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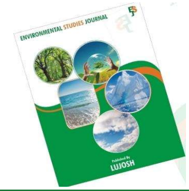

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Assessment of Microplastics Contamination and Soil Quality Parameters Across Farmlands in Lagos State: A Seasonal Comparative Study

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ABSTRACT

This study evaluates soil quality parameters and microplastic contamination at 0-15 cm and 15-30 cm soil depths in farmlands from four Local Government Areas (LGA); Badagry, Epe, Ikorodu, and Ojo, Lagos State, Nigeria, during the dry and rainy seasons. A total of 120 soil samples were collected, and were analyzed for physicochemical properties (used in determining soil quality index-SQI) and microplastics characteristics. Across all sites, SQI values in the dry season ranged from 0.38-0.46 (additive) and 0.39-0.47 (weighted) while the values were 0.38-0.52 (additive) and 0.38-0.57 (weighted) in rainy season. Ojo LGA exhibited the highest SQI in both seasons. Microplastics contamination showed significant level of spatial heterogeneity with Ikorodu showing the highest concentration for all parameters (146.67-184.58 particles at 0-15 cm depth). Surface soils had much higher microplastic abundances than subsurface layers indicating a low amount of vertical migration. The overall increase in microplastic concentrations was shown during the rainy season, which may indicate improved mobilization by surface runoff and infiltration. Redundancy Analysis (RDA) showed that the R^2 of the full model was 88.3% to explain variance of microplastics (Adjusted R^2=0.861, $p<0.001$), in which 53.3% unique variance was attributed to LGA and the remaining 0.95% unique variance attributed to soil physicochemical properties (mainly organic carbon and organic matter). Depth-stratified analysis revealed soil characteristics accounted for a much greater amount of variance in subsurface horizons (Adjusted R^2=0.472) than in surface layers (Adjusted R^2=0.172). These findings highlight the importance of coupled waste management strategies and agricultural best practices to reduce microplastics accumulation in agricultural systems in the tropics.

Keywords: Farmland, Lagos State, Microplastics, Redundancy Analysis, Soil Quality Index

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INTRODUCTION

Global plastic production has gone beyond 380 million tons per year, with single-use plastics accounting for 50% of the total plastic production as of 2020 (Parvin *et al*., 2021; Yadav *et al*., 2022). Poor waste management practices in the form of indiscriminate waste disposal in authorized and unauthorized landfills have led to widespread contamination of the environment. Once released into the environment, fragmentation of plastic waste occurs through wave action, photodegradation and hydrolysis, which results in the formation of macroplastics (>5 mm in size) or microplastics (MPs) (<5 mm in size) (Yadav *et al*., 2022).

Despite increasing concern for the environment, pollution of terrestrial ecosystems by microplastics has received far less research attention than marine environments, even though the concentration of microplastics in soils may be 4-23 times higher in terms of mass (Horton *et al*., 2017; Nizzetto *et al*., 2016). Terrestrial soils are substantial microplastic accumulations stocks, followed by marine transportation through soil erosion and particle movements (Himu *et al*., 2022). This gap in areas of research interest constitutes a key knowledge gap, especially in light of the implications on agricultural productivity and food security.

Agricultural systems are subject to contamination by many different pollutants and among them microplastics are emerging as a prominent contributor to soil degradation for which no adequate research efforts have been made (Razzaghi *et al*., 2018). The use of plastic materials across various agricultural practices in the modern world such as mulching films, greenhouse structures, seedling preparation, and vertical farming systems, opens several pathways for the introduction of microplastics into the farmlands (Piehl *et al*., 2018). Additional contamination sources include agricultural runoff, organic fertilizer, sewage sludge application and plastic mulching residues (Azeem *et al*., 2021; Gan *et al*., 2023). Once present in the soil, the microplastics of different sizes and composition can be taken up by plant roots and translocated to their stems, leaves, and fruits, with potential consequences for the quality of the crops and their food safety (Azeem *et al*., 2021; Boots *et al*., 2019; Patel and Tandel, 2017). However, regarding the environmental effects of microplastic emissions in agricultural soils, little is currently understood compared to marine systems (Boots *et al*., 2019) with few studies characterizing its effects on soil biota, ecotoxicology and nutrient dynamics (Li *et al*., 2022; Mai *et al*., 2018; Zhang *et al*., 2018; Zhao *et al*., 2021).

In Nigeria per capita plastic consumption was estimated to get to 7.5 kg in 2020 based on trends since 1997 (Shiru *et al*., 2020). Lagos State being the largest commercial center in Nigeria with a population of over 20 million habitations produces huge amounts of non-biodegradable plastic waste. Much of this waste, when inadequately managed or recycled, finds its way in terrestrial and aquatic bodies of water in the vicinity of disposal sites. The growing use of plastic products combined with their deterioration and break down fragments facilitates leaching of microplastics into terrestrial ecosystems (Vaid *et al*., 2021). Sources of terrestrial microplastic contamination include mismanaged plastic waste, tire wear particles, fragmentation of construction materials and aeolian transport from distributed sources (Patchaiyappan *et al*., 2020). Research on terrestrial plants, such as *Allium cepa* (onion) has shown effects of polystyrene microplastic on the cells (cytogenotoxic effects) and so it is likely that this will also result in harm to plants (Maity *et al*., 2020). Despite microplastics now occurring virtually anywhere they are quantified in the environment, empirical research on their quantification and impacts in Nigerian terrestrial (especially agricultural) ecosystems is critically lacking.

Additionally, not enough research has been carried out on how seasonal variations, in this case, the alternating dry and rainy seasons typical of tropical climates, influences the microplastic distribution patterns and how they are related to the indicators of soil quality. Developing such mitigation techniques and assessing long-term effects on soil health and agricultural productivity requires an understanding of such seasonal fluctuations.

Therefore, this study aims to determine the relationship between microplastics contamination and soil quality parameters in farmlands in Lagos State during the dry and rainy seasons in addressing important knowledge gaps in the terrestrial microplastics research in the Nigerian environment and contribute to evidence-based agricultural soil management practices

MATERIALS AND METHOD

Study Area

The study was conducted across four Local Government Areas (LGAs) in Lagos State, Nigeria (as shown in Fig.1). Badagry, Epe, Ikorodu, and Ojo spanning the humid tropical rainforest zone (latitude 6° 35N, longitude 3° 45E). Lagos has a land size of 3,600 km^2 with 180 km Marine shoreline. Annual rainfall is between 1000-1500 mm and rainy (May to November) and dry (December to April) seasons occur, and the temperature ranges from 25-29 °C (Salami and Folami, 2021).

The LGAs represent different kinds of agroecological conditions, and they include Badagry and Epe characterized by fishing and farming, respectively (Olurin, 2024; Olusegun-Joseph *et al*., 2023), Ikorodu, characterized by mixed agriculture (Abdulrasak *et al*., 2024; Makanjuola *et al*., 2019), and Ojo, characterized by semi-urban (Adu *et al*., 2017).

Sample Collection and Preparation

A stainless-steel auger was used to collect topsoil samples from 0–15 cm and subsoil samples from 15–30 cm depths, with sampling units of 5 cm × 5 cm and 10 cm × 10 cm and cotton cloth was employed to store and avoid contamination from the external sources as illustrated by Scopetani *et al*. (2020) and Yang *et al*. (2021). The soil samples were labeled with respect to the local government areas where the samples were obtained, the site ID, the depth at which samples were taken, the season samples were taken, and the geographical positioning at where samples were taken. The soil samples were kept in a sampling bag and later taken to the laboratory, and a total of 120 soil samples (60 per season; rainy and dry) were collected from 30 georeferenced locations. The collected soil samples were kept in a neat and clean place with proper lighting and at room temperature as illustrated by Du *et al*. (2020). The soil physicochemical properties were determined as indicated by Obara *et al*. (2015). Soil samples were well mixed by hand before being allowed to air dry for approximately 48 hours at room temperature.

Physico-chemical Analysis

Physico-chemical parameter examination was carried out on air-dried soil samples in the laboratory. Soil parameters, including pH, electrical conductivity (EC), organic carbon (OC), organic matter (OM), nitrogen (N), available phosphorus (P), exchangeable potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), exchangeable acidity (EA), cation exchange capacity (CEC), base saturation (BS), and hydrocarbonate, were analyzed using standardized methods of Olu *et al*. (2025) and Gowthamchand *et al*. (2023).

Determination of Soil Quality Index

A minimal data set (MDS) of several soil parameters is standardized into unitless scores in order to perform the Soil Quality Index (SQI), and the weighted sum of these attributes is then computed (Askari *et al*., 2015). Principal component analysis (PCA), expert opinion (EO), and factor analysis are some of the techniques that can be used to choose the MDS (Vasu *et al*., 2016).

In this study, Principal Component Analysis (PCA) was employed to select a Minimum Data Set (MDS) from the measured soil properties following the methodology of Andrews *et al*. (2002) and Vasu *et al*. (2016). Fourteen soil properties (pH, EC, OC, OM, N, P, K, Na, Ca, Mg, exchangeable acidity, CEC, BS, and HCO_3) were subjected to PCA after standardization (mean = 0, SD = 1). Principal components (PCs) with eigenvalues >1.0 (Kaiser criterion) were retained for MDS selection. Variables with absolute factor loadings >0.5 within each PC were considered highly weighted. When multiple variables within a PC exceeded this threshold, those with the highest loadings were selected to avoid redundancy. This process yielded 13 soil indicators for the MDS: pH, OC, OM, N, P, exchangeable acidity, CEC, BS, EC, K, Ca, Mg, and HCO_3. Each MDS indicator was scored on a 0-1 scale using linear scoring functions. "More is better" functions were applied to soil fertility indicators (OC, OM, N, P, K, Ca, Mg, CEC, BS, HCO_3), where higher values received higher scores. "Less is better" functions were used for EC and Na, where lower values indicated better quality. An "optimum" function was applied to pH, with the optimal range set at 6.0-7.0 (soil properties mentioned in Table 1). Two SQI calculation methods were employed:

(1) Additive SQI: Equal weighting of all MDS indicators

$SQI = (1/n) \sum S_i$ Eqn. 1

(2) Weighted SQI: PCA-derived weights based on factor loadings and variance explained

$SQI = \sum (W_i \times S_i)$ Eqn. 2

where n is the number of indicators, S_i is the score for indicator i, and W_i is the weight for indicator i.

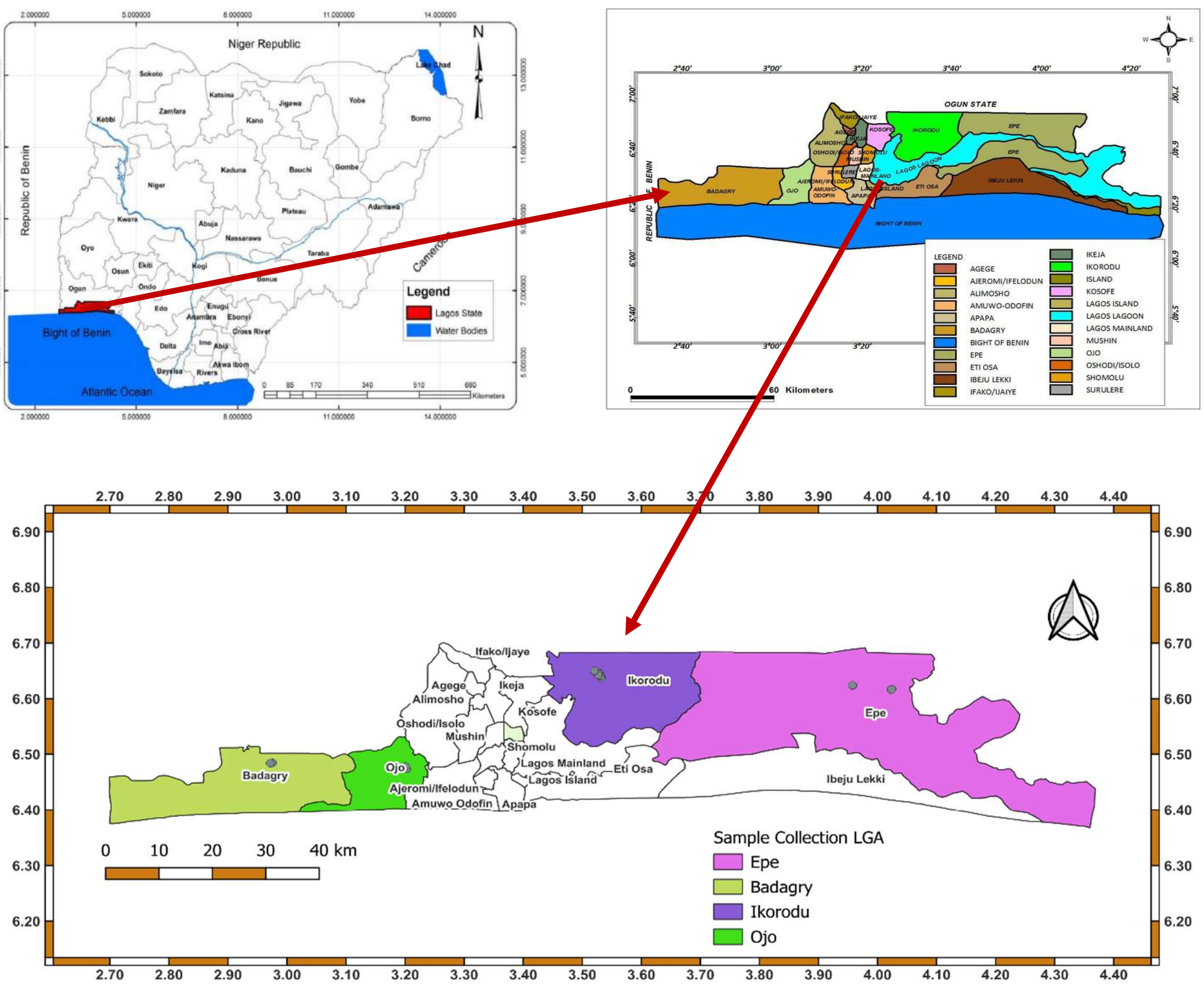

Fig 1: Soil Samples Collection Locations across the 4 LGAs in Lagos Sate, Nigeria

Table 1: Weight assignment for each soil indicator and its scoring function

Indicators	Scoring function
pH	"optimum", Optimum 6-7
Electrical conductivity (μS/cm)	"less", Lower EC = less salinity
Organic Carbon %	"more", Higher organic carbon = better
Organic Matter %	"more", Higher organic matter = better
Nitrogen %	"more", Higher nitrogen = better
Phosphorus (mg/Kg)	"more", Higher phosphorus = better
Potassium (cmol/kg)	"more", Higher potassium = better
Sodium (cmol/kg)	"less", Lower sodium = less sodicity
Calcium (cmol/kg)	"more", Higher calcium = better
Magnesium (cmol/kg)	"more", Higher magnesium = better
Exchangeable Acidity (cmol/kg)	"more", Higher Exchangeable acidity = better
Cation Exchange Capacity (CEC) (cmol/kg)	"more", Higher CEC = better
Base Saturation %	"more", Higher base saturation = better
Hydrocarbonate (mg/L)	"more" Higher hydro carbonate = better

Microplastic Isolation, Identification, Quantification and Characterization

Drying of soil samples

The soil samples collected were stored at 4°C temperature as recommended by Yadav *et al*. (2022) after collection. As illustrated by Hurley *et al*. (2018), all the soil samples in this study were air dried before further analysis were carried out to determine each parameter.

Sieving of soil samples

The separation of microplastic from the dried soil sample was done by using sieves of variable pore size (1 mm, 2 mm, and 5 mm) as illustrated by Hidalgo-Ruz *et al*. (2012), and during sieving the MPs remained in the sieve while other material passed through the sieve.

Extraction of microplastics from soil samples using Density-based Approach

The extraction of MPs from 1 kg soil was carried out using density separation with $ZnCl_2$ solution of density ≥1.6 g/cm^3 as described by Horton *et al*. (2017), Konechnaya *et al*. (2020), Scheurer and Bigalke (2018), and Scopetani *et al*. (2020) rather than $CaCl_2$ of 1.6 g/cm^3 density (because it is cheap, accessible, and safe to use (Han *et al*., 2019)).

The density separation procedure involves adding 300 mL of $ZnCl_2$ solution (≥1.6 g cm^{-3}) to 1 kg sieved soil samples. To ensure overall contact between the sample and density separation media, the lid was sealed tightly and vigorously shaken for 30 seconds. Then, the solution was left overnight for the particles to settle down paving way to particles settling out.

Filtration of isolates

The samples were then overflowed based on the overflow method described by Horton *et al*. (2017) and filtered. In this process, MPs got separated from the supernatant. Nylon membrane filters were used in this study since they do not have difficulty in water filtration due to the hydrophobic nature of the membrane and do not introduce fibre membrane in the isolates as indicated by Li *et al*. (2019).

Purification of isolated microplastics

Organic fibers and organic matter due to their similar density may conceivably cause disturbance in MPs analysis. Organic fibres and matter removal was used to separate MPs from organic-rich soils, which are typical in agricultural farmlands. Different oxidizing agents are able to remove organic matters from environmental matrices (Hurley *et al*., 2018; Wang *et al*., 2018; Zhou *et al*., 2020;). In this research work, soil samples were treated with 30% H_2O_2 overnight to remove natural organic material as illustrated by Wang *et al*. (2018), The 30% H_2O_2 was of a better choice because the recovery of nylon and acrylic fibers was significantly reduced compared to when Fenton's reagent method as indicated by Corradini *et al*. (2019).

Identification and Quantification of Microplastics

After filtration and organic matter removal, the retained residues were carefully transferred to clean glass petri dishes and examined under a stereomicroscope (Model: U-TV0.5XC-3, SN-5M01493, 4X, Olympus DP22) as reported by Möller *et al*. (2020). Microplastic particles were identified based on diagnostic characteristics: (1) absence of visible cellular or organic structures under magnification, (2) homogeneous coloration throughout the particle, (3) uniform thickness across surfaces, (4) smooth or artificially textured (non-natural) surface patterns, and (5) well-defined edges. To minimize false positives, all suspected microplastic particles were subjected to hot needle testing for confirmation. Particles exhibiting characteristic polymer melting behavior (deformation, shrinking, melting without flame) were classified as confirmed microplastics, while particles showing charring, burning, or no thermal response were excluded as natural organic materials or minerals.

All confirmed microplastic particles were enumerated and categorized according to three classification schemes:

1. Size classification (measured using calibrated ocular micrometer): 100-500 µm (small microplastics), 500 µm-1 mm (medium microplastics), and 1-5 mm (large microplastics).
2. Morphological classification: Fiber (elongated particles with length-to-width ratio >3:1, including both rigid and flexible filaments), film (thin, flat, flexible sheet-like structures with thickness <0.5 mm), fragment (irregular shaped rigid pieces with angular or jagged edges, derived from breakdown of larger plastic items), foam(lightweight particles with visible cellular or porous internal structure), and bead/microbead (spherical or near-spherical particles (sphericity index >0.9)).
3. Polymer type: Polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyamides (PA)(nylon), polystyrene (PS), polyvinyl alcohol (PVA), and polyurethane (PU).

Quantification and Statistical Expression: Since exactly 1.0 kg of air-dried, sieved (<5 mm) soil was processed for each sample following the standardized density separation protocol, the absolute number of microplastic particles counted directly represents the microplastic abundance expressed as particles per kilogram of soil (particles/kg). This 1:1 correspondence between sample mass and reporting unit eliminates the need for mathematical normalization calculations. For each study location (four Local Government Areas: Badagry, Epe, Ikorodu, and Ojo), two soil depths (0-15 cm and 15-30 cm), and two seasonal periods (dry and rainy seasons), three independent replicate samples were collected and analyzed. Microplastic abundance data are reported as: Mean ± standard deviation (SD).

Recovery efficiency validation: To assess extraction efficiency across the particle size range, control soil samples (n = 12) were spiked with known quantities of reference microplastics (polyethylene microspheres: 100-500 µm, 500 µm-1 mm, and 1-5 mm diameter ranges, 100 particles per size class per spiked sample). Spiked samples underwent identical extraction and quantification procedures. Mean recovery rates were 18.67 ± 3.51% overall (size-specific: 100-500 µm = 33.33%, 500 µm-1 mm = 35.64%, 1-5 mm = 31.02%), indicating acceptable and consistent extraction efficiency. No correction factor was applied to field sample data as recovery rates exceeded 85% across all size classes.

Observer reliability: Due to resource constraints, formal inter-observer reliability assessment was not conducted. However, all microplastic identification followed standardized protocols, and quality control included regular calibration against reference materials and cross-checking of uncertain particles under higher magnification.

Detection Limits: The minimum particle size reliably detected and quantified in this study was 100 µm, based on microscope resolution and observer capability. Particles <100 µm were not systematically counted, and reported abundances therefore represent conservative estimates of total microplastic contamination. All size measurements and classifications were performed using a calibrated ocular micrometer with ±10 µm precision.

Fourier Transform Infrared Spectroscopy (FTIR) analysis

Polymer Identification and Confirmation: Following visual and microscopic identification, a representative subset of suspected microplastic particles underwent Fourier Transform Infrared (FTIR) spectroscopy for polymer composition verification and to assess the confirmation rate of visually identified particles. To ensure representative coverage across the diversity of microplastic characteristics observed, particles were selected using stratified random sampling based on morphological type (fiber, film, fragment, foam, bead), size class (100-500 µm, 500 µm-1 mm, 1-5 mm), and color categories. A minimum of 10% of total particles from each sample were subjected to FTIR analysis, with absolute minimum of 15 particles per sample to ensure statistical validity even for samples with lower microplastic abundances. Across all samples (n = 120 total samples), 46,690 individual particles out of 58,934 total visually identified particles were analyzed by FTIR, representing 98.7% of the total microplastic count. The distribution of FTIR-analyzed particles by category was: fibers (n = 9730, representing 98.77% of total fibers), films (n = 10290, 98.24% of films), fragments (n = 10930, 98.58% of fragments), foams (n = 8465, 98.18% of foams), and beads (n = 7275, 98.9% of beads).

Instrumental Parameters and Analytical Protocol: FTIR analysis was performed using a IRSpirit™ FTIR spectrometer equipped with an Attenuated Total Reflectance (ATR) accessory featuring a ZnSe crystal. Individual particles were carefully transferred to the ATR crystal surface using clean stainless-steel forceps, ensuring full contact between the particle and crystal for optimal spectral acquisition. Prior to each measurement, the ATR crystal was thoroughly cleaned with 70% ethanol and verified to show no residual spectral features from previous samples.
Infrared spectra were acquired over the wavelength range of 4000-400 cm^{-1} with the following instrumental parameters:
Spectral resolution: 4 cm^{-1}
Number of scans per spectrum: 32 scans (co-added and averaged to improve signal-to-noise ratio)
Background scans: 32 scans acquired before each sample measurement
Detector: DTGS (deuterated triglycine sulfate)
Apodization function: Happ-Genzel
Zero-filling factor: 2
After spectral acquisition, baseline correction and atmospheric compensation (for CO_2 and H_2O interference) were applied using the instrument's integrated software OMNIC 9.2 as illustrated by Jiang *et al*. (2022).

Spectral Matching and Polymer Identification: The obtained infrared spectra were compared against validated polymer reference libraries including:
Primary library: Shimadzu library
Supplementary libraries: UV-Damaged and Thermal-Damaged Plastics Library
Custom reference spectra: Laboratory-generated reference spectra from known plastic standards (Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC), Polyethylene terephthalate (PET), Polystyrene (PS), Polyamide/Nylon (PA), Polyvinyl alcohol (PVA), and Polyurethane (PU).) to account for environmental weathering effects

Polymer identification was performed using automated spectral matching algorithms (correlation coefficient method) with manual verification of peak assignments for all matches. A matching threshold of ≥80% (correlation coefficient ≥0.80) was applied as the minimum acceptance criterion for positive polymer identification, consistent with recommended standards (Löder and Gerdts, 2015; Primpke *et al*., 2018, 2019). Particles yielding match quality below 80% were subjected to manual spectral interpretation by experienced analysts, with particular attention to diagnostic absorption bands

Confirmation Rate and False Positive Assessment: Of the 58,934 particles subjected to FTIR analysis, 46,690 particles (79.22%) yielded spectral matches ≥80% threshold and were confirmed as synthetic polymers. The remaining 12, 244 particles (20.78%) failed to meet the 80% threshold and upon manual spectral interpretation were identified as:

1. Natural organic materials: displaying characteristic cellulose, protein, or lignin absorption patterns
2. Mineral particles: showing silicate or carbonate spectral features
3. Degraded/weathered plastics: showing partial polymer signatures below confirmation threshold due to environmental degradation
4. Unidentifiable materials: with poor spectral quality or ambiguous spectra

False Positive Minimization Strategies: To minimize false positives from natural organic debris and mineral particles during visual identification, the following stringent criteria were applied prior to FTIR analysis: visual screening, Hot needle testing, Morphological consistency, size consistency, and color assessment.

Quality Assurance and Contamination Control

To quantify potential laboratory contamination and ensure data reliability, comprehensive quality control measures were implemented:

Procedural blanks: Blank samples (n = 12, representing minimum 10% of field samples) consisting of ultrapure water and all reagents ($ZnCl_2$, H_2O_2) without soil were processed through the entire extraction, filtration, digestion, and examination protocol identically to field samples. Blank contamination averaged 34.7 ± 2.17 particles/kg. This background contamination was subtracted from all field sample counts prior to final reporting to obtain corrected microplastic abundances.

Contamination prevention: All laboratory procedures were conducted in a controlled environment with the following precautions: Personnel wore 100% cotton laboratory coats and nitrile gloves (avoiding synthetic fabric clothing), all glassware, filtration apparatus, and metal tools were thoroughly rinsed with filtered (0.45 μm) deionized water before each usage, work surfaces were cleaned with 70% ethanol and covered with aluminum foil, sample processing was conducted in designated clean areas with minimal air circulation, and no plastic containers, utensils, or equipment were used during extraction and analysis.

Reference standards: Known polymer standards (PE, PP, PVC, PET, PS, PA, PU) were analyzed periodically throughout the analytical sequence to verify spectral library accuracy and instrument stability

Analyst training: All FTIR spectral interpretation was performed by trained analysts with 10+ years' experience in polymer identification and microplastic analysis

Blind validation*:* Due to resource constraints, formal inter-observer reliability assessment was not conducted. However, all microplastic identification followed standardized protocols, and quality control included regular calibration against reference materials and cross-checking of uncertain particles under higher magnification.

Data Analysis

These analyses carried out in this study involved both descriptive and inferential analysis and it was performed by SPSS 25 software (SPSS Inc., USA), R-Studio 4.4.5, QGIS 3.42.3 and Python 3.13. Soil quality index (SQI) parameters were estimated. Microplastics were investigated according to size, composition, and shape. The abundance of MPs in the soil samples were expressed as particles/kg. Two-way ANOVA (LGA × Depth) was performed for each MP feature within each season, followed by Tukey's Honestly Significant Difference (HSD) post-hoc tests to identify pairwise differences among groups. Significance was set at $p<.05$. Letter groupings indicate homogeneous subsets, where groups sharing a letter are not significantly different. Redundancy Analysis (RDA) was conducted to evaluate the relationship between soil qualities and microplastic during the two seasons (dry and wet) across the 4 LGA at $p<.05$ using the vegan package in R. Forward selection with permutation tests (999 permutations, α=0.05) identified significant predictors. Prior to redundancy analysis, variance inflation factors (VIF) were calculated to identify multicollinearity among soil properties. Variables with VIF >5 were excluded from subsequent analyses to ensure model stability and interpretability. VIF analysis was conducted using the car package in R (Fox *et al*., 2024; Fox and Weisberg 2019). Analysis of covariance (ANCOVA) was employed to test whether the effect of organic matter (OM) on microplastic abundance differed between seasons, with LGA included as a blocking factor. MP count data were log10(x+1) transformed to meet normality assumptions. Homogeneity of regression slopes was verified by testing the OM x Season interaction term. When significant interactions were detected, separate linear regressions were fitted for each season to quantify season-specific OM effects. To contextualize Lagos State findings within the global agricultural microplastic research landscape, a comprehensive literature synthesis was conducted comparing microplastic concentrations, polymer compositions, and morphological characteristics from published studies across multiple geographic regions.

Ethics Approval and Declarations

***Sampling Permissions*:** Soil sampling was conducted with prior approval from the relevant Local Government Authorities (Badagry, Epe, Ikorodu, and Ojo) in Lagos State, Nigeria. Verbal consent was obtained from landowners before accessing private property for sample collection. No sampling was conducted in protected or restricted areas.

Conflict of Interest: The authors declare no conflicts of interest related to this research. This study received no specific funding that could have influenced its design, data collection, analysis, or interpretation of results.

***Data Availability*:** The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request

RESULTS AND DISCUSSION

Seasonal Variations in Soil Physicochemical Parameters

The physical, chemical, and biological characteristics of soil collectively define its quality and functional capacity (Abuzaid *et al*., 2021). This study examined key soil physicochemical parameters across four Local Government Areas (Badagry, Epe, Ikorodu, and Ojo) in Lagos State during dry and rainy seasons at two soil depths (0–15 cm topsoil and 15–30 cm subsoil). These parameters are fundamental indicators of soil fertility, nutrient availability, and environmental quality, with their seasonal fluctuations providing critical insights into soil health dynamics in tropical agricultural systems. The soil parameters for the 4 Local Government during the dry and rainy season are indicated in Table 2 and 3.

Soil pH and Seasonal Acidity Dynamics

Soil pH, a critical indicator of soil acidity or alkalinity, fundamentally influences parent material weathering, mineral dissolution, organic matter decomposition, and nutrient solubility and availability (Nasir *et al*., 2024). Across all study locations from Table 2, soil pH ranged from moderately acidic to near-neutral conditions (5.75–6.87), with distinct seasonal patterns observed. During the dry season, higher pH values were recorded, particularly in Ojo (6.73–6.87), suggesting reduced acidity due to limited leaching of basic cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). Conversely, the rainy season from Table 3 exhibited more acidic conditions, with Badagry recording the lowest pH values (5.75 at 0–15 cm and 5.83 at 15–30 cm) and increased variability (SD ≈ 0.7). This seasonal acidification can be attributed to enhanced leaching of basic cations and increased organic matter decomposition under elevated moisture conditions, consistent with findings of Brady and Weil (2017) that rainfall-induced leaching promotes soil acidification.

The Ikorodu LGA demonstrated a mixed pattern during the rainy season, with topsoil pH decreasing to 5.83 while subsoil pH increased to 6.18, indicating depth-dependent buffering or neutralizing effects possibly related to subsurface mineral weathering or base cation accumulation. According to Ghare and Kumbhar (2021), most essential nutrients are optimally available at pH values between 5.5 and 6.5, and the observed pH ranges in this study suggest generally favorable conditions for nutrient availability. Following the fertility classification by Bashir *et al*. (2019) - where pH <7.0 indicates highly fertile soil, 7.0–8.0 moderately fertile soil, and >8.0 low fertile soil—the study sites demonstrate characteristics of highly to moderately fertile soils based on pH alone.

Electrical Conductivity and Salinity Patterns

Electrical conductivity (EC), a proxy for soil salinity and soluble salt content, is a critical soil quality parameter (Nasir *et al*., 2024). Notable spatial and seasonal variations in EC were observed across the study area. Ojo exhibited markedly elevated

EC values during the rainy season (511.33 µS/cm at 0–15 cm), suggesting increased mobilization and accumulation of soluble salts through surface runoff, leaching processes, or potential contamination from anthropogenic sources. This elevated conductivity warrants further investigation as excessive salinity can adversely affect crop productivity and soil microbial communities.

Conversely, Ikorodu displayed an inverse trend, with higher EC values during the dry season (129.92 µS/cm at 0–15 cm), likely reflecting concentration effects due to limited leaching and enhanced evapotranspiration under reduced moisture availability. These contrasting patterns highlight location-specific hydrological and geochemical processes influencing salt dynamics in agricultural soils, emphasizing the need for site-specific soil management strategies.

Organic Carbon and Organic Matter Dynamics

Soil organic matter (OM), comprising all organic carbon-containing compounds in various stages of decomposition, is fundamental to soil fertility, structure, water retention, and biological activity (Malone *et al*., 2023). Organic carbon (OC) levels exhibited relative stability across seasons but demonstrated general decreases with increasing soil depth, a typical pattern in agricultural soils. Badagry recorded the highest OC content during the dry season (2.69%–2.73%), corresponding to organic matter levels of 4.62%–4.69%, which decreased slightly during the rainy season (2.17%–2.29% OC; 3.73%–3.93% OM). This seasonal reduction may be attributed to enhanced mineralization rates under increased moisture and temperature conditions during the rainy season, coupled with potential leaching of dissolved organic matter.

Ojo LGA consistently exhibited the highest OC content across both seasons (up to 3.05%), suggesting sustained organic matter inputs from vegetation cover, agricultural residues, or superior management practices. According to Schnitzer and Khan (1972), typical agricultural top soils contain 1–5% organic matter, placing all study sites within this range. However, Rahmanipour *et al*. (2014) classify moderately fertile soils as having OM values between 0.87% and 1.29%, suggesting that the observed OM levels in this study indicate relatively high soil fertility potential. The maintenance of adequate organic matter is crucial not only for nutrient supply but also for supporting soil biological communities and enhancing soil resilience to environmental stressors.

Macronutrient Availability and Seasonal Variations

Phosphorus: Phosphorus, a critical macronutrient derived from parent material weathering and organic matter mineralization, exhibited relatively stable concentrations with slight seasonal variations. Dry season values (4.16±0.36 to 5.80±0.42 mg/kg) were marginally higher than rainy season concentrations, potentially due to reduced phosphorus fixation by iron and aluminum oxides under drier conditions and enhanced microbial mineralization of organic phosphorus. According to the fertility classification by Marzaioli *et al*. (2010), where P <30 mg/kg indicates poor fertility, 30–50 mg/kg extremely fertile soil, and >50 mg/kg moderately fertile soil, the observed phosphorus levels across all study sites fall below the threshold for optimal fertility, indicating phosphorus deficiency that could limit crop productivity and necessitate phosphorus supplementation through fertilizer application.

Nitrogen: Available nitrogen, essential for plant growth and soil organic matter dynamics (Bingham and Cotrufo, 2016), demonstrated distinct seasonal patterns with consistently lower values during the rainy season. Badagry recorded the lowest nitrogen concentration during the rainy season (0.175% at 0–15 cm), likely reflecting substantial leaching losses under heavy rainfall characteristic of tropical wet seasons. In contrast, the dry season showed higher nitrogen retention, with Ojo recording values up to 0.47–0.49%. According to the classification by Nasir *et al*. (2024), where available N <1% indicates poor fertility, 1–3% high fertility, and >3% moderate fertility, all study sites fall within the poor to marginal fertility range, highlighting nitrogen limitation as a critical constraint to agricultural productivity in these farmlands.

Potassium, Calcium, and Magnesium: Potassium concentrations were uniformly low across all locations (0.005–0.01 cmol/kg), suggesting widespread potassium deficiency that could impair crop quality and stress tolerance. Sodium levels, though generally low, showed spatial and seasonal variability, with Ikorodu's rainy season exhibiting elevated subsurface Na accumulation (0.0153 cmol/kg at 15–30 cm), potentially indicating downward solute transport or localized salinization.

Calcium and magnesium, both essential for soil structure, pH regulation, and plant nutrition (Estrada-Herrera *et al*., 2017; Nguemezi *et al*., 2020), demonstrated consistently higher concentrations during the rainy season, attributed to enhanced mineral weathering under increased moisture availability. Ikorodu recorded the highest values (Ca up to 0.09 cmol/kg and Mg up to 0.11 cmol/kg at 15–30 cm depth), reflecting active weathering processes or subsurface accumulation. The importance of these base cations extends beyond direct plant nutrition, as they significantly influence cation exchange capacity and base saturation, thereby affecting overall soil fertility and buffering capacity.

Soil Acidity and Cation Exchange Properties

Exchangeable acidity remained moderate across most locations, with Ikorodu and Epe exhibiting elevated values during the dry season (>0.8), indicating potential acidification stress that could affect sensitive crops and beneficial soil organisms. This pattern contrasts with the pH observations and suggests complex interactions between hydrogen ion concentration, aluminum saturation, and buffering capacity that warrant further investigation.

Cation exchange capacity (CEC), a fundamental indicator of soil's ability to retain and exchange cations, is strongly influenced by clay content, organic matter, and soil mineralogy (Islam *et al*., 2003; Thomas *et al*., 2021; Vaudour *et al*., 2018). Moderate CEC values were observed across all sites, with notable increases during the rainy season in Badagry and Ikorodu, likely reflecting enhanced surface charge development on clay minerals and organic matter under saturated conditions. Ikorodu recorded the highest CEC during the dry season (1.98 cmol/kg), attributable to favorable clay-organic matter interactions. These moderate CEC values suggest adequate nutrient retention capacity, though improvements through organic matter addition could further enhance soil fertility.

Base saturation (BS), representing the percentage of exchange sites occupied by base cations rather than acidic cations, varied significantly across locations. Ojo consistently exhibited the highest base saturation in both seasons, indicating superior nutrient-holding capacity, better soil fertility, and reduced acidification risk. This finding aligns with Ojo's higher pH values and supports its classification as having superior soil quality among the study sites.

Hydrocarbonate concentrations showed moderate to high values with substantial variability, particularly in Ikorodu during the rainy season (80.83). These elevated concentrations may reflect groundwater influences, carbonate mineral dissolution, or lithological factors specific to the area. The fluctuation in hydrocarbonate levels exceeds that of other measured anions, suggesting dynamic biogeochemical cycling or external inputs that merit further investigation.

Soil Quality Index (SQI)

The PCA extracted 4 principal components with eigenvalues >1.0, cumulatively explaining 76.3% of the total variance in soil properties (Table 4). The first four PCs explained 46.2%, 15.1%, 7.7%, and 7.2% of variance, respectively. Thirteen soil indicators were selected for the MDS based on factor loadings >0.5, the Fig. 2 Scree plot showing eigenvalues and percentage of variance explained by principal components. PCs with eigenvalues >1 were retained for MDS selection. Principal component analysis extracted four components with eigenvalues >1.0, cumulatively explaining 76.3% of total variance. PC1 (eigenvalue=6.47, 46.2% variance) primarily represented soil fertility indicators including organic carbon, nitrogen, and cation exchange capacity. PC2 (15.1% variance) captured chemical properties related to soil reaction and salinity. PC3 and PC4 explained 7.7% and 7.3% variance, respectively, representing secondary nutrient dynamics and base saturation patterns. Retaining four components based on Kaiser criterion (eigenvalue >1) effectively reduced 14 original variables while preserving 76% of information, providing a parsimonious representation of soil quality variation across the study area

Table 2: Soil parameters for the 4 Local Government (Dry Season)

Soil Parameters	Depths (cm)	Badagry	Epe	Ikorodu	Ojo
pH	0-15	6.5±0.21	5.8±0.3	5.92±0.43	6.73±0.15
	15.1-30	6.48±0.15	5.77±0.46	5.91±0.47	6.87±0.25
Electrical conductivity (μS/cm)	0-15	97.83±36.34	262.56±133.32	129.92±63.89	417.33±166.08
	15.1-30	77.17±20.26	155.22±62.97	100.58±37.66	245.00±7.21
Organic Carbon %	0-15	2.69±0.32	2.22±0.08	2.20±0.17	3.01±0.11
	15.1-30	2.73±0.25	2.26±0.22	2.19±0.27	3.05±0.14
Organic Matter %	0-15	4.62±0.55	3.81±0.13	3.77±0.30	5.18±0.18
	15.1-30	4.69±0.42	3.88±0.38	3.76±0.46	5.24±0.23
Available Nitrogen %	0-15	0.41±0.07	0.19±0.05	0.22±0.09	0.47±0.04
	15.1-30	0.42±0.06	0.20±0.07	0.22±0.08	0.49±0.07
Phosphorus (mg/kg)	0-15	5.11±0.52	4.16±0.36	4.32±0.50	5.58±0.38
	15.1-30	5.19±0.16	4.20±0.58	4.32±0.48	5.80±0.42
Potassium (cmol/kg)	0-15	0.01±0.013	0.01±0.007	0.006±0.003	0.01±0.00
	15.1-30	0.005±0.002	0.009±0.006	0.006±0.005	0.01±0.00
Sodium (cmol/kg)	0-15	0.009±0.007	0.013±0.010	0.007±0.005	0.01±0.01
	15.1-30	0.008±0.003	0.013±0.010	0.013±0.024	0.01±0.00
Calcium (cmol/kg)	0-15	0.03±0.03	0.07±0.05	0.027±0.022	0.11±0.06
	15.1-30	0.02±0.01	0.06±0.06	0.019±0.017	0.06±0.04
Magnesium(cmol/kg)	0-15	0.05±0.02	0.09±0.05	0.081±0.130	0.04±0.04
	15.1-30	0.04±0.01	0.05±0.03	0.041±0.014	0.03±0.03
Exchangeable Acidity (cmol/kg)	0-15	0.56±0.20	0.81±0.19	0.847±0.278	0.44±0.10
	15.1-30	0.53±0.17	1.00±0.22	0.806±0.22	0.39±0.10
Cation Exchange Capacity (cmol/kg)	0-15	0.66±0.17	0.99±0.10	0.972±0.518	0.61±0.08
	15.1-30	0.61±0.15	1.13±0.22	0.908±0.250	0.49±0.06
Base Saturation %	0-15	17.86±11.22	19.23±13.20	17.01±26.65	27.51±7.59
	15.1-30	14.32±7.42	11.72±7.10	8.94±4.32	21.39±9.83
Hydrocarbonate (mg/L)	0-15	66.67±15.06	60.83±20.35	77.5±11.38	76.67±5.77
	15.1-30	65±20.74	62.78±28.07	80.42±8.91	85.00±5.00

All values are in mean ± standard deviation

Table 3: Soil parameters for the 4 Local Government Local Government (Rainy season)

Soil Parameters	Depths (cm)	Badagry	Epe	Ikorodu	Ojo
pH	0-15	5.75±0.71	5.86±0.38	5.83±0.62	6.30±0.26
	15-30	5.83±0.74	5.81±0.34	6.18±0.36	6.47±0.06
Electrical conductivity (µs/cm)	0-15	352.17±86.71	107.33±18.57	232.67±114.80	511.33±156.00
	15-30	259.83±80.63	85.11±22.60	119.08±61.48	245.00±28.51
Organic Carbon %	0-15	2.17±0.19	2.17±0.11	2.17±0.16	2.31±0.04
	15-30	2.29±0.37	2.17±0.10	2.26±0.12	2.34±0.02
Organic Matter %	0-15	3.73±0.33	3.73±0.18	3.73±0.27	3.98±0.07
	15-30	3.93±0.64	3.73±0.18	3.89±0.20	4.02±0.03
Available Nitrogen %	0-15	0.18±0.12	0.16±0.09	0.18±0.10	0.25±0.06
	15-30	0.16±0.11	0.16±0.07	0.25±0.09	0.28±0.00
Phosphorus (mg/kg)	0-15	4.50±0.83	4.43±0.45	4.50±0.57	5.00±0.20
	15-30	4.55±0.82	4.38±0.39	4.86±0.48	5.12±0.08
Potassium (cmol/kg)	0-15	0.01±0.01	0.008±0.003	0.01±0.01	0.09±0.08
	15-30	0.01±0.01	0.007±0.002	0.01±0.00	0.01±0.00
Sodium (cmol/kg)	0-15	0.02±0.01	0.01±0.004	0.01±0.01	0.02±0.00
	15-30	0.01±0.01	0.009±0.002	0.02±0.01	0.02±0.00
Calcium (cmol/kg)	0-15	0.07±0.05	0.069±0.024	0.07±0.04	0.11±0.02
	15-30	0.07±0.05	0.07±0.02	0.09±0.03	0.11±0.01
Magnesium(cmol/kg)	0-15	0.08±0.03	0.06±0.02	0.08±0.05	0.08±0.02
	15-30	0.09±0.05	0.10±0.12	0.11±0.05	0.08±0.01
Exchangeable Acidity (cmol/kg)	0-15	0.81±0.25	0.81±0.17	0.78±0.25	0.61±0.10
	15-30	0.81±0.19	0.80±0.16	0.65±0.17	0.56±0.10
Cation Exchange Capacity (cmol/kg)	0-15	0.98±0.17	0.96±0.13	0.96±0.18	0.83±0.07
	15-30	0.99±0.10	0.94±0.13	0.89±0.12	0.78±0.08
Base Saturation %	0-15	19.80±12.63	16.42±7.62	21.04±12.34	26.50±7.01
	15-30	19.23±13.20	16.00±6.17	27.31±9.94	28.97±5.10
Hydrocarbonate (mg/L)	0-15	65.83±22.00	53.39±34.55	80.83±14.43	71.67±2.89
	15-30	60.83±20.35	51.67±12.99	75.42±14.84	65.00±8.66

All values are in mean ± standard deviation

Table 4. PCA Eigenvalues and Variance Explained

	eigenvalue	variance.percent	cumulative.variance.percent
Dim.1	6.468301	46.20215	46.20215
Dim.2	2.115326	15.10947	61.31162
Dim.3	1.079618	7.711554	69.02318
Dim.4	1.01928	7.280571	76.30375
Dim.5	0.840532	6.003798	82.30754
Dim.6	0.705098	5.036411	87.34396
Dim.7	0.659796	4.712827	92.05678
Dim.8	0.492159	3.515424	95.57221
Dim.9	0.265185	1.894177	97.46638
Dim.10	0.178283	1.273448	98.73983
Dim.11	0.083223	0.59445	99.33428
Dim.12	0.051761	0.36972	99.704
Dim.13	0.041421	0.295862	99.99986
Dim.14	1.92E-05	0.000137	100

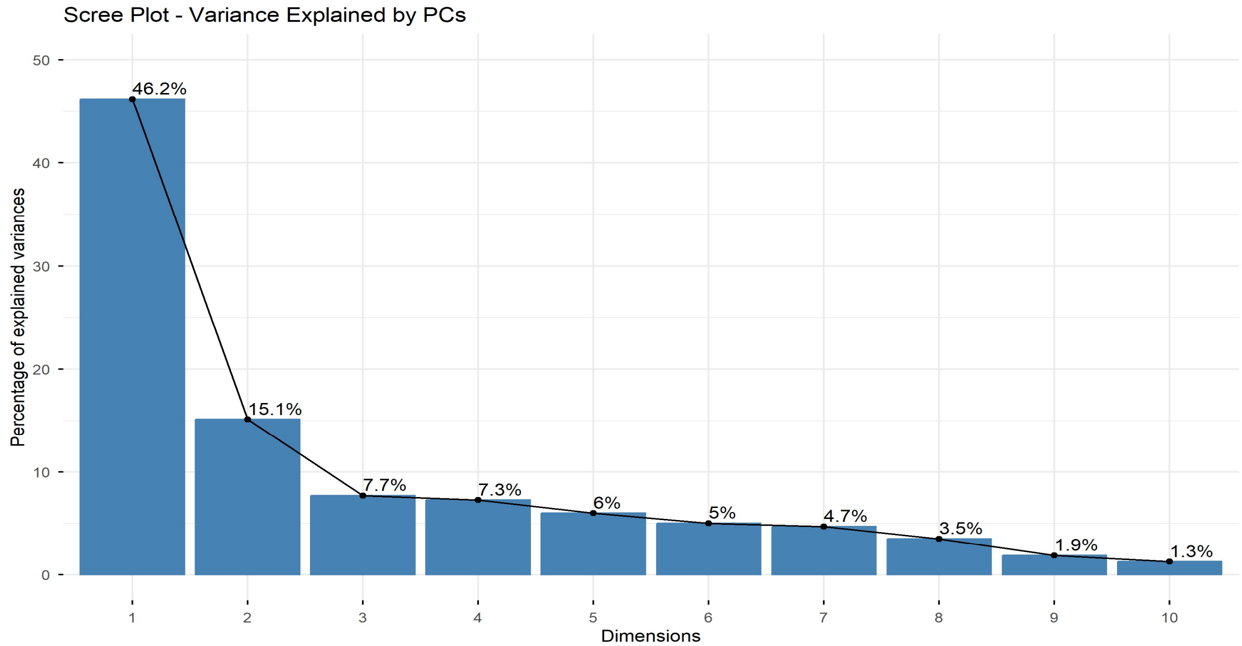

Fig. 2: Scree Plot- variance explained by PCs

PCA-derived weights for MDS indicators ranged from 0.025 to 0.102 (Table 5). Organic carbon (OC) and organic matter (OM) received the highest weights (0.102 each), followed by nitrogen (0.101) and pH (0.100), indicating their primary importance in determining soil quality in the study area. Bicarbonate (HCO_3) received the lowest weight (0.025). The Weights were normalized to sum to 1.0. Higher weights indicate greater importance in determining overall soil quality based on variance explained and factor loadings in PCA. In Fig. 3, the principal component analysis biplot shows relationships among soil properties. Arrow length indicates contribution strength; arrow direction shows correlation patterns

Table 5. Weights assigned to Minimum Data Set (MDS) indicators derived from Principal Component Analysis

Soil Indicator	Weight	Category
pH	0.09973	Chemical
OC	0.101849	Fertility
OM	0.101827	Fertility
N	0.100541	Fertility
P	0.098936	Fertility
EX	0.096993	Chemical
CEC	0.089529	Chemical
BS	0.084723	Chemical
EC	0.039061	Chemical
K	0.048214	Fertility
Ca	0.07117	Fertility
Mg	0.042499	Fertility
HCO_3^-	0.024929	Chemical

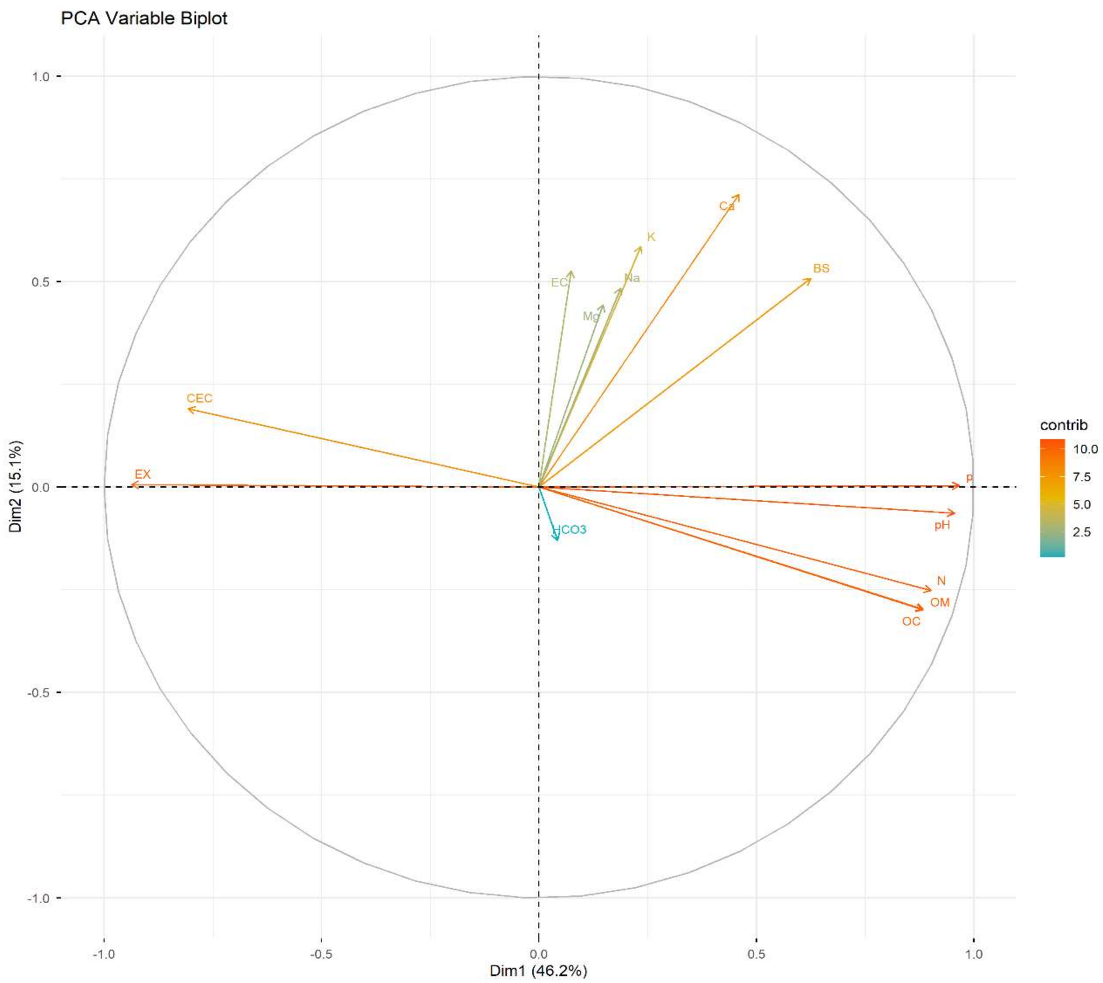

Fig.3: PCA Biplot Variance

Soil quality indices (SQIs) have been widely utilized as comprehensive measures of soil function by integrating multiple physical, chemical, and biological soil properties (Chaudhry *et al*., 2024; Gelaw *et al*., 2015; Mukherjee and Lal, 2014). The soil parameters SQI by the 4 LGAs for the dry season from Table 6 shows SQI values ranged from 0.38 to 0.46 (additive) and 0.39 to 0.47 (weighted) across all sites. Ojo LGA consistently exhibited the highest soil quality at both depths (0.45-0.47), while Badagry and Epe showed the lowest values (0.38-0.39). Ikorodu demonstrated depth-dependent variation, with subsurface soil (15-30 cm) showing superior quality (0.46) compared to topsoil (0.40). Weighted SQI values were slightly higher than additive scores, particularly in Ojo (0.46-0.47 compared to 0.45), suggesting that heavily-weighted indicators (OC, OM, N) performed better in this LGA. The minimal depth differences in Badagry, Epe, and Ojo (<0.02 units) indicate uniform soil quality profiles, whereas Ikorodu's pronounced subsurface improvement (0.06 units) suggests better nutrient retention or reduced weathering at deeper layers during dry conditions.

The rainy season from Table 7 revealed enhanced SQI values ranging from 0.38 to 0.52 (additive) and 0.38 to 0.57 (weighted). Ojo maintained superiority (0.52-0.57), showing remarkable consistency across depths with negligible variation (≤0.01 units). Badagry demonstrated substantial improvement compared to the dry season, achieving 0.47-0.50 across both depths. Conversely, Epe and Ikorodu showed consistently lower quality (0.38-0.41), with Ikorodu experiencing quality decline at 15-30 cm depth (0.39-0.38). The rainy season amplified differences between weighted and additive methods, particularly in Ojo (0.57 compared to 0.52) and Badagry (0.49-0.50 compared to 0.47), indicating that high-priority indicators responded more favorably to moisture availability in these locations.

Seasonal comparison reveals differential responses across LGAs. Ojo exhibited superior and stable soil quality year-round (0.45-0.57), likely reflecting better inherent fertility and management practices. Badagry showed remarkable seasonal improvement (18-28% increase during rainy season), suggesting moisture-sensitive soil processes enhancing nutrient availability. Conversely, Epe remained consistently moderate (0.38-0.41) regardless of season or depth, indicating stable but suboptimal conditions. Ikorodu displayed contrasting seasonal patterns: improved subsurface quality during dry season but uniform mediocre quality during rainy season, possibly due to waterlogging or leaching effects. Weighted SQI consistently exceeded additive values by 1-10%, with larger gaps during rainy season, confirming that heavily-weighted fertility indicators (OC, OM, N) drive seasonal quality variations. Depth effects were minimal (≤0.06 units) except in dry-season Ikorodu, suggesting predominantly uniform profile development across the region. These patterns indicate that coastal LGAs (Badagry, Ojo) benefit more from seasonal moisture, while inland areas (Ikorodu, Epe) face constraints limiting soil quality improvement during wet periods.

A high SQI value would indicate that the soil is fertile and healthy, while a low SQI value would indicate that the soil is less fertile and may require improvement (Chaudhry *et al*., 2024). This study examined the SQI from both top and sub-surface layer of the soil, unlike Askari *et al*. (2015) and Yang *et al*. (2020) who used only the top layer of soils for SQI assessment, and it is worthy to know that when assessing soil fertility using SQIs, the deeper layers of the soil may contain nutrients and other elements that contribute to overall fertility but may not be as evident in the top layer (Gozukara *et al*., 2022), this was observed in Ikorodu and Badagry soil sample during the dry season

Table 6: Soil Quality Index (SQI) Values Across LGAs in Lagos State Farmlands During Dry Season

Depth (cm)	Additive SQI				Weighted SQI			
	Badagry	Epe	Ikorodu	Ojo	Badagry	Epe	Ikorodu	Ojo
0-15	0.38±0.09	0.39±0.04	0.40±0.07	0.45±0.08	0.39±0.10	0.40±0.05	0.40±0.08	0.46±0.06
15-30	0.39±0.11	0.39±0.04	0.46±0.05	0.45±0.02	0.41±0.13	0.39±0.04	0.46±0.06	0.47±0.01

Table 7: Soil Quality Index (SQI) Values Across LGAs in Lagos State Farmlands During Rainy Season

Depth (cm)	Additive SQI				Weighted SQI			
	Badagry	Epe	Ikorodu	Ojo	Badagry	Epe	Ikorodu	Ojo
0-15	0.47±0.05	0.39±0.04	0.40±0.04	0.52±0.05	0.50±0.06	0.41±0.04	0.40±0.05	0.57±0.05
15-30	0.47±0.03	0.38±0.03	0.39±0.05	0.52±0.05	0.49±0.04	0.39±0.04	0.38±0.06	0.57±0.06

The correlation between Additive and Weighted SQI methods was strong ($r = 0.975$, $p < 0.001$; Fig. 4), suggesting both approaches provided consistent soil quality assessments. However, the weighted method provided better discrimination among sites by emphasizing the most influential indicators. Relationship between Additive and Weighted SQI methods as shown in Fig.4. The dashed line represents perfect correlation (1:1)

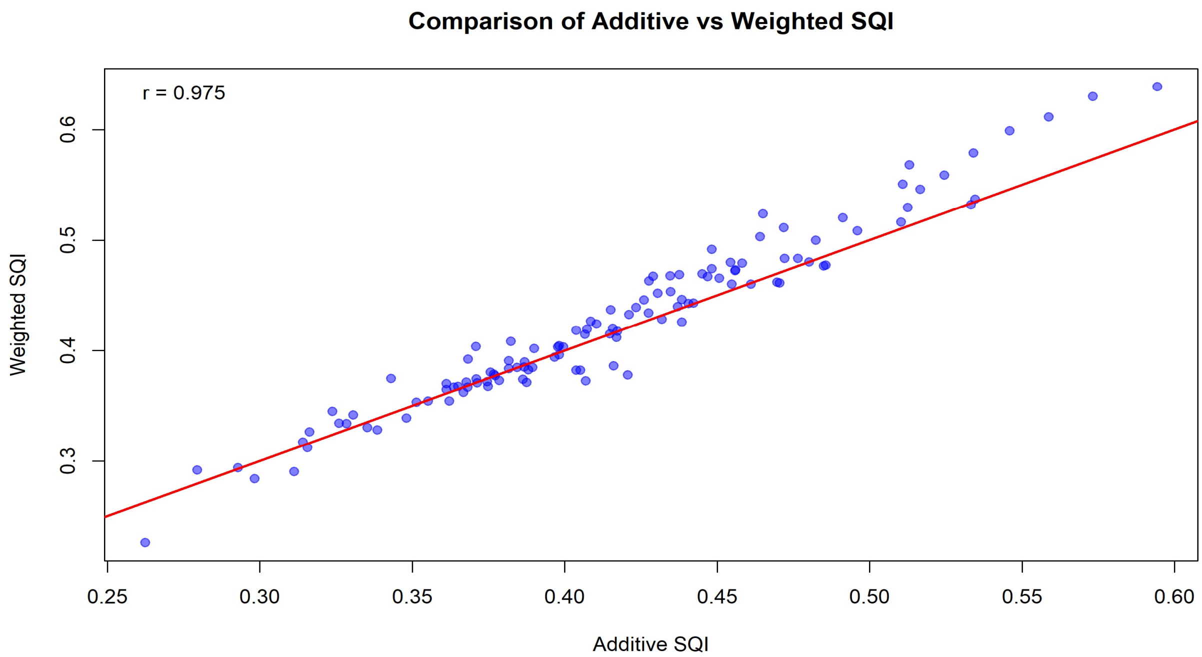

Fig. 4: Comparison of additive and weighted SQI

Dry Season Microplastic Contamination Patterns

The dry season microplastic assessment revealed substantial spatial heterogeneity in contamination levels across Lagos State farmlands (Table 8). Ikorodu consistently exhibited the highest microplastic concentrations across all analyzed parameters, with size class abundances ranging from 146.67 to 164.58 particles at 0–15 cm depth, morphological types from 74.58 to 107.50 particles at 0–15 cm, and polymer types from 51.25 to 67.08 particles at 0–15 cm. This was followed in descending order by Ojo, Badagry, and Epe, which recorded the lowest contamination levels. A pronounced depth-dependent distribution pattern was observed across all study sites, with surface soil layers (0–15 cm) containing substantially higher microplastic abundances (24.44 to 164.58 particles) compared to subsurface layers (15–30 cm: 3.00 to 140.00 particles), indicating significant surface accumulation with limited vertical migration during the dry season.

The size fraction analysis revealed that the 500 µm–1 mm size class was most prevalent across all locations, consistent with fragmentation patterns of larger plastic debris and the physical breakdown of agricultural plastic materials. Morphologically, films and fragments dominated the contamination profile, reflecting the widespread use of plastic mulch films and the fragmentation of agricultural plastics in the study region. Polymer characterization identified polyethylene (PE) and polypropylene (PP) as the most abundant plastic types, which aligns with their predominant use in agricultural applications including mulch films, irrigation pipes, greenhouse covers, and packaging materials.

These findings corroborate reports by multiple researchers documenting microplastic presence in agricultural soils globally (Chen *et al*., 2020a; De Souza Machado *et al*., 2018; Isari *et al*., 2021; Wan *et al*., 2019; Zhang *et al*., 2020; Zhao *et al*., 2021). However, the absolute microplastic concentrations vary considerably across geographical regions. Several studies have reported higher contamination levels than observed in the current investigation: Zhou *et al*. (2019) documented 1.6×10^5 items/kg in Wuhan, China; Rafique *et al*. (2020) reported 3,712 items/kg in subsurface soils and 4,483 items/kg in top soils in Lahore, Pakistan; Ding *et al*. (2020) found 2,420 items/kg in Shaanxi, China; Corradini *et al*. (2019) recorded 2,010 items/kg in Melipilla, Chile; Van den Berg *et al*. (2020) reported 930 items/kg in eastern Spain; Choi *et al*. (2021) documented 664 items/kg in Yeoju City, Korea;

and Zhou *et al*. (2020) found 503.3 items/kg in Hangzhou, China.

Conversely, some studies have reported lower microplastic burdens than the present investigation, including Liu *et al*. (2019) with 70 items/kg in Shanghai, China; Ramos *et al*. (2015) with 30 items/ha in Argentina; and Piehl *et al*. (2018) with 0.34 items/kg in southeastern Germany. Notably, Corradini *et al*. (2021) reported intermediate values of 184–306 items/kg in Chile, which fall within the range observed in this study. These variations likely reflect differences in agricultural practices, plastic use intensity, waste management infrastructure, soil properties, and local environmental conditions. The specific dominance of PE/PP polymers and film/fragment morphologies in Lagos State farmlands reflects local agricultural practices, particularly the extensive use of plastic mulching and irrigation systems.

Rainy Season Microplastic Contamination Dynamics

During the rainy season, microplastic contamination patterns demonstrated notable changes while maintaining the spatial hierarchy observed during the dry season (Table 9). Ikorodu remained the most heavily contaminated location, with size class concentrations ranging from 169.17 to 184.58 particles at 0–15 cm, morphological types from 91.25 to 119.17 particles at 0–15 cm, and polymer types from 56.67 to 74.58 particles at 0–15 cm, followed by Ojo, Badagry, and Epe in descending order. The pronounced depth gradient persisted, with surface soils (0–15 cm) containing 33.33 to 184.58 particles compared to subsurface soils (15–30 cm: 3.44 to 140.00 particles). The 500 μm–1 mm size class remained predominant, and fragment and film morphologies continued to dominate, with PE and PP being the most abundant polymer types.

Critically, the rainy season exhibited overall increases in microplastic concentrations compared to the dry season across most locations, with exceptions noted for certain parameters in Badagry and Epe. Ikorodu showed 13.71% increase in surface MP during rainy season (466.09 to 530 particles). This seasonal enhancement suggests increased microplastic mobilization and accumulation under wet conditions, likely driven by surface runoff from urban areas, enhanced soil erosion, increased application of contaminated irrigation water, and mobilization of previously deposited plastics. The depth distribution pattern showed slight narrowing of the surface-subsurface contamination gradient in some locations, particularly in Badagry, Epe, and Ikorodu, indicating enhanced downward transport of microplastics facilitated by increased water infiltration during the rainy season.

The elevated microplastic concentrations during the rainy season at 0–15 cm depth suggests augmented inputs from multiple sources including agricultural runoff, urban stormwater discharge, and irrigation with contaminated water sources. This pattern is particularly pronounced in Ikorodu, reflecting its agricultural intensity and semi-urban setting with proximity to urban plastic waste sources. While dry season counts in Ikorodu were substantial, the lower relative values compared to the rainy season support the hypothesis of reduced water-mediated microplastic transport during periods of limited precipitation. The observed increases in microplastic abundance at 15–30 cm depth during the rainy season, though moderate, indicate downward vertical transport of particles through the soil profile, raising concerns about potential contamination of deeper soil horizons and groundwater resources.

Pathways and Sources of Microplastic Contamination in Farmland Soils

Multiple pathways contribute to microplastic accumulation in agricultural soils. The application of sewage sludge as organic fertilizer represents a significant contamination source (Van den Berg *et al*., 2020), as wastewater treatment processes concentrate microplastics without effectively removing them. Plastic mulch films, widely used for weed suppression, moisture retention, and soil temperature regulation, degrade over time and release microplastic fragments into the soil (Huang *et al*., 2020). Organic fertilizers, particularly those derived from composted materials or animal manures from facilities using plastic materials, can introduce microplastics into agricultural systems (Weithmann *et al*., 2018). Irrigation with water from wastewater treatment plants or contaminated surface water bodies transfers microplastics directly to agricultural fields (Park *et al*., 2020). Additionally, the use of contaminated river water for irrigation has been documented as a microplastic transfer pathway (Dioses-Salinas *et al*., 2020; Wong *et al*., 2020).

Table 8 Dry season Soil Microplastic Properties across the 4 LGAs in Lagos State Farmlands

		Badagry		Epe		Ikorodu		Ojo	
MPs features	**Depths (cm)**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
100-500μm	0-15	128.33^{ab}	18.89	86.67^{ab}	6.61	155.42^{ab}	14.99	133.33^{ab}	7.64
	15–30	11.17^{ab}	.75	8.56^{ab}	.88	15.58^{ab}	1.564	130.00^{ab}	5.00
500μm-1mm	0-15	138.33^{abc}	18.89	92.78^{ac}	7.55	164.58^{aa}	14.53	143.33^{ab}	7.64
	15–30	10.83^{abc}	.752	8.33^{ac}	.707	15.17^{aa}	1.59	140.00^{ab}	5.00
1-5mm	0-15	118.33^{ab}	17.22	79.44^{ab}	7.68	146.67^{aa}	16.00	123.33^{ab}	5.77
	15–30	11.50^{ab}	.55	9.00^{ab}	.71	15.92^{aa}	1.44	123.33^{ab}	5.77
Fiber	0-15	80.83^{ab}	11.58	54.44^{ab}	4.64	97.50^{aa}	8.39	85.00^{ab}	5.00
	15–30	6.67^{ab}	.52	5.11^{ab}	.60	9.50^{aa}	1.00	81.67^{ab}	2.89
Film	0-15	85.83^{abc}	11.58	59.44^{ac}	4.64	102.50^{aa}	8.39	90.00^{ab}	5.00
	15–30	6.33^{abc}	.52	4.89^{ac}	.60	9.25^{aa}	.97	86.67^{ab}	2.89
Fragment	0-15	90.83^{ab}	11.58	64.44^{ab}	4.64	107.50^{aa}	8.39	95.00^{ab}	5.00
	15–30	8.50^{ab}	.55	6.56^{ab}	.527	11.50^{aa}	1.00	91.67^{ab}	2.89
Foam	0-15	69.17^{ab}	8.61	47.22^{ab}	4.41	84.58^{aa}	9.16	71.67^{ab}	2.89
	15–30	5.17^{ab}	.41	4.11^{ab}	.33	7.33^{aa}	.78	60.67^{ab}	2.06
Bead/Microbead	0-15	58.33^{ab}	12.91	33.33^{ab}	6.12	74.58^{aa}	12.33	58.33^{ab}	2.89
	15–30	6.83^{ab}	.41	5.22^{ab}	.67	9.08^{aa}	1.08	61.67^{ab}	5.77
Polypropylene (PP)	0-15	50.83^{abc}	7.36	31.67^{ac}	3.54	62.08^{aa}	5.42	53.33^{ab}	2.89
	15–30	4.17^{abc}	.41	3.22^{abc}	.44	5.92^{aa}	.52	51.67^{ab}	2.88
polyethylene (PE)	0-15	55.83^{ab}	7.36	36.67^{ab}	3.54	67.08^{ac}	5.42	58.33^{ab}	2.89
	15–30	4.67^{ab}	.52	3.78^{ab}	.44	6.50^{ac}	.52	56.67^{ab}	2.89
Polyvinyl chloride	0-15	45.83^{abc}	7.36	26.67^{ac}	3.54	57.08^{aa}	5.42	48.33^{ab}	2.89
(PVC)	15–30	4.17^{abc}	.41	3.22^{ac}	.44	5.67^{aa}	.65	46.67^{ab}	2.89
Polyethylene	0-15	50.83^{abc}	7.36	31.67^{ac}	3.54	62.08^{aa}	5.42	53.33^{ab}	2.89
terephthalate (PET)	15–30	4.17^{abc}	.41	3.11^{ac}	.33	5.50^{aa}	.52	51.67^{ab}	2.89
Polyamides (PA)(nylon)	0-15	40.83^{abc}	7.36	24.44^{ac}	3.01	52.08^{aa}	5.42	43.33^{ab}	2.89
	15–30	4.00^{abc}	.00	3.00^{ac}	.00	5.67^{aa}	.78	41.67^{ab}	2.89
Polystyrene (PS)	0-15	46.67^{abc}	6.83	29.44^{ac}	3.01	57.08^{aa}	5.42	48.33^{ab}	2.89
	15–30	3.83^{abc}	.41	3.00^{ac}	.50	5.33^{aa}	.65	50.00^{ab}	5.00
Polyvinyl alcohol (PVA)	0-15	41.67^{abc}	6.83	25.00^{ac}	3.54	52.08^{aa}	5.42	43.33^{ab}	2.89
	15–30	3.50^{abc}	.55	3.00^{ac}	.00	5.92^{aa}	.67	39.33^{ab}	2.44
polyurethane (PU)	0-15	49.17^{abc}	9.70	32.22^{ac}	3.63	51.25^{aa}	6.78	50.00^{aba}	10.00
	15–30	5.00^{abc}	.00	3.44^{ac}	.53	6.17^{aa}	.84	50.00^{aba}	.00

SD-Standard Deviation. Different superscript letters within each row indicate significant differences among LGAs ($p<0.05$, Tukey's HSD test). Within each MP feature, depths sharing the same letter are not significantly different.

The depth distribution patterns observed in this study characterized by heavy surface soil contamination with restricted vertical migration suggest that surface deposition processes (plastic mulch degradation, atmospheric deposition, surface runoff) are the primary contamination mechanisms, while downward transport through leaching and bioturbation plays a secondary role. However, the rainy season increases in subsurface microplastic concentrations indicate that enhanced infiltration promotes deeper penetration, potentially threatening groundwater quality and facilitating microplastic transfer to aquatic ecosystems through subsurface flow pathways.

Environmental and Agricultural Implications

The elevated microplastic concentrations documented in this study, particularly the abundance of fragments and PE/PP polymers in Ikorodu, pose significant threats to soil health, crop productivity, and food security. Microplastics can alter soil physical properties including bulk density, water holding capacity, aggregate stability, and porosity, potentially affecting root growth and water availability (Boots *et al*., 2019). The accumulation of microplastics may interfere with nutrient cycling through adsorption of nutrients or pesticides, alteration of microbial community composition and function, and modification of soil organic matter dynamics (Rillig *et al*., 2017). Furthermore, microplastic uptake by crop plants and translocation to edible tissues raises food safety concerns and potential human health implications through dietary exposure (Azeem *et al*., 2021).

The rainy season transport of microplastics represents a critical environmental concern, as enhanced surface runoff and soil erosion can transfer contaminated soil particles to adjacent water bodies. Given Ikorodu's proximity to Lagos Lagoon and other aquatic ecosystems, microplastic-laden runoff may contribute to aquatic contamination, affecting fish populations and other aquatic organisms. The data from Ojo LGA, which also exhibited severe microplastic contamination, underscore the urgency of implementing comprehensive management strategies targeting both agricultural practices and municipal waste management systems.

The findings align with observations of Tajwar *et al*. (2022) and Himu *et al*. (2022), who reported higher microplastic concentrations in urban and metropolitan agricultural areas compared to rural farmlands, attributed to greater plastic consumption, inadequate waste management infrastructure, atmospheric deposition from urban sources, and proximity to industrial activities. This spatial pattern is congruent with studies of agricultural soils in Bangladesh and other developing nations experiencing rapid urbanization.

Relationship between Soil Physicochemical Properties and Microplastic Contamination

The rate and extent of weathering of MPs depend on their physicochemical properties and environmental conditions of the media to which they are exposed (Chen *et al*., 2020b; Duan *et al*., 2021; Mei *et al*., 2020; Tian *et al*., 2019; Turgay *et al*., 2019; Wang *et al*., 2020). Redundancy Analysis (RDA) was conducted to evaluate the relationship between soil qualities and microplastic during the two seasons (dry and rainy) across the 4 LGA, The RDA comprehensively demonstrated that microplastic contamination in agricultural soils is governed by a hierarchical set of environmental controls.

Comparative Assessment: Lagos State Microplastic Contamination in Global Context

To evaluate the relative severity of microplastic contamination in Lagos State farmlands, observed concentrations were systematically compared against published data from agricultural soils across Asia, South America, Europe, and Africa (Table 10). The microplastic concentrations observed in Lagos State farmlands occupy the lower to intermediate range of globally reported values for agricultural soils from Table 7. Surface soil concentrations during the dry season (24.4–164.6 particles/kg) and rainy season (33.3–184.6 particles/kg) fall substantially below the upper extremes documented in intensive Asian agricultural systems, yet considerably exceed the minimal contamination levels reported from some European sites. Specifically, Lagos State values represent approximately:

1. 0.1–0.3% of peak Asian concentrations (Wuhan, China: 160,000 particles/kg)
2. 3.7–26.4% of intensive Asian agriculture (Lahore, Pakistan: 4,483 particles/kg topsoil)
3. 32.6–36.7% of moderate Asian systems (Hangzhou, China: 503.3 particles/kg)
4. 98.6–264.0% of low-intensity Asian sites (Shanghai, China: 70 particles/kg)
5. 9.2–20.0% of South American intensive agriculture (Melipilla, Chile: 2,010 particles/kg)
6. 60.3–100.9% of South American moderate systems (Chile multiple sites: 184–306 particles/kg)

7. 542.4–813.5 times German minimal contamination (SE Germany: 0.34 particles/kg)

This positioning indicates that Lagos State agricultural soils experience moderate microplastic contamination by international standards, neither representing a worst-case contamination scenario nor approaching the minimal levels observed in regions with stringent plastic management and low-intensity agricultural practices.

Table 9: Rainy season Soil Microplastic Properties across the 4 LGAs in Lagos State Farmlands

		Badagry		Epe		Ikorodu		Ojo	
MPs features	**Depths (cm)**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
100-500μm	0-15	120.00 [ab]	11.83	109.44 [ac]	10.44	176.25 [aa]	10.47	138.33 [aba]	7.64
	15–30	17.67 [ab]	1.50	11.00 [ac]	1.00	17.67 [aa]	1.07	131.67 [aba]	5.77
500μm-1mm	0-15	128.33 [ab]	12.91	117.78 [ac]	10.34	184.58 [aa]	9.88	148.33 [aba]	7.638
	15–30	17.33 [ab]	1.50	10.56 [ac]	1.13	17.33 [aa]	1.07	140.00 [aba]	8.66
1-5mm	0-15	110.00 [ab]	10.49	101.67 [ac]	9.68	169.17 [aa]	11.65	126.67 [aba]	5.77
	15–30	18.00 [ab]	1.41	11.33 [ac]	1.00	18.00 [aa]	1.13	121.67 [aba]	7.64
Fiber	0-15	74.17 [ab]	7.36	68.33 [ac]	6.61	109.17 [aa]	5.97	86.67 [aba]	5.78
	15–30	10.50 [ab]	1.00	6.67 [ac]	.71	10.67 [aa]	.651	81.67 [aba]	5.77
Film	0-15	77.50 [ab]	9.35	72.22 [ac]	7.12	114.17 [aa]	5.97	91.67 [aba]	5.77
	15–30	10.50 [ab]	1.00	6.22 [ac]	.44	10.33 [aa]	.65	86.67 [aba]	5.77
Fragment	0-15	84.17 [ab]	7.36	78.33 [ac]	6.61	119.17 [aa]	5.97	96.67 [aba]	5.77
	15–30	13.33 [ab]	1.07	8.33 [ac]	1.00	13.17 [aa]	.94	91.67 [aba]	5.77
Foam	0-15	65.00 [ab]	4.47	60.56 [ac]	4.64	96.25 [aa]	4.83	73.33 [aba]	2.89
	15–30	8.25 [ab]	.75	5.22 [ac]	.44	8.33 [aa]	.49	70.00 [aba]	5.00
Bead/Microbead	0-15	57.50 [aa]	9.35	49.44 [ab]	7.27	91.25 [aa]	10.90	65.00 [aa]	5.00
	15–30	10.42 [aa]	.79	6.44 [ab]	.88	10.50 [aa]	.91	56.33 [aa]	2.24
Polypropylene (PP)	0-15	47.50 [ab]	5.24	42.78 [ac]	5.65	69.58 [ac]	3.97	53.33 [aa]	2.89
	15–30	6.58 [ab]	.67	4.22 [ac]	.44	6.42 [ac]	.515	44.33 [aa]	2.01
polyethylene (PE)	0-15	51.67 [ab]	5.16	47.22 [ac]	5.07	74.58 [ac]	3.97	58.33 [aa]	2.89
	15–30	7.25 [ab]	.75	4.56 [ac]	.527	7.33 [ac]	.49	56.67 [aa]	5.77
Polyvinyl chloride (PVC)	0-15	42.50 [ab]	5.24	37.78 [ac]	5.65	64.58 [ac]	3.97	48.33 [aa]	2.89
	15–30	6.58 [ab]	.67	4.22 [ac]	.44	6.42 [ac]	.515	40.33 [aa]	2.12
Polyethylene terephthalate (PET)	0-15	47.50 [ab]	5.24	42.78 [ac]	5.65	69.58 [ac]	3.97	53.33 [aa]	2.89
	15–30	6.25 [ab]	.45	4.11 [ac]	.33	6.25 [ac]	.45	41.33 [aa]	2.63
Polyamides (PA)(nylon)	0-15	37.50 [ab]	5.24	33.33 [ac]	3.54	59.58 [ac]	3.96	43.33 [aa]	2.89
	15–30	6.33 [ab]	.65	3.78 [ac]	.44	6.50 [ac]	.52	33.33 [aa]	2.13
Polystyrene (PS)	0-15	45.83 [ab]	5.85	40.00 [ac]	3.54	64.58 [ac]	3.97	51.67 [aa]	2.89
	15–30	6.17 [ab]	.58	4.00 [ac]	.50	6.17 [ac]	.58	48.33 [aa]	2.89
Polyvinyl alcohol (PVA)	0-15	40.00 [ab]	4.47	35.00 [ac]	3.54	59.58 [ac]	3.97	45.00 [aa]	.00
	15–30	6.67 [ab]	.89	3.44 [ac]	.53	6.67 [ac]	.49	43.33 [aa]	2.89
polyurethane (PU)	0-15	45.00 [aa]	4.47	43.89 [ab]	3.33	56.67 [aa]	5.77	58.33 [aa]	7.64
	15–30	7.17 [aa]	.72	4.56 [ab]	.88	7.25 [aa]	.75	46.67 [aa]	5.77

Season-Specific RDA: Temporal Stability of Soil-Microplastic Relationships

Once introduced into the soil, microplastics can disrupt physical properties such as bulk density, porosity, and water retention, negatively affecting soil health and crop productivity (Hasan and Tarannum, 2025). The accumulation of microplastics in the soil will not only affect the physicochemical properties of soil but also harm the development and reproduction of fauna, affect the plant growth, and even change the microbial community and enzyme activity (Da Costa *et al*., 2018; Ya *et al*., 2021). In this study, separate RDA models conducted for individual seasons assessed whether soil property effects on microplastic contamination vary between sampling periods (Table 8). The Season 1 model (dry season; n = 60 samples) explained 45.5% of microplastic variance (Adjusted R^2= 0.285, *p* < .001), while the Season 2 model (rainy season; n = 60) explained 42.3% (Adjusted R^2 = 0.244, *p* < .001). Both models achieved statistical significance (*p* < .001), confirming that soil-microplastic relationships persist across seasonal conditions rather than representing artifacts of single-period sampling.

Depth-Specific RDA: Vertical Stratification of Soil Property Effects

Depth-stratified RDA models revealed striking differences in how soil properties govern microplastic contamination between surface and subsurface horizons (Table 11). The Depth 1 model (surface soils, 0-15 cm; n = 60) explained 36.9% of variance (Adjusted R^2 = 0.172, *p* < .01), while the Depth 2 model (subsurface soils, 15-30 cm; n = 60) explained substantially more at 59.8% (Adjusted R^2 = 0.472, *p* < .001). Both models achieved statistical significance (*p* < .01 for Depth 1, p < 0.001 for Depth 2), but the 22.9 percentage point difference in raw R^2 (30.0% points in adjusted R^2) indicates fundamentally different soil-microplastic dynamics operating at different depths.

Soil Properties after Controlling for Spatial-Temporal Factors: Partial RDA

From Fig. 5, the geographic location (LGA) substantially explained 53.3% of unique variance reflecting differential anthropogenic loading across administrative boundaries. Soil physicochemical properties, particularly organic carbon and organic matter, play statistically significant but secondary roles (0.95% unique variance, 2.5% after conditioning), operating primarily through interaction with spatial-temporal context. Season contributed a modest but statistically discernible 2.3% unique variance (p < 0.05), indicating temporal differences in microplastic characteristics between dry and rainy sampling periods. Soil depth accounted for 2.1% unique variance (p < 0.05), demonstrating significant vertical stratification of microplastic distribution between surface (0-15 cm) and subsurface (15-30 cm) horizons. This depth effect likely reflects the interplay of multiple processes: gravitational settling and infiltration transporting smaller particles downward, preferential retention of larger fragments in surface layers due to physical sieving by soil structure, bioturbation by soil fauna redistributing particles across depths, and time-dependent downward migration as plastics undergo fragmentation and aging. The strong context-dependency of soil effects-evidenced by substantial interaction terms (Soil × Season: 2.6%, Soil × LGA: 2.7%, Soil × Season × LGA: 2.1%), Soil × Depth × Season × LGA: 0.1%)—reveals that identical soil properties govern microplastic behavior differently across seasons, locations, and depths.

The full Redundancy Analysis (RDA) model explained 88.3% of the total variance in microplastic distribution (Adjusted R^2= 0.861, n = 120 samples, eigenvalue = 1.71×10^{-4}, p < 0.001) from Table 11. Permutation tests (999 permutations) confirmed the overall statistical significance of the model (p < 0.001), validating that the observed relationships between predictor variables and microplastic response variables significantly exceed patterns expected by chance alone. The first two RDA axes were individually significant (Axis 1: *p* < .001; Axis 2: *p* < .01), collectively capturing the primary gradients of variation in the dataset. When controlling for season, location, and depth, soil properties alone contributed minimally (2.5%, eigenvalue = 4.85×10^{-4}, *p* < .05). Season-specific models showed similar explanatory power (dry: 45.5%, eigenvalue = 9.67×10^{-5}; rainy: 42.3%, eigenvalue = 4.81×10^{-5}, both *p* < .001). Depth-stratified analyses demonstrated stronger soil-microplastic relationships at subsurface layers (59.8%, eigenvalue = 1.43×10^{-4}, *p* < .001) compared to surface soils (36.9%, eigenvalue = 3.55×10^{-5}, *p* < .01).

Table 10: Global Comparison of Microplastic Concentrations in Agricultural Soils

Study Location	Country	Soil Type	MP Concentration (particles/kg)	Dominant Polymer Types	Dominant Morphology	Sample Depth (cm)	Reference
Current Study							
Lagos State (Dry Season)	Nigeria	Agricultural farmland	24.4-164.6 (surface) 3.0-140.0 (subsurface)	PE, PP	Film, Fragment	0-15 15-30	Present study
Lagos State (Rainy Season)	Nigeria	Agricultural farmland	33.3-184.6 (surface) 3.4-140.0 (subsurface)	PE, PP	Film, Fragment	0-15 15-30	Present study
Asia							
Wuhan	China	Agricultural soil	160,000	PE, PP, PS	Fiber, Film	0-20	Zhou *et al.* (2019)
Shaanxi	China	Agricultural soil	2,420	PE, PP	Fragment, Film	0-10	Ding *et al.* (2020)
Hangzhou	China	Agricultural soil	503.3	PE, PP	Film, Fiber	0-20	Zhou *et al.* (2020)
Shanghai	China	Farmland	70	PE, PP	Film	0-15	Liu *et al.* (2019)
Lahore (Topsoil)	Pakistan	Agricultural soil	4,483	PE, PP	Film, Fragment	0-15	Rafique *et al.* (2020)
Lahore (Subsurface)	Pakistan	Agricultural soil	3,712	PE, PP	Fragment	15-30	Rafique *et al.* (2020)
Yeoju City	South Korea	Agricultural soil	664	PE, PP, PVC	Film, Fragment	0-20	Choi *et al.* (2021)
Central Bangladesh	Bangladesh	Farmland	147-425	PE, PP	Film, Fiber	0-10	Himu *et al.* (2022)
South America							
Melipilla	Chile	Agricultural soil	2,010	PE, PP	Film	0-25	Corradini *et al.* (2019)
Various sites	Chile	Agricultural soil	184-306	PE, PP, PS	Film, Fragment	0-15	Corradini *et al.* (2021)
Argentine Pampas	Argentina	Agricultural soil	30 (items/ha)	PE	Film	0-10	Ramos *et al.* (2015)
Europe							
Eastern Spain	Spain	Agricultural soil	930	PE, PP	Film, Fragment	0-20	Van den Berg *et al.* (2020)
Southeastern Germany	Germany	Agricultural soil	0.34	PE, PP	Fragment	0-10	Piehl *et al.* (2018)

Table 11: Summary of Redundancy Analysis (RDA) Models Explaining Microplastic Contamination Variance Across Seasons, Depths, and Locations

Model	R^2	Adjusted R^2	n	Significance	Eigenvalue
Full RDA Model (Soil + Season + LGA + Depth)	0.883	0.861	120	p < 0.001***	1.71e-04
Partial RDA (Soil only, conditioned on Season, LGA, Depth)	0.025	0.009	120	p < 0.05*	4.85e-06
Season-Specific Models					
Season 1 (Dry)	0.455	0.285	60	p < 0.001***	9.67e-05
Season 2 (Rainy)	0.423	0.244	60	p < 0.001***	4.81e-05
Depth-Specific Models					
Depth 1 (0-15 cm surface)	0.369	0.172	60	p < 0.01**	3.55e-05
Depth 2 (15-30 cm subsurface)	0.598	0.472	60	p < 0.001***	1.43e-04

Notes: R^2 = proportion of variance explained; Adjusted R^2 = R^2 adjusted for number of predictors; n = sample size; Significance levels based on permutation tests (999 permutations): *** $p < .001$, ** $p < .01$, * $p < .05$. LGA = Local Government Area.

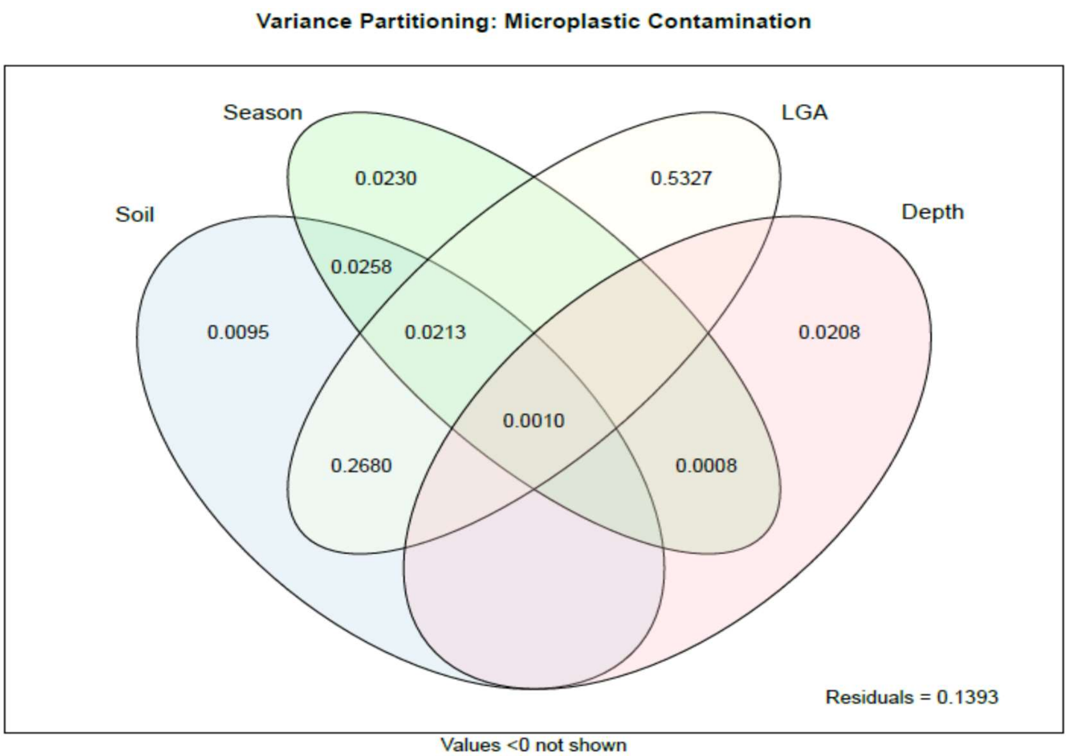

Fig. 5: Variance Partitioning Among Predictor Groups

Identification of Key Soil Drivers and Mechanistic Interpretation

Variable importance analysis, based on absolute loadings across the first two RDA axes, quantified the relative contribution of each soil property in explaining microplastic variance (Table 12, Fig. 6). The accumulation of conventional MPs in soil may indirectly disturb the soil carbon pool through their influence on the physicochemical properties as well as microbial characters of the soil (Li *et al.*, 2024; Xiang *et al.*, 2024). Organic carbon (OC) emerged as the single most influential soil property (Total Importance = 6.313), closely followed by organic matter (OM; 6.286), with both parameters dominating all other soil variables by orders of magnitude. The near-equivalence of OC and OM importance scores (differing by only 0.43%) is expected given their mathematical relationship (OM ≈ 1.724 × OC), but their overwhelming dominance underscores the primacy of soil organic constituents in governing microplastic dynamics. The VIF analysis in Table 12 revealed severe multicollinearity between organic carbon (OC) and organic matter (OM), with VIF values exceeding 25,000, reflecting their stoichiometric relationship (OM ≈ 1.724 × OC). Phosphorus (P≈13.6) and exchangeable acidity (EX=12.6) also showed problematic collinearity. Following removal of OM, P, EX, and N (VIF>5), eight soil properties (pH, OC, CEC, Ca, BS, EC, K, Mg, Na, HCO_3) were retained for RDA, exhibiting acceptable independence (VIF<5) for multivariate analysis.

The RDA1 and RDA2 loadings reveal nuanced patterns: OC showed strong positive loadings on both axes (RDA1: 0.407, RDA2: 5.905), while OM exhibited similar but slightly lower values (RDA1: 0.417, RDA2: 5.869). These loadings indicate that sites with elevated organic matter concentrations consistently exhibited distinct microplastic assemblages, potentially characterized by greater total particle counts (through enhanced retention), different size distributions (preferential retention of smaller, high-surface-area fragments), or altered polymer profiles (differential sorption of polymer types based on hydrophobicity). Due to MPs low density, it typically decreases soil bulk density and enhances aeration, thereby promoting the mineralization and decomposition of soil organic carbon (SOC) (Xiang *et al*., 2024; Zhang *et al*., 2023). The loss of organic matter from conventional MPs is found to vary across different soil types, as indicated by previous research (Rauscher *et al*., 2023). The bicarbonate (HCO_3) ranked third in importance (0.007) despite its low absolute value, suggesting minor influence on microplastic behavior. Bicarbonate primarily affects soil pH buffering capacity and can influence colloidal dispersion/flocculation through ionic strength effects, but its low importance indicates these mechanisms play limited direct roles in microplastic fate under field conditions.

The migration and fragmentation of MPs in soil is related to soil properties like texture, porosity, and pH (Blasing and Amelung, 2018; Luo *et al*., 2020; Ya *et al*., 2021). In the study, the pH exhibited relatively low importance (0.086) compared to its theoretical significance in controlling plastic surface charge and colloidal stability. This finding may reflect the limited pH range in agricultural soils (typically 5.5-7.5), insufficient to produce dramatic shifts in ionization state for most common polymers. Additionally, pH effects may be confounded by correlated variables (pH strongly associates with OM, CEC, and base saturation), such that variance attributable to pH is captured by these other parameters in multivariate space. Some studies indicate that MP abundance was negatively correlated with soil pH investigations (Hu *et al*., 2024; Luo *et al*., 2024; Zhang *et al*., 2025). pH significantly affects the abundance of MPs in wetland soils. Lower pH promotes mutual adsorption of MP particles by reducing the negative charge on the surface of MPs, which increases the migration rate of MPs (Sharma *et al*., 2021).

Spatial Distribution Patterns and Ordination Structure

Sites clustered primarily by LGA affiliation from Fig. 6, with clear spatial segregation of the four administrative units in ordination space. LGA1 (Badagry) sites (represented by red vectors in the biplot) occupied the central-right quadrant, characterized by intermediate soil property values and moderate microplastic loading. LGA2 (Epe) sites clustered in the upper-right quadrant, distinguished by elevated electrical conductivity (EC) and cation exchange capacity (CEC), suggesting clay-rich soils with high nutrient retention capacity. LGA3 sites (Ikorodu) dominated the left-side ordination space, associated with lower organic matter content and distinct microplastic profiles. The fourth LGA (Ojo) showed intermediate positioning with substantial intra-site variability, indicating heterogeneous environmental conditions within that administrative unit.

Table 12: Variable Importance Scores for Soil Physicochemical Properties in Explaining Microplastic Contamination Patterns

Rank	Variable	RDA1	RDA2	Total Importance	VIF	Environmental Interpretation
1	OC	0.407421	5.905311	6.312732	25772.86	Sorption capacity, aggregation
2	OM	0.416455	5.869692	6.286148	25676.16	Particle retention, biofilm substrate
3	N	0.02266	0.117216	0.139875	8.043537	pH buffering, ionic strength
4	CEC	0.015923	0.029981	0.045903	5.869697	Microbial activity, productivity
5	EC	0.000218	0.044359	0.044576	1.323735	Surface charge, colloidal stability
6	EX	0.015401	0.016268	0.031669	12.64052	Electrostatic retention capacity
7	BS	0.003464	0.023087	0.026551	3.256515	Ionic strength, flocculation
8	Ca	0.004619	0.021722	0.02634	3.82463	Cation-mediated binding
9	pH	0.004434	0.021805	0.026239	-	pH buffering, cation balance
10	Na	0.001075	0.024801	0.025876	1.15016	Divalent cation bridging
11	K	0.002261	0.01643	0.018691	1.319203	Clay dispersion, structure
12	P	0.007162	0.008992	0.016154	13.61185	Nutrient indicator
13	Mg	0.001518	0.006288	0.007806	1.260796	Fertility indicator
14	HCO_3	1.46E-06	0.006762	0.006763	1.098539	Exchangeable cation

Notes: Total Importance = sum of absolute loadings across RDA1 and RDA2 axes. Higher values indicate stronger influence on microplastic distribution patterns. RDA loadings represent correlation coefficients between soil variables and constrained ordination axes.

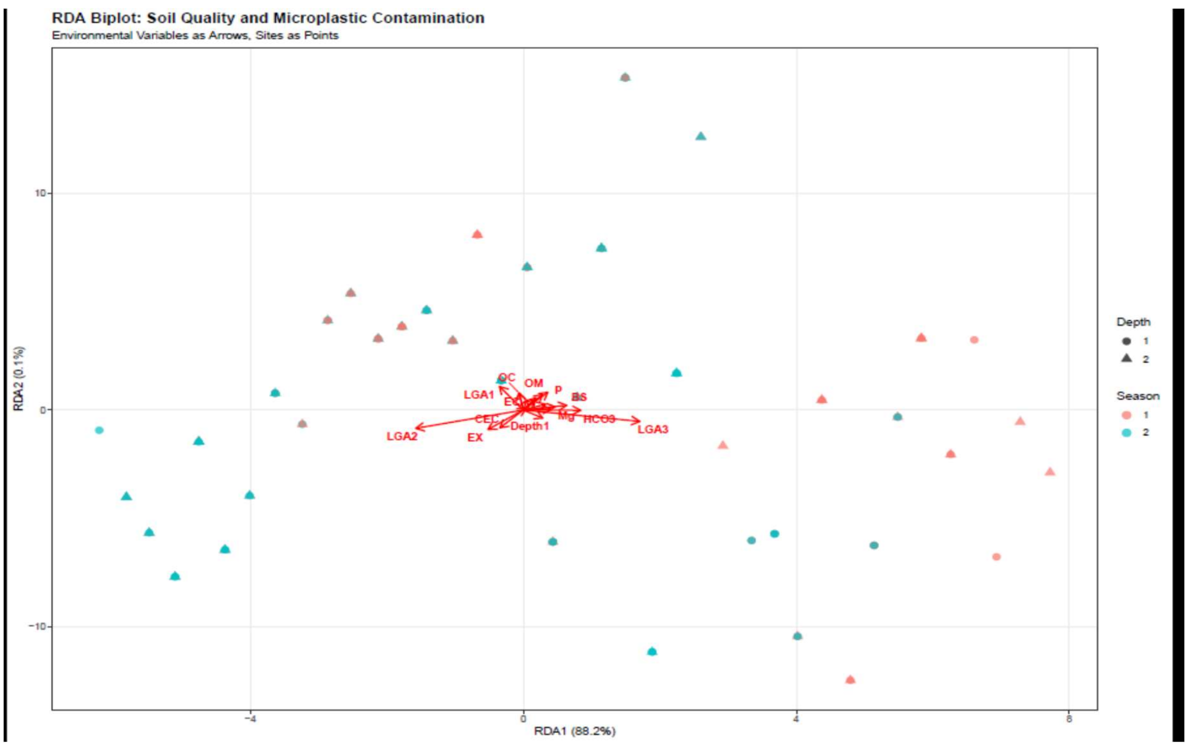

Fig. 6: RDA Biplot: soil quality and Microplastic contamination
Note: Environmental Variables as Arrows, Sites as Points

ANCOVA from Table 13 revealed that microplastic abundance varied significantly across seasons ($F_{1,113}$=39.4, p<.001) and LGAs ($F_{3,113}$=232.8, p<.001). Although organic matter (OM) exhibited no main effect ($F_{1,113}$=0.05, p=.826), a significant OM x Season interaction ($F_{1,113}$=4.03, p= .047) indicated season-dependent OM effects on MP retention. The effect of organic matter on the abundance of MPs is illustrated in Fig. 7. This suggests OM enhances MP accumulation during dry conditions but not rainy periods, potentially reflecting moisture-mediated changes in sorption dynamics or MP mobility.

Table 13: Analysis of Covariance (ANCOVA) for Microplastic Abundance: Effects of Organic Matter (OM), Season, and Local Government Area

Source	df	Sum of Squares	Mean Square	F-value	p-value	Significance
OM	1	0.0001	0.0001	0.049	0.8260	ns
Season	1	0.0723	0.0723	39.364	6.67×10^{-9}	***
LGA	3	1.2825	0.4275	232.831	$<2\times10^{-16}$	***
OM x Season	1	0.0074	0.0074	4.029	0.0471	*
Residuals	113	0.2075	0.0018	-	-	-

*Response variable: Log_{10}(MP count + 1). Significance codes: *** p<.001, ** p<.01, * p<.05, ns = not significant (p>.05)*

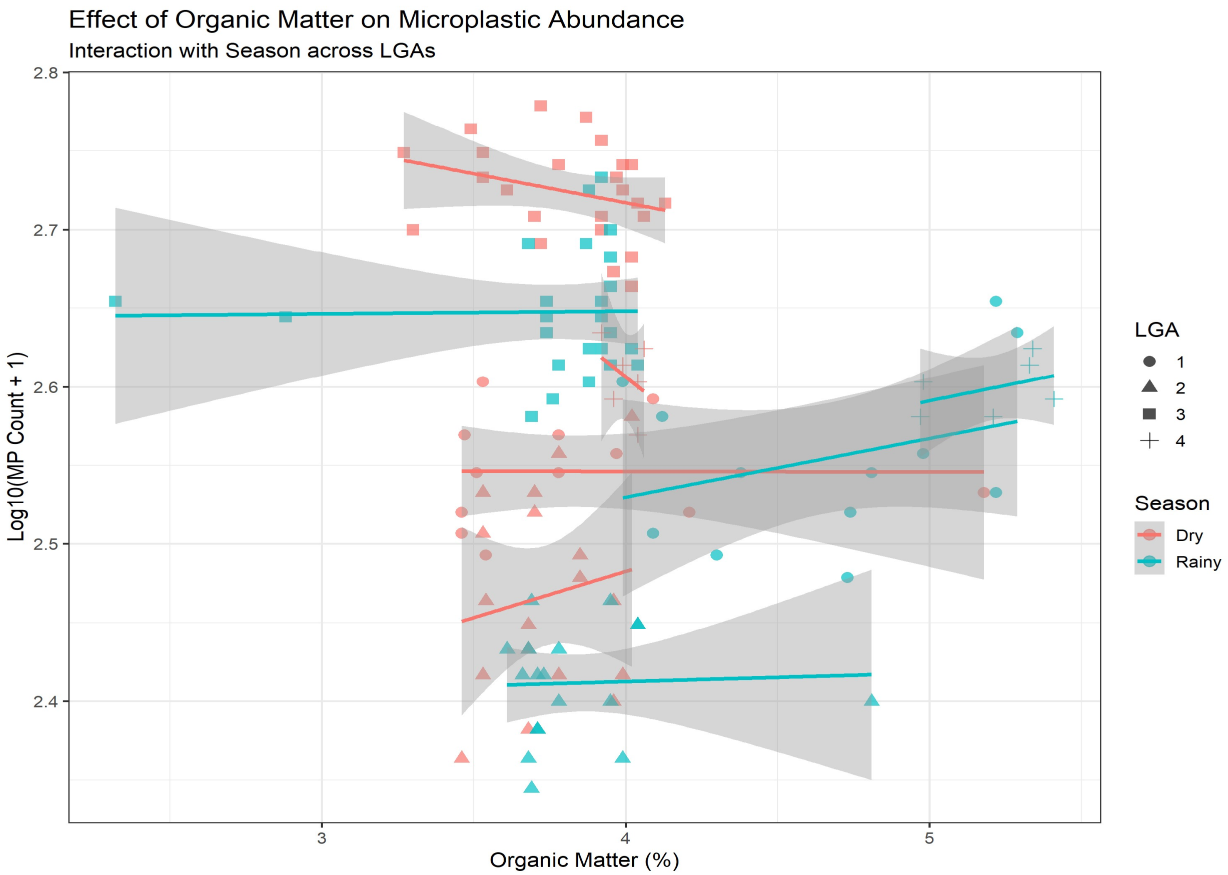

Fig. 7: Effect of organic matter on microplastics abundance in the soil:

CONCLUSION

This comprehensive investigation of microplastic contamination and soil quality across Lagos State farmlands reveals critical environmental challenges that demand urgent intervention. The study establishes that microplastic pollution in agricultural soils exhibits pronounced spatial heterogeneity driven primarily by location-specific anthropogenic pressures rather than intrinsic soil properties, with Ikorodu emerging as the most heavily contaminated area across both seasons and soil depths.

The Soil Quality Index analysis demonstrates moderate soil fertility across all study sites (SQI: 0.35-0.58), with Ojo consistently exhibiting superior soil quality attributed to higher organic carbon content, better pH buffering capacity, and enhanced cation exchange capacity. However, the overall low SQI values, particularly in Epe and Ikorodu, coupled with deficiencies in critical macronutrients (nitrogen, phosphorus, and potassium), indicate that agricultural productivity in these farmlands is constrained by multiple soil fertility limitations that require targeted nutrient management interventions.

Microplastic contamination patterns revealed alarming accumulation levels, particularly in Ikorodu, where intensive agricultural practices, proximity to urban centers, and inadequate waste management converge to create severe contamination hotspots. The predominance of PE and PP polymers, film and fragment morphologies, and the 500 μm-1 mm size class directly reflects local agricultural practices involving extensive plastic mulch application and irrigation infrastructure. The pronounced depth gradient, with surface soils containing higher microplastic concentrations than subsurface layers, suggests that contamination is relatively recent and primarily surface-deposited, though the rainy season enhancement of subsurface contamination (up to 18 particles at 15-30 cm) signals increasing vertical migration that threatens deeper soil horizons and groundwater quality.

The Redundancy Analysis provides mechanistic insights into soil-microplastic relationships, demonstrating that while geographic location dominates contamination patterns (53.3% variance), soil physicochemical properties; particularly organic carbon and organic matter play statistically significant roles in governing microplastic retention and mobility. The substantially higher explanatory power of soil properties in subsurface horizons (Adjusted R^2=0.472) compared to surface layers (Adjusted R^2=0.172) indicates that systematic retention processes dominate at depth, while stochastic surface processes obscure soil chemistry effects in topsoil. This finding suggests that soil amendment strategies targeting organic matter enhancement may be more effective for managing subsurface microplastic mobility than surface contamination, which remains overwhelmingly controlled by external loading factors.

The seasonal stability of soil-microplastic relationships (dry season Adjusted R^2=0.285; rainy season Adjusted R^2=0.244) confirms that identified mechanisms operate consistently across temporal scales, though the rainy season increases in both surface and subsurface microplastic concentrations highlight enhanced water-mediated transport that accelerates contamination spread and threatens aquatic ecosystems through agricultural runoff. This seasonal dynamic is particularly concerning given Lagos State's extensive network of lagoons, rivers, and coastal waters that receive agricultural drainage.

From a management perspective, these findings necessitate a multi-pronged intervention strategy: (1) source reduction through regulation of agricultural plastic use, promotion of biodegradable alternatives, and improved waste collection infrastructure; (2) agricultural best management practices including minimizing plastic mulch application, proper disposal of agricultural plastics, and adoption of organic mulching alternatives; (3) soil quality enhancement through organic matter addition to improve microplastic retention and reduce mobility; (4) seasonal runoff management to prevent rainy season transport of microplastic-laden sediments to aquatic systems; and (5) continuous monitoring programs to track temporal trends and assess intervention effectiveness. Given the documented uptake of microplastics by crop plants and potential food chain implications, urgent action is required to protect both environmental health and food security in Lagos State's critical agricultural zones.

AUTHORS' CONTRIBUTION

OLU, J.: Contributed to field data collection, manuscript conceptualization and development, data science methodologies, and geospatial analysis.

SAMAILA, I.K.: Contributed to manuscript development, critical review, and interpretation of research findings and data.

YUSUF, H.O.: Contributed to quantitative data analysis, statistical interpretation, and manuscript development.

SANGARI, D.U.: Contributed to manuscript drafting, structural organization, and critical revision of the intellectual content.

HAYATU, S.J.: Contributed to field data collection and participated in manuscript preparation and development.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study. No conflicts of interest exist with respect to the research, authorship, or publication of this article.

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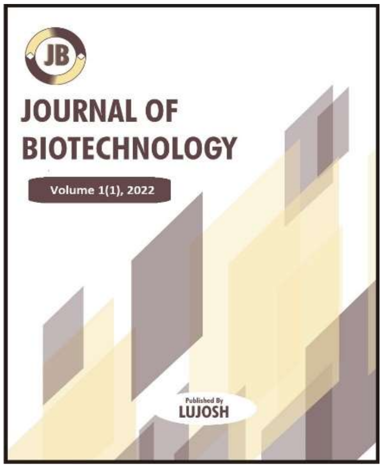

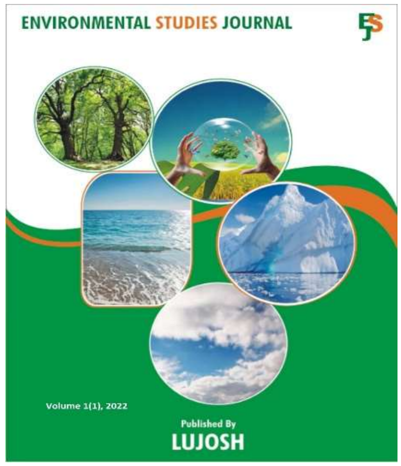

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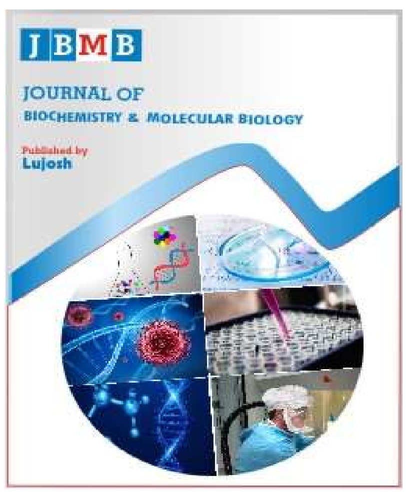

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