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Soil Quality Assessment for Urban Agriculture in Two Cities of Southwest Nigeria

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Abstract

Urban agriculture (UA) is increasingly becoming vital for food security and sustainable urban development, yet urban soils often face challenges like compaction, nutrient depletion, and poor soil structure. This study was carried out to assess soil quality across 12 UA sites in Akure and Okitipupa, southwest Nigeria, evaluating physical, chemical, and biological properties in order to guide management strategies. Soil samples were analyzed for texture, bulk density (BD), hydraulic conductivity (K_s), water-stable aggregates (WSA), pH, organic carbon (C_{org}), total nitrogen (N_{tot}), available phosphorus (AvP), exchangeable cations, microbial biomass carbon (C_{mic}), nitrogen (N_{mic}), and soil microbial respiration (SMR). Results showed that Akure soils were sandy loam, slightly acidic (pH 5.91–6.76), with variable C_{org} (6.05–19.65 g kg^{-1}) and low N_{tot} (0.73–3.63 g kg^{-1}). Okitipupa soils were loamy sand to sandy loam, moderately acidic (pH 4.93–5.96), with higher C_{org} (8.76–22.71 g kg^{-1}). Principal component analysis (PCA) revealed that the first two components explained 75.4% of the variance, with PC1 driven by texture and K_s, and PC2 by C_{org}, N_{tot}, and AvP. Hierarchical clustering grouped the UA sites into four clusters: Cluster 1 (sandy, acidic, nutrient-poor), Cluster 2 (compacted, poor soil structure), Cluster 3 (fertile, loamy, high C_{org}/N_{tot}), and Cluster 4 (moderate fertility, erosion-prone). Management recommendations include organic amendments and cover crops for Cluster 1, deep tillage and raised beds for Cluster 2, crop rotation and minimal tillage for Cluster 3, and mulching with conservation tillage for Cluster 4. These results highlight urban soil heterogeneity and provide tailored strategies to enhance agricultural productivity in southwest Nigeria.

Introduction

The re-localization of food systems is gaining attention due to various economic factors, the expansion of urban areas leading to a decrease in agricultural land, growing environmental and health concerns, and an increasing urban population. Consequently, urban residents are increasingly encouraged to cultivate their own food (Lamine and Marsden, 2023; Aduloju *et al*., 2024). Many experts argue that urban food production can enhance food accessibility and mitigate the environmental impacts of food transportation (Lee *et al*., 2015; Caputo, 2022). This has led to a notable surge in interest in urban agriculture for these reasons and more, although the advantages and disadvantages of urban agriculture remain a topic of discussion (Goldstein *et al*., 2016). Urban agriculture involves growing food in urban or densely populated areas, making significant contributions to social, economic, and ecological well-being (Salomon *et al*., 2020). It takes various forms, particularly in developed countries where advanced techniques like hydroponics, vertical gardening, and LED lighting are becoming popular. However, the most common method remains using natural soil or soil-based media in raised beds or containers (Eigenbrod and Gruda, 2015). Given its importance for sustainable urban development and food security, there is an urgent need for comprehensive studies on urban soil quality as it relates to food production.

One of the main challenges facing urban agriculture is the poor condition of urban soil, which is often unsuitable for cultivation. These soils frequently suffer from degradation due to factors such as compaction, the removal of topsoil, and

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inappropriate management practices. The process of urbanization significantly impacts soil quality, leading to reduced organic matter, increased heavy metal contamination, physical soil degradation, compaction, and a decline in the ability of water, air, and roots to penetrate the soil (Odewande and Abimbola, 2008; Adelana *et al*., 2023a; Adelana *et al*., 2023b). These changes negatively affect soil structure and fertility, making crop cultivation for food production more challenging. Evaluating the quality of urban soils for food production is crucial, as soil quality plays a vital role in determining the success and sustainability of agricultural endeavors in urban settings. Existing research on urban soil primarily focuses on the effects of urbanization on soil functionality and the resulting modifications to the physical and chemical properties of soils (McIvor *et al*., 2012; Joimel *et al*., 2016; Delbecque *et al*., 2022; Adelana *et al*., 2023a). However, there is a significant gap in studies addressing the overall quality of urban soils, encompassing their physical, chemical, and biological attributes, especially concerning urban agricultural practices in Nigeria.

Previous studies on urban soils in Nigeria have largely focused on the issue of heavy metal contamination (Olorundare *et al*., 2011; Abdu *et al*., 2011, 2012; Iwegbue and Martincigh, 2018; Famuyiwa *et al*., 2022; Kolawole *et al*., 2023). The results of these studies are often site-specific and show considerable variation influenced by distinct environmental conditions. However, there is a lack of comprehensive information regarding soil fertility, including available plant nutrients, soil physical characteristics, and microbial activity in the context of urban soil research in Nigeria (Abdulkadir *et al*., 2013). The existing literature suggests that urban agricultural sites benefit from a rich supply of plant nutrients sourced from various urban waste materials (Pasquini and Alexander, 2004; Alhassan *et al*., 2021). Additionally, findings indicate that the application of organic fertilizers tends to promote greater soil productivity compared to inorganic alternatives, primarily due to the carbon inputs they provide to the soil (Anikwe and Nwobodo, 2002). This study shows that the localization and assessment of soil quality are essential components for effective urban agricultural management. Consequently, a study was conducted in two urban locations, Akure and Okitipupa, located in southwest Nigeria. This investigation involved an assessment of the soil properties that influence its overall quality. The objectives were to 1) evaluate the existing soil conditions, and 2) propose management strategies for the areas utilized for urban agriculture in these cities.

Materials and Methods

Location description

The study was conducted at two locations in southwest Nigeria Akure and Okitipupa, located at coordinates 7° 17' N, 5° 13' E and 6° 30' N, 4° 42' E, respectively (Fig. 1). Both areas experience a humid tropical climate characterized by two main seasons: a brief dry season from December to February and a more extended wet season from March to November. The average annual temperatures are 27 °C in Akure and 25 °C in Okitipupa. In terms of rainfall, Akure receives an annual average of 1600 mm, while Okitipupa has a higher total of 2100 mm (Nigerian Meteorological Agency, 2020). As of 2025, Akure's estimated population is 665,238, with an urban population density of 5160 individuals per square kilometer. In contrast, Okitipupa has a projected population of 403,635 and an urban density of 4080 people per square kilometer (Macrotrends, 2025).

Field sampling

In this study, we evaluated 12 urban agricultural sites across two locations: 6 sites in Akure and 6 in Okitipupa, following the sampling criteria established by Pouyat *et al*. (2007) for urban environments. The urban agricultural plots have been used for the cultivation of maize (*Zea mays*), cassava (*Manihot esculenta*), and yam (*Dioscorea spp*.) for an average of 15 years, with annual slashing and burning of the litter. In some cases, mounds were created, and the plots were mulched with crop residues. No fertilizers were applied to these plots. Each plot was divided into four quadrants, and two random soil samples were collected at depth of 0–20 cm using a soil auger. The eight sub-samples at a site were mixed to form a single composite sample. Additionally, two undisturbed core samples, each 5 cm in length and with an inner diameter of 5 cm, were taken at each site using cylindrical core samplers. Penetration resistance (PR_{dry}) was measured with an Eijkelkamp field penetrologger (Eijkelkamp Agrisearch Equipment, Netherlands). Fresh samples were also collected at the sampling locations and stored in coolers with ice packs for subsequent biological analysis.

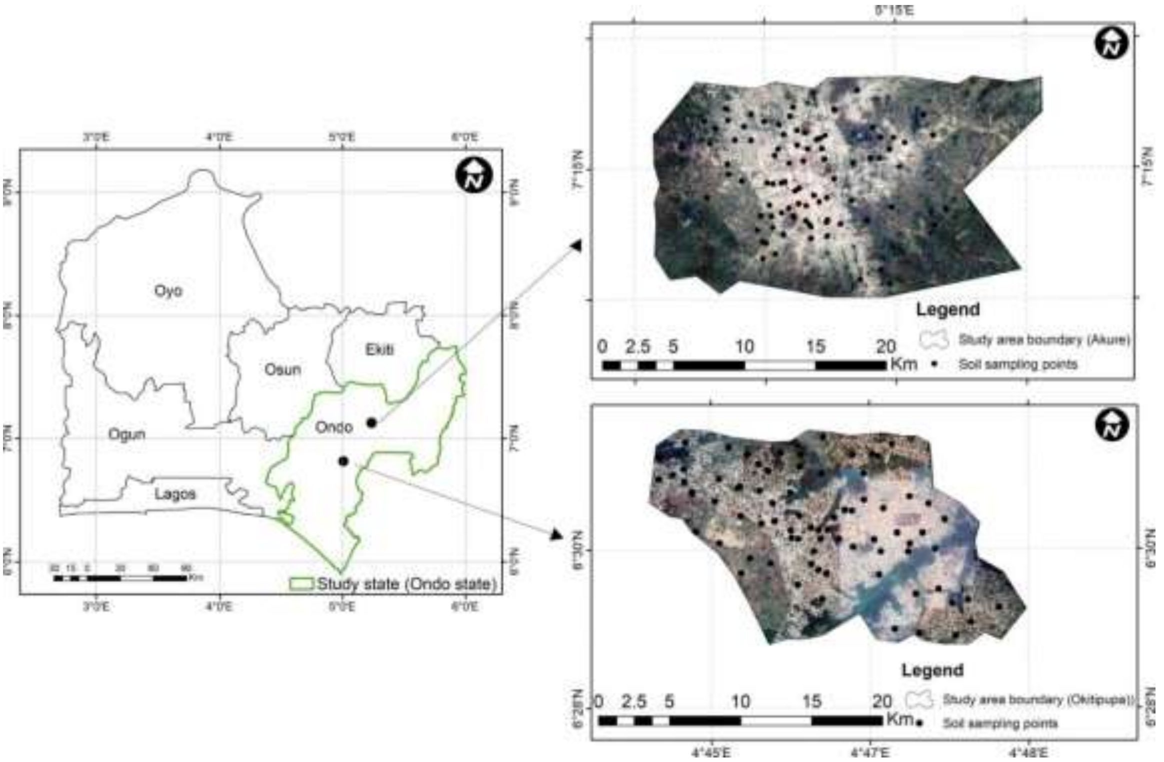

Fig. 1: Study locations in Akure and Okitipupa, southwest Nigeria

Laboratory analysis

Core samples were used to measure bulk density (BD) following Grossman and Reinsch (2002) and hydraulic conductivity (K_s) based on Reynolds *et al.* (2002). Water-stable aggregates (WSA) were determined using an Eijkelkamp wet sieving apparatus. Composite samples were air-dried, sieved through a 2-mm mesh, and analyzed for total nitrogen (N_{tot}) by the Kjeldahl method, organic carbon (C_{org}) by loss on ignition, and available phosphorus (AvP) by spectrophotometric absorbance after Mehlich III extraction. Soil pH was measured in a 1:2 soil-to-water suspension with a Jenway 3540 pH meter, and particle size distribution was determined using a modified Bouyoucos hydrometer method. Exchangeable cations (Mg, Ca, K, Na) were extracted with Mehlich III, after which Ca and Mg were determined by atomic absorption spectrophotometry, and K and Na by flame photometry. Microbial biomass carbon and nitrogen (C_{mic} and N_{mic}) were assessed in fresh soil samples using the chloroform fumigation extraction method. The amount of carbon dioxide emitted from the soil due to the action of microorganisms breaking down organic matter was measured as soil microbial respiration (SMR) (Zibilske, 1994).

Statistical analysis

Data analysis and graphical visualizations were performed using R statistical software version 4.2.1 (R Core Team, 2022). A descriptive analysis was performed on the individual soil variables from both locations. Data transformations were applied as necessary to address variance related to specific properties. Principal component analysis (PCA) was performed on the dataset to assess the differences in soil properties between the sites at each location. The PCA was executed using the "FactoMineR" package, while the R package "factoextra" was used for result visualization (Lê *et al.*, 2008). Additionally, hierarchical analysis was conducted to validate the PCA findings (Köhn and Hubert, 2015), providing a detailed examination of the similarities and differences among the sites. A one-way analysis of variance (ANOVA) was performed to assess the impact of soil properties on the variations between the sites, with mean separation conducted using the Duncan Multiple Range Test at $\alpha \leq 0.05$.

Results and Discussion

Soil physical properties in relation to soil quality

The soil physical properties in Akure indicate a sandy loam texture (Table 1). The Eyin Ala and Isinkan sites had significantly higher sand content and lower clay content, while the Ologede 2 site had the highest silt content. Despite the differences in sand, silt, and clay content, the textural class of the soil remained consistently sandy loam. Lal and Shukla (2004) reported that soil textural class is typically stable over time and is not easily altered by soil management practices. The average BD of the urban agricultural soils in Akure was measured at 1.31 Mg m^{-3}, varying between 1.11 and 1.59 Mg m^{-3} with a low coefficient of variation (CV = 11.8%). Significant differences in BD were observed across the urban agricultural sites, with Isinkan having the highest density of 1.56 Mg m^{-3} and Ologede 1 the lowest at 1.15 Mg m^{-3} (Table 1).

The soils at Emiloro and Eyin Ala sites were mulched with crop residues, contributing to their low BD values. The significantly lower BD at Ologede 1 could be attributed to the preparation of raised mounds for cultivation. These findings are consistent with previous studies that have shown lower BD in urban agricultural practices utilizing raised beds compared to cultivation on bare ground, and in mulched plots compared to un-mulched plots (Beniston *et al*., 2015; Ugarte and Taylor, 2020). The PR_{dry} showed a similar trend to BD, with greater variability (CV = 30.5%). The WSA varied from poor (35.8%) at Ologede 2 to high (56.8%) at the Emiloro site, which was not significantly different from Ologede 1 (56.4%). The addition of organic residue at the mulched Emiloro site could have contributed to the significantly higher WSA (Zhou *et al*., 2022).

The soil physical properties of the urban agricultural sites in Okitipupa are summarized in Table 2. The soil texture ranged from sandy loam to

Table 1: Soil physical properties of urban agricultural sites at Akure

Sites	Sand	Silt	Clay	Texture	BD	PR_{dry}	K_s	WSA
	($g\ kg^{-1}$)				($Mg\ m^{-3}$)	(MPa)	($cm\ hr^{-1}$)	(%)
Ologede 1	611^{b}	286^{b}	103^{b}	SL	1.15^{a}	0.68^{a}	25.8^{d}	56.4^{cd}
Kajola	614^{b}	282^{b}	104^{b}	SL	1.23^{b}	0.75^{ab}	15.4^{b}	50.9^{b}
Isinkan	694^{c}	232^{a}	74^{a}	SL	1.56^{d}	1.35^{c}	10.6^{a}	51.8^{b}
Ologede 2	548^{a}	358^{c}	94^{b}	SL	1.48^{c}	1.28^{c}	14.0^{b}	35.8^{a}
Eyin Ala	674^{c}	252^{ab}	74^{a}	SL	1.25^{b}	0.78^{b}	20.6^{c}	52.3^{bc}
Emiloro	624^{b}	282^{b}	94^{b}	SL	1.21^{b}	0.75^{ab}	15.5^{b}	56.8^{d}
Pr (>F)	0.001	0.01	0.005		0.001	0.03	0.001	0.009
min.	514	222	62		1.11	0.67	9.9	34.2
max.	697	392	107		1.59	1.40	27.0	58.7
mean	627	282	91		1.31	0.93	16.9	50.7
SD	51	44	15		0.16	0.29	5.2	7.4
CV (%)	8.2	15.6	16.1		11.8	30.5	30.8	14.7

Means followed by the same letter in a column are not statistically different at $\alpha \leq 0.05$. SD = standard deviation; CV = coefficient of variation. SL = Sandy loam.

Table 2: Soil physical properties of urban agricultural sites at Okitipupa

Sites	Sand	Silt	Clay	Texture	BD	PR_{dry}	K_s	WSA
	($g\ kg^{-1}$)				($Mg\ m^{-3}$)	(MPa)	($cm\ hr^{-1}$)	(%)
Oke Aye	798	105^{d}	97^{b}	LS	1.25^{b}	0.42^{a}	67.6	62.2^{d}
Ojokodo	811	102^{d}	87^{a}	LS	1.41^{c}	1.09^{b}	86.1	54.0^{bc}
Coastal Hotel	811	76^{ab}	113^{c}	SL	1.46^{c}	0.66^{ab}	72.3	50.3^{b}
Oyesanmi	826	75^{a}	99^{b}	LS	1.03^{a}	0.23^{a}	46.3	62.7^{d}
Farm Settlement	826	82^{ab}	92^{ab}	LS	1.05^{a}	0.28^{a}	47.8	58.7^{c}
Oke Oyinbo	798	85^{c}	117^{c}	SL	1.45^{c}	1.03^{b}	44.3	42.7^{a}
Pr (>F)	0.112	0.008	0.002		0.001	0.027	0.353	0.001
min.	781	62	67		0.87	0.07	30.9	39.9
max.	866	121	127		1.51	1.68	120.9	67.0
mean	818	85	96		1.27	0.62	60.7	58.4
SD	28	18	19		0.19	0.45	26.1	11.6
CV (%)	3.4	20.9	19.9		15.2	72.3	43.1	19.8

Means followed by the same letter in a column are not statistically different at $\alpha \leq 0.05$. SD = standard deviation; CV = coefficient of variation. LS = Loamy sand, SL = Sandy loam.

loamy sand. The soil texture ranged from sandy loam to loamy sand, with differences possibly attributed to the higher clay content at Coastal Hotel (Clay = 113 g kg^{-1}) and Oke Oyinbo (Clay = 117 g kg^{-1}) sites, resulting in a sandy loam texture. The BD in the urban agricultural sites in Okitipupa was generally low, ranging from 1.03 Mg m^{-3} at Oyesanmi to 1.46 Mg m^{-3} at Coastal Hotel site, with low variability (CV = 15.2%). The loose, non-compact, and sandy nature of the urban agricultural soils could have contributed to the generally low BD reported (Huang and Hartemink, 2020). The PR_{dry} was also low, showing a similar trend to BD, indicative of the non-compact nature of the urban agricultural soils. The soils are highly porous, with K_s values ranging from 30.9 to 120.9 cm hr^{-1}, with a mean of 60.7 cm hr^{-1}. The variability in K_s is high (CV = 43.1%), but there were no significant differences among the sites in Okitipupa. The highest K_s (86.1 cm hr^{-1}) was recorded at Ojokodo, while the lowest (44.3 cm hr^{-1}) was observed at the Oke Oyinbo site (Table 2). Olson *et al*. (2013) noted that the coarse texture, larger pore sizes, and lower clay content promote rapid water infiltration in non-compacted sandy soils.

Soil chemical properties in relation to soil quality

The results show that the soil pH levels across the urban agricultural sites in Akure were relatively consistent, with minimal variability (CV = 7.1%) as shown in Table 3. The pH ranged from 5.91 to 6.76, with an average of 6.39. Most of the soils were classified as slightly acidic (72.2%) and the rest as moderately acidic (27.8%). The C_{org} in the urban agricultural soil ranged from 6.05 to 19.65 g kg^{-1}, showing moderate variability (Table 3). Significant variations were observed among the sites, with the lowest C_{org} (7.21 g kg^{-1}) at Ologede 2 and the highest (16.51 g kg^{-1}) at Ologede 1, which was not significantly different from Eyin Ala (15.62 g kg^{-1}), Emiloro (15.45 g kg^{-1}), Isinkan (14.88 g kg^{-1}), and Kajola (14.07 g kg^{-1}). The C_{org} concentrations in this study were lower compared to previous studies on urban agricultural soils. For instance, Ugarte and Taylor (2020) reported C_{org} levels ranging from 53.0 to 179 g kg^{-1} in urban agricultural soils in Chicago, while McIvor *et al*. (2012) found C_{org} concentrations in urban garden plots ranging from 41.0 to 80.2 g kg^{-1}. The values for C_{org} in the soils studied were notably lower, indicating potential disturbances, limited vegetative biomass input, or minimal prior application of organic amendments (Beniston *et al*., 2015). The N_{tot} ranged from 0.73 g kg^{-1} to 3.63 g kg^{-1}, with an average content of 2.09 g kg^{-1}. The N_{tot} showed high variability with a CV of 41.6%. The N_{tot} in the urban agricultural sites was generally low and exhibited a trend that was consistent with C_{org} levels.

An analysis of the macro-nutrient content in the urban agricultural soils of Akure revealed low mean concentrations of Mg (48.1 mg kg^{-1}), Ca (142.4 mg kg^{-1}), and K (56.0 mg kg^{-1}). In contrast, AvP (9.25 mg kg^{-1}) and Na (139.0 mg kg^{-1}) were found to have moderate mean concentrations (Table 3). Significant variability in the levels of AvP, Mg, Ca, and Na were identified, with K showing moderate variability. From the ANOVA results, there were significant differences among the urban agricultural sites in AvP, Mg, and Ca concentrations. The rank for AvP concentration was Ologede 2 < Kajola < Isinkan < Eyin Ala < Ologede 1 ≤ Emiloro. For Mg, it was Kajola ≤ Ologede 2 ≤ Isinkan ≤ Emiloro < Eyin Ala ≤ Ologede 1, and for Ca, Kajola ≤ Ologede 2 < Emiloro ≤ Isinkan < Ologede 1 ≤ Eyin Ala. The macro-nutrient results in this study were within the range reported by Olaleye *et al*. (2020) from urban agricultural soils in Ilesha, southwest Nigeria.

The soil chemical properties of the urban agricultural sites in Okitipupa are presented in Table 4. Soil pH levels showed a high degree of consistency, exhibiting low variability (CV = 7.9%). The pH values varied between 4.93 and 5.96, with a mean of 5.64. All the soils were moderately acidic, except for the soils at the Ojokodo site, which were strongly acidic. High leaching of cations could have resulted in the acidic nature of the soils (Anikwe and Nwobodo, 2002). The C_{org} content in the urban agricultural soil ranged from 8.76 to 22.71 g kg^{-1}, showing moderate variability (CV = 27.6%) (Table 4). Significant differences in C_{org} were observed across the sites, with the lowest mean C_{org} recorded at Oke Oyinbo (9.37 g kg^{-1}) and the highest at Oyesanmi (22.10 g kg^{-1}), which was not significantly different from the value at Oke Aye (21.10 g kg^{-1}). The higher C_{org} levels at Oyesanmi and Oke Aye may be attributed to the greater vegetative biomass input at those sites (Beniston *et al*., 2015).

Table 3: Soil chemical properties of urban agricultural sites at Akure

Sites	pH	N_{tot}	C_{org}	AvP	Mg	Ca	K	Na
		(g kg^{-1})		(mg kg^{-1})				
Ologede 1	6.56	2.82^{c}	16.51^{b}	15.86^{e}	74.4^{c}	203.8^{c}	64.3	120.7
Kajola	6.70	1.29^{a}	14.07^{b}	6.25^{b}	15.7^{a}	65.7^{a}	37.0	108.7
Isinkan	6.26	1.93^{ab}	14.88^{b}	10.73^{c}	51.9^{bc}	160.0^{b}	60.7	139.3
Ologede 2	6.11	1.31^{a}	7.21^{a}	3.86^{a}	24.7^{ab}	66.0^{a}	51.7	141.7
Eyin Ala	6.42	2.69^{bc}	15.62^{b}	12.86^{d}	66.3^{c}	222.5^{c}	68.3	130.0
Emiloro	6.32	2.48^{bc}	15.45^{b}	15.92^{e}	55.5^{bc}	136.3^{b}	54.0	193.7
Pr (>F)	0.150	0.006	0.003	0.001	0.010	0.001	0.091	0.074
min.	5.91	0.73	6.05	3.16	15.2	55.0	33.0	100.0
max.	6.76	3.63	19.65	16.90	99.2	300.0	69.0	198.0
mean	6.39	2.09	13.96	9.25	48.1	142.4	56.0	139.0
SD	0.31	0.87	3.66	4.46	25.7	68.4	10.8	27.9
CV (%)	7.1	41.6	26.3	48.2	53.4	50.5	28.7	35.8

Means followed by the same letter in a column are not statistically different at $\alpha \leq 0.05$. SD = standard deviation; CV = coefficient of variation.

Table 4: Soil chemical properties of urban agricultural sites at Okitipupa

Sites	pH	N_{tot}	C_{org}	AvP	Mg	Ca	K	Na
		(g kg^{-1})		(mg kg^{-1})				
Oke Aye	5.75	3.38^{c}	21.20^{d}	7.78^{c}	116.5^{d}	279.2^{e}	63.3^{d}	63.3
Ojokodo	5.54	1.97^{a}	12.27^{b}	5.39^{a}	43.9^{ab}	37.1^{a}	27.5^{a}	63.0
Coastal Hotel	5.79	2.73^{b}	18.92^{c}	5.66^{a}	53.4^{bc}	113.3^{b}	37.5^{b}	62.3
Oyesanmi	5.95	3.60^{c}	22.10^{d}	7.11^{bc}	72.6^{c}	208.3^{d}	50.8^{c}	63.3
Farm Settlement	5.73	3.26^{c}	19.73^{c}	6.26^{ab}	71.1^{bc}	175.0^{c}	50.8^{c}	63.7
Oke Oyinbo	5.65	1.79^{a}	9.37^{a}	5.30^{a}	41.7^{a}	21.9^{a}	25.0^{a}	61.7
Pr (>F)	0.112	0.020	0.001	0.005	0.001	0.007	0.010	0.195
min.	4.93	1.63	8.76	4.46	24.8	11.3	22.5	56.0
max.	5.96	3.98	22.71	8.38	145.0	325.0	65.0	67.0
mean	5.64	2.79	16.93	6.25	66.5	139.1	42.5	62.8
SD	0.43	0.76	4.66	1.07	28.6	96.0	14.5	6.9
CV (%)	7.9	27.2	27.6	17.2	43.0	69.2	33.9	10.5

Means followed by the same letter in a column are not statistically different at $\alpha \leq 0.05$. SD = standard deviation; CV = coefficient of variation.

The N_{tot} levels ranged from 1.63 to 3.98 g kg^{-1}, with a mean of 2.79 g kg^{-1}. There was moderate variability in N_{tot}, with a coefficient of variation of 27.2%. In our urban agricultural sites, N_{tot} levels were generally low and correlated with C_{org} levels (Udom and Ogunwole, 2015).

The macro-nutrient composition of the urban agricultural soils in Okitipupa exhibited low mean values for AvP (6.25 mg kg^{-1}), K (42.5 mg kg^{-1}), Na (62.8 mg kg^{-1}), Ca (139.1 mg kg^{-1}), and Mg (48.1 mg kg^{-1}) (Table 4). These low values suggest high leaching in the loose, sandy soils of Okitipupa (Esu *et al*. 2013). The study found that Ca (CV = 69.2%), Mg (CV = 43.0%), and K (CV = 33.9%) concentrations showed high variability, while Na (CV = 10.5%) and AvP (CV = 17.2%) levels exhibited moderate variability. Significant variations in AvP, Mg, Ca, and K concentrations were observed among the urban agricultural sites, as indicated by the ANOVA results. The macro-nutrients were consistently higher at Oke Aye site, and this could be because of the high SOC in this site. Lal (2016) reported that SOC is a critical component that provides adsorption sites for cations such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}. It was emphasized that SOC enhances nutrient storage, making cations more available for plant uptake.

Soil biological properties in relation to soil quality

The results of the biological characteristics at the Akure urban agricultural sites are shown in Fig. 2. When compared to other urban agricultural sites, C_{mic} was significantly higher in Ologede 1 and Eyin Ala sites. This was probably due to the large amount of carbon substrate available for breakdown and the increased soil aggregation (Beniston *et al*., 2015). The extremely low C_{mic} values found at the Ologede 2 site imply that soil microbial activity could have been significantly reduced by human disturbances and the ensuing compaction (Tan *et al*., 2008).

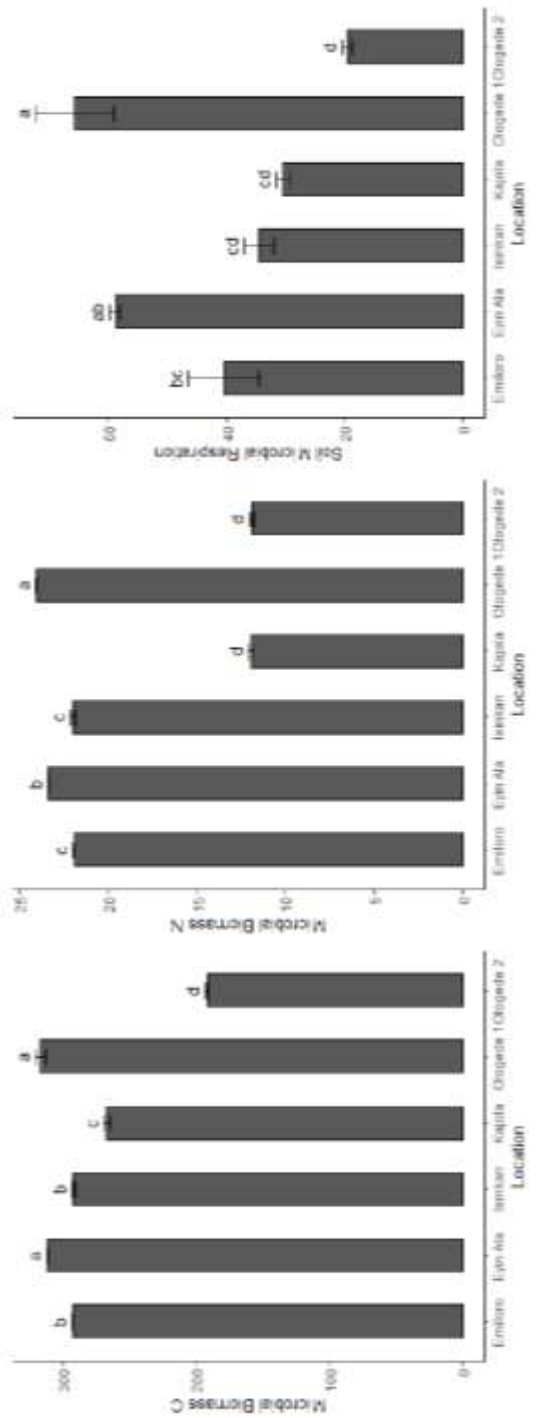

Fig. 2: Soil biological properties of urban agricultural sites in Akure

Means with the same letter are not statistically different at α ≤ 0.05. Error bars indicate standard error.

Microbial biomass N (N_{mic}) had a similar trend to C_{mic}. The concentration of N_{mic} was in the order Ologede 1 > Eyin Ala > Isinkan ≥ Emiloro > Kajola ≥ Ologede 2. According to Nugent and Allison (2022), removal of grass clippings and plant biomass was shown to decrease C_{mic} and ultimately N_{mic} in urban ecosystems. Soil microbial respiration (SMR) in the urban agricultural sites in Akure was moderately variable with a CV of 21.9%. The SMR ranged from 22.58 to 42.09 mg CO_2-C g^{-1} soil with a mean of 27.49 mg CO_2-C g^{-1} soil. The highest SMR was at Ologede 1, which reflected an active decomposition of SOM by microbial activities.

The biological characteristics at the Okitipupa urban agricultural sites show that C_{mic} and N_{mic} levels were significantly higher at the Oke Aye site compared to other urban agricultural sites (Fig. 3). This increase is likely due to the high input of SOM for microbial decomposition and favorable moisture conditions. In contrast, Oke Oyinbo has the lowest C_{mic} and N_{mic} levels, possibly due to limited organic inputs or intensive soil disturbance (Tan *et al*., 2008). Soil microbial respiration in the urban agricultural sites in Okitipupa reflects microbial activities. The highest SMR was recorded in the Oke Aye site (35.79 mg CO_2-C g^{-1} soil), which was significantly different from Oke Oyinbo (23.87 mg CO_2-C g^{-1} soil) but not from Oyesanmi (28.51 mg CO_2-C g^{-1} soil), Farm Settlement (26.25 mg CO_2-C g^{-1} soil), Coastal Hotel (25.51 mg CO_2-C g^{-1} soil), and Ojokodo (25.01 mg CO_2-C g^{-1} soil) sites.

Inter-relationship between urban agricultural sites and management options

Principal Component Analysis (PCA) was conducted on the dataset of 12 urban agricultural sites (Akure and Okitipupa) with 18 soil properties to identify key patterns in soil variability. The analysis reduced the dataset dimensionality, with the first two principal components (PCs) explaining 75.4% of the variance. PC1 captures physical properties such as texture and K_s, while PC2 reflects chemical fertility driven by C_{org}, N_{tot}, and AvP. Sites like Oke Oyinbo, Ojokodo, and Coastal Hotel with high K_s and sand content score high on PC1, indicating coarse-textured, well-drained soils. On the other hand, sites like Isinkan, Emiloro, Eyin Ala, and Ologede 1 with higher C_{org} and nutrient levels align with PC2, reflecting fertile soils.

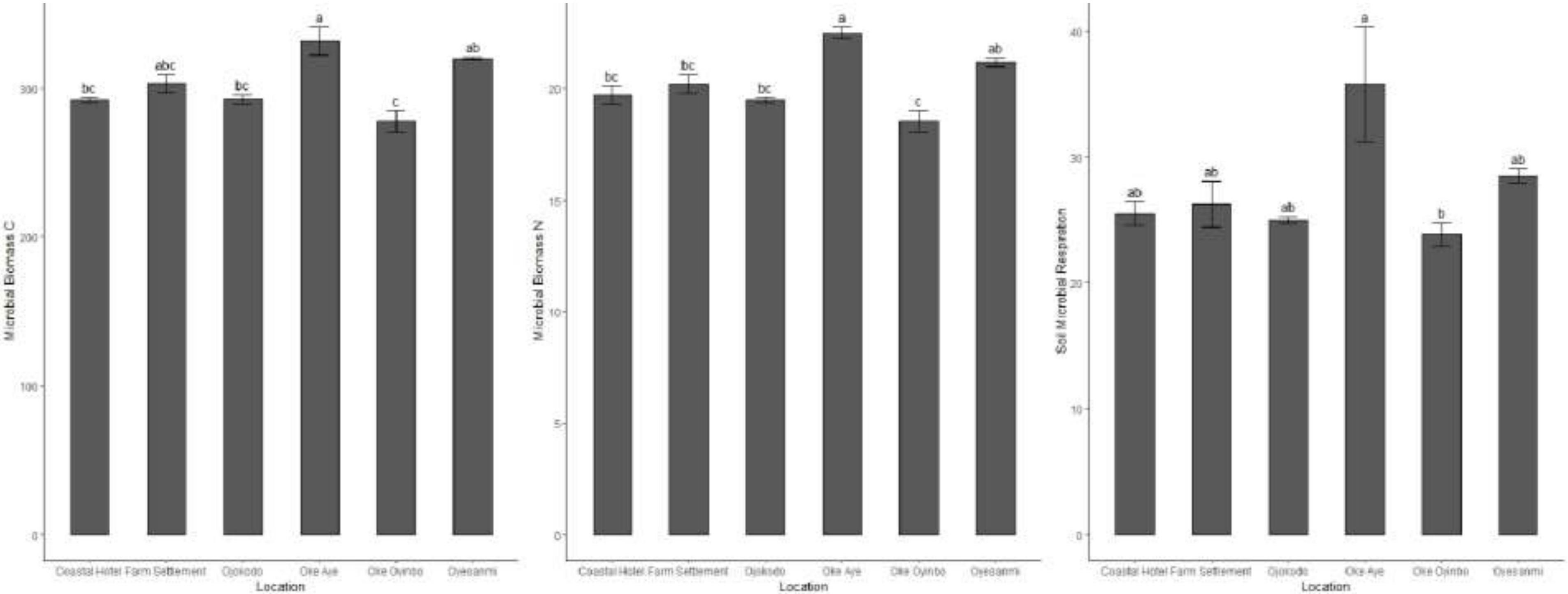

Fig. 3: Soil biological properties of urban agricultural sites in Okitipupa

Means with the same letter are not statistically different at $\alpha \leq 0.05$. Error bars indicate standard error.

The PCA biplot illustrates site dispersion, with clusters of sites like Oyesanmi, Oke Aye, and Farm Settlement near nutrient vectors with high microbial activity, and Ologede 2 and Kajola in a distinct region with high soil compaction and poor WSA, highlighting urban soil heterogeneity (Fig 4). Urban soil heterogeneity is usually driven by texture, fertility, and management practices (Pickett and Cadenasso, 2009; Nugent and Allison, 2022).

Hierarchical clustering grouped the 12 sites into 4 clusters based on texture, compaction, and fertility gradients, as shown by the dendrogram. This can guide site-specific management strategies (Fig. 5). Cluster 1 includes Oke Oyinbo, Coastal Hotel, and Ojokodo sites with sandy, acidic, and well-drained nutrient-poor soils, presenting challenges for agriculture without interventions. To improve these soils, incorporating organic amendments like compost and manure to enhance nutrient retention and microbial activity is crucial. Additionally, using leguminous cover crops and targeted nitrogen and phosphorus fertilizer applications are recommended management options for these soils (Beniston *et al*., 2015). Cluster 2 comprises Ologede 2 and Kajola, characterized by compacted soils with poor structure. To address this, deep tillage and planting deep-rooted cover crops are recommended to enhance porosity. Over-tilling should be avoided as this can destroy soil aggregates and exacerbate compaction in the long term. Incorporating organic amendments can improve aggregate stability, while raised beds can also alleviate compaction issues by offering loose growing media (Pickett and Cadenasso, 2009; Bodner *et al*., 2021). Cluster 3 comprises Oke Aye, Farm Settlement, and Oyesanmi, characterized by fertile, loamy soils with high C_{org}, N_{tot}, and microbial activity (C_{mic} and N_{mic}), making them ideal for agriculture. To maintain soil quality and prevent degradation, it is recommended to regularly add OM. Crop rotation with legumes and cover cropping can help maintain N levels, prevent nutrient depletion, and enhance soil biodiversity. Cluster 4 includes Isinkan, Ologede 1, Emiloro, and Eyin Ala. These sites have moderate fertility and soils that are prone to erosion. They may be suitable for specific crops but may require amendments. The use of cover crops and mulching can enhance fertility and reduce erosion in these sites. Implementing minimal or conservation tillage practices can also help reduce soil disturbance and erosion. The PCA and hierarchical clustering in this study help guide urban agriculture by identifying sites needing remediation, amendments, or immediate use.

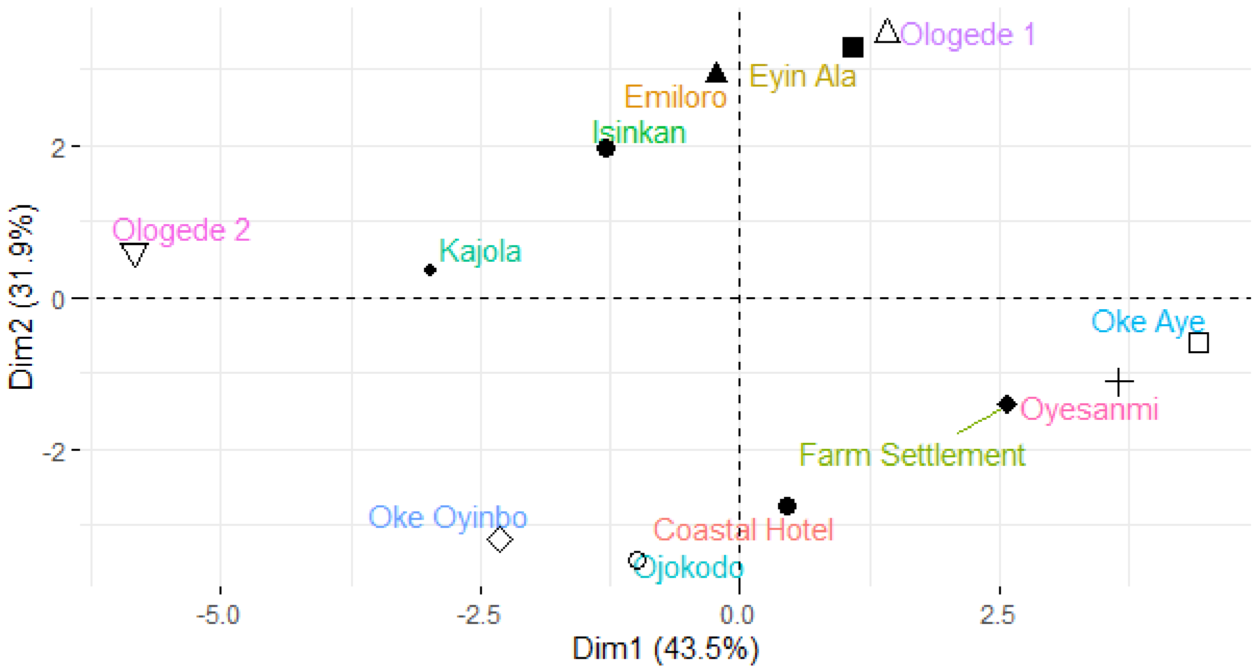

Fig. 4: PCA relationship among studied urban agricultural sites in respect to soil properties

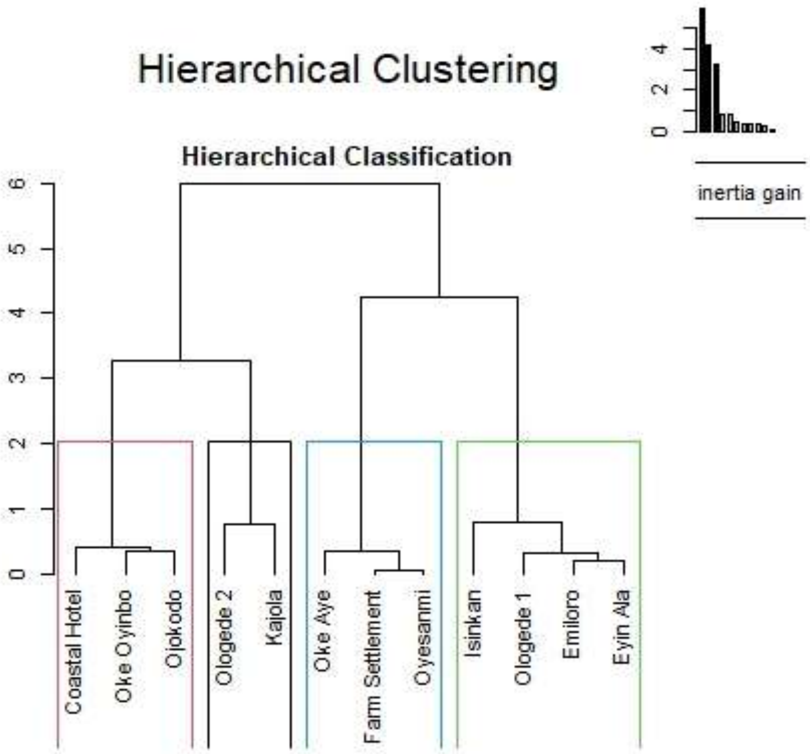

Fig. 5: Hierarchical clustering of 12 urban agricultural sites calculated based on soil properties

Conclusions

An assessment of soil quality across 12 urban agricultural sites in Akure and Okitipupa, southwest, Nigeria, was carried out revealing significant heterogeneity in physical, chemical, and biological properties that influenced the sites' potentials for agriculture. Principal component analysis and hierarchical clustering identified four distinct soil clusters, ranging from sandy, nutrient-poor soils to fertile, loamy soils, each requiring specific management strategies to optimize productivity. Sandy, acidic soils (Oke Oyinbo, Coastal Hotel, and Ojokodo) benefit from organic amendments and cover crops, compacted soils (Ologede 2 and Kajola) require deep tillage and raised beds, fertile loamy soils (Oke Aye, Farm Settlement, and Oyesanmi) need crop rotation and minimal tillage, and erosion-prone soils (Isinkan, Ologede 1, Emiloro, and Eyin Ala) demand mulching and conservation tillage. These tailored interventions address challenges like compaction, nutrient deficiency, and erosion, enhancing the sustainability of urban agriculture. The results underscore the importance of site-specific soil management to support food security and sustainable urban development in Nigeria, with implications for other tropical urban regions. Future research should focus on long-term monitoring of soil health and crop performance under these management practices to validate their efficacy and adaptability.

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