Eagle International Journal of Research, Innovation and Health Sciences
An International Peer Reviewed, Open-Access and Multidisciplinary Journal
Volume 1 | Issue 2 | May 2026 |ISSN:3141-4907
Website: https://eijrihs.com

Spatial Distribution of Microplastics and Soil Physical Properties Across Different Land Uses in Central Cross River State, Nigeria.

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Abstract

This study investigated the spatial variability of microplastic contamination and selected soil physical properties across four land-use types residential, commercial, agricultural, and forest in three Local Government Areas (LGAs) of Central Cross River State, Nigeria: Boki, Ikom, and Obubra. A total of 48 sampling points were established across twelve villages, and soil samples were analyzed for microplastic concentration, particle size distribution, bulk density, porosity, gravimetric and volumetric moisture content, available moisture holding capacity, air-filled porosity, degree of saturation, and void ratio. Results revealed that commercial land use consistently recorded the highest microplastic concentrations (mean: 12.12 g kg^{-1}; 150.87 kg ha^{-1}), while forest soils recorded the lowest (mean: 0.995 g kg^{-1}; 10.65 kg ha^{-1}). Soil textural classification was predominantly sandy loam across all LGAs. Bulk density was highest under residential land use (1.317 g cm^{-3}), while forest soils exhibited the highest porosity (60.22%) and gravimetric moisture content (23.22%). These findings highlight the differential impact of anthropogenic land-use activities on microplastic accumulation and soil physical quality, with implications for sustainable soil management and agricultural productivity in the region.

Keywords: Microplastics, Soil Physical Properties, Land Use, Cross River State, Spatial Distribution, Tropical Soils

1. INTRODUCTION

The contamination of terrestrial ecosystems with microplastics has become an environmental global problem, and the adverse effects of plastic on soil structural properties, biological activity of soil organisms, or crop biomass have been shown (Andrady 2011). Soil environments, as an important sink for plastic pollutants mediated by agricultural mulching, sewage sludge application, littering and atmospheric deposition (Cozar et al., 2014), have been relatively little studied in comparison with aquatic systems where microplastic research is more advanced.

Rapid urbanization, increasing agricultural frontiers and insufficient solid waste management infrastructures have further aggravated the entry of plastics into the soil environment in Nigeria. Central Cross River State comprising Ikom, Boki and Obubra LGAs is an environmentally and agriculturally important location within the southern Nigeria tropical rainforest belt (Ekong, 2020). As these land-use activities and forest conservation represent a gradient of human activity, we chose this area as a field experiment setting to assess microplastic accumulation along with soil physical property changes as related to land use.

Soil physical properties such as texture, bulk density, porosity and moisture retention characteristics are the major determinants of soil health and why soil is important for water regulation and plant growth. Microplastic particles can alter some of these properties by changing soil aggregation, pore structure and water-holding capacity, the extent of which is based on their morphology, size and concentration (Okwakpam, 2018). Thus, it is crucial to understand how the spatial distribution of microplastics in relation to these physical parameters behaves across contrasting land uses as this information can be directly incorporated into sustainable land management and environmental policy.

This study aimed to:

i. Quantify and compare microplastic concentrations in soils under residential, commercial, agricultural, and forest land uses across twelve villages in three LGAs of Central Cross River State;

ii. Characterize the spatial variability of key soil physical properties across these land uses;

iii. Assess the relationship between land-use type, microplastic loading, and soil physical quality.

2. MATERIALS AND METHODS

2.1 Study Area

2.1.1 Location

The study was conducted in Central Cross River State, Nigeria, encompassing Ikom, Boki, and Obubra Local Government Areas (LGAs). The region is geographically situated between Latitude 5.0° N to 6.0° N and Longitude 8.0° E to 9.0° E, placing it within the tropical rainforest ecosystem of southeastern Nigeria (Ekong, 2020). The area is characterized by high humidity and substantial annual rainfall, which significantly influence biodiversity and agricultural practices in the region.

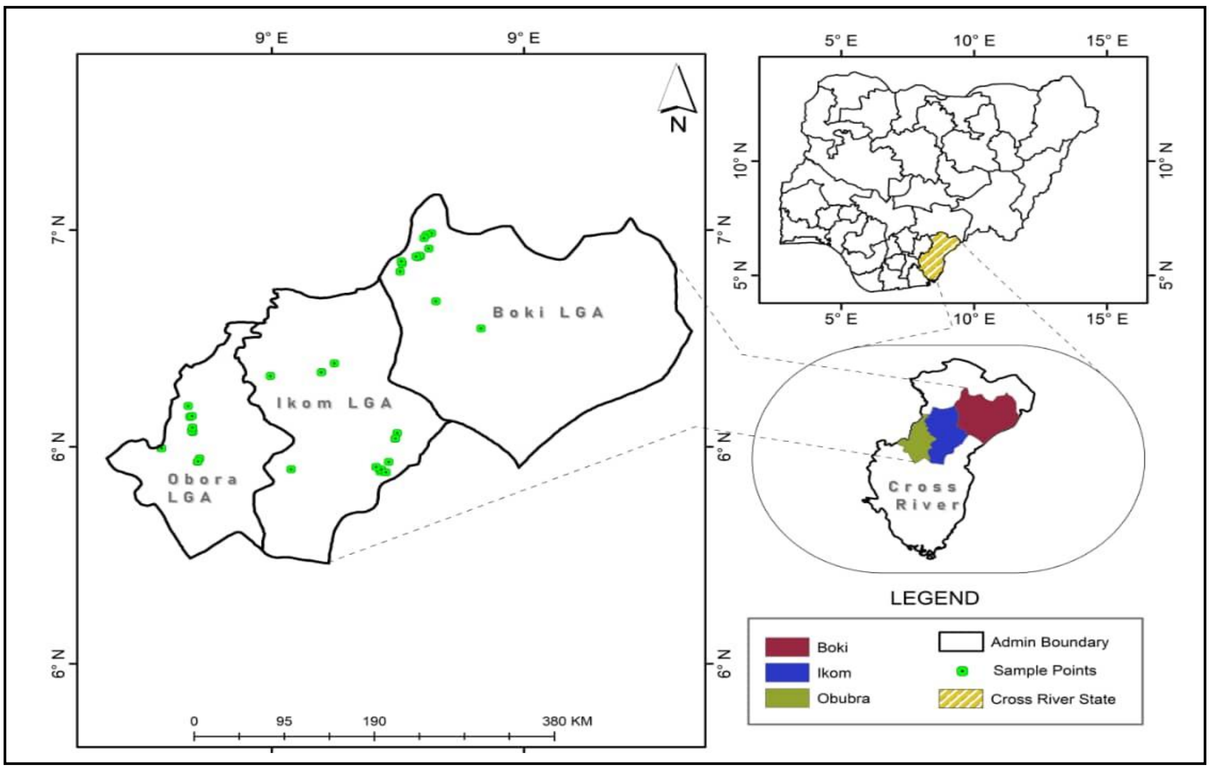

Fig. 1. Map of the study area showing sampled points across the three Local Government Areas.

2.1.2 Climate

The study area exhibits a tropical rainforest climate characterized by a bimodal rainfall pattern, high humidity, and relatively stable temperatures. The rainy season spans April to October, with peak rainfall occurring between June and September; average monthly rainfall during this period can reach up to 300 mm, contributing to an annual total ranging from 2,000 to 3,500 mm (Okwakpam, 2018). Mean annual temperatures range from 25°C to 30°C, and relative humidity regularly exceeds 80%, particularly during the wet season (Eze, 2020; Nigerian Meteorological Agency, 2022).

2.1.3 Vegetation

The area supports rich tropical rainforest vegetation dominated by tall hardwood species, including mahogany (Swietenia macrophylla) and iroko (Milicia excelsa), which can exceed 30 metres in height. The understory comprises smaller trees, shrubs, and ferns, with oil palm (Elaeis guineensis) being notably abundant. The vegetation sustains diverse wildlife populations critical for ecosystem functions such as pollination (Eze, 2020; Cross River National Park, 2021).

2.1.4 Geology and Soils

The geological composition varies across the three LGAs. Ikom is characterized by sedimentary formations of the Benue Trough, including sandstone, shale, and limestone deposits (Ofoegbu, 1990). Boki is underlain predominantly by Precambrian crystalline rocks gneisses and schists influenced by the Cameroon Volcanic Line (Ofoegbu, 1995). Obubra features a combination of sedimentary and metamorphic rocks with significant alluvial deposits along the Cross River corridor (Ajayi and Ojo, 2008). Soils across the region are primarily Ultisols clay-rich with low nutrient content and Entisols, younger fertile soils found in riverine environments (Okwakol, 2019; Adebayo and Ojo, 2021).

2.1.5 Land Use

Land use in Central Cross River is predominantly agricultural, with maize, cassava, yam, and plantain as principal subsistence crops. Cash crops including cocoa and oil palm are increasingly significant to the local economy. Urban centres such as Ikom and Ugep support commercial and residential land uses, while substantial areas remain under natural forest cover, partly protected within the Cross River-National Park (Ekong, 2020; IUCN, 2021).

2.2 Sample Collection

Soil samples were collected from four land-use categories Residential, Commercial, Agricultural, and Forest across four villages in each of the three LGAs: Boki (Boje, Kakwagom, Okundi, and Ntamante), Obubra (Obubra, Owakande, Apiapum, and Iyamoyong), and Ikom (Ikom, Nta/Nselle, Akparabong, and Ofutop). This design yielded a total of 48 sampling points. Geographic coordinates of all sampling locations are presented in Table 1.

Table 1. Sampled locations, land-use types, and their GPS coordinates.

S/N.	Location/ Land-use	Latitude	Longitude
	Boki/Boje		
1	Residential	6.534721	8.695433
2	Commercial	9.081998	8.675277
3	Agricultural	6.335944	8.825422
4	Forest	6.273279	8.914703
	Boki/Kakwakom		
5	Residential	6.492865	8.816601
6	Commercial	6.489081	8.806820
7	Agricultural	6.481587	8.801654
8	Forest	6.457355	8.811298
	Boki/Okundi		
9	Residential	6.441238	8.792355
10	Commercial	6.440046	8.794157
11	Agricultural	6.437336	8.789056
12	Forest	6.441238	8.792355
	Boki/Ntamante		
13	Residential	6.439005	8.786157
14	Commercial	6.422849	8.758255
15	Agricultural	6.404553	8.754478
16	Forest	6.428289	8.756882
	Obubra/Obubra		
17	Residential	6.069942	8.338790
18	Commercial	6.069302	8.337763
19	Agricultural	6.094510	8.334115
20	Forest	6.071363	8.341730
	Obubra/Owakande		
21	Residential	6.034474	8.343241
22	Commercial	6.037042	8.346259
23	Agricultural	6.360751	8.345637
24	Forest	6.044954	8.342854
	Obubra/Apiapum		
25	Residential	5.997093	8.280961
26	Commercial	6.576054	9.431336
27	Agricultural	5.997088	8.280303
28	Forest	5.996895	8.281646
	Obubra/Iyamoyong		
29	Residential	5.965882	8.352827
30	Commercial	5.973327	8.356764
31	Agricultural	5.968953	8.356673
32	Forest	5.966800	8.353814
	Ikom/Ikom		
33	Residential	5.943077	8.714479
34	Commercial	5.948245	8.717015
35	Agricultural	5.964181	8.726391
36	Forest	5.953859	8.706654
	Ikom/Nta/Nselle		
37	Residential	6.172462	8.598374
38	Commercial	6.163812	8.497223
39	Agricultural	6.192726	8.624141
40	Forest	6.172014	8.598117
	Ikom/Akparabong		
41	Residential	6.031945	8.748584

42	Commercial	5.965382	8.731684
43	Agricultural	6.019285	8.744470
44	Forest	6.019546	8.745134
	Ikom/Ofutop		
45	Residential		
46	Commercial	5.948644	8.538286
47	Agricultural		
48	Forest		

2.3 Experimental Design

The study was conducted in two sequential phases combining field sampling with controlled experimental assessment of microplastic impacts on soil properties. A factorial experimental design with a nested structure was employed.

Phase 1 involved completely randomized sampling of soils from four land-use categories (Forest, Residential, Agricultural, and Commercial) across three LGAs, replicated four times per location, to investigate microplastic presence and establish baseline soil physical variability data (Cozar *et al*., 2014).

Each sampling site included a minimum of three to four replicates to account for spatial variability and improve the statistical robustness of the data.

2.4 Microplastic Extraction

2.4.1 Pre-Treatment and Density Separation

Soil samples were air-dried and sieved through a 5 mm mesh to remove coarse debris prior to microplastic extraction (Andrady, 2011). Density separation was performed using a saturated sodium chloride (NaCl) solution (375 g L^{-1}) to exploit the density differential between microplastic particles and mineral soil fractions. The floating fraction was subsequently collected, filtered, and examined under a stereo microscope for microplastic identification and quantification.

2.5 Soil Physical Analyses

Standard laboratory procedures were employed to determine soil particle size distribution (hydrometer method), bulk density (core sampling method), total porosity (calculated from bulk and particle density), gravimetric moisture content (oven-drying at 105°C), volumetric moisture content, available moisture-holding capacity, air-filled porosity, degree of saturation, and void ratio. Soil textural classification followed the USDA textural triangle.

3. RESULTS

3.1 Soil Particle Size Distribution and Texture

The spatial variability of soil particle sizes across land uses in the three LGAs is presented in Table 2. Sandy loam (SL) was the dominant textural class across the majority of sampling points in all three LGAs, reflecting the generally sandy nature of soils in the region.

In Boki LGA, mean sand content was 71.6% (SD = 7.38; CV = 10.31%), mean silt was 15.6% (SD = 5.20; CV = 33.29%), and mean clay was 12.8% (SD = 2.54; CV = 19.94%). Sand content ranged from 58% (Kakwagom Agricultural) to 82% (Ntamante Forest), with sandy clay loam (SCL) observed only at Kakwagom under agricultural land use.

In Obubra LGA (presented under the Ikom header in the original dataset), mean sand content was 71.8% (SD = 6.84; CV = 9.53%), mean silt was 14.1% (SD = 4.16; CV = 29.46%), and mean clay was 14.1% (SD = 3.16; CV = 22.37%). Loamy sand (LS) texture occurred at Apiapum under forest and commercial land uses.

In Ikom LGA, the highest spatial variability in particle size was observed, with mean sand content of 61.9% (SD = 14.84; CV = 23.97%), mean silt of 22.6% (SD = 12.11; CV = 53.64%), and mean clay of 15.5% (SD = 3.67; CV = 23.72%). Loam (L) texture was recorded at Nta/Nselle under residential and agricultural land uses and at Akparabong under residential and commercial land uses, indicating finer-textured soils in this LGA.

Table 2. Spatial variability and distribution of soil particle sizes across different land uses and LGAs.

BOKI L.G.A.

	LAND USE.																		
	BOJE				KAKWAGOM				OKUNDI				NTAMANTE						
SOIL PROPERTIES	Rs.	Com.	Agr.	For.	Rs.	Com.	Agr.	For.	Rs.	Com.	Agr.	For.	Rs.	Com.	Agr.	For.	Mean	SD	CV
Sand %	67	80	64	74	78	63	58	74	75	72	66	62	78	73	80	82	**71.6**	**7.38**	**10.31**
Silt %	20	9	20	14	11	23	22	14	13	16	21	23	11	15	10	8	**15.6**	**5.20**	**33.29**
Clay %	13	11	16	12	11	14	20	12	12	12	13	15	11	12	10	10	**12.8**	**2.54**	**19.94**
Texture	SL	LS	SL	SL	SL	SL	SCL	SL	SL	SL	SL	SL	SL	SL	LS	LS	SL		

IKOM L.G.A.

	LAND USE																		
	OBUBRA				OWAKANDE				APIAPUM				IYAMOYONG						
SOIL PROPERTIES	Rs.	Com.	Agr.	For.	Rs.	Com.	Agr.	For.	Rs.	Com.	Agr.	For.	Rs.	Com.	Agr.	For.	Mean	SD	CV
Sand %	62	68	64	72	64	66	74	81	73	82	78	80	72	72	62	78	**71.8**	**6.84**	**9.53**
Silt %	18	16	18	16	20	19	14	8	14	8	11	10	11	13	20	10	**14.1**	**4.16**	**29.46**
Clay %	20	16	18	12	16	15	12	11	13	10	11	10	17	15	18	12	**14.1**	**3.16**	**22.37**
Texture	SCL	SL	SL	SL	SL	SL	SL	LS	SL	LS	SL	LS	SL	SL	SL	SL	SL		

OBUBRA L.G.A.

	LAND USE																		
	IKOM				NTA/NSELLE				AKPARABONG				OFUTOP						
SOIL PROPERTIES	Rs.	Com.	Agr.	For.	Rs.	Com.	Agr.	For.	Rs.	Com.	Agr.	For.	Rs.	Com.	Agr.	For.	Mean	SD	CV
Sand %	74	72	80	84	40	70	32	66	44	48	64	69	53	63	59	73	**61.9**	**14.84**	**23.97**
Silt %	12	13	8	6	40	12	43	19	42	34	23	19	31	20	25	15	**22.6**	**12.11**	**53.64**
Clay %	14	15	12	10	20	18	25	15	14	18	13	12	16	17	16	12	**15.5**	**3.67**	**23.72**
Texture	SL	SL	LS	LS	L	SL	L	SL	L	L	SL	SL	SL	SL	SL	SL	SL		

3.2 Spatial Distribution of Microplastics

3.2.1 Microplastic Concentration in g kg^{-1}

The spatial distribution of microplastics expressed in g kg^{-1} of dry soil is presented in Table 3. Commercial land use recorded the highest overall mean microplastic concentration (12.12 ± 5.83 g kg^{-1}; CV = 48.07%), followed by residential (5.40 ± 1.48 g kg^{-1}; CV = 27.45%), agricultural (3.09 ± 1.58 g kg^{-1}; CV = 51.01%), and forest (0.995 ± 0.70 g kg^{-1}; CV = 70.50%) land uses.

Among all locations, Ikom commercial site recorded the single highest microplastic concentration (25.82 g kg^{-1}), followed by Nta/Nselle commercial (21.96 g kg^{-1}). The highest location-level mean was recorded at Ikom (8.07 g kg^{-1}) and Nta/Nselle (8.00 g kg^{-1}), both within the Ikom LGA. The Boje location in Boki LGA recorded the lowest location mean (3.82 g kg^{-1}).

Table 3. Spatial distribution of microplastics (g kg^{-1} dry soil) under different land uses.

	LAND USE						
Location	**Residential**	**Commercial**	**Agricultural**	**Forest**	**Mean**	**SD**	**CV**
Boje	5.26	8.02	0.68	1.30	**3.82**	**3.46**	**90.71**
Kakwagom	7.20	8.34	2.24	0.46	**4.56**	**3.81**	**83.46**
Okundi	5.64	11.68	6.68	2.80	**6.70**	**3.70**	**55.27**
Ntamante	6.18	8.38	3.02	0.56	**4.54**	**3.44**	**75.95**
Obubra	5.88	14.38	3.62	0.18	**6.02**	**6.05**	**100.57**
Owakande	7.80	4.90	3.04	0.62	**4.09**	**3.03**	**74.11**
Apiapum	5.36	10.70	3.38	1.00	**5.11**	**4.13**	**80.84**
Iyamoyong	5.56	9.22	3.52	1.32	**4.91**	**3.36**	**68.45**
Ikom	3.76	25.82	2.44	0.26	**8.07**	**11.92**	**147.72**
Nta/Nselle	5.70	21.96	3.66	0.68	**8.00**	**9.53**	**119.15**
Akparabong	4.74	9.10	0.38	1.72	**3.99**	**3.87**	**97.04**
Ofutop	1.76	12.94	4.40	1.04	**5.04**	**5.46**	**108.53**
Mean	**5.403**	**12.120**	**3.088**	**0.995**			
SD	**1.483**	**5.826**	**1.575**	**0.701**			
CV	**27.45**	**48.07**	**51.01**	**70.50**			

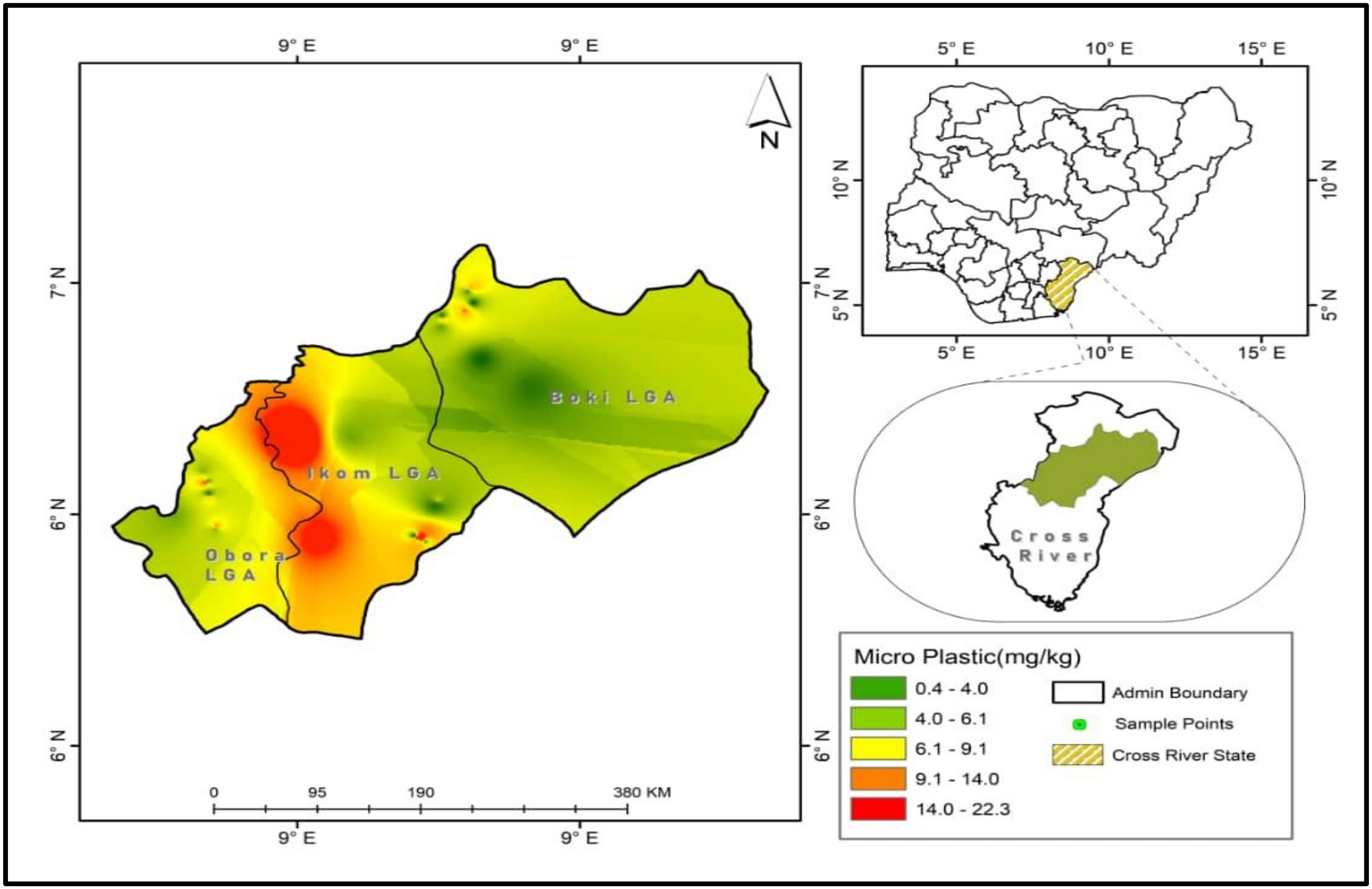

Figure 2. Spatial distribution of microplastics across the three L.G.A's.

3.2.2 Estimated Microplastic Load in kg ha⁻¹

When expressed on an area basis (kg ha^{-1} for 10 cm soil depth), commercial land use again recorded the highest mean microplastic load (150.87 ± 75.53 kg ha^{-1}; CV = 50.07%), followed by residential (70.08 ± 20.68 kg ha^{-1}; CV = 29.51%), agricultural (39.50 ± 24.28 kg ha^{-1}; CV = 61.46%), and forest (10.65 ± 8.95 kg ha^{-1}; CV = 84.04%) land uses (Table 4).

The highest individual value was recorded at Nta/Nselle commercial (327.20 kg ha^{-1}), followed by Ikom commercial (247.87 kg ha^{-1}). Forest land use consistently recorded the lowest values across all twelve locations, with a minimum of 2.30 kg ha^{-1} at Obubra forest site.

Table 4. Estimated microplastic loads (kg ha^{-1}) at 10 cm soil depth under different land uses.

LOCATION	LAND USE				Mean	SD	CV
	Residential	Commercial	Agricultural	Forest			
Boje	68.91	106.67	6.19	13.00	**48.69**	**47.79**	**98.14**
Kakwagom	85.68	113.42	31.81	4.00	**58.73**	**49.79**	**84.78**
Okundi	78.96	114.46	98.20	33.04	**81.17**	**35.21**	**43.38**
Ntamante	96.41	87.99	36.54	3.58	**56.13**	**43.90**	**78.22**
Obubra	69.38	165.37	47.06	2.30	**71.03**	**68.80**	**96.87**
Owakande	73.32	63.70	37.09	8.31	**45.61**	**29.21**	**64.04**
Apiapum	60.03	173.34	50.02	12.80	**74.05**	**69.24**	**93.51**
Iyamoyong	100.08	82.98	41.54	8.58	**58.30**	**41.26**	**70.78**
Ikom	52.26	247.87	22.45	2.89	**81.37**	**112.84**	**138.68**
Nta/Nselle	57.57	327.20	47.21	6.39	**109.59**	**146.74**	**133.90**
Akparabong	74.89	150.15	4.86	21.50	**62.85**	**65.42**	**104.09**
Ofutop	23.41	177.28	51.04	11.44	**65.79**	**76.15**	**115.75**
Mean	**70.08**	**150.87**	**39.50**	**10.65**			
SD	**20.68**	**75.53**	**24.28**	**8.95**			
CV	**29.51**	**50.07**	**61.46**	**84.04**			

3.3 Soil Bulk Density

Spatial distribution of soil bulk density (Bd) across land uses is presented in Table 5. Overall, residential land use recorded the highest mean Bd (1.317 ± 0.238 g cm^{-3}), followed by commercial (1.263 ± 0.243 g cm^{-3}), agricultural (1.237 ± 0.176 g cm^{-3}), and forest (1.054 ± 0.228 g cm^{-3}). Forest soils consistently exhibited lower bulk density values, reflecting the beneficial effects of organic matter accumulation and reduced compaction under undisturbed vegetation cover.

The highest individual Bd value was recorded at Iyamoyong under residential land use (1.80 g cm^{-3}), while the lowest was at Ntamante forest (0.64 g cm^{-3}). High within-location variability was evident at Iyamoyong (CV = 43.70%) and Ntamante (CV = 34.23%), suggesting heterogeneous soil management or disturbance histories at these sites.

Table 5. Spatial distribution of bulk density (g cm^{-3}) under different land uses.

	LAND USE						
LOCATION	Residential	Commercial	Agricultural	Forest	Mean	SD	CV
Boje	1.31	1.33	0.91	1.00	**1.14**	**0.21**	**18.82**
Kakwagom	1.19	1.36	1.42	0.87	**1.21**	**0.25**	**20.39**
Okundi	1.40	0.98	1.47	1.18	**1.26**	**0.22**	**17.69**
Ntamante	1.56	1.05	1.21	0.64	**1.12**	**0.38**	**34.23**
Obubra	1.18	1.15	1.30	1.28	**1.23**	**0.07**	**6.00**
Owakande	0.94	1.30	1.22	1.34	**1.20**	**0.18**	**15.03**
Apiapum	1.12	1.62	1.48	1.28	**1.38**	**0.22**	**15.99**
Iyamoyong	1.80	0.90	1.18	0.65	**1.13**	**0.49**	**43.70**
Ikom	1.39	0.96	0.92	1.11	**1.10**	**0.21**	**19.45**
Nta/Nselle	1.01	1.49	1.29	0.94	**1.18**	**0.25**	**21.54**
Akparabong	1.58	1.65	1.28	1.25	**1.44**	**0.20**	**14.20**
Ofutop	1.33	1.37	1.16	1.10	**1.24**	**0.13**	**10.51**
Mean	**1.317**	**1.263**	**1.237**	**1.054**			
SD	**0.238**	**0.243**	**0.176**	**0.228**			
CV	**18.11**	**19.20**	**14.25**	**21.66**			

3.4 Soil Porosity

Total soil porosity values are presented in Table 6. Forest soils recorded the highest mean porosity (60.22 ± 8.62%), followed by agricultural (53.30 ± 6.66%), commercial (52.33 ± 9.15%), and residential (50.30 ± 9.00%) land uses. This inverse relationship between bulk density and porosity across land-use types is consistent with the compaction effect of anthropogenic activities on soil structure.

The highest porosity was recorded at Ntamante forest (75.91%) and Iyamoyong forest (75.35%), while the lowest was at Iyamoyong residential (32.19%). High spatial variability in porosity was observed at Iyamoyong (CV = 32.47%) and Ntamante (CV = 25.00%).

Table 6. Spatial distribution of soil porosity (%) under different land uses.

	LAND USE						
LOCATION	Residential	Commercial	Agricultural	Forest	Mean	SD	CV
Boje	50.56	49.97	65.57	62.35	**57.11**	**8.02**	**14.04**
Kakwagom	55.17	48.78	46.25	67.02	**54.30**	**9.27**	**17.07**
Okundi	47.22	62.84	44.59	55.37	**52.50**	**8.28**	**15.77**
Ntamante	41.01	60.25	54.31	75.91	**57.87**	**14.47**	**25.00**
Obubra	55.33	56.46	50.99	51.84	**53.65**	**2.65**	**4.94**
Owakande	64.66	50.84	53.87	49.51	**54.72**	**6.87**	**12.56**
Apiapum	57.68	38.98	44.23	51.54	**48.11**	**8.20**	**17.05**
Iyamoyong	32.19	66.04	55.37	75.35	**57.24**	**18.59**	**32.47**
Ikom	47.50	63.70	65.44	58.15	**58.70**	**8.09**	**13.78**
Nta/Nselle	61.85	43.94	51.18	64.42	**55.35**	**9.52**	**17.21**
Akparabong	40.46	37.70	51.76	52.71	**45.66**	**7.69**	**16.84**
Ofutop	49.94	48.45	56.12	58.43	**53.24**	**4.80**	**9.01**
Mean	**50.297**	**52.329**	**53.304**	**60.216**			
SD	**8.999**	**9.153**	**6.656**	**8.619**			
CV	**17.89**	**17.49**	**12.49**	**14.31**			

3.5 Gravimetric Moisture Content

Gravimetric moisture content (θ) values are presented in Table 7. Forest soils recorded the highest mean gravimetric moisture content (23.22 ± 7.68%), followed by commercial (19.41 ± 8.75%), residential (17.56 ± 5.91%), and agricultural (16.61 ± 9.76%) land uses. The higher moisture retention in forest soils is attributable to greater organic matter content, enhanced soil structure, and reduced evapotranspiration under continuous canopy cover.

High spatial variability in gravimetric moisture was observed across locations, particularly at Iyamoyong (CV = 66.37%) and Ntamante (CV = 64.92%), suggesting strong micro-scale heterogeneity in soil water retention. The anomalously low value recorded at Iyamoyong residential (2.51%) contrasts sharply with its commercial counterpart (39.15%), indicating localized compaction and surface sealing effects under residential infrastructure.

Table 7. Spatial distribution of gravimetric moisture content (%) under different land uses.

	LAND USE						
LOCATION	**Residential**	**Commercial**	**Agricultural**	**Forest**	**Mean**	**SD**	**CV**
Boje	21.13	21.40	45.06	30.23	**29.45**	**11.23**	**38.13**
Kakwagom	20.99	19.51	13.97	33.38	**21.96**	**8.19**	**37.30**
Okundi	19.42	33.27	12.98	18.54	**21.05**	**8.63**	**41.00**
Ntamante	14.62	13.00	8.76	34.65	**17.76**	**11.53**	**64.92**
Obubra	20.54	21.18	13.09	16.97	**17.95**	**3.73**	**20.78**
Owakande	20.80	15.73	15.95	23.83	**19.08**	**3.94**	**20.65**
Apiapum	18.73	11.85	11.81	15.15	**14.39**	**3.29**	**22.86**
Iyamoyong	2.51	39.15	22.42	34.30	**24.59**	**16.32**	**66.37**
Ikom	14.88	23.75	22.52	12.50	**18.41**	**5.56**	**30.20**
Nta/Nselle	28.02	10.35	14.48	17.06	**17.48**	**7.55**	**43.19**
Akparabong	14.54	13.25	13.09	18.48	**14.84**	**2.51**	**16.91**
Ofutop	14.56	10.49	5.20	23.50	**13.43**	**7.72**	**57.48**
Mean	**17.560**	**19.410**	**16.611**	**23.216**			
SD	**5.906**	**8.751**	**9.758**	**7.680**			
CV	**33.64**	**45.09**	**58.75**	**33.08**			

3.6 Available Moisture Holding Capacity

Available moisture holding capacity (AMHC) data are presented in Table 8. The highest mean AMHC was recorded under residential land use (13.064 ± 17.957%), followed by agricultural (10.051 ± 5.619%), commercial (7.942 ± 3.906%), and forest (5.642 ± 2.538%) land uses. The exceptionally high CV under residential land use (137.45%) is driven largely by the extreme outlier recorded at Iyamoyong residential (71.70%), which may reflect localized soil conditions or measurement anomaly requiring further investigation.

Excluding the Iyamoyong residential outlier, commercial soils generally showed moderate AMHC values across locations, while forest soils consistently recorded the lowest AMHC, suggesting that despite higher total moisture content, forest soils may have a narrower range of plant-available water, possibly due to tighter pore size distributions and stronger matric potentials.

Table 8. Spatial distribution of available moisture holding capacity under different land uses.

	LAND USE						
LOCATION	**Residential**	**Commercial**	**Agricultural**	**Forest**	**Mean**	**SD**	**CV**
Boje	6.20	6.20	2.03	3.30	**4.43**	**2.11**	**47.63**
Kakwagom	5.66	6.96	10.20	2.62	**6.36**	**3.14**	**49.37**
Okundi	7.20	2.96	11.31	6.38	**6.96**	**3.43**	**49.28**
Ntamate	10.69	8.10	13.82	1.84	**8.61**	**5.08**	**59.00**
Obubra	5.76	5.45	9.92	7.52	**7.16**	**2.05**	**28.63**
Owakande	4.50	8.28	7.66	5.61	**6.52**	**1.76**	**26.99**
Apiapum	5.99	13.65	12.51	8.48	**10.16**	**3.56**	**35.04**
Iyamoyong	71.70	2.30	5.28	1.90	**20.29**	**34.30**	**169.05**
Ikom	9.35	4.05	4.07	8.87	**6.59**	**2.92**	**44.31**
Nta/Nselle	3.61	14.36	8.94	5.53	**8.11**	**4.71**	**58.08**
Akparabong	10.85	12.46	9.76	6.78	**9.96**	**2.39**	**24.00**
Ofutop	15.25	10.55	25.12	8.87	**14.95**	**7.30**	**48.83**
Mean	**13.064**	**7.942**	**10.051**	**5.642**			
SD	**17.957**	**3.906**	**5.619**	**2.538**			
CV	**137.45**	**49.18**	**55.91**	**44.98**			

3.7 Volumetric Moisture Content

Volumetric moisture content values are presented in Table 9. Commercial land use recorded the highest mean volumetric moisture content (23.40 ± 6.20%), followed closely by forest (22.47 ± 5.33%), residential (22.32 ± 6.00%), and agricultural (20.50 ± 7.10%) soils. The narrow range of means across land-use types (20.50–23.40%) suggests that volumetric moisture content was less discriminating between land uses than gravimetric moisture, likely due to the compensating effect of bulk density differences in the conversion from gravimetric to volumetric basis.

The highest within-location variability was recorded at Iyamoyong (CV = 58.34%) and Ntamante (CV = 35.26%), consistent with patterns observed for other moisture-related parameters.

Table 9. Spatial distribution of volumetric moisture content (%) under different land uses.

	LAND USE						
LOCATION	**Residential**	**Commercial**	**Agricultural**	**Forest**	**Mean**	**SD**	**CV**
Boje	27.68	28.37	41.12	30.16	**31.83**	**6.28**	**19.72**
Kakwagom	24.94	26.48	19.90	29.17	**25.12**	**3.90**	**15.51**
Okundi	27.16	32.77	19.06	21.93	**25.23**	**6.04**	**23.94**
Ntamante	22.86	13.69	10.61	22.12	**17.32**	**6.11**	**35.26**
Obubra	24.31	24.44	17.01	21.66	**21.85**	**3.48**	**15.91**
Owakande	19.48	20.50	19.50	31.89	**22.84**	**6.05**	**26.49**
Apiapum	21.00	19.16	17.46	19.45	**19.27**	**1.45**	**7.53**
Iyamoyong	4.50	35.22	26.52	22.41	**22.16**	**12.93**	**58.34**
Ikom	20.70	22.85	20.63	13.86	**19.51**	**3.90**	**20.00**
Nta/Nselle	28.32	15.37	18.73	16.08	**19.63**	**5.98**	**30.44**
Akparabong	22.94	21.88	16.74	23.16	**21.18**	**3.01**	**14.22**
Ofutop	23.99	20.03	18.70	17.70	**20.11**	**2.76**	**13.72**
Mean	**22.32**	**23.40**	**20.50**	**22.47**			
SD	**6.00**	**6.20**	**7.10**	**5.33**			
CV	**26.89**	**26.52**	**34.63**	**23.73**			

3.8 Air-Filled Porosity

Air-filled porosity (f_a) data are presented in Table 10. Forest soils recorded the highest mean air-filled porosity (37.75 ± 10.26%), followed by agricultural (32.81 ± 6.52%), commercial (28.93 ± 8.28%), and residential (27.97 ± 7.73%) land uses. The greater air-filled porosity in forest soils complements the pattern observed for total porosity and is consistent with lower bulk density and higher organic matter inputs in undisturbed forest environments.

Residential soils, characterized by the highest bulk density and lowest total porosity, exhibited the lowest air-filled porosity, indicating reduced aeration capacity. This has direct implications for microbial activity, root respiration, and the decomposition of organic contaminants, including microplastics, in these soils.

Table 10. Spatial distribution of air-filled porosity (%) under different land uses.

	LAND USE						
LOCATION	**Residential**	**Commercial**	**Agricultural**	**Forest**	**Mean**	**SD**	**CV**
Boje	22.87	21.60	24.45	32.18	**25.28**	**4.75**	**18.79**
Kakwagom	30.23	22.30	26.35	37.85	**29.18**	**6.62**	**22.69**
Okundi	20.06	30.07	25.52	33.44	**27.27**	**5.80**	**21.26**
Ntamante	18.16	46.56	43.70	53.79	**40.55**	**15.52**	**38.28**
Obubra	31.02	32.02	33.98	30.18	**31.80**	**1.64**	**5.14**
Owakande	45.19	30.34	34.37	17.62	**31.88**	**11.39**	**35.72**
Apiapum	36.68	19.82	26.76	32.08	**28.84**	**7.25**	**25.13**
Iyamoyong	27.68	30.82	28.85	52.94	**35.07**	**11.98**	**34.16**
Ikom	26.80	40.85	44.81	44.28	**39.19**	**8.44**	**21.55**
Nta/Nselle	33.53	28.57	32.45	48.34	**35.72**	**8.68**	**24.29**
Akparabong	17.52	15.82	35.02	29.56	**24.48**	**9.31**	**38.04**
Ofutop	25.95	28.41	37.43	40.73	**33.13**	**7.07**	**21.34**
Mean	**27.97**	**28.93**	**32.81**	**37.75**			
SD	**7.73**	**8.28**	**6.52**	**10.26**			
CV	**27.63**	**28.60**	**19.87**	**27.18**			

3.9 Degree of Saturation

The spatial distribution of degree of saturation is presented in Table 11. Residential and commercial land uses recorded similar mean degrees of saturation (44.37 ± 12.16% and 45.32 ± 10.16%, respectively), while agricultural (38.24 ± 10.08%) and forest (38.17 ± 11.01%) soils recorded lower and comparable values. The relatively higher degree of saturation in residential and commercial soils, despite lower total porosity in these land uses, suggests that a greater proportion of the available pore space in anthropogenically disturbed soils is water-filled, possibly reflecting surface runoff infiltration and reduced drainage capacity associated with soil compaction.High within-location variability was evident at Ntamante (CV = 51.78%) and Iyamoyong (CV = 49.50%), consistent with the broad range of land-use activities and associated soil management practices within these villages.

Table 11. Spatial distribution of degree of saturation (%) under different land uses.

	LAND USE						
LOCATION	**Residential**	**Commercial**	**Agricultural**	**Forest**	**Mean**	**SD**	**CV**
Boje	54.76	56.77	62.71	48.38	**55.65**	**5.91**	**10.62**
Kakwagom	45.21	54.28	43.03	43.53	**46.51**	**5.26**	**11.31**
Okundi	57.52	52.15	42.75	39.61	**48.01**	**8.28**	**17.25**
Ntamante	55.73	22.73	19.53	29.14	**31.78**	**16.46**	**51.78**
Obubra	43.94	43.29	33.35	41.78	**40.59**	**4.91**	**12.09**
Owakande	30.12	40.32	36.20	64.42	**42.76**	**15.03**	**35.15**
Apiapum	36.41	49.15	39.48	37.75	**40.70**	**5.77**	**14.18**
Iyamoyong	13.99	53.33	47.89	29.74	**36.24**	**17.94**	**49.50**
Ikom	43.58	35.87	31.52	23.84	**33.70**	**8.25**	**24.49**
Nta/Nselle	45.79	34.97	36.60	24.97	**35.58**	**8.53**	**23.98**
Akparabong	56.70	58.03	32.34	43.93	**47.75**	**12.08**	**25.29**
Ofutop	48.69	42.96	33.49	30.91	**39.01**	**8.27**	**21.21**
Mean	**44.37**	**45.32**	**38.24**	**38.17**			
SD	**12.16**	**10.16**	**10.08**	**11.01**			
CV	**27.40**	**22.43**	**26.37**	**28.85**			

3.10 Void Ratio

Spatial distribution of void ratio is presented in Table 12. Commercial land use recorded the highest mean void ratio (22.314 ± 16.892), followed by agricultural (19.900 ± 15.283), forest (14.295 ± 10.236), and residential (11.489 ± 10.121) land uses. The exceptionally high variability across all land-use types (CV range: 71.60–88.09%) reflects the heterogeneous nature of soil pore architecture across the study area. The high void ratio under commercial land use may appear counterintuitive given its elevated bulk density relative to forest soils; however, this may reflect localized disturbances from market activities, including periodic digging, waste burial, and irregular wetting and drying cycles.

Table 12. Spatial distribution of void ratio under different land uses.

	LAND USES						
LOCATION	**Residential**	**Commercial**	**Agricultural**	**Forest**	**MEAN**	**SD**	**CV**
Boje	0.75	12.59	0.59	21.41	**8.84**	**10.09**	**114.20**
Kakwagom	0.00	22.56	34.72	7.06	**16.08**	**15.59**	**96.94**
Okundi	11.50	11.40	0.45	0.53	**5.97**	**6.33**	**105.94**
Ntamate	2.10	22.53	43.90	32.76	**25.32**	**17.77**	**70.18**
Obubra	5.23	2.59	5.79	8.45	**5.51**	**2.40**	**43.60**
Owakande	3.16	26.50	11.94	19.46	**15.26**	**10.02**	**65.68**
Apiapum	22.62	32.83	25.96	33.31	**28.68**	**5.25**	**18.32**
Iyamoyong	9.41	42.30	18.42	8.39	**19.63**	**15.77**	**80.35**
Ikom	35.16	6.55	0.09	2.12	**10.98**	**16.35**	**148.86**
Nta/Nselle	14.39	62.56	37.53	14.00	**32.12**	**23.08**	**71.87**
Akparabong	12.78	1.73	35.16	14.00	**15.92**	**13.96**	**87.73**
Ofutop	20.78	23.61	24.26	10.04	**19.67**	**6.60**	**33.53**
Mean	**11.489**	**22.314**	**19.900**	**14.295**			
SD	**10.121**	**16.892**	**15.283**	**10.236**			
CV	**88.09**	**75.70**	**76.80**	**71.60**			

4. DISCUSSION

4.1 Soil Texture and Particle Size Distribution

The predominance of sandy loam texture across the study area is consistent with the geology of Central Cross River State, particularly the sandstone-dominated formations of the Benue Trough and the weathered Precambrian basement complex of Boki LGA (Ofoegbu, 1990; 1995). The relatively low clay content across all LGAs (mean range: 12.8–15.5%) suggests moderate structural stability, though the presence of loam-textured soils at several Ikom LGA sites indicates potentially higher water and nutrient retention capacity in that sub-region.

The higher spatial variability of particle size distribution in Ikom LGA (sand CV = 23.97%; silt CV = 53.64%) compared to Boki (sand CV = 10.31%) and Obubra LGAs (sand CV =

9.53%) likely reflects the geologically diverse setting of Ikom, which encompasses both sedimentary and alluvial formations (Ofoegbu, 1990; Adebayo and Ojo, 2021). These findings are consistent with Okwakol (2019), who noted marked textural variability in Ultisol-dominated tropical soils across southeastern Nigeria.

4.2 Microplastic Distribution and Land-Use Influence

The observed clear land-use gradient in concentration of microplastics (commercial > residential > agricultural > forest) is well documented in terrestrial microplastic investigations and is directly linked to the degree of human activity and the amount of plastic waste produced (Andrady, 2011; Cozar et al., 2014). The top spots in terms of plastic packaging use and disposal are commercial markets, with the highest microplastic concentrations being detected in this sector (overall mean: 12.12 g kg^{-1}; up to 25.82 g kg^{-1} at Ikom commercial). The concentrations measured in market sites in the study area were significantly higher than background levels found in sub-Saharan agricultural soils (0.1–5.0 g kg−1, Andrady 2011), indicating the extent of plastic contamination at the markets.

The very low levels of forest microplastic deposition (overall mean: 0.995 g kg-1) is consistent with the protection that forest vegetation can provide against microplastic deposition, since the forest canopy can intercept the deposition from the atmosphere and human activity does not create direct plastic deposition in the forest. The relatively lower CoV values for residential microplastic concentrations (CV = 27.45%) than for commercial (CV = 48.07%) and forest (CV = 70.50%) sites indicate that the distribution of microplastics is more uniform in residential areas, possibly due to the uniform domestic waste management practices observed across the villages surveyed.

The particularly high microplastic concentrations at Ikom and Nta/Nselle commercial sites (247.87 kg ha^{-1} and 327.20 kg ha^{-1}, respectively) warrant special attention and may be due to the higher urbanization level and commercial activity density at Ikom LGA which provides close proximity to major road networks that promote economic activity and plastic waste transportation (NWAFOR et al., 2022; Nigerian Meteorological Agency, 2022).

4.3 Bulk Density and Porosity

The inverse relationship between bulk density and porosity observed across land-use types with residential soils recording the highest bulk density (1.317 g cm^{-3}) and lowest total porosity (50.30%), while forest soils recorded the lowest bulk density (1.054 g cm^{-3}) and highest porosity (60.22%) is consistent with well-established principles of soil physics and the documented effects of land-use change on soil structural properties (Okwakpam, 2018). Compaction under foot traffic, vehicular movement, and building foundations in residential and commercial zones reduces macroporosity and disrupts soil aggregation, leading to the elevated bulk density values recorded.

The bulk density values recorded for residential soils (mean: 1.317 g cm^{-3}) approach or exceed the commonly cited threshold of 1.4–1.6 g cm^{-3} for root growth restriction in sandy loam soils (Okwakol, 2019), with individual values at Iyamoyong residential (1.80 g cm^{-3}) and Akparabong commercial (1.65 g cm^{-3}) surpassing these thresholds. These findings suggest that soil compaction at certain residential and commercial sites in the study area may already be limiting agricultural productivity and root development.

Forest soils maintained the most favourable physical structure for plant growth and water regulation, reflecting the ongoing inputs of organic matter from leaf litter and root decomposition that improve soil aggregation and macropore connectivity (Cross River National Park, 2021). These results highlight the importance of maintaining forest cover for soil quality preservation in Central Cross River State.

4.4 Soil Moisture Parameters

The consistently higher gravimetric moisture content in forest soils (mean: 23.22%) compared to anthropogenically disturbed land uses reflects the synergistic effects of greater organic matter content, higher porosity, reduced surface evaporation under canopy shade, and lower surface runoff generation in forest environments (Eze, 2020). Conversely, agricultural soils, which are subjected to tillage and seasonal crop removal, exhibited the highest agricultural moisture variability (CV = 58.75%), reflecting the dynamic influence of crop cycles, irrigation practices, and seasonal rainfall patterns on soil water status.

The high variability in AMHC across all land-use types particularly under residential land use (CV = 137.45%) reflects the complex interaction between soil texture, organic matter content, pore size distribution, and land-use history in determining plant-available water. The anomalously high AMHC at Iyamoyong residential (71.70%) may warrant re-measurement or may reflect localized conditions such as proximity to a drainage channel or exceptional organic matter accumulation.

The air-filled porosity data (Table 10) reinforce the conclusion that forest soils maintain the most aerated pore environment (mean f_a = 37.75%), which supports aerobic microbial activity and efficient gas exchange, while residential soils exhibit the most restricted aeration (mean f_a = 27.97%). Given that microplastic degradation in soils is partly mediated by soil microbial communities, the reduced aeration in high-microplastic-load commercial and residential soils may further constrain the natural attenuation of plastic contaminants in these environments (Andrady, 2011).

4.5 Void Ratio

The high spatial variability in void ratio across all land-use types (CV range: 71.60–88.09%) reflects the complex and heterogeneous nature of soil pore architecture across the study area. The elevated mean void ratio under commercial land use (22.314) relative to residential (11.489), despite similar or higher bulk density values, suggests that pore geometry in commercial soils may be disproportionately dominated by large, irregular pores resulting from periodic mechanical disturbance, waste burial, and heterogeneous organic matter incorporation. Future studies employing soil thin sections or X-ray computed tomography would provide more definitive characterization of pore architecture across these land-use types.

5. Conclusion

This study provides the first comprehensive baseline characterization of microplastic spatial distribution and associated soil physical properties across contrasting land-use types in Central Cross River State, Nigeria. The following key conclusions are drawn:

Commercial land use is the most severely microplastic-contaminated land-use category in the study area, with mean concentrations of 12.12 g kg^{-1} (150.87 kg ha^{-1}), more than twelve times higher than forest soils (0.995 g kg^{-1}; 10.65 kg ha^{-1}), confirming market activities as primary sources of terrestrial microplastic pollution in the region.

Ikom LGA, particularly the Ikom and Nta/Nselle commercial sites, recorded the highest absolute microplastic loads in the study area, reflecting the greater urban and commercial activity density of this LGA relative to Boki and Obubra.

Forest soils consistently exhibited the most favourable physical properties for plant growth and water regulation - including the lowest bulk density, highest total and air-filled porosity, and highest gravimetric moisture content - reinforcing the critical importance of forest conservation for maintaining soil quality in this ecologically sensitive region.

Residential land use was associated with the highest soil compaction (bulk density: 1.317 g cm^{-3}) and lowest porosity (50.30%), with several individual sites recording bulk density values exceeding critical root growth restriction thresholds.

Pronounced spatial variability in both microplastic concentrations and soil physical properties was observed across all LGAs and land-use types, emphasizing the importance of site-specific soil management strategies rather than broad generalizations for land-use planning and remediation interventions.

These findings underscore the urgent need for integrated solid waste management policies, particularly targeting market areas in Ikom LGA, as well as soil conservation strategies to mitigate the progressive degradation of soil physical quality under expanding residential and commercial land uses in Central Cross River State.

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Author Contributions

All authors contributed to the conceptualization and design of the study. Field sampling and laboratory analysis were conducted by the research team. Data analysis, interpretation, and manuscript preparation were carried out collaboratively. All authors reviewed and approved the final manuscript.

Conflict of Interest

The authors declare no conflict of interest in the conduct of this study or in the preparation of this manuscript.

Acknowledgements

The authors gratefully acknowledge the support of community leaders and residents of Boje, Kakwagom, Okundi, Ntamante, Obubra, Owakande, Apiapum, Iyamoyong, Ikom, Nta/Nselle, and Akparabong, for granting access to sampling sites. The technical assistance provided by the Soil Science Laboratory, University of Calabar, is also gratefully acknowledged.

Data Availability Statement

All data generated and analyzed during this study are presented within the tables of this article. Raw data are available from the corresponding author upon reasonable request.