Microplastics and Organic Leachates in PET Bottled Water Under Heat/Sunlight and Freezing Storage in Port Harcourt, Nigeria

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Abstract
The widespread dependence on polyethylene terephthalate (PET) bottled water in Nigeria, combined with tropical storage conditions and common consumer practices such as freezing, raises concerns about microplastic and chemical leachate contamination. This study assessed the occurrence, abundance, and morphological characteristics of microplastics, alongside organic chemical leachate profiles, in commercially available PET bottled water (1.5 L) subjected to three storage conditions over five days: unexposed control (22 ± 2°C, dark), heat/sunlight exposure (outdoor, direct sunlight), and freezing (−18°C with one thaw cycle at 72 hours). Each condition was represented by one bottle, split into two aliquots for microplastic characterisation and Gas Chromatography-Mass Spectrometry (GC-MS) analysis. Particles were identified by stereomicroscopy and optical microscopy using standardised visual criteria; polymer identity was not confirmed by FTIR or Raman spectroscopy. Results showed a mean particle count of 20.00 ± 2.00 in the control, 10.00 ± 2.00 under cold storage, and 27.00 ± 2.00 under heat exposure, with statistically significant differences among all groups (one-way ANOVA: $F(2,6) = 54.750$, $p < 0.001$; Tukey HSD: all pairwise $p < 0.05$). Fragments dominated (64.3%), followed by fibres (32.2%) and films (3.5%); films occurred only in the heat-exposed sample. Most particles (67.8%) were 1–5 mm. GC-MS screening produced tentative phthalate-related library matches in all samples, with the principal dimethyl phthalate (DMP)-associated peak Area% following the order heat exposure (0.76%) > control (0.46%) > cold storage (0.11%). The parallel ranking of particle abundance and DMP-associated signal (heat > control > cold) provides preliminary evidence that heat exposure may elevate both particulate and chemical contamination burdens in PET bottled water. These findings suggest the need for larger, spectroscopically confirmed studies to inform regulatory standards for microplastics in Nigerian packaged water.

Keywords: *Microplastics, bottled water, heat exposure, freezing, phthalates, Port Harcourt, Nigeria*

1.0 Introduction

Water is the most essential resource for human survival, and access to safe drinking water constitutes a fundamental public health imperative globally. In Nigeria, the widespread inadequacy of functional piped-water infrastructure has driven a massive and sustained dependence on commercially packaged water, principally bottled water sold in polyethylene terephthalate (PET) containers (Stoler, 2017; Umoafia et al., 2023). Despite its ubiquity and

perceived safety, plastic-packaged water carries a well-documented but underappreciated risk: the leaching of microplastic particles from the packaging material into the water itself.

Microplastics, defined as synthetic polymer particles with a longest dimension of less than 5 mm (Thompson et al., 2004), have been detected across virtually every environmental matrix studied, including marine systems, freshwater bodies, soils, air, and human food and beverages (Sajjad et al., 2022). Their presence in commercially bottled drinking water is now established in the scientific literature across numerous brands and countries (Mason et al., 2018; Oßmann et al., 2018).

The conditions under which bottled water is stored and distributed are particularly relevant to the Nigerian context. Ambient temperatures in the Niger Delta region, including Rivers State, routinely exceed 30°C, with daily maxima in exposed outdoor environments regularly surpassing 38–45°C during the dry season (NIMET, 2022). In parallel, the consumer practice of refrigerating and, in some cases, freezing bottled water for extended cooling is widespread across southern Nigerian communities. Both thermal extremes have been shown in international studies to accelerate polymer degradation and the consequent release of microplastic particles into packaged water (Zuccarello et al., 2019; Akhbarizadeh et al., 2022).

Nigeria's packaged water industry operates within a regulatory framework that currently contains no enforceable standards governing microplastic contamination in drinking water. While the National Agency for Food and Drug Administration and Control (NAFDAC) prescribes microbiological and physicochemical quality standards for packaged water, microplastics are not addressed by any existing NAFDAC regulation or Standards Organisation of Nigeria (SON) specification (Standards Organisation of Nigeria, 2015; NAFDAC, 2023). This regulatory gap persists notwithstanding the World Health Organisation's (2019) identification of microplastics as a priority emerging contaminant requiring urgent further research and precautionary policy attention.

This study therefore assessed the occurrence, abundance, and morphological characteristics of microplastics, and the associated organic chemical leachate profile, in commercially available bottled water in Port Harcourt, Nigeria, under three storage conditions: unexposed control, sunlight exposure, and freezing storage over a defined five-day experimental period. The specific objectives were to determine baseline particle concentrations; explore how sunlight exposure and freezing storage relate to particle abundance and morphology; characterise morphological types and size distribution; and characterise and compare organic chemical profiles using Gas Chromatography-Mass Spectrometry (GC-MS).

2.0 Methodology

2.1 Study Area

This study was conducted in Port Harcourt, capital of Rivers State, Nigeria (latitude 4°47′N, longitude 7°01′E). Port Harcourt has a tropical monsoon climate with a wet season (April–October) and dry season (November–March). Mean monthly temperatures range from approximately 25°C to 32°C, with daily maximum temperatures at exposed outdoor locations regularly exceeding 38–45°C during the dry season (NIMET, 2022).

2.2 Sample Collection and Handling

Commercially available bottled water in 1.5 L PET bottles, bearing current NAFDAC registration numbers, was purchased as generic, commercially available PET bottled water from a retail outlet in Port Harcourt. All products were collected and transported to the laboratory in sealed polyethylene bags inside insulated boxes, and randomly assigned to treatment groups immediately upon arrival to prevent inadvertent pre-study exposure differences.

2.3 Experimental Design

A one-way design with three treatment levels was employed: storage/exposure condition (control, heat/sunlight, freezing). Each treatment condition was represented by a single 1.5 L bottled water unit, for a total of three units analysed. Each unit was split into two aliquots: Aliquot A for microplastic morphological characterisation and Aliquot B for organic chemical leachate determination by GC-MS. Within each aliquot, analytical replicate readings/injections were taken (n = 3 per endpoint) to characterise measurement variability. All exposure conditions ran concurrently over the same five-day period to eliminate temporal confounds.

2.4 Exposure Protocols

Control samples were maintained at 22 ± 2°C in a temperature-controlled room under dark conditions (UV-excluded) for five consecutive days. Samples assigned to the heat/sunlight treatment were placed outdoors on a clean, elevated platform at the research facility, positioned to receive direct sunlight between 08:00 and 17:00 daily. The samples were arranged to avoid shading and ensure uniform exposure over a five-day period during conditions of consistent daytime sunlight. Samples in the freezing group were stored continuously at −18°C in a domestic-grade chest freezer for five days, with one thaw cycle introduced at the 72-hour mark by transferring samples to ambient room temperature (approximately 28–30°C) for 12 hours before re-freezing for the remaining two days. This single freeze-thaw cycle reflects a typical Nigerian consumer pattern of removing chilled/frozen bottled water for partial use before returning the remainder to the freezer.

2.5 Contamination Control

All personnel wore 100% cotton laboratory coats and nitrile gloves during sample processing. All glassware, filtration equipment, and analytical tools were triple-rinsed with deionised water and oven-dried at 400°C for four hours before use. Sample processing was conducted inside a laminar flow cabinet or under a prewashed aluminium foil clean bench to minimise airborne particle deposition. All plastic laboratory materials were excluded from the analytical environment to the maximum extent practicable.

2.6 Physicochemical Analysis

On day 5, pH and electrical conductivity (EC) of the water samples were determined ex situ under laboratory conditions. pH was measured using a calibrated pH meter, and EC was determined using a calibrated digital conductivity meter with standard potassium chloride (KCl) solution. The probe was rinsed between measurements to avoid cross-contamination.

2.7 Sample Preparation, Filtration, and Microscopy

Following the five-day exposure period, each treatment unit was opened under the clean bench and its contents poured into a pre-cleaned 2 L glass beaker. The inner surfaces of the container were rinsed three times with 100 mL of deionised water each, and the rinse was added to the beaker. The combined sample was thoroughly mixed and then divided into Aliquot A and Aliquot B. Aliquot A was passed sequentially through a stainless-steel filtration cascade consisting of 500µm, 100µm, and 20µm mesh filters, enabling size-fractional analysis of three particle classes: >500µm, 100–500µm, and 20–100µm. Each filter was subjected to organic matter digestion using 30% H_2O_2 at 50°C for 24 hours, followed by gentle rinsing with deionised water and drying at 40°C for 12 hours, prior to microscopic examination. Dried filter membranes were examined under a stereomicroscope (Olympus SZ61, 10×–40×) for particles ≥100µm. An optical microscope (Olympus CX23, 100×–400×) was used for particles between 20 and 100µm. All potential microplastics were recorded by morphological type (fibre, fragment, film, pellet), colour, and longest dimension (calibrated eyepiece micrometre). Visual

identification criteria followed Cowger et al. (2020): particles had to be homogeneously coloured or transparent with no visible cellular structure, exhibit synthetic morphological characteristics, and not crumble under gentle needle pressure. No spectroscopic (FTIR) polymer confirmation was performed; all reported counts and morphological classifications are the product of this visual screening protocol alone and should be regarded as microplastic particles.

2.8 GC-MS Determination of Chemical Leachates

Aliquot B was not subjected to H_2O_2 digestion, as oxidative treatment would degrade the target organic compounds. It was instead stored in pre-cleaned amber glass vials at 4°C, protected from light, and processed within 48 hours. Semi-volatile target analytes (phthalate esters and bisphenol A) were recovered by liquid-liquid extraction with dichloromethane, concentrated under a gentle nitrogen stream, and reconstituted prior to injection. Volatile carbonyl compounds (acetaldehyde and formaldehyde) were derivatised with 2,4-dinitrophenylhydrazine (2,4-DNPH) to improve chromatographic separation and detection sensitivity (Bach et al., 2012; Fan et al., 2014). Extracts were analysed on a GC-MS system operated in full-scan and selected-ion monitoring modes, with compound identification based on a minimum 80% match against the NIST mass spectral library and confirmation by retention time matching against authentic reference standards. Quantification used five-point external calibration curves prepared from certified reference standards. As antimony and other inorganic PET migrants are not amenable to GC-MS, they were excluded from this analysis; the method targeted organic leachates only.

2.9 Quality Assurance and Quality Control

Microscope micrometres were calibrated against a stage micrometre at the start of each analytical session. A solvent (extraction) blank was carried through the full extraction procedure alongside each treatment unit to identify and correct for background contamination. Matrix spikes of known concentration were added to a subset of extracts to verify percentage recovery for each target compound, and method detection limits were established from replicate blank analyses.

2.10 Statistical Analysis

Data were analysed 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, followed by Tukey's Honestly Significant Difference (HSD) post-hoc test for pairwise comparisons. Statistical significance was set at $p < 0.05$ (95% confidence level). GC-MS results were evaluated using retention time, peak Area%, and spectral library-match quality. Identified compounds were reported as tentative library matches, while Area% was interpreted as a relative chromatographic response rather than an absolute chemical concentration.

3.0 Results

3.1 Physicochemical Parameters

Table 1: Physicochemical parameters of water stored under different conditions

Sample	pH (Mean ± SD)	EC (Mean ± SD)
C (Control)	6.84 ± 0.02	14.00 ± 1.00
F (Cold storage)	6.87 ± 0.02	15.00 ± 1.00
H (Heat exposure)	6.88 ± 0.02	17.00 ± 1.00

Source: Researcher's compilation, 2026

The pH values ranged from 6.84 ± 0.02 to 6.88 ± 0.02, with the control sample recording the lowest value and heat exposure the highest. Electrical conductivity increased from 14.00 ± 1.00 µS/cm in the control to 15.00 ± 1.00 µS/cm under cold storage and 17.00 ± 1.00 µS/cm following heat exposure. All pH values remained within the NAFDAC/SON permissible range for drinking water.

3.2 Abundance of Microplastic Particles

The control group recorded a mean particle count of 20.00 ± 2.00. This was higher than the mean particle count of 10.00 ± 2.00 observed under cold storage but lower than the 27.00 ± 2.00 recorded under heat exposure (Figure 1). Relative to the control, cold storage showed a 50% reduction in particle count, while heat exposure showed a 35% increase.

Table 2: One-Way Analysis of Variance (ANOVA) of Mean Particle Counts Among Different Storage Conditions

Source	Sum of Squares	df	Mean Square	F	p-value
Between Groups	438.000	2	219.000	54.750	<0.001
Within Groups	24.000	6	4.000		
Total	462.000	8			

Source: Researcher's compilation, 2026

The one-way ANOVA showed a statistically significant difference in particle counts among the control, cold-storage, and heat-exposure groups ($F(2,6) = 54.750$, $p < 0.001$), indicating that variation between treatment groups was substantially greater than variation within groups.

Table 3: Tukey HSD Post-Hoc Comparison of Particle Counts Under Different Storage Conditions

Treatment comparison	Mean difference	Standard Error	p-value	Significance
Control vs Cold Storage	10.00	1.633	0.002	Significant
Control vs Heat Exposure	−7.00	1.633	0.012	Significant
Cold Storage vs Heat Exposure	−17.00	1.633	<0.001	Significant

Source: Researcher's compilation, 2026

The Tukey HSD post-hoc test revealed statistically significant differences in mean particle counts among all three storage conditions ($p < 0.05$). The heat-exposure group had the highest mean particle count, followed by the control, while the cold-storage group had the lowest.

3.3 Morphological Distribution of Particles

Table 4: Distribution of Microplastic Shapes Identified in All Samples

Shape	Frequency (n)	Percentage (%)
Fibre	55	32.16
Film	6	3.51
Fragment	110	64.33
Total	171	100.00

Source: Researcher's compilation, 2026

Fragments were the dominant particle morphology across all storage conditions, accounting for 110 of the 171 particles (64.3%). Fibres accounted for 55 particles (32.2%), while films were the least abundant, with 6 particles (3.5%). Fragments predominated in all three treatment groups, representing 65.0% of particles in the control, 66.7% under cold storage, and 63.0%

under heat exposure. Fibres accounted for 35.0%, 33.3%, and 29.6% of particles in the control, cold-storage, and heat-exposure groups, respectively. Films were observed only in the heat-exposed group, where they constituted 7.4% of the particles.

3.4 Size Distribution of Particles

Table 5: Size Distribution of Microplastic Particles Under Different Storage Conditions

Size category	Frequency	Percentage (%)
1–5 mm	116	67.8
>5–10 mm	31	18.1
>10 mm	24	14.0
Total	171	100.00

Source: Researcher's compilation, 2026

The particle size distribution showed that the majority of microplastic particles were within the 1–5 mm size category, accounting for 116 particles (67.8%) of the total 171 particles recorded. This was followed by the >5–10 mm category (31 particles; 18.1%), while particles larger than 10 mm accounted for 24 particles (14.0%).

3.5 GC-MS Chemical Screening

Table 6: Selected phthalate-related GC-MS library matches

Treatment	Compound	RT (min)	Peak Area%	Match quality
Control	Dimethyl phthalate (DMP)	2.343	0.46	64
Control	Diethyl phthalate (DEP)	4.016	0.63	43
Freezing	Dimethyl phthalate (DMP)	2.228	0.11	87
Freezing	Diethyl phthalate (DEP)	4.022	0.03	43
Heat	Dimethyl phthalate (DMP)	3.306	0.76	76
Heat	Diethyl phthalate (DEP)	3.878	0.67	67

Source: Researcher's compilation, 2026

GC-MS analysis produced chromatographic peaks that were compared with the NIST14 mass-spectral library. The principal DMP-associated peak Area% followed the descriptive order: heat exposure (0.76%) > control (0.46%) > cold storage (0.11%). The heat-exposed sample also produced a DEP candidate with a higher library match quality (67) than the corresponding DEP candidates in the control and cold-storage reports (43 each). These Area% values represent relative chromatographic responses and not absolute chemical concentrations.

4.0 Discussion

4.1 Baseline Particle Abundance in Unexposed Bottled Water

The control sample had a mean concentration of 20 particles, including fibres and fragments. This baseline is important because it shows that particulate material was present even without experimental heat or cold treatment. Thus, the study does not support the proposition that all particles in the treated samples were generated by treatment. Possible contributions include pre-existing particles in the water, packaging-related particles, handling, or laboratory contamination; the present design cannot apportion these sources. The presence of microplastics in untreated bottled water is consistent with findings reported in previous studies. Mason et al. (2018), examining 259 bottles from 11 brands, reported microplastic contamination in 93% of bottles analysed, with an average of 10.4 particles/L for particles larger than 100 µm after correction for laboratory blanks, and fragments being the predominant morphology. The authors suggested that at least part of the contamination could originate from packaging materials or the bottling process itself. This is relevant to the present study because

fragments were also identified in the control sample, suggesting that the presence of such particles does not necessarily require subsequent exposure to elevated temperature.

4.2 Heat/Sunlight Exposure and Particle Release

The heat-exposed bottle had a mean concentration of 27 particles, 35.0% more than the control, and was the only sample in which films were observed. Its principal DMP-associated peak also had the highest Area% (0.76%). These findings are consistent with Ogbolei et al. (2026), who, in a larger study of bottled and sachet water in Port Harcourt, reported progressively higher microplastic concentrations under harsher storage conditions, with the highest levels under elevated temperature and direct sunlight. The authors interpreted the pattern as consistent with thermal stress and ultraviolet radiation promoting polymer degradation, fragmentation, and particle release. Akhbarizadeh et al. (2022) experimentally demonstrated that PET bottled water subjected to sunlight exposure and elevated temperatures showed significantly higher microplastic particle concentrations than unexposed controls, confirming a direct relationship between thermal stress and particle release. Anayo et al. (2018) similarly found progressive increases in microplastic detection in packaged water with each additional day of sunlight exposure at 31–33°C. UV radiation in the 290–400 nm wavelength range is absorbed by PET, initiating chain-scission reactions that reduce molecular weight and cause surface embrittlement (Andrady, 2011). Solar UV irradiance in Port Harcourt falls within the 'High' to 'Very High' classification during peak daily hours, particularly during the dry season (Egbuim et al., 2022), creating conditions conducive to photodegradation of packaged water stored outdoors.

4.3 Freezing/Cold Storage and Particle Release

The cold-stored sample had a mean concentration of 10 particles, representing a 50% lower particle count than the control sample and the lowest count among the three experimental conditions. The GC-MS analysis showed a similar descriptive pattern, as the cold-stored sample also recorded the lowest principal DMP-associated chromatographic signal (Area% = 0.11%), compared with 0.46% in the control and 0.76% in the heat-exposed sample. Although these observations suggest lower particulate occurrence and a lower relative DMP-associated signal under the cold-storage condition, they should not be interpreted as evidence that cold storage prevented microplastic formation or chemical migration. Nevertheless, the observed pattern is broadly consistent with recent experimental evidence concerning the influence of storage temperature on microplastic release from plastic bottles. Alibekov et al. (2026) reported microplastic concentrations of 37 ± 6.7 MP/L and 38 ± 4.7 MP/L in bottled water stored at 4°C and 22°C, respectively, compared with 80 ± 29.8 MP/L following freezing at −18°C and 92 ± 35.1 MP/L following exposure to 45°C. Their findings suggest that moderate refrigeration may be associated with less particle release than extreme thermal conditions. Although this pattern provides useful context for the lower particle count observed in the cold-stored sample of the present study, the discrepancy between the present finding and the freezing-associated increase reported by Alibekov et al. (2026) and Akhbarizadeh et al. (2022) may reflect differences in freezing duration, number of freeze-thaw cycles, and the single-bottle design of the present study. The migration of chemical compounds from PET packaging is influenced by both temperature and the physicochemical characteristics of the individual compounds. Bach et al. (2013) investigated PET-bottled water stored at 40, 50 and 60°C and reported that elevated temperature increased the release of formaldehyde, acetaldehyde and antimony into the water, whereas phthalates were not detected in their PET-bottled water extracts. This finding is important in interpreting the phthalate-related compounds tentatively identified in the present study, as their detection cannot, by itself, establish that they originated directly from the PET bottle.

4.4 Morphological Patterns and Source Attribution

Fragments were the dominant particle morphology in the present study, accounting for 64.33% of all particles observed, followed by fibres (32.16%) and films (3.51%). This pattern is broadly consistent with Ogbolei et al. (2026), who reported fragments (40.3%) and fibres (34.4%) as the predominant morphologies in packaged drinking water studied under different environmental storage conditions in Port Harcourt. However, similarity in particle morphology between studies does not establish a common source. Fragment dominance has also been reported in bottled-water studies outside Nigeria. Mason et al. (2018) reported that fragments constituted 66% of particles larger than 100 µm, followed by fibres (13%) and films (12%), with polypropylene, commonly used in bottle caps, being the most frequently identified polymer among larger particles subjected to FTIR analysis. Schymanski et al. (2018), using micro-Raman spectroscopy, reported that 84% of particles identified in water from returnable PET bottles consisted of polyester, predominantly PET, while 7% were polypropylene, indicative of possible particle release from packaging materials. Morphological patterns are not uniform across bottled-water studies. Kankanige and Babel (2020), for example, reported that fibres accounted for 62.8% of particles detected in single-use PET-bottled water in Thailand, followed by fragments. These differences among studies indicate that the morphology and abundance of recovered particles may be influenced by packaging type, production processes, previous storage and handling, particle-size range and analytical methodology. Consequently, the predominance of fragments in the present study may be compatible with, but does not prove, degradation or abrasion of plastic packaging. This distinction is particularly important because the particles recovered in the present study were classified visually and were not subsequently confirmed by FTIR or Raman spectroscopy; they should therefore be regarded as microplastic particles rather than chemically confirmed microplastics. Definitive source attribution would require direct analysis and spectral comparison of recovered particles with the corresponding packaging materials.

4.5 Organic Chemical Profiles

The GC-MS analysis provided an additional chemical-screening dimension to the assessment of microplastic particles in the bottled-water samples. Phthalate-related compounds were returned as candidate matches by the NIST mass-spectral library in all three experimental conditions. A principal DMP-associated peak was observed in the control sample (Area% = 0.46%), indicating that this signal was not unique to heat exposure. However, the heat-exposed sample recorded the highest principal DMP-associated Area% (0.76%), compared with the control (0.46%) and cold-stored sample (0.11%). A DEP-related candidate was also observed in the heat-exposed sample with a higher library-match quality than the corresponding DEP candidates in the control and cold-stored samples. These differences indicate variation in the relative chromatographic profiles of the samples rather than differences in absolute chemical concentrations. The occurrence of GC-MS-detectable organic compounds in packaged water following environmental exposure has also been reported by Okpashi et al. (2021). In their study, sachet water was exposed to sunlight at approximately 31–33°C for periods ranging from 24 to 120 hours and subsequently analysed by GC-MS. The analysis produced multiple chromatographic peaks corresponding to various candidate organic compounds in both exposed and unexposed samples, discussed in relation to polymer degradation and the potential release of plastic-associated chemicals following exposure to heat or radiation. Although the study involved polyethylene sachet packaging rather than PET bottles, it demonstrates the relevance of evaluating the chemical profile of packaged water alongside particulate contamination. An interesting descriptive pattern was observed when the particle and GC-MS results were considered together. The heat-exposed sample had both the highest particle count (27) and the highest principal DMP-associated Area% (0.76%), whereas the cold-stored sample

had the lowest particle count (10) and lowest DMP-associated Area% (0.11%). The control showed intermediate values of 20 particles and 0.46% DMP-associated Area%. This parallel ordering (heat > control > cold) provides converging descriptive evidence that the samples differed in both particulate and chemical profiles. However, these observations should be interpreted cautiously given the single-bottle design, tentative library matches, and the possibility that detected phthalates may originate from sources other than the PET bottle itself, including laboratory contamination or the analytical procedure.

4.6 Limitations

This study has some important limitations. First, each treatment condition was represented by a single 1.5 L bottle, limiting statistical power and impeding generalisation to the broader population of bottled water products. Second, polymer identity was not confirmed by FTIR or Raman spectroscopy; all particle identifications are presumptive and based on visual morphological criteria. Third, GC-MS compound identifications are tentative library matches, and Area% values represent relative chromatographic responses rather than absolute concentrations. Fourth, the five-day exposure window, while ecologically valid, may not capture longer-term degradation dynamics. Fifth, the study did not include a direct human health risk assessment; potential health implications are inferred from existing literature rather than established through epidemiological analysis. Finally, findings are specific to the packaging type, retail sourcing, and exposure conditions studied and should not be generalised to all packaged water in Nigeria without further investigation.

5.0 Conclusion

This study compared microplastic particles and organic chemical leachates in PET bottled water stored under three conditions: control, heat/sunlight, and freezing, over five days. The heat-exposed sample had the most particles (mean 27.00 ± 2.00) and the highest DMP-related peak area (0.76%). The cold-stored sample had the fewest particles (mean 10.00 ± 2.00) and the lowest DMP-related peak area (0.11%). The control was in between (20.00 ± 2.00; 0.46%). Particle counts differed significantly across all three groups (ANOVA: $F(2,6) = 54.750$, $p < 0.001$). Fragments were the most common particle shape (64.3%), and films appeared only in the heat-exposed sample. Particle identity was not confirmed by FTIR, and GC-MS results were tentative library matches with relative peak areas, not absolute concentrations. Because of this, the results show patterns, not proof. The findings suggest that heat and sunlight exposure may increase both particle release and chemical migration from PET bottles, while cold storage may reduce them. Consumers should keep bottled water cool and out of direct sunlight. Regulators should develop standard methods for monitoring particles in packaged water. Future studies need more bottles per condition, multiple brands, and spectroscopic confirmation to confirm these patterns and support regulatory limits.

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