DOI: https://doi.org/10.59983/s2025030405
AgroEnvironmental Sustainability, 2025, 3(4), 360–373

RESEARCH

Characterization and Nutrient Imbalance Diagnosis of Important Humid Tropical Acidic Coastal Soils of Yenagoa, Bayelsa State, Nigeria

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ARTICLE HISTORY

Received: 5 October 2025
Revised: 21 November 2025
Accepted: 23 November 2025
Published: 15 December 2025

KEYWORDS

soil acidity
nutrient imbalance
organic carbon
SAR
liming strategy

Abstract

The worlds population is growing at an alarming rate amidst global hunger and soil nutrient deterioration. The objective of this study was the assessment characterization and nutrient imbalance diagnosis of important humid tropical acidic coastal soils of Yenagoa, Bayelsa State, Nigeria. Soil samples were collected in triplicates from each of the five locations using an auger at 0–20 cm depth The samples were prepared and subjected to standard laboratory procedures. The experiment was laid in randomized complete block design (RCBD). Generated data were analyzed using analyses of variance and significant means were separated using LSD at 5% probability level. Results showed that soil pH ranged from 4.60 in Akaba to 5.40 in Ogbogoro, indicating strongly to moderately acidity. Soil organic carbon (SOC) ranged from 10.0 g/kg in Ikpetiama to 16.20 gkg^{-1} in Kpansia. Available phosphorus ranged from 3.75 $mgkg^{-1}$ in Gbarama to 9.45 $mgkg^{-1}$ in Kpansia, suggesting moderate availability. Exchangeable bases, calcium (4.78–7.58 $cmolkg^{-1}$), magnesium (2.59–4.31 $cmolkg^{-1}$), potassium (0.31–0.73 $cmolkg^{-1}$). Fertility indexing showed that Akaba and Kpansia possessed comparatively better soil quality, Ogbogoro and Gbarama fell within the low fertility category, and Ikpetiama rated poorest due to combined acidity stress (1.43–1.85 $cmolkg^{-1}$). Strong correlations between soil organic carbon, nitrogen, and base saturation underscore the importance of maintaining organic matter for sustained fertility. The obtained results of this study necessitates, pressing need for location- specific liming and nutrient management strategies to ameliorate soil acidity and optimize crop productivity in the soils of Yenagoa.

Citation: Victor, E. J. *et al.* (2025). Characterization and Nutrient Imbalance Diagnosis of Important Humid Tropical Acidic Coastal Soils of Yenagoa, Bayelsa State, Nigeria. *AgroEnvironmental Sustainability*, 3(4), 360–373. https://doi.org/10.59983/s2025030405

Statement of Sustainability: This study contributes to SDG 2 (Zero Hunger) by providing invaluable insights into the soils of the study area. By assessing the effects of low pH, soil organic carbon, variable total nitrogen, available phosphorus and potassium, and exchangeable bases, the research underscores the need for targeted soil management practices such as liming and composting. Implementing these strategies can enhance nutrient availability, improve soil health, and support sustainable crop productivity.

1. Introduction

Coastal soils within humid tropical estuarine environments have been found to be ecologically delicate and highly dynamic, accompanied by the integrated effects of hydrological activities, sediment transportation and deposition, and anthropogenic influences. These soils are posed with acidic degradation issues, due to oil extraction, expanding urbanization, and unsustainable land-use practices and climatic factors (Adesemuyi and Adekayode, 2020; Ayadei Dickson, 2021). Despite these environmental threats, they are effective in delivering crucial ecosystem services. These soils often exhibit inherent challenges such as strong acidity, low nutrient availability, and weak structural stability factors exacerbated by intense rainfall, persistent nutrient leaching, and insufficient organic matter replenishment (Ogunwale et al., 2002, Okunsebor et al., 2024).

Soils with pH levels below 5.5 can limit the availability of key essential nutrients like phosphorus, calcium (Ca^{2+}), and magnesium (Mg^{2+}), while encouraging the solubilization of toxic aluminium (Al^{3+}) ions that can adversely affect plant development (Brady and Weil, 2016). These chemical limitations not only reduce crop productivity but also disrupt microbial activity and nutrient cycling, thereby undermining the overall resilience of the ecosystem (Ishola, 2024, Hazelton and Murphy, 2007). Moreover, the spatial variability of estuarine soils driven by factors such as topography, vegetation, land use, and river proximity makes it difficult to apply uniform soil management approaches because it can lead to cascades of environmental problems such as eutrophication, rapid leaching, and runoff sensitivity (Okunsebor et al., 2024, Reynolds et al., 2009).

Despite some research by Adesemuyi and Adekayode (2020), Ayadei Dickson (2021), Osuji and Nwoye (2007) in the area, integrated analyses that capture both the distribution patterns and nutrient imbalances remain limited. In light of these challenges, this study made a comprehensive assessment of characterization and nutrient imbalance of important humid tropical acidic coastal soils of Yenagoa. This investigation aims to fill that gap by mapping key fertility indicators, pinpointing major soil fertility constraints, and recommending location-specific soil management strategies tailored for acid-affected coastal environments.

2. Materials and Methods

2.1. Study Location

The study was conducted in Yenagoa Local Government Area (LGA) of Bayelsa State, located within the humid coastal belt of the Niger Delta region in southern Nigeria. Five communities were selected based on their landscape position, land use patterns, and accessibility. These included: Ogbogoro (Latitude 4.8667° N, Longitude 6.2833° E), Ikpetiama (Latitude 4.8832° N, Longitude 6.2156° E), Kpansia (Latitude 4.9424° N, Longitude 6.2812° E), Akaba (Latitude 4.8973° N, Longitude 6.3309° E), Gbarama (Latitude 4.8790° N, Longitude 6.2450° E). These locations as shown in **Figure 1** are situated within low-lying coastal ecosystems and reflect a range of soil development conditions under natural and human-modified landscapes. Farming though at subsistence level is the major occupation of the people.

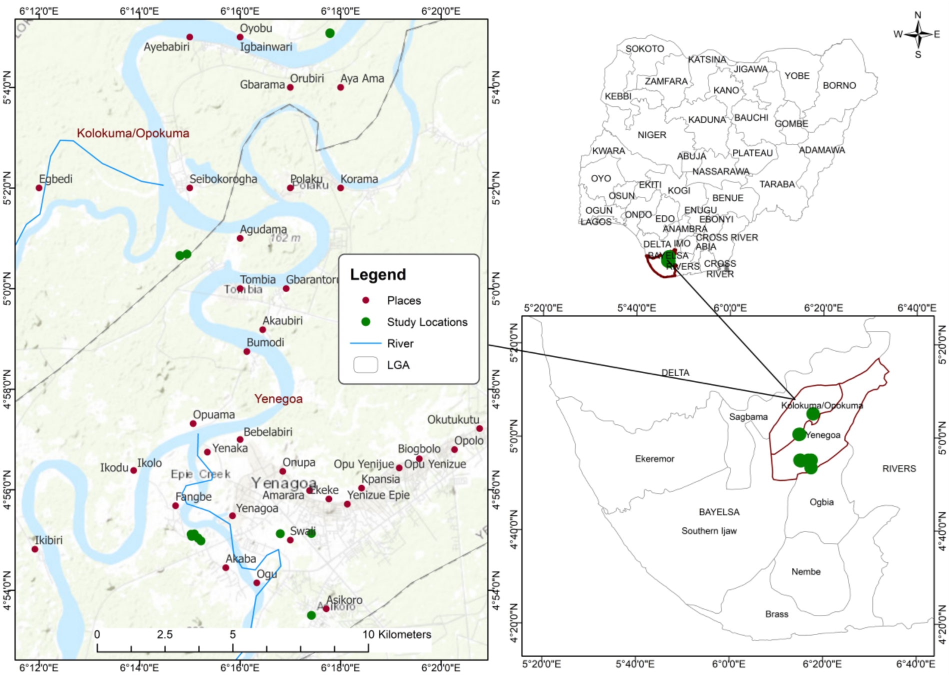

Figure 1. Map of study locations showing sampling points

2.1.1 Geology and Geomorphology

Bayelsa State lies within the Quaternary sedimentary basin of the Niger Delta, composed of unconsolidated materials such as sands, silts, clays, and peats deposited by the Niger River and its tributaries (Osuji and Nwoye 2007). The geomorphology is characterized by flat to gently undulating terrain, meander belts, freshwater swamps, and backswamps.

The dominant parent material is clay shale, contributing to poorly drained soils and seasonal inundation common in wetland environments (Reyment, 1965).

2.1.2 Climatic Conditions

The region experiences a humid tropical monsoon climate, with an average annual rainfall exceeding 2,500 mm. Rainfall follows a bimodal pattern, with peaks in April–July and September–November. Mean annual temperatures range from 25°C to 32°C, and relative humidity remains high year-round. These climatic conditions support rapid vegetation growth and intense weathering of parent materials (Osuji and Nwoye 2007).

2.1.3. Land Use Patterns

Land use in the study area is a mixture of subsistence agriculture, fishing, and oil-related industrial activities. Communities rely primarily on cassava, yam, plantain, rice, and sugarcane farming. However, land degradation and nutrient depletion are increasingly common due to over-cultivation, deforestation, and the impacts of gas flaring and oil pollution.

2.2. Soil Sampling

Soil samples were collected from the topsoil layer (0–20 cm) using soil auger across the five communities. In each location, three replicate samples were collected using a soil auger for chemical analysis and core samplers for physical property determination. A total of 15 samples were obtained. The coordinates of each sampling point were georeferenced using a GPS receiver, and slope and elevation were recorded in situ

2.3. Experimental Design

The experiment was arranged in randomized complete block design (RCBD).

2.4. Laboratory Analyses

Soil pH (H_2O) was measured in a 1:2.5 soil-to-water suspension using a calibrated digital pH meter following Van Reeuwijk (2002). Soil organic carbon (SOC) was determined using the Walkley and Black dichromate oxidation method (Nelson and Sommersm 1982). Soil Organic Matter (SOM) was estimated by multiplying OC by 1.724, based on Van Bemmelen's factor. Total Nitrogen (TN) was determined via the Macro-Kjeldahl digestion technique as described in Van Reeuwijk (2002). Available Phosphorus (Av. P) was analyzed using Bray II extraction and quantified calorimetrically via the molybdenum blue method (Olsen and Sommers, 1990). Exchangeable Bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were extracted with 1N ammonium acetate (NH_4OAc) at pH 7.0 (Van Reeuwijk, 2002). Ca^{2+} and Mg^{2+} were determined using atomic absorption spectrophotometry, while potassium (K^+) and sodium (Na^+) were measured using a flame photometer. Exchangeable Acidity (H^+ + Al^{3+}) was determined using 1N KCl extraction, followed by titration with NaOH (Juo, 1978). Cation Exchange Capacity (CEC) was determined using 1N NH_4OAc at pH 7.0 (Van Reeuwijk, 2002). Effective Cation Exchange Capacity (ECEC) was calculated by summing the exchangeable bases and exchangeable acidity (Brady and Weil, 2002). Total Exchangeable Bases (TEB) was obtained by summing the concentrations of Ca^{2+}, Mg^{2+}, K^+, and Na^+. Base Saturation (BS%) was computed using the Base Saturation (BS %) was computed as Brady and Weil (2017):

$$BS\,(\%) = \frac{Total\ Exchangeable\ basic\ cations}{ECEC} \times \frac{100}{1} \tag{1}$$

Adsorption Ratio (SAR) was calculated based on Richards (1954):

$$Sodium\ Adsorption\ Ratio\ (SAR) = \frac{[Na^+]}{\sqrt{\frac{Ca^{2+}}{2} + \frac{Mg^{2+}}{2}}} \tag{2}$$

Soil fertility index (SFI) was computed using weighted quality index (WQI) assessment method as prescribed by Chen et al. (2021), Brady and Weil, (2017), and FAO (2006), respectively, and the rating class as shown in **Table 1**. The WQI was computed as shown in:

$$WQI = \sum_{i=1}^{n} W_i \times S_i \tag{3}$$

Where, n total number of soil parameters considered; *Wi*: weight assigned to the parameter, *Si*: standardized score of the parameter.

Table 1. Fertility Class ratings of the studied soils.

Fertility Class	Rating
Good	0.80 ≤ WQI ≤ 1.00
Moderate	0.60 ≤ WQI ≤ 0.80
Low	0. 40 ≤ WQI ≤ 0.80
Poor	WQI ≤ 0. 04

WQI: Weighted quality index.

The soil fertility ratios were computed as Brady and Weil (2017) documented as follows

$$Carbon\ Nitrogen\ Ratio\ (C:N)\ ratio\ = \frac{C}{N} \tag{4}$$

$$Carbon\ Magnesium\ Ratio\ (C:Mg)\ = \frac{C}{Mg} \tag{5}$$

$$Calcium\ Potassium\ Ratio\ (Ca:K)\ = \frac{Ca}{NK} \tag{6}$$

2.5. Environmental Quality Index Assessment

This was assessed using a weighted index scoring method, where each parameter was normalized and weighted based on agronomic relevance, following Chen et al. (2021). The composite score was computed as:

$$WQI = \sum (Wi \times Si) \tag{7}$$

Where *Wi* is the weight and *Si* the standardized score, then classified into fertility levels using thresholds from Brady and Weil (2017) and FAO (2006).

2.6. Statistical Analysis and Data Presentation

The collected data were analyzed using Analyses of variance suitable for n randomized block design (RCBD). Significant means were separated using Fisher's Least Significant Difference (FLSD) at a 5% significance level. Correlation among selected soil properties were done using SPSS statistical soft ware.

3. Results and Discussion

The result of the chemical properties of the studied soils are presented in **Tables 2** and **3** respectively.

3.1. Soil pH

Soil pH varied from 4.60 in Akaba to 5.40 in Ogbogoro, with a mean of 5.04 (**Table 2**), signifying strong to moderate acidity (USDA-NRCS 2004), Brady and Weil, 2016). Such acidity levels can pose nutrient deficiency to crop production by reducing the availability of essential nutrients like phosphorus (P), Ca^{2+}, Mg^{2+} (Mg^{2+}), and molybdenum (Mo), particularly when pH drops below 5.5. Although differences in soil pH across the studied locations were statistically insignificant (LSD, P < 0.05), the agronomic and ecological implications remain significant. Highly acidic soils are known to increase the solubility of toxic elements such as aluminum (Al^{3+}) and manganese (Mn^{2+}), (Richards, 1954) which can be deleterious to root damage, reduce nutrient absorption efficiency, and suppress microbial activity (Sanchez, 2019). These challenges are typical in humid tropical climates, where intense rainfall, run-off and prolonged leaching deplete basic cations and intensify acidity in soils (Osuji and Nwoye, 2007; FAO, 2006; Hazelton and Murphy, 2007).

To alleviate these adverse effects on the studied soils, applying lime materials such as calcium carbonate ($CaCO_3$) or dolomitic lime is imperative to raise soil pH to optimum conditions (approximately 6.0–6.5). This adjustment can improve nutrient solubility, enhance microbial functions, and restore soil productivity. Similar conclusions were drawn by Ishola (2024), who documented reduced crop yields and heightened aluminum Al^{3+} toxicity in southern Nigerian soils with pH below 5.5 as well as recommending liming and organic inputs as effective remedies. Moreover, Lal and Shukla (2004) highlighted the unique role of pH in controlling cation solubility and exchangeability, making it a critical parameter in soil fertility management.

3.2. Soil Organic Carbon

Soil organic carbon (SOC) concentrations varied significantly across the studied soil (LSD, $p < 0.05$), ranging from 10.00 $g\,kg^{-1}$ in Ikpetiama to 16.20 $g\,kg^{-1}$ in Kpansia, with an average value of 12.80 $g\,kg^{-1}$ (**Table 3**). These values were rated moderate according to FAO (2006), and Obalum et al. (2017). The observed trends are consistent with Okebalama et al. (2017), Utin and Oguike, 2023; Osuji and Nwoye (2007), and Udom et al.,(2023), who recorded similar spatial variability in SOC levels in coastal and coastal plain soils of Southern Nigeria. The result in Kpansia and Akaba likely reflects more favorable inputs from organic residues, vegetation cover, or microclimatic conditions that promote organic matter accumulation. These results enhance workability, biological resilience, and sustainable productivity of the soils (Blanco and Lal, 2008).

Conversely, the lowest values recorded in Ogbogoro and Ikpetiama could be due to more intensive land use, limited organic inputs, or faster decomposition rates. Such soils are more prone to degradation, compaction, and erosion (Brady and Weil, 2016). Gbarama presented intermediate SOC content, further illustrating the variability in organic matter dynamics across the region. SOC is a critical component of soil health, influencing aggregation, water retention, microbial processes, and nutrient cycling. These findings align with Hazelton and Murphy (2007), who emphasized the role of SOC as a key determinant of soil quality in humid tropical environments.

Generally, the SOC results reflect the region's high rainfall and temperatures, which impact accelerated decomposition of organic materials. Obalum et al. (2017) caution that when SOC concentrations approach the lower end of the moderate fertility range (<12 $g\,kg^{-1}$), as in Ogbogoro and Ikpetiama, targeted interventions are necessary to prevent a decline into low fertility status.

Table 2. Characterization of the chemical and nutrient properties of the soil.

Location	pH (water)	Base Saturation	Soil Organic Carbon (gkg^{-1})	Total Nitrogen	Available Phosphorus ($mgkg^{-1}$)	Sodium Adsorption Ratio
Kpansia	5.03	802.80	16.20	2.10	6.09	1.56
Ogbogoro	5.40	781.00	11.10	1.70	4.42	1.61
Gbarama	5.09	754.00	13.00	1.90	9.45	2.21
Ikpetiama	5.08	768.00	10.00	1.60	3.75	2.13
Akaba	4.60	829.00	13.70	1.80	8.031	1.52
Mean	5.04	787.10	12.80	1.80	6.35	1.81
L.S.D(P<0.05)	*NS*	30.56*	0.314*	0.03*	2.16*	0.04*

LSD: Least significant difference, NS=Not significant, * Significant.

3.3. Total Nitrogen

Total nitrogen (TN) concentrations in the soils varied between 1.60 $g\,kg^{-1}$ in Ikpetiama and 2.10 $g\,kg^{-1}$ in Kpansia, with an overall mean of 1.80 $g\,kg^{-1}$ (**Table 2**). These values were low to moderate (Obalum et al., 2017), characteristic of many tropical soils where high rainfall promotes nutrient leaching and rapid organic matter breakdown. The result in Kpansia, which marginally exceeded the moderate fertility range, may be attributed to its relatively higher organic matter content. In contrast, soils of Ikpetiama (1.60 $g\,kg^{-1}$) and Ogbogoro (1.70 $g\,kg^{-1}$), which recorded lower nitrogen levels, highlight the need for supplementary nitrogen inputs to support robust crop development. Statistical analysis revealed significant differences among the sites (LSD, $P < 0.05$), suggesting that the observed TN variability is substantial and not due to random variation.

Nitrogen plays a vital role in plant physiological processes such as protein formation and chlorophyll synthesis. Deficiency in TN often results in reduced productivity, particularly when soils are under continuous cultivation without nutrient replenishment. As outlined by Lal and Shukla (2004) and Brady and Weil (2016), the close relationship between TN and soil organic carbon (SOC) means that nitrogen availability tends to decline where SOC is depleted. This trend is consistent with findings from Ishola (2024) and Hazelton and Murphy (2007), who observed that tropical soils under natural vegetation or limited tillage maintain better nitrogen reserves, whereas intensively farmed soils lacking organic amendments deteriorate quickly in nitrogen content. Therefore, locations such as Ikpetiama and Ogbogoro would benefit enormously from integrated soil fertility management (ISFM) approaches incorporating organic amendments like compost, animal manure, or leguminous cover crops to boost nitrogen reserves. Kpansia, by contrast, exhibits a relatively better nitrogen status that supports moderate fertility without immediate intervention. Gbarama lies in an intermediate position and could still see improvement through SOM enhancement strategies. These outcomes underscore the importance of adopting site-specific nutrient management plans to sustain soil nitrogen levels across the humid tropical environment of Yenagoa.

3.4. Available Phosphorus

Available phosphorus (Av. P) levels across the studied soils varied between 3.75 and 9.45 mg kg^{-1} in Gbarama and Ikpetiama, averaging 5.90 mg kg^{-1} (**Table 2**). The results fall within the low phosphorus range with the exception of Gbarama (9.45 mg kg^{-1}) and Akaba (8.03 mg kg^{-1}), which fall within the moderate range (FAO, 2006). This result signals widespread phosphorus deficiency in the studied soils. Acidic soils (mean pH < 5.5) favor phosphorus fixation by Al^{3+} and iron oxides (Brady and Weil, 2016), limiting its availability even in areas with appreciable organic matter such as Kpansia and Akaba.

Appropriate nutrient management strategies are required, including judicious application of phosphorus-based fertilizers, incorporation of phosphate rocks alongside organic materials such as compost or biochar, and pH correction through liming to reduce Al^{3+} toxicity. Adoption of phosphorus-efficient cultivars and phosphate-solubilizing microbes could further enhance phosphorus uptake and utilization. These integrated approaches are crucial for enhancing soil fertility and promoting sustainable crop production in the coastal ecosystems under study.

3.5. Exchangeable Calcium (Ca^{2+})

Exchangeable Ca^{2+} levels as shown in **Table 3** ranged from 4.78 cmolkg^{-1} in Gbarama to 7.58 cmolkg^{-1} in Akaba, with an average of 6.44 cmolkg−1 across the study area. These values were low to moderate and is typical of tropical soil systems. Using this framework, the Ca^{2+} status of soils in Akaba, Kpansia, Ogbogoro, and Ikpetiama can be interpreted as moderately sufficient, reflecting favorable conditions for nutrient uptake, root development, and soil aggregation. In contrast, Gbarama falls within the low range, indicating a possible Ca^{2+} shortfall that may negatively affect physiological processes in plants and limit the flocculation of clay minerals. Ca^{2+} is fundamental in several soil-plant interactions, particularly in enhancing root elongation, stabilizing cell walls, and regulating enzyme activity. In highly weathered, acidic soils common in Bayelsa State, low Ca^{2+} levels are often worsened by leaching and cation competition from Al3+ and H+ ions. This presents a potential limitation in Gbarama, where both reduced Ca^{2+} and moderately acidic pH could impede crop growth and root system development. Higher Ca^{2+}concentrations in Akaba and Kpansia suggest improved base saturation and a more balanced cation exchange environment, factors known to support soil structure, buffering capacity, and fertility. These conditions can reduce nutrient leaching and soil particle dispersion problems often associated with coarse-textured soils found in the Niger Delta. As highlighted by FAO (2006) and Obalum et al. (2017) maintaining at least moderate Ca^{2+} levels is critical for sustaining cation exchange processes and preventing acidification-related degradation. The findings align with studies by Barthès and Roose (2002) and Lal and Shukla (2004), who demonstrated that adequate Ca^{2+} supports better aggregate stability and water flow by enhancing clay flocculation.

3.6. Exchangeable Magnesium (Mg^{2+})

Exchangeable Mg^{2+} concentrations across the studied locations varied from 2.59 cmolkg^{-1} in Ikpetiama to a peak of 4.31 cmolkg^{-1} in Akaba, averaging 3.63 cmolkg^{-1}. Referencing the soil fertility benchmarks outlined by Hazelton and Murphy (2007) and Brady and Weil (2016), soil under Akaba, Kpansia, Gbarama, and Ogbogoro are moderates

Table 3. Characterization of the chemical and nutrient properties (unit: cmolkg^{-1}) of the soil continued.

Location	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	H^{+}	AL^{3+}	TEA	TEB	ECEC
Kpansia	7.01	4.11	0.31	1.43	2.41	0.56	2.97	11.73	14.71
Ogbogoro	6.60	3.50	0.73	1.45	2.78	0.57	3.16	11.12	14.30
Gbarama	4.78	2.59	0.65	1.85	2.71	0.41	2.98	8.37	11.30
Ikpetiama	6.25	3.64	0.56	1.73	2.90	0.51	3.40	10.83	14.20
Akaba	7.58	4.31	0.41	1.34	2.11	0.92	2.72	12.59	15.30
Mean	6.44	3.63	0.53	1.56	2.58	0.58	3.05	10.93	13.98
L.S.D (P<0.05)	2.09*	1.05*	0.28*	0.07*	NS	0.75*	0.16*	2.95*	2.78*

Ca^{2+}: Calcium, Mg^{2+}: Magnesium, K^{+}: potassium, Na^{+}: sodium, TEA: Total exchangeable acidity, TEB: Total exchangeable bases, ECEE: Effective cation exchange capacity.

in Exchangeable magnesim. This indicates that these soils can support essential plant physiological activities such as chlorophyll synthesis, energy transfer via phosphate metabolism, and enzymatic functions. In contrast, the Mg^{2+} level in Ikpetiama is moderately low, which may predispose the soil to deficiency under intensive cultivation or conditions of high rainfall, common in humid tropical zones. The observed differences in Mg^{2+} content across locations were statistically significant at $P < 0.05$ (LSD), indicating clear spatial variability in Mg^{2+} availability. The elevated Mg^{2+} concentrations in Akaba and Kpansia may reflect higher base saturation and reduced leaching risk, both of which enhance soil structural quality. Mg^{2+}, a divalent cation, plays a critical role in promoting clay particle flocculation and maintaining aggregate stability, especially when present in balanced proportions alongside Ca^{2+} and K^{+}. Previous research by Obalum et al. (2017) and Lal and Shukla (2004) has shown that adequate Mg^{2+} levels can improve soil friability and overall crop productivity, particularly in acidic environments where H^{+} and Al^{3+} ions may otherwise compete with Mg^{2+} for plant uptake. Soils with marginal Mg^{2+} levels, such as those in Ikpetiama, are more prone to structural breakdown, nutrient leaching, and cation imbalance. To correct this, agronomic interventions such as the application of dolomitic lime or Mg^{2+}-rich fertilizers are advised.

3.7. Exchangeable Potassium (K^{+})

Exchangeable K^{+} which differed significantly ($P<0.05$) across the studied locations is generally moderate to high, with Akaba (0.73 cmolkg^{-1}) and Kpansia (0.65 cmolkg^{-1}) (**Table 3**) being the most K^{+}-rich sites. Soils of Gbarama (0.31 cmolkg^{-1}) requires close monitoring to prevent potential deficiencies. The significant differences observed reinforce the importance of site-specific nutrient management plans to sustain crop productivity and soil health in the region's diverse agro-ecological zones. These findings are consistent with Obalum et al. (2017), who emphasized that well-structured soils rich in organic residues improve nutrient retention and reduce leaching losses. This relatively lower value may reflect reduced organic carbon, lower base saturation, or lighter-textured soils that tend to have weaker cation retention capacities. Continuous cultivation without adequate replenishment and high rainfall conditions could exacerbate K loss in such soils. Maintaining exchangeable K^{+} levels above 0.2 cmolkg^{-1} is essential for crops such as maize, cassava, plantain, and vegetables commonly grown in southern Nigeria (FAO, 2006).

3.8. Exchangeable Sodium (Na^{+})

Na^{+} content in the soils ranged from 1.34 cmolkg-1 in Akaba to 1.85 cmolkg^{-1} in Gbarama, and a mean value of 1.56 cmolkg^{-1} (**Table 3**). These levels exceed the commonly accepted non-sodic threshold of 0.7 cmolkg^{-1} (Hazelton and Murphy, 2007; USDA-NRCS, 2020), indicating a transition toward sodicity concerns. Gbarama recorded the highest Na^{+} content (1.85 cmolkg^{-1}), suggesting a potential onset of Na^{+}-induced structural challenges likely driven by inadequate drainage, estuarine influence, or saline water intrusion. The statistically significant variation across locations (LSD, $p < 0.05$) confirms pronounced spatial disparity in Na^{+} distribution within the region. This high Na^{+} content heightens the risk of soil structural deterioration, such as clay dispersion, reduced permeability, and surface crusting, especially in areas with high rainfall or limited leaching. The values observed across all locations signify varying degrees of sodicity threat. While Akaba and Kpansia, with relatively lower Na^{+} levels, may still retain moderate soil structural integrity, they are not exempt from risk under prolonged or intensified environmental stressors such as water logging or irrigation.

Given these findings, management strategies must be refocused toward Na^{+} mitigation. As emphasized by Rowley et al. (2018), maintaining Ca^{2+} dominance in the exchange complex is critical for preventing dispersion and preserving aggregate stability in highly weathered tropical soils.

3.9. Exchangeable Hydrogen (H^{+})

Exchangeable Hydrogen (H^{+}) concentrations ranged from 2.11 cmolkg-1 in Akaba to 2.98 cmolkg^{-1} in Ogbogoro, with a mean value of 2.58 cmolkg^{-1}. The differences were statistically significant (LSD, $P < 0.05$), suggesting notable spatial variability. According to FAO (2006), H^{+} concentrations above 0.2 cmolkg^{-1} are indicative of moderate to high acid saturation, potentially inhibiting nutrient uptake and microbial processes. Ikpetiama (2.90 cmolkg^{-1}) and Ogbogoro (2.98 cmolkg^{-1}) recorded the highest H^{+} levels, reflecting elevated proton activity in the soil exchange complex, which, when combined with a low pH (often below 5.5), can significantly reduce the availability of essential base cations like Ca^{2+} and Mg^{2+}. Akaba, despite its lower H^{+} value (2.11cmolkg^{-1}), still reflects strong soil acidity when considered alongside its low pH and high aluminium content, indicating that H^{+} alone is not the sole contributor to acid stress in these soils.

3.10. Exchangeable Aluminium (Al^{3+})

The levels of Exchangeable Al^{3+} varied from 2.41-3.16 cmolkg^{-1} in Kpansia and Ogbogoro respectively with a mean value of 2.71 cmolkg^{-1} (**Table 3**). Though the variation was not statistically significant (LSD), these values remain agronomically critical. According to USDA-NRCS (2004) and Landon (1991), Al^{3+} concentrations above 1.0 cmolkg^{-1} are considered toxic to most crops, as Al^{3+} disrupts root growth, cell elongation, and nutrient uptake especially phosphorus. All the soils studied exceed this toxicity threshold, with the highest levels found in Ogbogoro and Ikpetiama.

3.11. Total Exchangeable Bases

Total Exchangeable Bases (TEB) varied significantly ($P<0.05$) across the sampled sites. The values ranged from 2.72 - 3.40 cmolkg^{-1} in Akaba and Ikpetiama respectively (**Table 3**). The variation was statistically significant (LSD, $p < 0.05$), indicating the influence of factors such as parent material, organic matter levels, and leaching on the accumulation and retention of base cations. TEB is a critical fertility indicator as it reflects the total concentration of essential base cations Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} that are accessible for plant nutrition (Hazelton and Murphy, 2007).

Although Akaba exhibited relatively high individual levels of Mg^{2+} and K^{+}, it had the lowest TEB among all sites. This apparent contradiction can be explained by its high total exchangeable acidity (0.92 cmolkg^{-1}) and strongly acidic pH (4.60), which suggest that acid cations like H^{+} and Al^{3+} dominate the exchange sites, thereby reducing the proportion of base cations relative to the total cation exchange capacity (Obalum et al., 2017). Such conditions are common in tropical acidic soils and typically require corrective measures such as liming or the addition of organic matter to enhance base saturation and nutrient availability (FAO, 2006).

In contrast, Ikpetiama recorded the highest TEB value (3.40 g/kg), indicating better base saturation and higher inherent fertility, even though its organic carbon and nitrogen contents were low. This may result from a more favorable composition of Ca^{2+} and Mg^{2+}, coupled with moderate levels of exchangeable acidity, enabling greater retention and availability of nutrients. Gbarama (2.98 cmolkg^{-1}) and Kpansia (2.97 cmolkg^{-1}) also displayed relatively high TEB values, suggesting that these locations, while acidic, maintain a reasonable level of essential base cations required for productive agriculture. Ogbogoro's TEB value of 3.16 cmolkg-1, in combination with a moderately acidic pH (5.40) and mid-range exchangeable acidity, indicates a balanced nutrient profile. This implies a good potential for agricultural productivity, particularly if complemented by organic matter additions to stabilize pH and minimize leaching losses. As noted by Lal and Shukla (2004), soils with TEB values in the range of 2.5–5.0 g/kg are considered to have moderate fertility, especially when supported by proper management of exchangeable acidity and organic inputs.

3.12. Effective Cation Exchange Capacity

ECEC of the soils, varied statistically from 11.30 cmolkg-1 to 15.30 cmolkg^{-1} in Gbarama and Akaba respectively, with a mean value of 13.98 cmolkg^{-1} (**Table 3**). This variation was significant (LSD, $p < 0.05$), highlighting spatial variabilities in soils' capacity to retain and supply essential cations. Akaba soils, despite being the most acidic location (pH 4.60), recorded the highest ECEC (15.30 cmolkg^{-1}). This may be attributed to its high organic matter content, high Mg^{2+}

DOI: https://doi.org/10.59983/s2025030405
AgroEnvironmental Sustainability, 2025, 3(4), 360–373

and K^+ levels. The presence of both basic and acidic exchangeable cations on the colloidal surfaces elevates the ECEC, albeit under unfavorable pH conditions. Similar trends have been reported by Obalum et al. (2017) and FAO (2006), and Enwezor et al. (1990), who noted that organic matter in acidic tropical soils significantly enhances ECEC, even when base saturation remains low. Kpansia and Ogbogoro recorded ECEC values of 14.71 and 14.30 cmolkg^{-1}, respectively, both above the group mean. These locations also had high base saturation and moderate acidity, which supports effective nutrient retention and reduced leaching losses. High ECEC in these sites implies that with proper liming and nutrient management, the soils have good potential to support continuous cropping and sustainable yield performance (Lal and Shukla, 2004). Ikpetiama soils recorded an ECEC value of 14.20, slightly above the mean, while Gbarama soils recorded the lowest ECEC, which suggests a reduced ability to retain nutrients. This may result from lower SOM, reduced organic carbon, and lower concentrations of exchangeable bases, particularly K^+ and Ca^{2+}.

3.13. Sodium Adsorption Ratio (SAR)

Sodium Adsorption Ratio (SAR) across the study locations ranged from 1.51 in Akaba to 2.21 in Gbarama, with an average value of 1.81 (**Table 3**). The least significant difference (LSD at $p < 0.05$) indicates that the observed differences in SAR values were statistically significant, pointing to variability in sodicity potential among the soils. SAR is a critical index used to assess the sodic hazard of soils and is computed based on the relative concentrations of Na^+, Ca^{2+}, and Mg^{2+}. It serves as a predictor of Na^+-induced dispersion, which negatively affects soil structure, water infiltration, aeration, and increases susceptibility to erosion (USDA-NRCS, 2004). All the soils examined are non-sodic and pose minimal immediate risk to soil structural stability.

3.14. Soil fertility Index (SFI) Ranking

The result of the fertility ranking of the soils are presented in **Table 4**. Result showed that Kpansia and Akaba soils were moderately fertile and require targeted management to optimize crop productivity. Ogbogoro, and Gbarama, were as low fertility, whereas Ikpetiama is poor category indicating significant nutrient imbalance and acidity constraints, and would benefit from liming and nutrient amendments.

Table 4. Soil fertility Index (SFI) ranking.

Location	WQI Scores	Fertility Class
Kpansia	0.710	Moderate
Ogbogoro	0.487	low
Gbarama	0.447	low
Ikpetiama	0.327	Poor
Akaba	0.667	Moderate

3.15. Environmental Quality Index (EQI) Fertility Ranking of Studied Soils

Among the studied locations, Akaba demonstrated superior soil fertility, attributed to its very high base saturation, substantial organic carbon and soil organic matter levels, and a moderately acidic pH. The presence of adequate Ca^{2+} and Mg^{2+} further enhances its soil structural quality and nutrient retention capacity (**Table 5**) . Kpansia also reflected good soil quality, particularly with respect to its high organic carbon content and nutrient availability. Nevertheless, its slightly stronger acidity and reduced available phosphorus (Av. P) content slightly limited its overall fertility status.

The soils in Ogbogoro were generally fertile but exhibited lower Ca^{2+} levels and higher concentrations of exchangeable hydrogen (H^+), which may compromise nutrient uptake and soil health due to increased acidity stress. Ikpetiama maintained fair nutrient levels; however, its relatively low organic carbon and phosphorus availability could hinder plant growth and reduce long-term soil productivity. Gbarama showed the poorest fertility indicators among the soils. This was mainly due to low total exchangeable bases (TEB), insufficient Mg^{2+}, and severe acidity issues reflected by high levels of H^+ and Al^{3+}, all of which can negatively impact crop performance and soil functionality.

Table 5. Environmental Quality Index (EQI) the studied soils.

Location	EQI Score	Rank
Kpansia	95.7	1st
Ogbogoro	94.1	2nd
Gbarama	93.8	3rd
Ikpetiama	92.3	4th
Akaba	89.6	5th

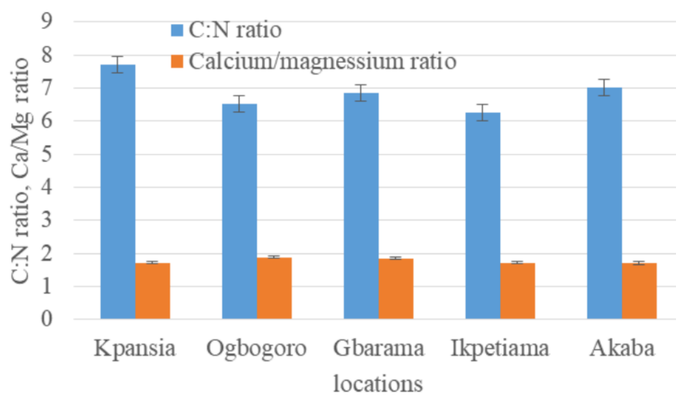

Figure 2. Carbon nitrogen ratio and calcium magnesium ratio of studied soils.

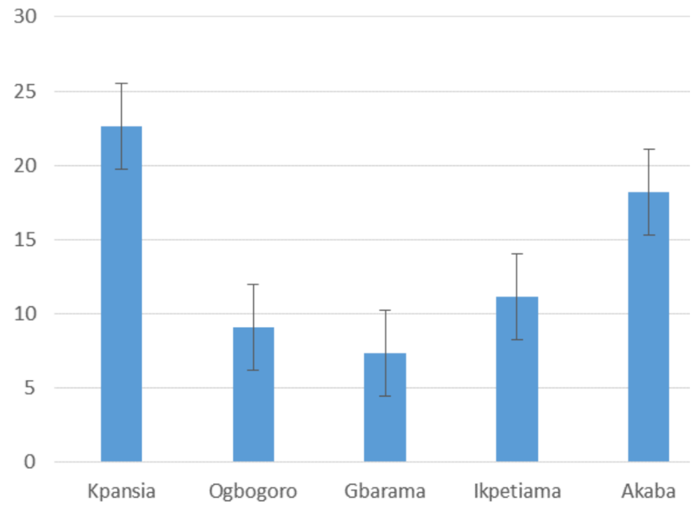

Figure 3. Calcium potassium ratio of studied soil.

3.16. Fertility Ratios of Studied Soil

Selected fertility ratios of studied soils are presented in **Figures 2** and **3**, respectively. C:N ratio ratio ranged from 6.25 -7.71 in Ikpetima and Kpansia respectively (**Figure 2**). These values show rapid mineralisation taking place in all the soils suggesting good decomposition and fast release of nutrients to the plants. The implication of rapid decomposition and mineralisation is that there will be need for nutrient supply to augment they fast release to crops. On the other hand, soils of Ogbogoro and Gbarama showed higher Ca;Mg ration (**Figure 2**) compared to others. However, all the values were less than three (<3) indicating Mg^{2+} dominance (Brady and Weil, 2017) in all the soils which limiting Ca^{2+} availability to crops and soil structural development. In the same vein, Ca^{2+} to K^{+} ratios followed the trend Kpansia> Akaba >Ikpetime>Ogbogoro> Gbarama (**Figure 3**). Comparing them with standards documented by Brady and Weil (2017), Chude et al., (2011), soils of Kpansia may be relatively low in K^{+} compared to others where as others may be low in Ca^{2+} implying low postassium uptake by crops by the former and Ca^{2+} uptake by crops in the later.

3.17. Correlation Matrix Among Selected Chemical Properties of Soil

The correlation of among selected fertility properties of the studied soils are presented in **Table 6** and **Figures 4** and **5**. Results showed significant positive relations between total nitrogen and soil organic carbon (R^2= 0.85) (**Table 6**). A predictive equation: total nitrogen = 0.0752 soil organic carbon + 0.8796 (**Figure 4**) was also generated. Other positive but significant relations were noted of SOC and total exchangeable bases (R^2=0.67), TN and base saturation (R^2=0.76) (**Table 6**). On the other hand, soil pH negatively related with base saturation (R^2= - 0.30) implying that the lowering of pH decreases base saturation of the soil and can be predicted with the equation: Base saturation = - 45.411 pH (water) 1018.9 (**Figure 5**). These values were similar to those of Okunsebor et al. (2024).

Table 5. Correlation matrix among selected chemical properties of studied soils.

Parameter	Units	pH (water)	SOC	TN	Av. P	ECEC	B.S	TEB	TEA
pH (water)	-	1							
SOC	gkg^{-1}	0.22 *NS*	1						
TN	gkg^{-1}	0.39*	0.85**	1					
AP	$mgkg^{-1}$	0.32*NS*	0.12 *NS*	0.25 *NS*	1				
ECEC	$Cmolkg^{-1}$	0.01 *NS*	0.56*	0.19 *NS*	0.39*	1			
BS	gkg^{-1}	-0.30*	0.38*	0.76*	0.58*	0. 40*	1		
TEB	$Cmolkg^{-1}$	0.57*	0.67*	0.29 *NS*	0.67*	0.32*	0.67*	1	
TE	$Cmolkg^{-1}$	0.55*	0.71**	0.38*	0.37*	0.24*NS*	0.32	0.18 *NS*	1

NS: not significant; *: significant.

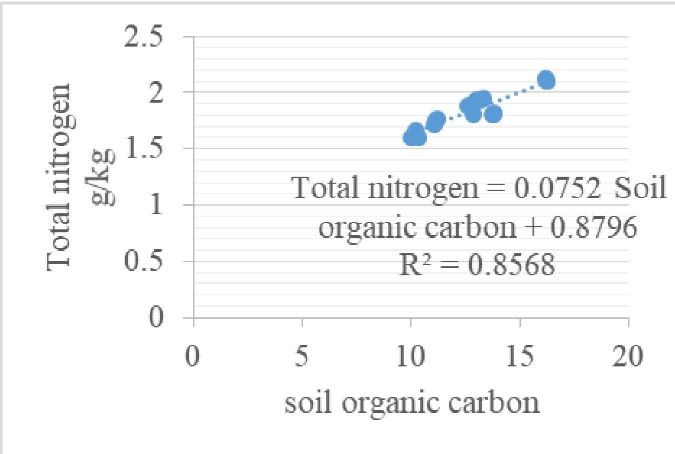

Figure 4 . Correlation between total nitrogen and organic carbon of studied soils.

3.18. Limitations of Study

Although this study provides valuable insight into fertility status of coastal soils in Yenegoa, certain limitations such as sample size, localized differences in land use, micro topography etc may influence nutrient distribution beyond what the sample size can reflect. Additionally, while standard laboratory procedures were followed, analytical measurements may still carry minor precision limitations that could influence the interpretation of specific nutrient values and fertility indices.

4. Conclusion

This study examined the variation and fertility challenges of acidic soils across five locations in Yenagoa Local Government Area. The results revealed that soils within Yenagoa LGA are predominantly acidic, with moderate levels of organic matter and variable nutrient status. Locations such as Kpansia and Akaba demonstrated relatively better fertility conditions due to higher organic carbon, and exchangeable base levels. Again, sites like Ikpetiama and Ogbogoro

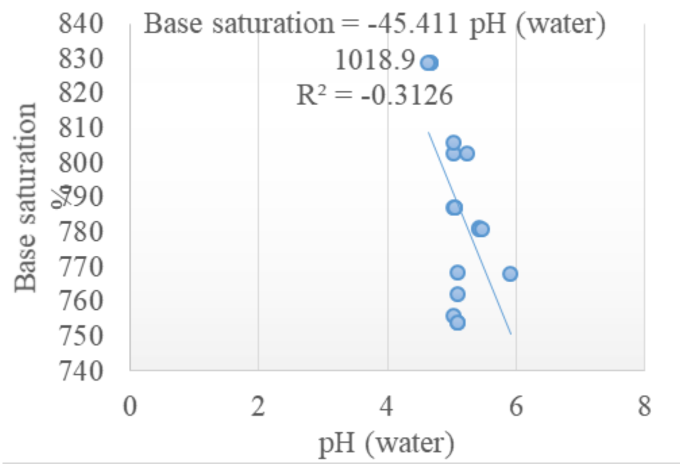

Figure 5. Correlation between base saturation and pH (water).

exhibited lower fertility, particularly in terms of nitrogen and organic matter content. The acidic nature of the soils, especially in Akaba and Kpansia, poses challenges related to nutrient availability and Al^{3+} toxicity. These findings confirm the complexity of soil fertility in humid tropical environments, where high rainfall, leaching, and land use intensity contribute to significant spatial differences in soil health and productivity. Fertility indexing showed that Akaba and Kpansia possessed comparatively better soil quality, while Ogbogoro and Gbarama fell within the low fertility category, and Ikpetiama rated poorest due to combined acidity stress, low organic carbon, and weak nutrient reserves. Strong correlations between soil organic carbon, nitrogen, and base saturation underscore the importance of maintaining organic matter for sustained fertility

Based on the findings, location- specific soil improvement strategies are necessary to optimize land productivity in Yenagoa. Liming should be prioritized in strongly acidic locations such as Akaba, Kpansia, and Ikpetiama to correct soil pH and mitigate the effects of Al^{3+} toxicity. Organic matter restoration is crucial for soil improvement in areas with low SOC, particularly in Ikpetiama and Ogbogoro. This can be achieved through the application of compost, animal manure, or cover cropping systems. Integrated soil fertility management, including the use of phosphorus-efficient crop varieties and judicious fertilizer application, should be promoted to enhance nutrient availability in phosphorus-limited and nitrogen-deficient soils. Finally, sustained soil monitoring and periodic testing should be institutionalized to support evidence-based decision-making for agricultural planning and sustainable land management in the region.

Authors' Contributions

Leonard Chimaobi Agim: Conceptualization; study design; supervision; Ebitari Jimme Victor: Field investigation; laboratory analysis; manuscript drafting; contribution to data interpretation; Michael Akaninyene Okon: Co-supervision; statistical analysis; Lilian Onyinyechi Moses-Okoro: Contribution to manuscript discussion; proofreading.

Funding

This research is self funded.

Acknowledgements

The authors appreciate the technical and laboratory staff of Soil Science Department certified laboratory. We are indebted to our families, colleagues and friends.

Declarations

Conflict of Interests: There is no conflict of interest in this work by the authors

Institutional/Ethical Approval: Not applicable.

Data Availability/Sharing: The datasets used and analyzed during the current study will be made available from the corresponding author upon a reasonable request.

Supplementary Information Availability: Not applicable.

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