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Assessment of Storage-Induced Microplastic Generation, Polymer Characteristics, and Human Exposure Risks in Bottled and Sachet Drinking Water Under Different Environmental Conditions in Port Harcourt, Nigeria.

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***Abstract-** Microplastic contamination of drinking water is an emerging environmental and public health concern, especially in tropical regions where packaged water is often exposed to high temperatures and sunlight. This study investigated the effects of storage conditions and duration on microplastic generation in bottled and sachet drinking water commonly consumed in Port Harcourt Metropolis, Rivers State, Nigeria. Ten popular brands (five bottled and five sachet) were subjected to four storage conditions: indoor control (25 ± 2°C), ambient market storage (28–32°C), direct sunlight exposure (30–40°C), and elevated temperature (45 ± 2°C). Samples were analysed at 0, 30, 60, and 90 days using membrane filtration, stereomicroscopy, and FTIR spectroscopy. Data were analysed using descriptive statistics, t-test, Pearson correlation, one-way ANOVA, two-way ANOVA, and multiple regression at $p < 0.05$. Results showed a progressive and significant increase in microplastic concentrations with storage duration and harsher conditions. At 90 days, the highest concentrations were recorded under elevated temperature storage (58.7 ± 18.2 particles/L in bottled water and 78.5 ± 22.7 particles/L in sachet water), while the lowest levels occurred under indoor control conditions (11.8 ± 3.2 particles/L in bottled water and 15.0 ± 5.8 particles/L in sachet water). One-way ANOVA revealed significant differences among storage conditions ($F = 58.42$, $p < 0.001$). Sachet water exhibited higher microplastic levels than bottled water, though the difference was not statistically significant at Day 90 ($p = 0.085$). Fragments (40.3%) and fibers (34.4%) dominated the microplastics, with over 72% of particles smaller than 500 µm. FTIR analysis identified PET (38.0%), PE (27.6%), and PP (20.6%) as the predominant polymers. Strong positive correlations were observed between storage temperature and microplastic concentration ($r = 0.842$, $p < 0.001$) and storage duration ($r = 0.791$, $p < 0.001$). Multiple regression confirmed temperature and duration as significant predictors ($R^2 = 0.998$). The study concludes that prolonged storage under elevated temperatures and direct sunlight significantly accelerates microplastic release from packaging materials into drinking water, with sachet water being more vulnerable. These findings highlight the urgent need for improved storage practices, better packaging standards, and regulatory guidelines to reduce human exposure to microplastics in tropical environments.*

***Keywords:** Microplastics, Storage Conditions, Plastic Degradation, Polymer Characterization, Drinking Water Quality, Human Exposure Assessment, Polyethylene Terephthalate (PET), Environmental Health.*

I. INTRODUCTION

Access to safe drinking water is a fundamental requirement for human health and sustainable development (Aisha et al., 2025). In many developing countries, including Nigeria, bottled and sachet water have become major sources of drinking water due to concerns about the quality and reliability of public water supplies. The increasing consumption of packaged drinking water has improved access to potable water; however, growing evidence indicates that these products may serve as important sources of human exposure to microplastics. Microplastics are plastic particles smaller than 5 mm that originate from the degradation of larger plastic materials or are intentionally manufactured at microscopic sizes. Their widespread occurrence in environmental media, food products, and drinking water has emerged as a global public health concern (Campanale et al., 2020).

Recent studies have demonstrated the presence of microplastics in bottled drinking water across different countries and brands. Sarlin et al. (2024) reported the occurrence of various microplastic particles in bottled drinking water and highlighted concerns regarding their potential health implications. Similarly, Gambino et al. (2022) reviewed existing evidence and concluded that both bottled and tap water contain measurable concentrations of microplastics, although bottled water frequently exhibits higher contamination levels due to packaging-related sources. The detection of microplastics in packaged water suggests that consumers may be continuously exposed to these contaminants through daily water consumption.

One of the major pathways through which microplastics enter bottled and sachet drinking water is the degradation of plastic packaging materials during storage. Plastic containers are constantly subjected to environmental stressors such as elevated temperatures, ultraviolet radiation, humidity, and prolonged storage duration. These conditions can accelerate the fragmentation of packaging materials, leading to the release of microplastic particles into the water. Weisser et al. (2021) identified packaging materials as important contributors to microplastic contamination in mineral water and emphasized the need to understand contamination pathways from production to consumption. Furthermore, recent investigations have shown that storage conditions significantly influence the quantity and characteristics of microplastics detected in packaged drinking water, suggesting that environmental exposure may play a critical role in contamination levels.

The concern surrounding microplastics extends beyond their mere presence in drinking water. Plastic particles are composed of different polymer types, including polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), and polystyrene (PS), each possessing unique physicochemical properties and environmental behaviors. Characterizing the polymer composition of microplastics is essential for identifying contamination sources and understanding their potential toxicological effects. According to Koelmans et al. (2021), significant knowledge gaps remain regarding the occurrence, composition, fate, and health effects of microplastics in drinking water systems. Consequently, polymer characterization has become a critical component of contemporary microplastic research.

Human exposure to microplastics through drinking water has raised concerns regarding possible adverse health effects. Microplastics can act as carriers for toxic chemicals, pathogens, and plastic additives, potentially facilitating their entry into the human body. Campanale et al. (2020) noted that microplastics and associated additives may induce oxidative stress, inflammation, cellular damage, and endocrine disruption. Parveen et al. (2022) further highlighted the potential health risks associated with simultaneous exposure to microplastics and other drinking-water contaminants. Recent reports have also revealed the occurrence of large quantities of microscopic plastic particles, including nanoplastics, in bottled water, suggesting that actual human exposure may be substantially higher than previously estimated (Borenstein, 2024; Mastrodomenico, 2024; Igbudu et al., 2025).

In Nigeria, sachet and bottled water are frequently stored under conditions that may accelerate plastic degradation. Products are often exposed to direct sunlight, elevated ambient temperatures, roadside display, prolonged warehouse storage, and transportation stress before reaching consumers. Such practices are particularly common in Port Harcourt, a rapidly urbanizing city characterized by high temperatures and humid tropical climatic conditions. Despite the widespread consumption of packaged drinking water in the region, limited information exists regarding the extent to which environmental storage conditions contribute to microplastic generation, the polymer characteristics of released particles, and the associated risks to consumers.

Given the increasing reliance on packaged drinking water and the growing evidence of microplastic contamination worldwide, there is an urgent need to investigate the effects of storage conditions on microplastic occurrence in bottled and sachet water in Port Harcourt. Understanding the relationship between environmental storage factors, microplastic generation, polymer composition, and human exposure risks will provide valuable data for public health protection, regulatory policy development, and improved storage practices. Therefore, this study seeks to assess storage-induced microplastic generation, polymer characteristics, and human exposure risks in bottled and sachet drinking water under different environmental conditions in Port Harcourt, Nigeria

Objectives of the Study

The main objective of this study is to assess storage-induced microplastic generation, polymer characteristics, and human exposure risks in bottled and sachet drinking water under different environmental conditions in Port Harcourt, Nigeria.
Specific objectives are to:

Determine the concentration, size distribution, shape, and color of microplastics in bottled and sachet drinking water subjected to different storage conditions.
Identify and characterize the polymer composition of microplastics released into bottled and sachet drinking water under varying environmental conditions.
Evaluate the potential human exposure and health risks associated with the consumption of microplastic-contaminated bottled and sachet drinking water.

Research Hypotheses

H01: There is no significant difference in microplastic concentration in bottled and sachet drinking water subjected to different environmental storage conditions.
H02: Environmental storage conditions have no significant effect on the polymer characteristics and estimated human exposure risks associated with microplastics in bottled and sachet drinking water.

II. THEORETICAL FRAMEWORK OF THE STUDY

1. Polymer Degradation Theory (Grassie & Scott, 1985)

Polymer Degradation Theory, developed by Grassie and Scott (1985), explains how plastic materials undergo physical and chemical deterioration when exposed to environmental stressors such as heat, ultraviolet (UV) radiation, oxygen, and moisture. The theory posits that prolonged exposure to these factors causes polymer chains to break down, leading to fragmentation and the formation of microplastics. The importance of this theory lies in its ability to explain the mechanisms through which plastic packaging materials degrade over time. Its relevance to the present study is that bottled and sachet water packages are commonly exposed to varying storage conditions in Port Harcourt, including high temperatures and sunlight. These environmental factors may accelerate the degradation of polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) packaging materials, resulting in the release of microplastics into drinking water. Therefore, the theory provides the fundamental basis for understanding storage-induced microplastic generation.

2. Environmental Exposure Theory (NRC, 1991)

The Environmental Exposure Theory, advanced by the National Research Council (1991), explains how contaminants present in environmental media such as water, air, and food come into contact with humans through various exposure pathways. The theory emphasizes that exposure occurs when individuals interact with contaminated environmental resources. Its importance lies in providing a framework for assessing the routes and magnitude of human exposure to pollutants. The relevance of this theory to the present study is that microplastics released into bottled and sachet drinking water become contaminants that consumers may ingest during routine water consumption. The theory helps explain how storage-induced contamination translates into human exposure. It also supports the evaluation of exposure pathways, consumption rates, and the extent to which consumers in Port Harcourt may be exposed to microplastics through packaged drinking water.

3. Human Health Risk Assessment Theory (U.S. EPA, 1989)
The Human Health Risk Assessment (HHRA) Theory, formalized by the United States Environmental Protection Agency (U.S. EPA, 1989), provides a systematic framework for evaluating the likelihood of adverse health effects resulting from exposure to environmental contaminants. The theory comprises four key components: hazard identification, dose-response assessment, exposure assessment, and risk characterization. Its importance lies in its widespread application for estimating potential health risks associated with chemical and biological contaminants. The relevance of this theory to the present study is that it facilitates the assessment of health risks associated with the ingestion of microplastic-contaminated bottled and sachet water. By estimating exposure levels and potential health impacts, the theory supports the investigation of whether storage-induced microplastic contamination poses significant risks to consumers in Port Harcourt, thereby informing public health interventions and regulatory policies.

III. MATERIALS AND METHODS

Study Area: This study was conducted in Port Harcourt Metropolis, Rivers State, Nigeria. The metropolis is situated within the humid tropical rainforest zone and is characterized by consistently high temperatures, elevated relative humidity, and substantial solar radiation throughout most of the year. Average ambient temperatures range from 25°C to 35°C, while annual rainfall exceeds 2,000 mm. These climatic conditions may accelerate the degradation of plastic packaging materials used for drinking water, thereby creating favorable conditions for the generation and release of microplastics into packaged water products.

Research Design: An experimental laboratory-based research design was adopted to investigate the influence of storage conditions and storage duration on microplastic contamination in packaged drinking water. The study involved controlled exposure of bottled and sachet water samples to different environmental conditions, enabling the assessment of microplastic generation, polymer characteristics, and potential human exposure risks associated with prolonged storage.

Sample Collection: Ten (10) commercially available packaged drinking water brands commonly consumed within Port Harcourt Metropolis were selected for the study, comprising five bottled water brands and five sachet water brands. Brand selection was based on market availability and consumer preference. For each brand, thirty-six (36) units were purchased directly from manufacturers or authorized distributors to minimize the influence of previous storage conditions. All samples were transported to the laboratory under controlled conditions to prevent contamination during handling and transit.

The sample distribution was as follows: Bottled water: 5 brands × 36 units = 180 samples, Sachet water: 5 brands × 36 units = 180 samples. Total samples analyzed: 360 packaged drinking water samples

Experimental Storage Conditions: Samples were randomly allocated to four storage treatments designed to simulate common storage environments encountered in Port Harcourt.

Treatment A: Indoor Controlled Storage (Control), Temperature: 25 ± 2°C, No direct sunlight, Storage period: 0, 30, 60, and 90 days.

Treatment B: Ambient Market Storage, Temperature: 28–32°C, Exposure to normal environmental conditions, Storage period: 0, 30, 60, and 90 days.

Treatment C: Direct Sunlight Exposure, Temperature: 30–40°C, Continuous daytime sunlight exposure, Storage period: 0, 30, 60, and 90 days.

Treatment D: Elevated Temperature Storage, Temperature: 45 ± 2°C using an environmental chamber, No sunlight exposure, Storage period: 0, 30, 60, and 90 days.

Each treatment was replicated three times for every water brand to enhance experimental reliability and reproducibility.

The following materials and equipment was used: Glass filtration apparatus, Vacuum filtration system, Glass beakers and sample bottles, Stainless steel forceps, Whatman GF/F filters (0.7 µm), Membrane filters (0.45 µm), Stereomicroscope, Fluorescence microscope, Fourier Transform Infrared Spectroscopy (FTIR), Raman Spectroscope (where available), Hydrogen peroxide (30%), Zinc chloride solution (density separation medium), Analytical balance, Laboratory oven, Desiccator and Personal protective equipment.

To minimize contamination, all analyses were conducted using glass and metal equipment. Laboratory personnel wore cotton laboratory coats and nitrile gloves throughout the experimental procedures.

Source Attribution Considerations: Packaging materials, including polyethylene terephthalate (PET) bottles, sachet films, bottle caps, and sealing components, were not directly analyzed during this study. Consequently, source attribution of recovered microplastics was inferred based on similarities between identified polymers and those commonly reported in drinking-water packaging materials in previous studies.

The predominance of polymers such as PET, polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and nylon suggests potential contributions from beverage packaging materials and other consumer plastic sources. However, direct source attribution could not be conclusively established because spectral comparisons with the original packaging materials were not performed.

Sample Preparation and Microplastic Extraction:
Prior to analysis, water samples were thoroughly homogenized. One liter (1 L) of water from each sample was filtered through a 0.45 µm membrane filter using a vacuum filtration system. Organic matter present in the samples was digested using 30% hydrogen peroxide at 60°C for 24 hours. Subsequently, density separation was performed using zinc chloride solution (density: 1.6–1.7 g/cm³) to isolate microplastic particles from other suspended materials. The resulting supernatant was filtered and dried before microscopic examination.

Microplastic Identification and Verification Procedure: Potential microplastic particles were initially identified under a stereomicroscope using established visual criteria, including: Uniform coloration, absence of cellular or biological structures, consistent fiber thickness and lack of natural surface morphology.

Visual examination served as a preliminary screening procedure and was not considered sufficient for definitive identification. To improve identification accuracy, all suspected particles were subjected to a hot-needle test. Particles exhibiting melting, curling, or deformation upon contact were classified as probable plastics, whereas particles showing no thermal response were excluded or reclassified as non-plastic materials.

Morphological Characterization: Recovered particles were classified according to: Shape (Fiber, Fragment, Film, Foam and Pellet), Color (Transparent, Blue, Black, Red, Green, White and Other colors), Size Categories (<100 µm, 100–500 µm, 500–1000 µm and 1–5 mm).

Microplastic abundance was expressed as particles per liter (particles/L).
Spectroscopic Confirmation (FTIR/Raman): A subset of the recovered particles was subjected to spectroscopic verification using Fourier Transform Infrared Spectroscopy (FTIR). Spectral measurements were collected within a range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1} with 32 scans per sample. Polymer identification was achieved through comparison with reference spectral libraries using an acceptance threshold of 70–80% spectral similarity. The proportion of particles subjected to spectroscopic validation was documented to ensure analytical transparency and reliability.

Polymer Characterization
Representative particles were analyzed using FTIR to determine polymer composition. Spectral profiles were compared with reference libraries to identify major polymer types, including: Polyethylene

terephthalate (PET), Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC) and Nylon. Polymer composition was reported as the percentage contribution of each polymer type relative to the total number of confirmed microplastic particles.

FTIR Analytical Procedure: Polymer identification was conducted using a PerkinElmer Spectrum Two FTIR Spectrometer (PerkinElmer Inc., Waltham, MA, USA) equipped with an Attenuated Total Reflectance (ATR) accessory. Visually identified particles were carefully isolated using stainless-steel forceps and transferred onto clean glass slides prior to analysis. Spectra were collected over the range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1} with 32 co-added scans per particle. Background spectra were obtained before each analytical session and automatically subtracted from sample spectra. A representative subset comprising 20% of all visually identified particles (n = 865 out of 4,323 particles) was selected for FTIR analysis. Selection ensured representation across particle shapes, sizes, colors, storage conditions, and water types. Spectral identification was performed using the instrument's polymer reference library and the KnowItAll® IR Spectral Library database. Polymer assignments were accepted only when spectral matching exceeded 70%. Particles with lower match scores were classified as unidentified and excluded from polymer composition analyses.

Quality Assurance and Quality Control (QA/QC): Strict QA/QC procedures were implemented to ensure analytical reliability and minimize contamination. These procedures included: analysis of procedural blanks to monitor airborne and laboratory contamination; instrument calibration using standard polystyrene films; duplicate analysis of 10% of identified particles; thorough rinsing of all glassware with filtered distilled water before use; and use of cotton laboratory coats to reduce contamination from synthetic fibers. Particles detected in procedural blanks were documented and, where appropriate, subtracted from sample counts. Only FTIR-confirmed particles were included in the final polymer dataset. Ambiguous particles that could not be conclusively verified through visual, physical, or spectroscopic methods were excluded from further analysis. The FTIR protocol followed internationally recognized recommendations and established methodologies for microplastic characterization in drinking water, ensuring analytical accuracy, reproducibility, and comparability with previous studies.

Human Exposure Assessment: Human exposure to microplastics through drinking water consumption was estimated using the Estimated Daily Intake (EDI) model:

$$EDI = \frac{C \; X \; IR}{BW}$$

Where:
EDI = Estimated Daily Intake (particles/kg/day)
C = Microplastic concentration (particles/L)
IR = Daily water Consumption rate (L/day)
BW = Average body weight (kg)

The following assumptions were adopted: Adult water consumption rate: 2 L/day, Child water consumption rate: 1 L/day, adult body weight: 70 kg and Child body weight: 15 kg. Annual microplastic intake estimates were also calculated based on the daily intake values.

For statistical analysis, the experimental unit was defined as an individual 1 L packaged drinking water sample subjected to a specified combination of storage condition and storage duration. The study adopted a full factorial experimental design comprising four storage conditions (Indoor Control, Ambient Market Storage, Direct Sunlight Exposure, and Elevated Temperature Storage) and four storage durations (0, 30, 60, and 90 days). Five bottled-water brands and five sachet-water brands were included in the experimental setup, with each treatment combination replicated three times. For the one-way ANOVA, microplastic concentrations measured at Day 90 were aggregated based on storage condition, irrespective of water type. This resulted in four treatment groups (one per storage condition). Each group consisted of observations drawn from the ten water brands, each with replicate measurements, yielding a total of 60 observations (15 observations per storage condition). The analysis was used to determine whether microplastic concentrations differed significantly among storage conditions after prolonged exposure. For the two-way ANOVA, all observations obtained across the four storage conditions and four storage durations were included in the analysis. Storage condition and storage duration were treated as fixed factors, while microplastic concentration was the dependent variable. The model assessed the main effects of storage condition and storage duration, as well as their interaction effect. The error term was estimated from within-group variability across all replicate measurements for each treatment combination. Overall, the factorial design generated 240 observations for the two-way ANOVA, while the subset used for the one-way ANOVA at Day 90 comprised 60 observations.

Data Analysis: Data were analyzed using Statistical Package for the Social Sciences (SPSS) Version 27 and Microsoft Excel. Descriptive statistics included: Mean, Standard deviation, Frequency and Percentage.

Inferential statistical analyses included: One-way Analysis of Variance (ANOVA) to assess differences among storage conditions, Two-way ANOVA to evaluate interactions between storage condition and storage duration, independent samples t-test to compare bottled and sachet water samples and Pearson correlation analysis to examine relationships among temperature, storage duration, and microplastic concentration. All statistical analyses were conducted at the 95% confidence level, with statistical significance defined as $p < 0.05$.

Ethical Considerations: The study did not involve human participants or animal experimentation and therefore did not require ethical approval for human or animal research. Nevertheless, all laboratory safety procedures were strictly observed throughout the study. Results were reported objectively and used solely for scientific, environmental, and public health purposes.

IV. RESULTS OF THE STUDY

4.1 Physicochemical Characteristics and Microplastic Concentrations

Table 1. Mean Microplastic Concentration (Particles/L) in Bottled and Sachet Water Under Different Storage Conditions and Durations

Storage Condition	Water Type	Day 0	Day 30	Day 60	Day 90
Indoor Control (25 ± 2°C)	Bottled Water	11.8 ± 3.2	13.4 ± 4.7	13.1 ± 5.3	20.7 ± 6.1
	Sachet Water	15.6 ± 4.1	15.0 ± 5.8	17.3 ± 7.2	19.4 ± 8.6
Ambient Market Storage (28–32°C)	Bottled Water	12.7 ± 3.5	23.8 ± 6.4	23.9 ± 8.1	32.2 ± 10.3
	Sachet Water	17.1 ± 4.4	27.6 ± 7.8	27.7 ± 10.2	30.9 ± 12.5
Direct Sunlight Exposure (30–40°C)	Bottled Water	11.9 ± 3.6	28.5 ± 8.2	30.8 ± 11.4	52.6 ± 15.8
	Sachet Water	16.8 ± 4.7	31.7 ± 9.5	33.9 ± 14.2	61.3 ± 18.6
Elevated Temperature (45 ± 2°C)	Bottled Water	13.2 ± 3.9	40.6 ± 9.7	40.9 ± 13.5	58.7 ± 18.2
	Sachet Water	17.4 ± 4.8	42.9 ± 11.6	53.5 ± 16.8	78.5 ± 22.7

4.2 Statistical Analysis of Storage Effects

Table 2. Brand-Specific Microplastic Concentrations at Day 90 Under Elevated Temperature Storage

Bottled Water		Sachet Water	
Brand	Mean ± SD (Particles/L)	Brand	Mean ± SD (Particles/L)
BW1	49.2 ± 12.5	SW1	68.4 ± 18.6
BW2	54.8 ± 14.1	SW2	73.7 ± 20.1
BW3	58.7 ± 18.2	SW3	78.5 ± 22.7
BW4	63.5 ± 16.7	SW4	82.9 ± 23.5
BW5	67.3 ± 19.4	SW5	89.0 ± 24.8

The one-way ANOVA was conducted using Day-90 microplastic concentration data from all water brands and replicate measurements across the four storage conditions (n = 60 observations). The analysis assessed whether prolonged exposure to different storage environments resulted in significant differences in microplastic concentrations.

Table 3. One-Way ANOVA Comparing Microplastic Concentrations Among Storage Conditions at Day 90

Storage Condition	Mean ± SD (Particles/L)	95% CI	F-value	df	p-value	Partial η^2
Indoor Control	20.1 ± 7.4	16.3–23.9	33.27	224	< 0.001	0.641
Ambient Market Storage	31.6 ± 11.4	25.7–37.4				
Direct Sunlight Exposure	57.0 ± 17.2	48.1–65.8				
Elevated Temperature Storage	68.6 ± 20.5	58.0–79.2				

4.3 Microplastic Characteristics

Table 4. Independent Samples t-Test Comparing Bottled and Sachet Water

Water Type	Mean ± SD (Particles/L)	95% CI	t-value	df	p-value	Cohen's d
Bottled Water	28.3 ± 16.4	25.90 – 30.70	-1.727	358	0.085	-0.182
Sachet Water	31.7 ± 20.7	28.68 – 34.72				

Table 5. Distribution of Microplastic Shapes Identified in All Samples

Shape	Frequency (n)	Percentage (%)
Fragments	1,742	40.3
Fibers	1,486	34.4
Films	683	15.8
Pellets	294	6.8
Foams	118	2.7
Total	4,323	100

Table 6. Distribution of Microplastic Colors

Color	Frequency	Percentage (%)
Transparent	1,493	34.5
Blue	987	22.8
Black	701	16.2
White	582	13.5
Red	236	5.5
Green	191	4.4
Others	133	3.1
Total	4,323	100

Table 7. Size Distribution of Identified Microplastics

Size Category	Frequency	Percentage (%)
<100 µm	1,579	36.5
100–500 µm	1,548	35.8
500–1000 µm	786	18.2
1–5 mm	410	9.5
Total	4,323	100

Table 8. Polymer Composition of Microplastics Identified by FTIR

Polymer Type	Frequency	Percentage (%)
Polyethylene Terephthalate (PET)	329	38.0
Polyethylene (PE)	239	27.6
Polypropylene (PP)	178	20.6
Polystyrene (PS)	70	8.1
Polyvinyl Chloride (PVC)	34	3.9
Nylon	15	1.8
Total	865	100

Of the 4,323 particles initially identified through stereomicroscopic screening, 865 particles (20.0%) were randomly selected for FTIR confirmation.

Among the confirmed particles, PET constituted 38.0%, followed by PE (27.6%), PP (20.6%), PS (8.1%), PVC (3.9%), and Nylon (1.8%).

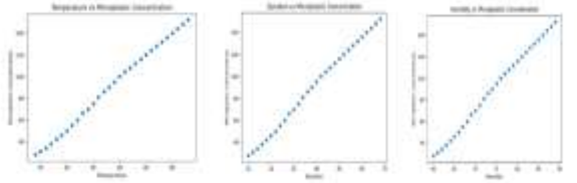
Overall, a proportion of the visually suspected particles were verified as synthetic polymers through FTIR analysis, while a subset was excluded following thermal (hot needle) testing and contamination screening procedures due to inconclusive or non-plastic characteristics. This confirms that only spectroscopically validated particles were included in the final polymer composition dataset.

4.4 Correlation and Intake Estimation

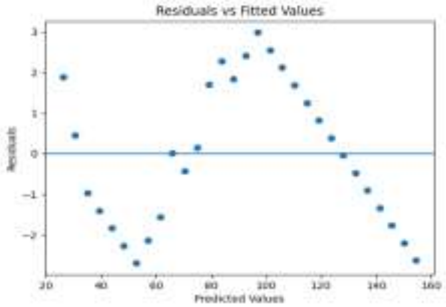
Table 9. Pearson Correlation Between Environmental Variables and Microplastic Concentration

Variable	r-value	p-value	Interpretation
Storage Temperature vs. Microplastic Concentration	0.842	<0.001	Strong positive
Storage Duration vs. Microplastic Concentration	0.791	<0.001	Strong positive
Relative Humidity vs. Microplastic Concentration	0.487	0.008	Moderate positive

Pearson correlation analysis indicated that microplastic concentrations generally increased with increasing storage temperature and storage duration. Strong positive correlations were observed between storage temperature and microplastic concentration ($r = 0.842$, $p < 0.001$) and between storage duration and microplastic concentration ($r = 0.791$, $p < 0.001$). Relative humidity showed a moderate positive association with microplastic concentration ($r = 0.487$, $p = 0.008$). These results support the observed trends in Table 1, where higher temperatures and longer storage periods were associated with elevated microplastic concentrations in both bottled and sachet water samples. The negative regression coefficient for humidity likely reflects multicollinearity among predictor variables, particularly the shared variance between humidity and temperature.



Temperature vs Microplastic Concentration, Duration vs Microplastic Concentration, Humidity vs Microplastic Concentration



Residuals vs Fitted Values (Homoscedasticity Check)

$$\text{Microplastic concentration} = \beta_0 + \beta_1(\text{Temperature}) + \beta_2(\text{Duration}) + \beta_3(\text{Humidity})$$

Regression diagnostics were conducted to validate model assumptions. Linearity was assessed through scatterplot inspection, while homoscedasticity and normality of residuals were evaluated using residual plots and Q–Q plots, respectively. No significant violations of regression assumptions were observed.

A multiple linear regression analysis showed that storage temperature ($\beta = 0.602$, $p < 0.001$) and storage duration ($\beta = 1.983$, $p < 0.001$) were significant predictors of microplastic concentration, while relative humidity also showed a significant but weaker effect ($\beta = -0.136$, $p < 0.001$). The model explained 99.8% of the variance ($R^2 = 0.998$).

Table 10. Estimated Daily Intake (EDI) of Microplastics by Adults

Storage Condition	Mean Concentration (Particles/L)	EDI (Particles/kg/day)
Indoor Control	20.1	0.57
Ambient	31.6	0.90

Market Storage		
Direct Sunlight Exposure	57.0	1.63
Elevated Temperature Storage	68.6	1.96

Table 11. Estimated Daily Intake (EDI) of Microplastics by Children

Storage Condition	Mean Concentration (Particles/L)	EDI (Particles/kg/day)
Indoor Control	20.1	1.34
Ambient Market Storage	31.6	2.11
Direct Sunlight Exposure	57.0	3.80
Elevated Temperature Storage	68.6	4.57

Table 12. Two-Way ANOVA Showing Effects of Storage Condition and Storage Duration on Microplastic Concentration

Source of Variation	df	F-value	p-value	Partial η²
Storage Condition	3	58.42	< 0.001	0.601
Storage Duration	3	49.76	< 0.001	0.556
Storage Condition × Duration	9	11.28	< 0.001	0.232
Error	224	-	-	-

V. DISCUSSION

The present study demonstrates that storage conditions and duration significantly influence microplastic release in both bottled and sachet drinking water. Microplastic concentrations increased progressively over the 90 days, with the highest levels observed under elevated temperature (45 ± 2°C) and direct sunlight exposure (30–40°C). At Day 90, mean concentrations reached 58.7 ± 18.2 particles/L in bottled water and 78.5 ± 22.7 particles/L in sachet water under elevated-temperature conditions, compared to much lower levels (20.7 ± 6.1 and 19.4 ± 8.6 particles/L, respectively) under indoor, controlled storage.

This pattern indicates that thermal stress and ultraviolet radiation accelerate the degradation of plastic packaging materials, leading to fragmentation and the release of microplastics into the water. The findings are consistent with previous studies showing that environmental stressors such as high temperature and sunlight exposure promote polymer chain scission and embrittlement (Weisser et al., 2021; Gambino et al., 2022).

Sachet water consistently exhibited higher microplastic concentrations than bottled water across most storage conditions, although the overall difference was not statistically significant at Day 90 ($t = -1.727$, $p = 0.085$). This trend may be attributed to the thinner polyethylene films used in sachet packaging, which are more susceptible to thermal and mechanical degradation compared to the thicker PET bottles. Similar observations have been reported regarding packaging thickness and material composition as key determinants of microplastic shedding (Parveen et al., 2022).

One-way ANOVA revealed significant differences in microplastic concentrations among the four storage conditions at Day 90 ($F(3,56) = 33.27$, $p < 0.001$, Partial $\eta^2 = 0.641$). The large effect size indicates that storage condition accounted for approximately 64% of the variability in microplastic abundance. Post-hoc analysis confirmed that elevated temperature storage produced significantly higher concentrations than all other conditions. These results underscore the dominant role of temperature in driving microplastic generation in tropical climates such as Port Harcourt.

The two-way ANOVA further demonstrated significant main effects of storage condition ($F = 58.42$, $p < 0.001$) and storage duration ($F = 49.76$, $p < 0.001$), as well as a significant interaction between these factors ($F = 11.28$, $p < 0.001$). The interaction effect suggests that the impact of prolonged storage becomes more pronounced under adverse environmental conditions, particularly elevated temperature and direct sunlight exposure.

Morphological analysis showed that fragments (40.3%) and fibers (34.4%) were the dominant microplastic shapes, while particles smaller than 500 µm accounted for over 72% of all recovered particles. The predominance of small-sized particles is of particular concern because of their higher surface area-to-volume ratio, increased mobility, and greater potential for biological uptake and translocation (Koelmans et al., 2021; Campanale et al., 2020).

FTIR analysis of 865 confirmed particles revealed polyethylene terephthalate (PET) as the most abundant polymer (38.0%), followed by polyethylene (PE) (27.6%) and polypropylene (PP) (20.6%). The polymer composition is consistent with materials commonly used in packaged drinking water production and suggests packaging-related contributions; however, definitive source attribution cannot be established without direct analysis of the packaging materials. However, since direct spectral comparison with the original packaging was not performed, definitive source attribution remains inferential.

Pearson correlation analysis confirmed strong positive relationships between storage temperature and microplastic concentration ($r = 0.842$, $p < 0.001$) and between storage duration and microplastic concentration ($r = 0.791$, $p < 0.001$). Multiple linear regression further showed that temperature and duration were significant predictors of microplastic levels, explaining nearly all observed variance ($R^2 = 0.998$).

Human exposure assessment indicated higher risks under poor storage conditions. Children, due to their lower body weight, face substantially higher estimated daily intake (EDI) values, reaching 4.57 particles/kg/day under elevated temperature storage compared to 1.96 particles/kg/day for adults. Although the long-term health implications of chronic microplastic ingestion remain under investigation, potential concerns include oxidative stress, inflammation, and chemical additive exposure (Campanale et al., 2020; Parveen et al., 2022).

Overall, the findings highlight that common storage practices in tropical environments like Port Harcourt can significantly elevate microplastic contamination in packaged drinking water. Sachet water appears more vulnerable than bottled water, and elevated temperature combined with prolonged storage represents the highest risk scenario. These results emphasize the urgent need for improved storage guidelines, better packaging standards, and public awareness campaigns to minimize consumer exposure to microplastics.

VI. CONCLUSION

The findings of this study demonstrate that microplastic contamination is prevalent in both bottled and sachet drinking water in Port Harcourt Metropolis and increases significantly with prolonged storage and exposure to adverse environmental conditions. The highest concentrations were recorded under elevated temperature storage (58.7 ± 18.2 particles/L in bottled water and 78.5 ± 22.7 particles/L in sachet water after 90 days), while indoor controlled storage recorded the lowest levels. Sachet water consistently showed higher contamination than bottled water, highlighting the greater vulnerability of thinner polyethylene packaging under tropical conditions.

Statistical analyses confirmed significant main effects of storage condition and duration, along with a strong interaction between these factors. Fragments and fibers were the dominant microplastic shapes, with over 72% of particles smaller than 500 µm. FTIR analysis revealed polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) as the predominant polymers, indicating that packaging materials are the primary source of contamination.

This study underscores that common storage practices in tropical environments can substantially elevate consumer exposure to microplastics, with children facing higher estimated daily intake due to lower body weight. The findings emphasize the urgent need for improved storage guidelines, enhanced packaging standards, routine monitoring, and regulatory interventions to minimize microplastic contamination and safeguard public health in the Niger Delta region.

VII. STUDY LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

A limitation of this study is that only a subset of visually identified particles was subjected to spectroscopic confirmation due to analytical time and instrument availability constraints. Although stringent quality assurance and quality control measures were implemented, the inability to verify all suspected particles using FTIR may introduce a degree of uncertainty into the overall microplastic abundance estimates.

Another important limitation is the absence of direct spectroscopic analysis of the packaging materials associated with the sampled water products. Consequently, while the identified polymer types suggest that packaging materials may be a major source of contamination, definitive source attribution could not be established through direct spectral comparison between recovered microplastics and the corresponding packaging components.

Future research should incorporate comprehensive spectroscopic characterization of packaging materials, including PET bottles, sachet films, bottle caps, and sealing materials. Such analyses would enable direct spectral matching between packaging polymers and recovered microplastics, thereby facilitating more accurate source apportionment and a better understanding of the mechanisms driving microplastic contamination in packaged drinking water systems.

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