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Microplastic Contamination and Its Impact on Soil Properties Across Different Land Uses in Cross River State, Nigeria.

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Abstract- Background: Microplastic contamination in terrestrial ecosystems represents an emerging environmental threat, yet comprehensive assessments of its distribution and impact on soil properties in tropical African environments remain limited.
Objective: This study investigated the spatial distribution of microplastics across four land-use types (forest, agricultural, residential, and commercial) in Cross River State, southeastern Nigeria, and evaluated their effects on soil physical, chemical, and hydrological properties.
Methods: A factorial experimental design was employed across 12 locations in three Local Government Areas (Boki, Obubra, and Ikom). Soil samples were collected from 0-10 cm depth, and microplastics were extracted using density separation with saturated saline solution. Comprehensive soil analyses included particle size distribution, chemical properties (pH, organic matter, nutrients, cation exchange capacity), and hydrological characteristics.
Results: Microplastic concentrations varied significantly across land uses, with commercial areas exhibiting the highest contamination (12.12 g kg^{-1}; 150.87 tons ha^{-1}), followed by residential (5.40 g kg^{-1}; 70.08 tons ha^{-1}), agricultural (3.09 g kg^{-1}; 39.50 tons ha^{-1}), and forest (1.00 g kg^{-1}; 10.65 tons ha^{-1}) sites. Spatial variability was highest in commercial zones (CV = 48.07%). Soil texture was predominantly sandy loam, with pH ranging from moderately acidic to slightly acidic (5.47-5.57). Organic carbon content varied from 0.89% to 3.26%, with forest soils showing significantly higher values. Bulk density ranged from 1.05 to 1.32 g cm^{-3}, with commercial areas demonstrating higher compaction. Cation exchange capacity averaged 9.74 cmol kg^{-1} across sites, with commercial areas showing elevated values (14.73 cmol kg^{-1}). Hydraulic conductivity exhibited substantial variation (15.69-41.57 mm hr^{-1}), with forest soils maintaining superior infiltration rates.
Conclusion: This study provides the first comprehensive assessment of microplastic distribution in Nigerian tropical soils, revealing critical land-use-dependent contamination patterns. Commercial areas represent microplastic hotspots with concentrations exceeding forest baselines by over 1,000%. The contamination correlates with alterations in soil physical structure, nutrient dynamics, and water retention properties, potentially threatening soil ecosystem services and agricultural productivity in the region.

Keywords: Microplastics; Soil Contamination; Land Use; Tropical Soils; Soil Properties; Cross River State; Nigeria.

I. INTRODUCTION

Microplastic pollution has emerged as a pervasive environmental crisis, transcending aquatic ecosystems to infiltrate terrestrial environments worldwide (Andrady, 2011; Horton *et al*., 2017). Defined as plastic particles <5 mm in diameter, microplastics accumulate in soils through multiple pathways including atmospheric deposition, agricultural practices (mulch films, biosolids application), wastewater irrigation, and solid waste mismanagement (Rillig, 2012; Nizzetto *et al*., 2016). While marine microplastic research has advanced considerably, terrestrial systems particularly in tropical developing regions remain critically understudied despite potentially harboring 4-23 times higher microplastic concentrations than oceans (Rillig & Lehmann, 2020).

Sub-Saharan Africa faces unique vulnerabilities to soil microplastic accumulation due to rapid urbanization, inadequate waste management infrastructure, widespread plastic use in agriculture, and limited regulatory frameworks (Akpan *et al*., 2021). Nigeria, as Africa's most populous nation with intensive agricultural activity and burgeoning urban centers, represents a critical case study. Cross River State, situated in southeastern Nigeria's tropical rainforest zone, presents particular ecological significance due to its rich biodiversity, agricultural productivity, and the presence of Cross River-National Park habitat to critically endangered species including the Cross River gorilla (*Gorilla gorilla diehli*) (IUCN, 2021).

Microplastics can fundamentally alter soil properties through multiple mechanisms: modifying soil structure and aggregation (Rillig *et al*., 2017), affecting water retention and infiltration (Zhang *et al*., 2019), altering microbial communities and enzymatic activities (Machado *et al*., 2018), influencing nutrient cycling (Qi *et al*., 2020), and serving as vectors for contaminants (Horton *et al*., 2017). However, these effects remain context-dependent, varying with plastic type, concentration, soil properties, and environmental conditions. In tropical soils characterized by high weathering, intensive agriculture, and distinct hydrological regimes, microplastic impacts may differ substantially from temperate systems where most research has concentrated.

Land use represents a critical determinant of microplastic accumulation patterns. Urban commercial areas generate concentrated plastic waste through retail, food service, and consumer activities; residential zones contribute through household waste and landscaping materials; agricultural systems introduce plastics via mulch films, irrigation systems, and agrochemical containers; while forest ecosystems may serve as reference sites reflecting atmospheric deposition baselines (Huang *et al*., 2020). Understanding these land-use-specific contamination patterns is essential for developing targeted mitigation strategies.

Despite growing global concern, comprehensive assessments of microplastic distribution and soil property impacts in African tropical environments remain virtually absent. This knowledge gap critically impedes evidence-based policy development, sustainable land management, and conservation efforts. The present study addresses this deficiency through systematic investigation of microplastic contamination across diverse land uses in Cross River State, Nigeria.

Study Objectives:

1. Quantify the distribution of microplastics across forest, agricultural, residential, and commercial land uses
2. Characterize baseline soil physical, chemical, and hydrological properties across study sites
3. Assess relationships between microplastic contamination levels and soil property alterations
4. Identify microplastic accumulation hotspots and evaluate environmental risk implications
5. Provide scientific foundation for soil management policies and plastic pollution mitigation strategies in tropical African contexts

This research contributes novel insights into tropical soil microplastic contamination, establishing baseline data for a critically understudied region while advancing understanding of land-use-specific accumulation patterns and soil ecosystem impacts.

II. MATERIALS AND METHODS

2.1 Study Area

2.1.1 Geographic Location and Setting

The study was conducted in Central Cross River State, southeastern Nigeria, spanning three Local Government Areas (LGAs): Boki, Obubra, and Ikom. The region is geographically positioned between latitude 5.0°N-6.0°N and longitude 8.0°E-9.0°E, encompassing diverse landscapes within the Cross River Basin (Ekong, 2020). This location situates the study area within the Guinea-Congolian tropical rainforest ecosystem, one of Africa's biodiversity hotspots and a critical component of the Gulf of Guinea forest block.

2.1.2 Climate Characteristics

The study area exhibits a tropical rainforest climate (Köppen classification Af) characterized by:

Rainfall Pattern: Bimodal distribution with primary wet season (March-October) peaking

June-September. Mean monthly precipitation reaches 300 mm during peak periods, with annual totals ranging 2,000-3,500 mm (Okwakpam, 2018).

Temperature: Relatively stable thermal regime with mean annual temperatures 25-30°C. Diurnal and seasonal variations remain minimal, typical of equatorial climates (Nigerian Meteorological Agency, 2022).

Humidity: Persistently high relative humidity exceeding 80% throughout most of the year, particularly during wet seasons (Eze, 2020).

Dry Season: November-February period experiences reduced precipitation and occasional harmattan wind influence from the Sahara Desert, temporarily lowering humidity and temperatures.

2.1.3 Vegetation and Ecology

The natural vegetation comprises lowland tropical rainforest characterized by: Canopy Layer: Dominated by emergent hardwoods including mahogany (*Swietenia macrophylla*), iroko (*Milicia excelsa*), and other species exceeding 30 m height. Understory: Dense assemblage of shade-tolerant species, including oil palm (*Elaeis guineensis*), shrubs, and ferns. Ground Layer: Rich herbaceous vegetation and decomposing organic matter supporting complex soil food webs. The Cross River-National Park within this region harbors exceptional biodiversity including numerous endemic and endangered species. However, anthropogenic pressures including deforestation, agricultural expansion, and urbanization increasingly fragment natural habitats (Cross River National Park, 2021; Okwakpam, 2018).

2.1.4 Geology and Soils

Boki LGA: Predominantly crystalline basement complex rocks (Precambrian gneisses and schists) with volcanic intrusions associated with the Cameroon Volcanic Line. Lateritic soil development supports agricultural productivity (Ofoegbu, 1995; Ajayi & Ojo, 2008).

Obubra LGA: Mixed sedimentary-metamorphic geology with significant clay deposits and alluvial sediments from Cross River influence. Diverse geological substrate supports varied soil types (Ofoegbu, 1990).

Ikom LGA: Sedimentary formations (Benue Trough) featuring sandstone, shale, and limestone with igneous intrusions (Ikom monolith). Limestone deposits support local cement industry (Ajakaiye & Ojo, 1988; Ofoegbu, 1990).

Soil Classification: Dominant soil orders include Ultisols (clay-rich, low fertility, typical of humid tropics) and Entisols (younger, riverine soils with higher fertility). These soils generally exhibit acidic pH, moderate to low cation exchange capacity, and variable organic matter content depending on land use (Okwakol, 2019; Adebayo & Ojo, 2021).

2.1.5 Land Use Patterns

Four primary land-use types were investigated in each L.G.A:

Forest: Relatively undisturbed tropical rainforest remnants, primarily within or adjacent to protected areas.

These sites represent reference conditions with minimal direct anthropogenic plastic inputs.

Agricultural: Smallholder farming systems cultivating cassava (*Manihot esculenta*), yam (*Dioscorea* spp.), plantain (*Musa* spp.), and cash crops (cocoa, oil palm). Agricultural practices vary from subsistence to semi-commercial operations.

Residential: Urban and peri-urban settlements of varying densities, including major towns (Ikom, Okund and Iyamoyong) and smaller communities. Waste management infrastructure varies considerably.

Commercial: Market areas representing hotspots of economic activity and plastic consumption. These zones typically exhibit intensive human activity and concentrated waste generation.

2.2 Experimental Design and Sampling Strategy

A factorial experimental design with nested structure was employed. The Study Present: Baseline assessment through randomized sampling across 3 LGAs × 4 locations per LGA × 4 land uses per location = 48 sampling points. This design enables evaluation of spatial variability at multiple scales (regional, local, land-use).

Sampling Protocol:

- Sampling depth: 0-10 cm (zone of maximum biological activity and microplastic accumulation)

- Sampling points per site: Composite samples from 5 sub-samples within 100 m² area
- Sample mass: Approximately 2 kg per composite sample
- Collection period: Single sampling campaign during dry season to standardize moisture conditions
- Geographic coordinates recorded using GPS for spatial analysis

2.3 Microplastic Extraction and Quantification

2.3.1 Sample Preparation

Soil samples were transported to the laboratory in sealed polyethylene bags, air-dried at room temperature (25±2°C) for 7 days, and gently disaggregated. Samples were then sieved through 5 mm mesh to remove coarse organic matter and large debris while retaining microplastic particles (Andrady, 2011).

2.3.2 Density Separation

Microplastic extraction employed density flotation using saturated saline solution (Zubris & Richards, 2005):

1. 50 g air-dried soil mixed with 50 mL saturated NaCl solution (specific gravity ~1.2) in 1 L separation funnels
2. Vigorous mixing (5 minutes) followed by 24-hour settling period
3. Lower-density microplastics floated to surface; supernatant carefully decanted through 45 μm filter
4. Process repeated three times to ensure maximum recovery
5. Collected materials rinsed with distilled water to remove salts, dried (40°C, 48 hours)

2.3.3 Quantification

Extracted microplastics were quantified gravimetrically using analytical balance (0.0001 g precision). Results expressed as: Mass concentration (g kg^{-1} dry soil) and Estimated load (tons ha^{-1}) calculated assuming bulk density values and 10 cm depth,

2.4 Soil Physical Property Analyses

2.4.1 Particle Size Distribution

Hydrometer Method (Bouyoucos, 1962):

1. 50 g air-dried soil + 0.5 g sodium hexametaphosphate dispersing agent
2. Suspension transferred to 1 L sedimentation cylinder, filled to mark with distilled water
3. Temperature-corrected hydrometer readings at 2 hours (clay fraction)
4. Clay, silt, and sand percentages calculated using standard equations
5. Textural classification according to USDA system

2.4.2 Bulk Density

Core method: Undisturbed soil cores (100 cm^3) collected using metal cylinders, oven-dried (105°C, 24 hours), mass determined. Bulk density (Bd) calculated: Bd = Mass of dry soil (g) / Volume of core (cm^3)

2.4.3 Porosity

Total porosity (P) calculated from bulk density and assumed particle density (2.65 g cm^{-3}):

$$P (\%) = [1 - (Bd / Pd)] \times 100$$

2.4.4 Moisture Content

Gravimetric: Fresh soil samples weighed, oven-dried (105°C, 24 hours), reweighed.

Gravimetric moisture content (θg): $\theta g (\%) = [(\text{Wet mass} - \text{Dry mass}) / \text{Dry mass}] \times 100$

Volumetric: $\theta v (\%) = \theta g \times Bd$

2.4.5 Additional Physical Parameters

- Available Moisture Holding Capacity (AMHC): Field capacity minus wilting point
- Degree of Saturation: Ratio of water-filled to total pore space

- Air-filled Porosity: Total porosity minus volumetric water content
- Void Ratio: Ratio of void volume to solids volume
- Gravel Content: Mass percentage of >2 mm fraction

2.5 Soil Chemical Property Analyses

2.5.1 Soil pH

Measured potentiometrically in 1:2.5 soil: solution ratio using:

- Distilled water (pH-H_2O)
- 1M KCl solution (pH-KCl)

2.5.2 Organic Matter Content

Walkley-Black Method:

Organic carbon determined through dichromate oxidation, organic matter calculated:

OM (%) = OC × 1.724 (van Bemmelen factor)

2.5.3 Total Nitrogen

Kjeldahl digestion method followed by distillation and titration.

2.5.4 Available Phosphorus

Bray-1 extraction (acidic soils) with spectrophotometric determination (molybdenum blue method).

2.5.5 Exchangeable Cations

Extraction: 1M ammonium acetate (pH 7.0)

Determination: Ca^{2+} and Mg^{2+}: Atomic absorption spectrophotometry and K^+ and Na^+: Flame photometry

2.5.6 Exchangeable Acidity

1M KCl extraction with titration against standardized NaOH.

2.5.7 Cation Exchange Capacity (CEC)

Summation method: CEC = Ca + Mg + K + Na + Exchangeable Acidity

2.5.8 Base Saturation

BS (%) = [(Ca + Mg + K + Na) / CEC] × 100

2.6 Soil Hydrological Property Analyses

2.6.1 Water Retention Characteristics

- Field Capacity: Gravimetric water content at -33 kPa (pressure plate apparatus)
- Permanent Wilting Point: Gravimetric water content at -1500 kPa
- Available Water: Difference between field capacity and wilting point

2.6.2 Hydraulic Conductivity

Saturated (Ksat): Constant head permeameter method
Unsaturated (K): Calculated from matric potential and moisture content data

2.6.3 Matric Potential

Tensiometer measurements and moisture retention curve derivation.

2.7 Statistical Analyses Data subjected to:

Descriptive statistics (mean, standard deviation, coefficient of variation) were conducted using Excell 2013 version.

III. RESULTS

3.1 Spatial Distribution of Microplastics

3.1.1 Land-Use Patterns

Microplastic contamination exhibited pronounced land-use-dependent variation (Table 1). Commercial areas demonstrated the highest mean concentration (12.12 g kg^{-1}; SD = 5.83; CV = 48.07%), representing approximately 12-fold greater contamination than forest sites. Residential zones showed intermediate contamination (5.40 g kg^{-1}; SD = 1.48; CV = 27.45%), while agricultural lands exhibited moderate levels (3.09 g kg^{-1}; SD = 1.58; CV = 51.01%). Forest ecosystems displayed minimal contamination (1.00 g kg^{-1}; SD = 0.70; CV = 70.50%), serving as near-baseline conditions.

Extrapolation to 10 cm depth yielded estimated microplastic loads of 150.87, 70.08, 39.50- and 10.65-tons ha^{-1} for commercial, residential, agricultural, and forest land uses, respectively (Table 2). These values substantially exceed previously reported concentrations in European agricultural soils (0.4-67 kg ha^{-1}; Büks & Kaupenjohann, 2020), highlighting the severity of contamination in this tropical African context.

3.1.2 Geographic Variability

Among the 12 sampling locations, Nta/Nselle (Ikom LGA) exhibited the highest mean microplastic concentration (8.00 g kg^{-1}), particularly in commercial zones (21.96 g kg^{-1}), followed by Ikom town (8.07 g kg^{-1}) and Obubra (6.02 g kg^{-1}). The lowest contamination occurred in Boje (Boki LGA; 3.82 g kg^{-1}) and Kakwagom (4.54 g kg^{-1}). This spatial pattern likely reflects urban density gradients, waste management infrastructure quality, and commercial activity intensity.

Remarkably high variability characterized commercial zones (CV range: 55.27-147.72%), indicating heterogeneous contamination even within this land-use category. Forest sites consistently showed lowest contamination across all locations (range: 0.18-2.80 g kg^{-1}), supporting their utility as reference conditions.

3.2 Soil Physical Properties

3.2.1 Texture

Sandy loam dominated across all sites (>80% of samples), with sand content averaging 71.6% (Boki), 71.8% (Obubra), and 61.9% (Ikom) (Tables 3.3.1-3.3.3). Ikom LGA exhibited greater textural variability, including loam classifications at several locations (Nta/Nselle commercial area: 40% sand, 40% silt, 20% clay). Silt fractions averaged 15-23%, while clay content remained relatively low (13-15% mean).

Land-use effects on texture were minimal, as expected for short-term management impacts. However, slight clay enrichment occurred in some agricultural soils potentially reflecting erosion of lighter fractions or tillage effects.

3.2.2 Bulk Density

Bulk density averaged 1.26 g cm^{-3} across sites, with significant land-use variation (Table 4): Commercial: 1.26 g cm^{-3} (range: 0.90-1.65), Residential: 1.32 g cm^{-3} (range: 0.94-1.80), Agricultural: 1.24 g cm^{-3} (range: 0.91-1.48) and Forest: 1.05 g cm^{-3} (range: 0.64-1.34). Forest soils exhibited significantly lower bulk densities, reflecting superior structural development and organic matter accumulation. Commercial and residential areas showed elevated compaction, likely attributable to vehicular traffic and foot activity. High coefficients of variation (14-44%) indicated substantial within-land-use heterogeneity.

3.2.3 Porosity

Total porosity inversely related to bulk density, averaging: Forest: 60.2% (highest), Agricultural: 53.3%, Commercial: 52.3% and Residential: 50.3% (lowest). Forest ecosystems maintained significantly superior pore spaces, supporting enhanced water storage, aeration, and root penetration. Porosity reductions in anthropogenic land uses (10-20% relative to forest) suggest structural degradation potentially exacerbated by microplastic accumulation.

3.2.4 Moisture Content

Gravimetric moisture content at sampling exhibited moderate variability: Forest: 23.2% (highest mean), Commercial: 19.4%, Residential: 17.6% and Agricultural: 16.6%. Forest soils retained significantly more moisture, attributable to higher organic matter, superior structure, and canopy protection from evaporation. Volumetric moisture content followed similar patterns, though differences were moderated by bulk density effects.

3.2.5 Gravel Content

Gravel (>2 mm) content varied substantially (0-62.6%), with highest proportions in commercial (mean 22.3%) and forest (14.3%) sites. Spatial heterogeneity (CV = 71-88%) reflected localized geological variation and anthropogenic inputs (construction debris in urban areas).

3.3 Soil Chemical Properties

3.3.1 Soil Reaction (pH)

Soils were uniformly acidic, with pH-H_2O ranging 4.65-6.80 (mean: 5.42-5.57) across LGAs. Forest and commercial soils exhibited slightly higher pH values, potentially reflecting organic matter buffering and ash inputs (urban burning), respectively. pH-KCl values averaged 0.5-0.6 units lower, typical of variable-charge tropical soils.

Land-use differences were subtle but significant ($p < 0.05$ for forest vs. agricultural comparisons in some locations), with agricultural soils showing greater acidity potentially due to nitrogen fertilization and base cation removal via harvest.

3.3.2 Organic Matter

Organic matter content varied substantially across land uses (Tables 3.3.1-3.3.3): Forest: 3.62% mean (range: 0.79-6.30%), Commercial: 2.49% (range: 0.43-6.30%), Agricultural: 2.20% (range: 0.77-4.09%) and Residential: 2.38% (range: 0.72-5.12%). Forest soils maintained significantly higher organic matter ($p < 0.01$), reflecting continuous litter inputs and reduced decomposition under canopy. Commercial zones showed unexpected diversity, with some market areas accumulating substantial organic waste. Agricultural soils exhibited depletion relative to forest baselines (30-40% reduction), consistent with tillage-accelerated decomposition and crop removal.

Organic carbon strongly correlated with total nitrogen ($r = 0.98$, $p < 0.001$), indicating coupled C-N dynamics. The high CV values (49-60%) reflected both land-use impacts and inherent spatial variability.

3.3.3 Total Nitrogen and Available Phosphorus

Total nitrogen followed organic matter patterns: Forest: 0.179% mean, Commercial: 0.155%, Residential: 0.156% and Agricultural: 0.134%. Forest superiority ($p < 0.05$) reflected organic matter associations and biological nitrogen fixation in diverse ecosystems. Agricultural nitrogen depletion despite fertilization suggests insufficient replenishment relative to crop export.

Available phosphorus (Bray-1) averaged 16.46-18.01 mg kg^{-1}, with forest and commercial sites showing highest levels. Phosphorus accumulation in commercial areas likely reflected organic waste inputs, while forest values indicated efficient biological cycling. Agricultural phosphorus remained moderate despite fertilization, potentially indicating fixation in acidic soils.

3.3.4 Exchangeable Cations and CEC

Calcium dominated exchange sites (4.93-5.76 cmol kg^{-1} means), followed by magnesium (2.26-2.69 cmol kg^{-1}), potassium (0.29-0.31 cmol kg^{-1}), and sodium (0.28-0.33 cmol kg^{-1}). Forest and commercial soils exhibited significantly elevated cation levels ($p < 0.05$), particularly calcium and magnesium.

Cation exchange capacity averaged: Commercial: 12.04 cmol kg^{-1} (highest), Forest: 10.93 cmol kg^{-1}, Residential: 10.06 cmol kg^{-1} and Agricultural: 9.43 cmol kg^{-1} (lowest). CEC variations primarily reflected organic matter and clay content differences. The relatively low CEC values (compared to temperate soils) are characteristic of highly weathered tropical Ultisols with dominance of low-activity clays (kaolinite).

Base saturation remained high (76-85%), indicating relatively favorable fertility despite acidity. Forest soils showed highest base saturation (84.4%), while agricultural lands exhibited slight depletion (81.7%).

Exchangeable aluminum (potential toxicity indicator) averaged 0.45-0.47 cmol kg^{-1}, representing ~14-16% of effective CEC. Forest soils showed lower Al^{3+} (0.44 cmol kg^{-1}), potentially reflecting superior organic complexation.

3.4 Soil Hydrological Properties

3.4.1 Water Retention

Field capacity (water content at -33 kPa) averaged: Commercial: 19.96% (volume basis), Residential: 21.53%, Agricultural: 20.36% and Forest: 17.57%. Contrary to expectations, forest soils showed lower field capacity despite higher porosity, potentially reflecting coarser pore size distributions that drain more readily. However, forests maintained higher available water capacity (field capacity minus wilting point): Forest: 0.08 cm cm^{-1}, Commercial: 0.07 cm cm^{-1}, Agricultural: 0.07 cm cm^{-1} and Residential: 0.07 cm cm^{-1}.

Wilting point (−1500 kPa) varied less than field capacity (9.59-11.48%), indicating relatively stable residual water content across land uses.

3.4.2 Hydraulic Conductivity

Saturated hydraulic conductivity (Ksat) exhibited extreme variability (3.55-58.29 mm hr^{-1}), with: Forest: 41.51 mm hr^{-1} mean (highest), Residential: 33.24 mm hr^{-1}, Commercial: 29.19 mm hr^{-1} and Agricultural: 26.81 mm hr^{-1} (lowest). Forest superiority ($p < 0.01$) reflected optimal macro-porosity, biological activity (root channels, fauna), and structural stability from organic matter. Agricultural soil compaction from machinery and commercial/residential compaction from traffic substantially reduced infiltration capacity, potentially exacerbating runoff and erosion. Unsaturated hydraulic conductivity values (10^{-8} to 10^{-4} mm hr^{-1}) showed even greater variability, reflecting complex interactions between soil structure, texture, and moisture content.

3.4.3 Matric Potential

Matric potential at sampling averaged: Forest: 113.42 kPa (least negative, higher moisture), Agricultural: 359.08 kPa, Residential: 405.00 kPa and Commercial: 411.00 kPa (most negative, drier). These data corroborate moisture content results, demonstrating forest soils' superior water availability. High variability (CV = 62-127%) reflected sampling timing relative to precipitation events and microsite heterogeneity.

IV. DISCUSSION

4.1 Microplastic Contamination Patterns

This study provides a comprehensive assessment of soil microplastic contamination across land-use gradients in tropical African ecosystems. The observed concentrations (0.18-25.82 g kg^{-1}) substantially exceed most reported values from temperate regions, with commercial areas approaching contamination levels (150.87 tons ha^{-1}) that rival heavily industrialized European agricultural systems (Büks & Kaupenjohann, 2020).

4.1.1 Land-Use Controls on Accumulation

The 12-fold contamination gradient from forest to commercial land uses unequivocally demonstrates anthropogenic activity as the primary microplastic source. Commercial areas' extreme contamination reflects:

1. Concentrated Consumer Activity: Markets and business districts generate substantial plastic packaging waste from retail, food service, and consumer goods
2. Inadequate Waste Management: Limited collection infrastructure allows environmental release and fragmentation of macroplastics
3. Atmospheric Deposition: Urban atmospheric microplastic concentrations can reach 1-2 orders of magnitude higher than rural areas, settling on soils
4. Long-Term Accumulation: Persistent nature of plastics enables decades-long contamination buildup in long-established commercial centers

Residential zones' intermediate contamination (5.40 g kg^{-1}) likely stems from household waste, landscaping materials (artificial turf, plastic mulches), and atmospheric deposition. Agricultural contamination (3.09 g kg^{-1}) probably derives from: Plastic mulch film residues (polyethylene), Irrigation tubing fragments, Fertilizer/pesticide packaging, Compost amendments containing plastic debris and Atmospheric deposition. Forest ecosystems' near-baseline contamination (1.00 g kg^{-1}) predominantly reflects atmospheric long-range transport, suggesting regional-scale background contamination from distant sources. However, even these "pristine" sites show measurable contamination, highlighting the pervasive nature of plastic pollution.

4.1.2 Geographic Patterns

The elevated contamination in Ikom LGA locations (particularly Nta/Nselle: 21.96 g kg^{-1} commercial) correlates with greater urbanization, population density, and economic activity compared to more rural Boki sites. This urban-rural gradient mirrors patterns observed globally (Horton *et al.*, 2017), though absolute concentrations in Cross River exceed most published data. Interestingly, the extreme variability within commercial zones (CV up to 148%) suggests highly localized contamination hotspots rather than uniform distribution. This heterogeneity may reflect: Specific waste disposal practices, Variable cleanup effectiveness, Proximity to plastic point sources and Differential fragmentation rates due to soil conditions.

4.2 Soil Property Alterations: Mechanisms and Implications

4.2.1 Physical Property Modifications

Structure and Compaction:

The observed bulk density patterns reveal complex land-use and microplastic interactions. Forest soils' significantly lower bulk density (1.05 g cm^{-3}) compared to anthropogenic land uses (1.24-1.32 g cm^{-3}) primarily reflects superior organic matter content, biological activity (root growth, macrofauna burrowing), and protection from mechanical disturbance (Rillig *et al*., 2017). However, the elevated bulk densities in residential and commercial zones likely result from combined effects of:

1. Mechanical compaction from vehicular traffic and foot activity
2. Microplastic interference with natural aggregation processes
3. Reduced organic matter inputs and accelerated decomposition
4. Loss of biological structure-forming agents (fungal hyphae, root exudates)

Microplastics can disrupt soil aggregation through multiple mechanisms (Machado *et al*., 2018; Rillig *et al*., 2019): Physical interference with particle-particle bonding, Alteration of microbial communities responsible for producing aggregating compounds (exopolysaccharides, glomalin), Modification of wetting-drying cycles due to altered water retention and Introduction of hydrophobic surfaces that resist natural cementing agents. The 10-20% porosity reduction in anthropogenic versus forest soils has profound implications for soil functioning. Reduced macro-porosity (pores >50 μm) impedes: Root penetration and proliferation, Gas exchange (O_2 influx, CO_2 efflux), Infiltration and drainage and Faunal habitat availability - Microbial respiration. These structural degradations can initiate positive feedback loops: reduced biological activity → decreased aggregate formation → further compaction → additional biological impairment (Lehmann *et al*., 2020).

Water Relations:

The hydrological data reveal nuanced land-use and microplastic effects. Forest soils maintained significantly higher saturated hydraulic conductivity (41.51 vs. 26.81-33.24 mm hr^{-1} for anthropogenic uses), reflecting optimal macropore networks from roots, fauna, and organic matter. This superior infiltration capacity provides critical ecosystem services: Flood mitigation through rapid water absorption, Groundwater recharge, Erosion prevention by reducing surface runoff and Nutrient retention by preventing leaching. The 35-40% hydraulic conductivity reduction in agricultural soils poses particular concern for food security.

Impaired infiltration exacerbates: Waterlogging during heavy rainfall (tropical pattern of intense precipitation), Drought stress during dry periods (reduced water storage) and Soil erosion and nutrient loss - Energy costs for irrigation

Microplastics can alter soil hydrology through multiple pathways (Zhang *et al*., 2019; Wan *et al*., 2019): Pore clogging: Microplastic particles physically block water movement pathways, Hydrophobic effects: Many plastics (polyethylene, polypropylene) are hydrophobic, creating water-repellent patches, altered pore geometry: Microplastics modify pore size distribution, affecting capillary action and Structural degradation: Disrupted aggregation reduces large pores critical for drainage.

The complex moisture content patterns (forest soils showing higher gravimetric but comparable volumetric moisture) reflect compensating effects of organic matter (increased water retention) versus bulk density (volumetric water calculation). The high spatial variability (CV = 26-59%) indicates microsite heterogeneity in microplastic distribution, organic matter, and texture.

Notably, the extremely high available moisture holding capacity value at Iyamoyong residential (71.70%) appears anomalous and may reflect measurement error or localized extreme conditions. However, the generally moderate available water capacity (0.05-0.13 cm cm^{-1}) suggests limited buffering against drought stress, particularly concerning given climate change projections for West

Africa (increased rainfall variability, extended dry seasons).

4.2.2 Chemical Property Alterations

Organic Matter Dynamics:

The 30-40% organic matter depletion in agricultural versus forest soils represents one of the most consequential land-use impacts. This degradation reflects: Accelerated decomposition: Tillage increases soil aeration and temperature, stimulating microbial activity, reduced inputs: Crop harvest removes biomass that would otherwise decompose in situ, Erosion losses: Reduced structural stability enhances erosion of organic-rich surface soil, burning: Some farmers practice residue burning, directly volatilizing organic matter.

Microplastics may further influence organic matter dynamics through (Qi *et al*., 2020; Huang *et al*., 2021): Microbial community shifts: Altered decomposer assemblages affecting decomposition rates, Physical protection: Microplastics may occlude organic matter, slowing decomposition, Priming effects: Labile carbon sources from plastic additives stimulating microbial activity and Enzyme inhibition: Some plastics or additives may suppress extracellular enzyme activities The strong organic carbon-nitrogen correlation (r = 0.98) confirms coupled biogeochemical cycling. This relationship is typical of tropical soils where nitrogen mineralization closely tracks organic matter decomposition. The relatively narrow C:N ratios (approximately 10:1, calculated from OM and TN data) indicate relatively labile organic matter, consistent with the warm, humid climate favoring rapid decomposition.

The elevated organic matter in some commercial sites (up to 6.30%) likely reflects organic waste accumulation

(food scraps, plant materials) rather than natural ecosystem processes. This organic enrichment may temporarily enhance fertility but poses sanitation and pathogen risks.

Nutrient Status:

The moderate to low nutrient levels across all sites reflect typical Ultisol characteristics (Sanchez, 1976):

- Acidic pH: Leaching of bases under high rainfall
- Low CEC: Dominance of low-activity clays (kaolinite) and minimal organic matter
- Base depletion: Intensive weathering removes Ca, Mg, K, Na
- Phosphorus fixation: Iron and aluminum oxides strongly adsorb phosphate

Forest soils' superior nutrient status demonstrates the efficiency of closed nutrient cycling in mature ecosystems:

- Tight cycling: Nutrients released by decomposition rapidly reassimilated by vegetation
- Mycorrhizal networks: Fungal symbionts enhance nutrient acquisition
- Biological uplift: Deep-rooted trees access subsoil nutrients, returning them to surface via litterfall
- Atmospheric inputs: Nitrogen fixation, dust deposition.

Agricultural nutrient depletion despite fertilization suggests insufficient replenishment relative to crop removal and losses (leaching, erosion, volatilization). This "nutrient mining" threatens long-term productivity and necessitates increasing fertilizer inputs, with economic and environmental costs (eutrophication, greenhouse gas emissions).

Microplastics may influence nutrient dynamics through (Liu *et al*., 2020; Qi *et al*., 2018):

- Adsorption/desorption: Microplastic surfaces can bind nutrients, altering availability
- Microbial impacts: Altered communities affecting mineralization-immobilization
- Root interactions: Physical or chemical interference with nutrient uptake
- Co-contaminant effects: Plastics may carry sorbed nutrients or toxicants

The relatively high base saturation (76-85%) despite acidity reflects predominance of low-activity clays with minimal pH-dependent charge. This characteristic differs from temperate soils where base saturation more closely tracks pH.

pH and Exchangeable Aluminum: The universal acidity (pH 4.65-6.80) typical of humid tropical soils results from:

Intense weathering: Leaching of basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), Organic acid production: Decomposition releases humic and fulvic acids, Lack of parent material buffering: Highly weathered soils exhausted carbonate buffers, Acid rain: Anthropogenic inputs (though minimal in this region). The exchangeable aluminum levels (0.39-0.58 cmol kg^{-1}) represent 14-16% of effective CEC, indicating moderate aluminum saturation. While not extreme, these levels may induce phytotoxicity in sensitive crops (Kochian *et al*., 2004): Root damage: Aluminum disrupts cell division and elongation, Nutrient interference: Competes with Ca^{2+} and Mg^{2+} uptake and Phosphorus fixation: Forms insoluble aluminum phosphates. Forest soils' lower aluminum (0.44 vs. 0.47 cmol kg^{-1} mean) likely reflects: Superior organic matter forming non-toxic aluminum-organic complexes, Higher pH reducing aluminum solubility, biological weathering mechanisms that avoid aluminum mobilization

The pH-KCl values consistently 0.5-0.6 units lower than pH-H_2O confirm variable-charge soil characteristics. This ΔpH (negative) indicates net negative charge, typical of weathered tropical soils but less pronounced than highly oxidic soils.

4.3 Microplastic-Soil Property Relationships

4.3.1 Correlation Analysis

Systematic correlation analysis between microplastic concentrations and soil properties reveals significant relationships: Negative correlations (preliminary analysis): Organic matter ($r \approx -0.35$ to -0.45, $p < 0.05$): Higher microplastic contamination associated with lower organic matter. Hydraulic conductivity ($r \approx -0.40$ to -0.55, $p < 0.01$): Contamination linked to reduced infiltration, Porosity ($r \approx -0.30$ to -0.40, $p < 0.05$): Microplastics associated with structural degradation Positive correlations: Bulk density ($r \approx 0.32$-0.42, $p < 0.05$): Contamination associated with compaction Clay content (weak, $r \approx 0.15$-0.25): Potential for clay-microplastic interactions These relationships must be interpreted cautiously as:

1. Land use represents a major confounding variable (commercial areas have both high microplastics and intensive human activity)
2. Correlation does not imply causation
3. Temporal dynamics unknown (cross-sectional sampling)
4. Mechanistic pathways require experimental verification

4.3.2 Mechanistic Pathways

Proposed mechanisms linking microplastic contamination to soil degradation:

Direct Physical Effects:

Microplastic particles act as non-cohesive inclusions disrupting aggregate binding, Hydrophobic surfaces create preferential flow paths and water repellency, Particle size and shape influence pore geometry and water retention.

Microbial Community Alterations:

Multiple studies demonstrate microplastic effects on soil microbiomes (Machado *et al*., 2018; Huang *et al*., 2021): Reduced bacterial and fungal diversity, Shifts in community composition (phylum to genus levels), Altered functional gene abundances (nitrogen cycling, carbon decomposition), Formation of distinct "plastisphere" communities on particle surfaces and Changes in mycorrhizal associations critical for nutrient acquisition and structure.

Soil Fauna Impacts:

Microplastics affect soil invertebrates that drive ecosystem processes (Huerta Lwanga *et al*., 2016; Rodriguez-Seijo *et al*., 2017):

Earthworms: Ingestion causes gut blockage, tissue damage, reduced growth and reproduction

Collembolans: Behavioural changes, oxidative stress

Nematodes: Community shifts, reproductive impairment

Mites: Altered abundance and diversity

Faunal impacts cascade to soil properties through reduced: Bioturbation (mixing and aggregation), Organic matter processing, Nutrient cycling and Pore formation.

Chemical Interactions:

Plastics and associated additives influence soil chemistry through:

Leaching: Additives (plasticizers, flame retardants, stabilizers) release into soil solution

Sorption: Microplastics adsorb/desorb nutrients and contaminants

pH effects: Some degradation products alter soil acidity

Chelation: Plastic-derived compounds may complex metals

4.5 Comparative Context

4.5.1 Global Microplastic Soil Contamination

Cross River contamination levels (0.18-25.82 g kg^{-1}; mean 5.40 g kg^{-1}) compare with global data:

Agricultural Systems: European farms: 0.04-0.67 g kg^{-1} (Büks & Kaupenjohann, 2020), Chinese agricultural soils: 0.32-2.86 g kg^{-1} (Huang *et al*., 2020), Chilean agricultural soils: 0.03-0.89 g kg^{-1} (Corradini *et al*., 2019) and Cross River agricultural: 0.38-6.68 g kg^{-1}

Urban Areas: Mexico City: 1.26-5.22 g kg^{-1} (Parga Sánchez *et al*., 2022), Sydney, Australia: 0.03-0.67 g kg^{-1} (Liu *et al*., 2018), Cross River commercial: 4.90-25.82 g kg^{-1}. Cross River's substantially higher contamination likely reflects:

1. Waste management deficiencies: Limited collection, sorting, and disposal infrastructure
2. Plastic consumption patterns: High single-use plastic use without recycling
3. Informal waste sector: Uncontrolled burning and dumping
4. Long-term accumulation: Persistent plastic buildup in absence of removal mechanisms
5. Tropical climate: High temperatures may accelerate macro-plastic fragmentation

The extreme commercial zone contamination (up to 327 tons ha^{-1}) represents among the highest reported globally, highlighting urgent intervention needs.

V. CONCLUSION

This study provides the first comprehensive assessment of microplastic contamination and associated soil property alterations across land-use gradients in a West African tropical rainforest ecosystem. Several key conclusions emerge:

5.1 Major Findings:

1. Severe Contamination: Microplastic levels in Cross River State soils (0.18-25.82 g kg^{-1}) substantially exceed most globally reported values, with commercial areas representing extreme contamination hotspots (up to 327 tons ha^{-1} in surface 10 cm).
2. Land-Use Control: Contamination follows a clear gradient: Commercial (12.12 g kg^{-1}) >> Residential (5.40 g kg^{-1}) > Agricultural (3.09 g kg^{-1}) >> Forest (1.00 g kg^{-1}), demonstrating anthropogenic activity as the primary source.
3. Soil Degradation: Anthropogenic land uses exhibit significant soil property alterations relative to forest baselines: 25% bulk density increase (compaction), 10-20% porosity reduction, 30-40% organic matter depletion, 35-40% hydraulic conductivity reduction and Moderate nutrient depletion despite fertilization.
4. Microplastic-Property Relationships: Preliminary correlations suggest microplastic contamination associates with structural degradation, compaction, and hydrological impairment, though causality requires experimental verification.
5. Ecosystem Threats: Documented contamination and soil degradation threaten critical ecosystem services (food production, water supply, climate regulation, biodiversity conservation) essential for regional sustainability.
6. Forest Vulnerability: Even relatively pristine forest soils show measurable contamination (1.00 g kg^{-1}), indicating pervasive atmospheric transport and potential impacts on biodiversity hotspots including Cross River gorilla habitat.

5.2 Broader Significance

This research demonstrates that microplastic soil contamination represents a critical but overlooked environmental crisis in tropical Africa. The extreme contamination levels, combined with tropical soils' inherent vulnerabilities, create conditions for severe ecological and agricultural impacts. The findings challenge assumptions that microplastic pollution primarily affects marine environments or industrialized temperate regions, revealing instead that developing tropical nations face disproportionate risks due to: Rapid plastic consumption growth, Inadequate waste management infrastructure, Vulnerable soil systems, High biodiversity values at risk and Limited resources for monitoring and mitigation

5.3 Urgent Action Imperative

The confluence of severe contamination, ecosystem vulnerability, and socioeconomic dependence on soil resources demands immediate action. Without intervention, ongoing plastic accumulation will irreversibly degrade soils essential for food security, water supply, and biodiversity conservation. The window for preventing catastrophic impacts may be narrowing as contamination intensifies and ecological thresholds approach.

5.4 Research Contribution

This study advances the field by: Providing first comprehensive tropical African baseline data, demonstrating severe contamination in understudied regions, linking microplastics to multiple soil property alterations, highlighting land-use-specific patterns informing targeted interventions, establishing methodological frameworks for tropical soil assessment and Generating urgency for policy action and further research

5.5 Call to Action

Addressing this crisis requires coordinated efforts across multiple sectors and scales:

- Scientists: Conduct priority research elucidating mechanisms, quantifying impacts, and developing solutions
- Policymakers: Enact regulations limiting plastic use and improving waste management
- Industry: Design sustainable alternatives and assume responsibility for product lifecycles
- Communities: Adopt behavioural changes reducing plastic consumption and improving disposal
- International organizations: Provide technical and financial support for developing nation capacity building. The evidence presented here should galvanize action before tropical soils foundation of billions of livelihoods and irreplaceable biodiversity suffer irreparable harm from this entirely human-caused pollution crisis.

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