 0.36, 0.24, and 0.14 mg/kg, respectively. The highest levels were observed in Kwale and Emevor, followed by Effurun and Olomoro. Notably, cadmium was undetectable in the control site. Long-term exposure to cadmium is known to have severe health implications, including kidney damage, anemia, bone marrow suppression, liver and brain disorders, bronchitis, and various forms of cancer [67, 68]. In a related study, Nwankwo et al. [47] reported a cadmium concentration of 7.031 mg/kg in oil spill-impacted soils in Akinima, Rivers State.

Table 2: Heavy metal content of soil at different locations

Parameters	**Site 1 Control (Sapele)** $\bar{x}$±SD (Min-Max)	**Site 2 Kwale** $\bar{x}$±SD (Min-Max)	**Site 3 Emevor** $\bar{x}$±SD (Min-Max)	**Site 4 Effurun (Warri)** $\bar{x}$±SD (Min-Max)	**Site 5 Olomoro** $\bar{x}$±SD (Min-Max)	p-Value
Fe (mg/kg)	26.30 ^{c} ±14.14 (9.60-45.96)	299.51 ^{a} ±191.66 (111.80-552.87)	243.44 ^{a} ±107.17 (160.00-403.43)	196.40 ^{a} ±131.84 (100.00-385.45)	131.62 ^{b} ±20.57 (100.10-153.99)	p<0.01
Cr (mg/kg)	0.95±1.25 (0.03-2.32)	7.52±7.87 (0.07-16.21)	2.87±2.61 (0.05-5.20)	4.35±3.91 (0.07-7.41)	9.25±9.20 (0.09-18.72)	p>0.05
Cd (mg/kg)	0.00 ^{c} ±0.00 (0.00-0.00)	0.36 ^{a} ±0.05 (0.30-0.40)	0.36 ^{a} ±0.13 (0.20-0.50)	0.24 ^{a} ±0.05 (0.20-0.30)	0.14 ^{b} ±0.13 (0.00-0.30)	p<0.01
Cu (mg/kg)	0.19 ^{c} ±0.19 (0.01-0.40)	7.74 ^{a} ±3.03 (5.11-11.00)	2.29 ^{b} ±0.19 (2.13-2.50)	6.60 ^{a} ±2.33 (4.24-8.90)	2.30 ^{b} ±0.20 (2.10-2.50)	p<0.01
Zn (mg/kg)	3.70 ^{c} ±0.46 (3.20-4.10)	29.12 ^{b} ±8.00 (20.46-35.90)	7.68 ^{c} ±4.25 (5.20-15.20)	88.04 ^{a} ±21.06 (65.01-104.40)	14.07 ^{c} ±0.84 (12.60-14.60)	p<0.01
Mn (mg/kg)	4.23 ^{b} ±0.66 (3.26-5.10)	36.73 ^{a} ±36.47 (10.21-81.50)	13.50 ^{a} ±3.14 (10.24-16.50)	28.42 ^{a} ±3.67 (22.70-32.70)	14.54 ^{a} ±3.64 (8.03-16.30)	p<0.01
Pb (mg/kg)	0.00 ^{c} ±0.00 (0.00-0.00)	11.78 ^{a} ±3.41 (5.87-14.50)	7.22 ^{b} ±0.41 (6.50-7.50)	12.11 ^{a} ±2.03 (10.03-14.50)	12.31 ^{a} ±2.01 (10.50-14.50)	p<0.01
THC (mg/kg)	65.01 ^{c} ±61.72 (6.91-164.68)	4289.33 ^{b} ±4934.50 (493.50-9688.38)	63830.73 ^{a} ±86690.15 (228.90-158794.22)	1539.19 ^{b} ±1658.86 (87.85-3348.94)	1120.66 ^{b} ±1269.94 (42.30-2507.99)	p<0.05

x ± SD refers to the average derived from monthly measurements at each site, with the ± symbol representing the standard deviation. **Min–Max** indicates the range of observed values (minimum to maximum) for each parameter at each location. **Post hoc analysis** signifies that values labeled with different superscript letters (where a > b > c > d) exhibit statistically significant differences (**$p < 0.05$** or **$p < 0.01$**), whereas values with identical superscripts are not significantly different (**$p > 0.05$**). An asterisk (*) denotes significance at the **$p < 0.05$** level, while a double asterisk (**) indicates a highly significant difference at the **$p < 0.01$** level.

In comparison, the levels identified in the present study fall below the Environmental Guidelines and Standards for the Petroleum Industry in Nigeria [65] threshold of 0.8 mg/kg. Cadmium is a highly toxic heavy metal with no known beneficial role in higher organisms [69]. Chronic exposure can result in kidney dysfunction, skeletal abnormalities, and cardiovascular issues [47, 69]. For copper (Cu), the mean concentrations detected were 7.74 mg/kg in Kwale, 2.29 mg/kg in Emevor, 6.60 mg/kg in Effurun, and 2.30 mg/kg in Olomoro. The highest copper levels were noted in Kwale and Effurun, while Emevor and Olomoro had relatively lower values. The control location exhibited the lowest copper concentration at 0.19 mg/kg. Statistical analysis confirmed that copper levels were significantly higher ($p<0.01$) in all sampled sites compared to the control. Excessive ingestion of copper compounds can lead to its buildup in the liver, potentially disrupting normal copper regulation and impairing its excretion. This imbalance may cause copper to leak into the bloodstream, leading to red blood cell breakdown (hemolysis) [70, 71].

The mean concentrations of Zn at Kwale, Emevor, Effurun, and Olomoro were 29.12, 7.68, 88.04, and 14.07 mg/kg, respectively. The values recorded in the control, Kwale, Emevor, and Olomoro communities in this investigation were inferior to those reported by Nwankwo et al. [47], however the value measured at Effurun in this study exceeded the zinc value reported by Nwankwo et al. [47]. This value was below the maximum allowable limit of 140 mg/kg in soil for EGASPIN, [65]. Zinc is a crucial element and a fundamental component of numerous coenzymes; it is essential for DNA and RNA production, although it becomes detrimental in excessive quantities while remaining vital for health in minimal amounts [47].

Manganese is a micronutrient essential for both plants and humans, present in the organic matter of soil. The mean manganese values in Kwale, Emevor, Effurun, and Olomoro were 36.73, 13.50, 28.42, and 14.54 mg/kg, respectively. Mn concentrations were minimal in Emevor, succeeded by Olomoro, while they were maximal at Kwale, followed by Effurun. The control setting exhibited a markedly reduced Mn concentration (4.23 mg/kg) relative to the other research sites ($p<0.01$). The concentrations of Mn in the coastal wetlands of Delta State were below the critical thresholds of 600 mg/kg established by Lindsay and Norvell [72] and 550 mg/kg reported by the EPA [73] in [63]. The reduced Mn content may be ascribed to the acidic characteristics of the soils [74]. Sillanpaa [75] showed that when soil pH exceeds 7.5, manganese availability diminishes significantly due to the development of hydroxides and carbonates. Nevertheless, the pH values of the soils in this investigation were lower and exhibited mild acidity.

Atuanya and Oseghe [76] demonstrated that elevated Pb concentrations in soils exert a harmful effect on soil-dwelling microorganisms, hence modifying the local flora and fauna [63]. The mean values of Pb at Kwale, Emevor, Effurun, and Olomoro were 11.78, 7.22, 12.11, and 12.31 mg/kg, respectively. Olomoro exhibited the greatest quantities of Pb, succeeded by Effurun, Kwale, and Emevor, whereas no Pb was detected in the control environment. The coastal wetlands exhibited markedly elevated Pb levels ($p<0.01$) compared to the control setting.

Lead poisoning ($Pb2+$) has been identified as the primary contributor to renal dysfunction, hypertension, central nervous system impairment, gastrointestinal damage, cognitive deficits in children, reproductive and pregnancy abnormalities, cardiovascular issues, and various respiratory complications in adults [67, 77, 78]. Children exhibit heightened vulnerability to lead (Pb) toxicity, since their intestinal absorption of Pb is fivefold larger than that of adults [78]. The concentrations of Cr, Cd, Cu, Zn, and Pb in the soils of the coastal wetlands of Delta State were significantly below the critical thresholds of 100 mgkg-1 [79], 100 mgkg-1 [80], and 70-300 mgkg-1 [81], as well as beneath the maximum allowable limits for heavy metals in soils of Austria (100 mgkg-1), Canada

(200 mgkg-1), Poland (100 mgkg-1), Japan (400 mgkg-1), Great Britain (100 mgkg-1), and Germany (500 mgkg-1) [56, 82, 83]. Numerous health risks have been linked to the ingestion of elevated levels of heavy metals [84, 85]. The health risks encompass mild ailments including ulcers, diarrhea, nausea, abdominal pain, gastrointestinal disorders, respiratory issues, cough, neurological disorders, and psychological disturbances, as well as life-threatening conditions such as cancers, cardiovascular diseases, asthma, renal and hepatic damage, coma, and diabetes [85, 86].

The mean THC values in Kwale, Emevor, Effurun, and Olomoro were 4289.33, 63830.73, 1539.19, and 1120.66 mg/kg, respectively. The greatest concentration of THC was identified in Emevor, succeeded by Kwale, Effurun, and Olomoro. The control environment exhibited the lowest THC concentration at 65.01 mg/kg. The hydrocarbon concentration of 3,400 - 6,800 mg/kg signifies a substantial degree of pollution at the site [17]. This assumption parallels the THC levels identified in this study. THC levels in coastal wetland soils were markedly elevated ($p<0.05$) compared to the control setting. A review of existing data on the Niger Delta by NDES [18] and confirms that elevated hydrocarbon levels impact both terrestrial and subterranean flora and fauna, which are critical components in the biogeochemical cycle influencing the availability of plant nutrients [17]. This study's elevated hydrocarbon levels indicate significant hydrocarbon pollution in the soil. These conditions typically indicate diminished soil fertility, which consequently results in decreased agricultural productivity and a diminished source of livelihood in the impacted region. Exposure to elevated amounts of hydrocarbons is associated with toxicological issues such as hematological and renal complications, central nervous system illnesses resulting from myelin degradation, and dermatitis upon dermal contact [47, 87].

3.3. Cluster Analysis

Figure 2 depicts a dendrogram for cluster analysis based on physicochemistry, including heavy metal concentrations measured in soils from Delta State coastal wetlands. The research region is divided into five distinct locations: Sapele (control environment), Kwale, Emevor, Effurun, and Olomoro.

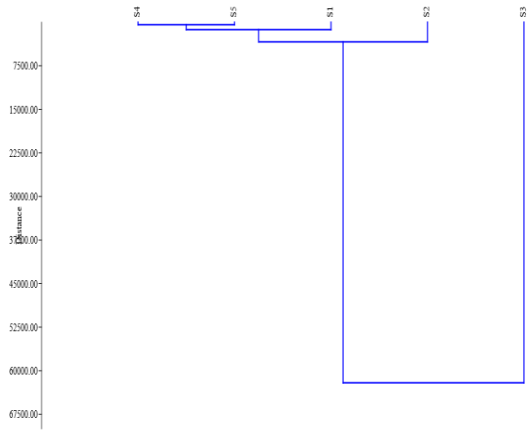

Figure 2: Dendrogram for cluster analysis based on the concentrations of all evaluated soil characteristics. Dissimilarity is determined via Euclidean distance, and cluster amalgamation is conducted using the Ward method.

Euclidean dissimilarity and distance indices revealed that the dissimilarity between the control environment and the following sites such as Kwale, Emevor, Effurun, and Olomoro were 4234.104, 63766.136, 1487.572, and 1063.297. The dendrogram clustering indicates that the conditions at the

Sapele (control) site at the time of sampling are markedly different from those at other research locations, yet exhibit closer similarities to the conditions observed at Effurun and Olomoro. The existing conditions in Kwale differ from those in Emevor, Effurun, and Olomoro. Nonetheless, the prevailing conditions in Kwale are more akin to those at Sapele when compared to Effurun and Olomoro but different from the prevailing conditions of Emevor. The prevailing circumstances in Effurun at the time of sampling were comparable to those at Olomoro. The circumstances in Emevor at the time of sampling differed from those in the other research regions. The research regions' values differ from the control environment. The physicochemistry of soils, including heavy metals, in Delta State's coastal wetlands followed the pattern Emevor>Kwale>Effurun>Olomoro>Sapele (control).

3.4. Principal Components Analysis

Table 3 presents six principal components (PCs), each with eigenvalues equal to or greater than one, accounting for a cumulative variance of 82.217% in the soils of the coastal wetlands of Delta State. These components contributed as follows: Dimension 1 explained 34.601% of the variance, followed by Dimension 2 with 19.906%, Dimension 3 with 13.303%, Dimension 4 with 7.436%, Dimension 5 with 6.954%, and Dimension 6 with 5.018%. Dimension 1 showed high eigenvector loadings for electrical conductivity (EC) (-0.658), organic carbon, sodium (Na), sand, clay, iron (Fe), cadmium (Cd), copper (Cu), zinc (Zn), manganese (Mn), lead (Pb), and total hydrocarbon content (THC). Dimension 2 exhibited strong contributions from available phosphorus, calcium (Ca), magnesium (Mg), cation exchange capacity (CEC), sand, silt, clay, and zinc (Zn). In Dimension 3, electrical conductivity (EC), moisture content (-0.728), potassium (K), and chromium (Cr) had notable loadings. Dimension 4 emphasized variables such as pH and total nitrogen, while Dimension 5 featured significant contributions from sodium (Na) and calcium (Ca). Figure 3 displays the correlation plots of variables along the principal component dimensions, and Figure 4 shows the biplots generated from principal component analysis (PCA) following varimax rotation.

The closeness of lines between variable pairs on these plots illustrates the degree and nature of their interrelationships, reflecting how they jointly contribute to the variability observed in the coastal wetland soils. The combination of Dimensions 1 and 2, which together explain 54.907% of the total dataset variance, includes strong associations among parameters such as electrical conductivity, organic carbon, Na, sand, clay, Fe, Cd, Cu, Zn, Mn, Pb, and THC in Dimension 1, and available phosphorus, Ca, Mg, CEC, sand, silt, clay, and Zn in Dimension 2.

The physicochemical parameters of the soil and certain heavy metals demonstrated a robust association with the total hydrocarbon concentration in Dim 1. The PCA Bi-plot illustrating the variations of analyzed parameters within the research areas in Dimensions 1 and 2 demonstrated the impact of the defined parameters throughout the study site. Soil physicochemistry and certain heavy metals were predominantly associated with Kwale (S2) and Emevor (S3) compared to the control, which indicated that only electrical conductivity (EC) was linked to the control environment (S1). Other physicochemical parameters, including the analyzed heavy metals, exhibited a heterogeneous distribution across the study areas. The results of this investigation, along with those of Nnoli et al. [88], indicate that a significant volume of crude oil has been discharged into the study areas; however, the concentration of heavy metals in terrestrial and aquatic habitats may differ across the many communities in this region.

The levels of heavy metals in terrestrial environments across various communities within the coastal wetlands of Delta State may comply with acceptable safety thresholds in some locations, while surpassing them in others, thereby elevating the potential for toxic exposure. A thorough assessment

of heavy metal concentrations across the region is crucial for identifying communities at risk and determining the extent of toxicity hazards in other parts of Delta State.

3.6. Correlation Matrix for Soil Physico-Chemical Properties and Heavy Metals

To explore the interrelationships among the soil characteristics from selected coastal wetland sites, correlation statistics were applied (Figure 5). Positive correlations are illustrated in blue, while negative correlations are shown in red. Statistically significant correlations are marked with a square, whereas non-significant associations lack this indicator. According to Otari and Dabiri [89], analyzing correlations among key geochemical properties can help uncover influential factors and likely sources of contamination ([90, 91]. The correlation analysis revealed both significant positive and negative associations among the measured parameters, offering insights into their potential sources and interactions.

Table 3: **Loadings from Principal Component Analysis (PCA), displaying eigenvectors, eigenvalues, and the cumulative variance explained**.

Parameters	Dim.1	Dim.2	Dim.3	Dim.4	Dim.5	Dim.6
Ph	0.070	-0.248	0.086	0.865*	-0.006	-0.087
EC	-0.658*	0.118	0.598*	0.055	-0.078	0.125
Organic C	0.743*	-0.091	-0.335	-0.081	0.196	-0.161
Moisture Content	0.282	0.070	-0.728*	0.481	0.000	-0.064
Available P	-0.432	0.803*	0.032	0.189	0.185	-0.066
Total N	0.424	0.009	-0.214	0.617*	0.073	0.282
Na	-0.543*	0.345	-0.290	0.017	-0.572*	0.033
Ca	-0.421	0.531*	0.230	-0.123	0.599*	-0.135
Mg	-0.159	0.653*	-0.192	0.105	0.247	0.489
K	0.083	0.070	0.705*	0.326	-0.343	-0.418
CEC	-0.365	0.729*	0.437	0.200	0.093	-0.167
Sand	-0.575*	-0.656*	0.192	0.139	0.339	0.152
Silt	0.418	0.788*	-0.162	-0.072	-0.254	-0.195
Clay	0.570*	0.602*	-0.285	-0.072	-0.312	0.116
Fe	0.899*	-0.178	0.238	0.022	-0.032	0.068
Cr	0.369	0.138	0.648*	-0.008	-0.331	0.328
Cd	0.753*	-0.381	-0.048	-0.053	0.188	-0.411
Cu	0.887*	0.267	0.304	0.002	0.062	-0.135
Zn	0.654*	0.570*	0.193	0.077	0.329	-0.035
Mn	0.823*	0.180	0.287	-0.035	0.183	0.239
Pb	0.928*	0.170	-0.034	-0.131	0.012	0.109
THC	0.667*	-0.463	0.417	0.018	-0.074	0.248
Eigenvalue	**7.612**	**4.379**	**2.927**	**1.636**	**1.530**	**1.104**
Variance percent	**34.601**	**19.906**	**13.303**	**7.436**	**6.954**	**5.018**
Cumulative variance percent	**34.601**	**54.506**	**67.810**	**75.246**	**82.200**	**87.217**

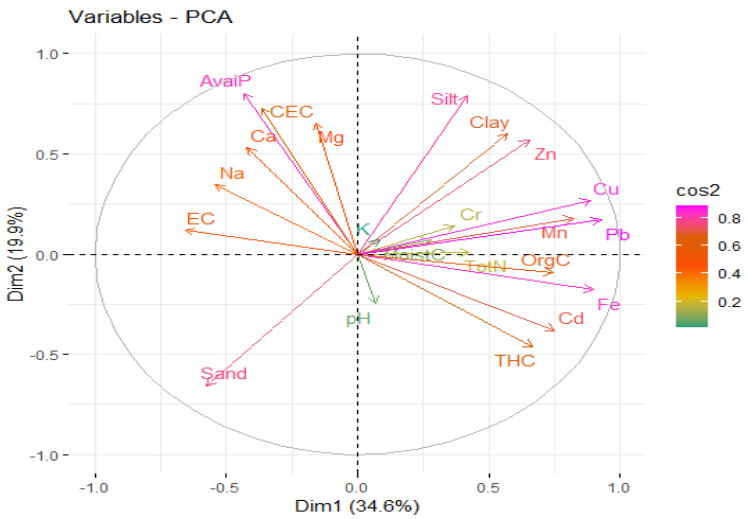

Figure 3: **Principal Component Analysis (PCA) loadings illustrating eigenvectors, eigenvalues, and the cumulative variance explained—Variable correlation plot for soil parameters. (OrgC = Organic Carbon; MoistC = Moisture Content; AvaiP = Available Phosphorus; TotN = Total Nitrogen)**

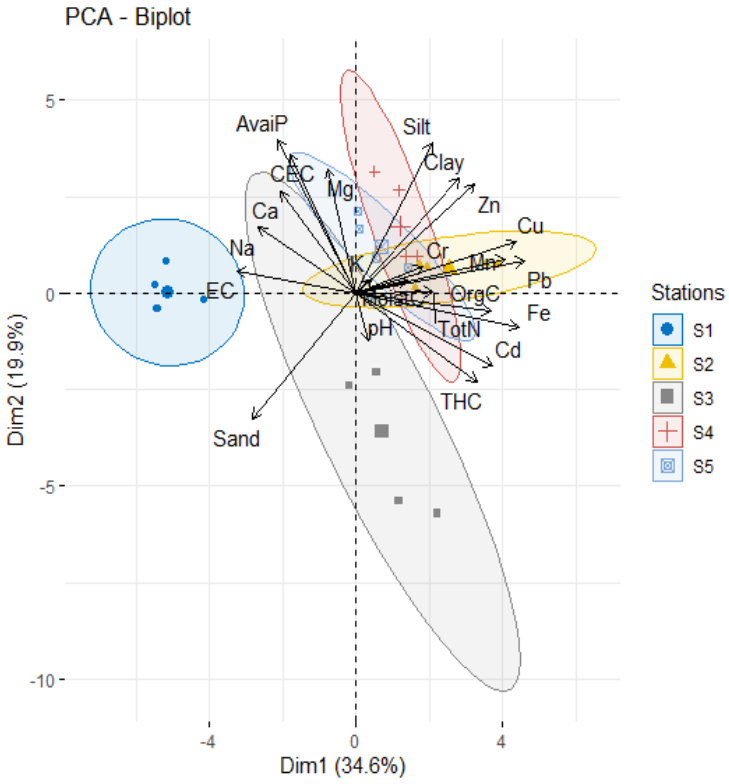

Figure 4: **PCA biplot after varimax rotation for Dimensions 1 and 2, illustrating the distribution of variables. (OrgC = Organic Carbon; MoistC = Moisture Content; AvaiP = Available Phosphorus; TotN Total Nitrogen**

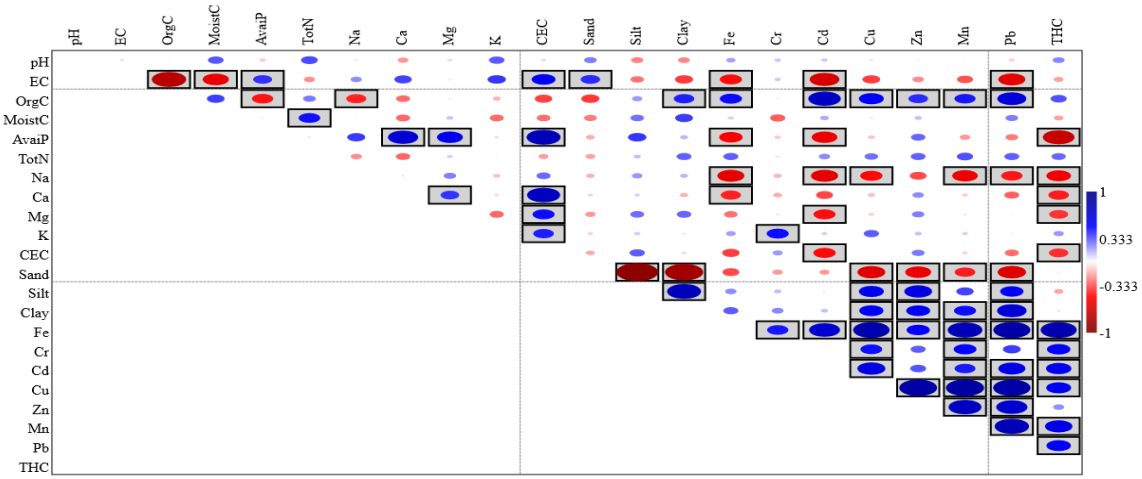

Figure 5: Correlation matrix illustrating the relationships between physicochemical parameters and heavy metal concentrations in soil samples.

Sodium (Na) displayed a strong negative correlation with iron (Fe), cadmium (Cd), copper (Cu), manganese (Mn), lead (Pb), and total hydrocarbon content (THC). Calcium (Ca) showed a positive and significant association with both magnesium (Mg) and cation exchange capacity (CEC), whereas it was negatively and significantly correlated with iron and THC. Magnesium was also positively and significantly correlated with CEC, but it had a significant negative correlation with both cadmium and THC.

Furthermore, silt content had a positive and significant correlation with clay, as well as with copper, zinc (Zn), and lead, while showing no statistically meaningful relationship with other parameters ($p > 0.05$). Clay content in the soil showed a strong and statistically significant positive relationship with copper (Cu), zinc (Zn), manganese (Mn), and lead (Pb). Iron (Fe) was positively and significantly correlated with several other elements, including chromium (Cr), cadmium (Cd), copper (Cu), zinc (Zn), manganese (Mn), lead (Pb), and total hydrocarbon content (THC). Additionally, chromium (Cr) demonstrated a positive and significant correlation with copper (Cu), manganese (Mn), and THC. Cadmium (Cd) demonstrated a significant positive correlation with copper (Cu), manganese (Mn), lead (Pb), and total hydrocarbon content (THC). Similarly, Cu exhibited strong positive correlations with zinc (Zn), Mn, Pb, and THC. Zn was also positively and significantly associated with Mn and Pb. Both Pb and THC showed positive correlations with Mn, and Mn in turn had a significant correlation with THC. The observed positive associations between heavy metals and THC suggest a potential shared origin, likely stemming from industrial and commercial activities as well as oil spill incidents in the study areas. These connections point to common pollution sources [89], emphasizing the importance of not overlooking the contamination of coastal wetland soils by Fe, Cr, Cd, Cu, Zn, Mn, Pb, and THC in the affected regions.

4. Conclusion

The findings of this research reveal significant contamination across the terrestrial ecosystems of the study locations, including Sapele (the control site), Kwale, Emevor, Effurun, and Olomoro. Even in the absence of ongoing pollution, the substantial degradation of wetland and mangrove habitats suggests that ecological recovery in these areas may take years or even decades. The study highlights

the effectiveness of Principal Component Analysis (PCA) in assessing soil quality and identifying potential sources of pollution, with results pointing to anthropogenic influences as key contributors to changes in soil characteristics in the evaluated regions.

It is recommended that both the State and Federal Ministries of Environment take proactive steps to address soil degradation in these locations. Additionally, multivariate tools such as CA and PCA proved useful in understanding the influence of human activity on soil quality. This research underscores the urgency of implementing the recommendations from the United Nations Environment Programme's 2021 and aligning with the goals set out in the 2030 Agenda for Sustainable Development. Such actions are crucial for the restoration and protection of ecosystems in the Niger Delta, which are vital for sustaining human and ecological health in the region.

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