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From Bottle to Body: Source and Storage-Driven Microplastic Release, Contamination Profiles, and Human Exposure from Drinking Water

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From Bottle to Body: Source and Storage-Driven Microplastic Release, Contamination Profiles, and Human Exposure from Drinking Water

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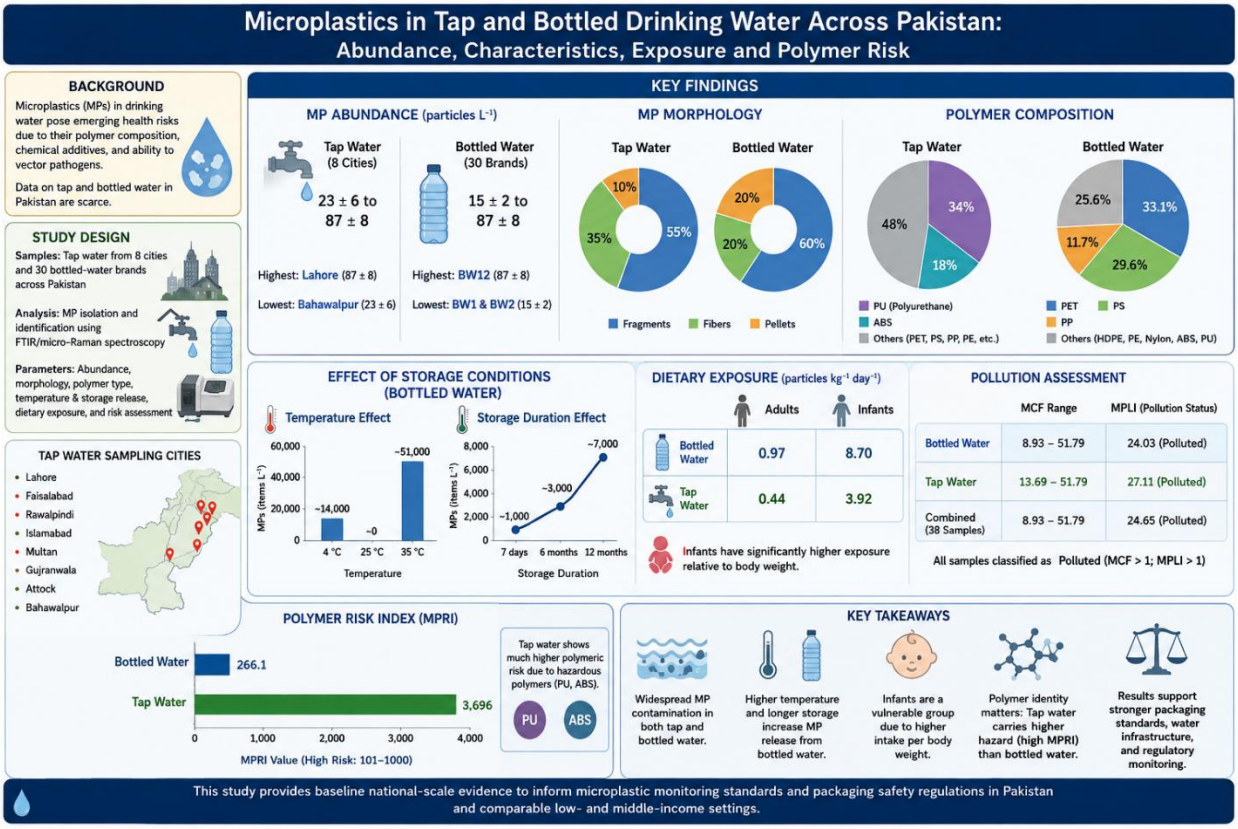
Abstract

Human exposure to microplastics (MPs) via drinking water is an emerging environmental and health concern worldwide. This study was conducted to assess MPa abundance, morphology, storage-dependent release, dietary exposure, and polymer-associated risk in water. MPs particles ranged from 23-87 per liter in tap water and 15-87 particlesL^{-1} in bottled water dominated (55-60%) with fragments type particles. Chemically, tap water was dominated by polyurethane (PU, 34%) and acrylonitrile butadiene styrene (ABS, 18%), while bottled water was dominated by PET (33%), PS (29%), and PP (12%) with PET and HDPE as primary packaging-derived polymers. MP release from bottled water increased sharply with temperature (~51,000 items L^{-1} at 35 °C) and storage duration (~3,000 items L^{-1} at 12 months). All samples were classified as polluted (MPLI: 24.03 bottled, 27.11 tap; MCF > 1), while the Polymer Risk Index was markedly higher for tap water (3696) than bottled water (250) due to higher PU and ABS content. These findings reveal a dual exposure–hazard profile requiring improved packaging, water infrastructure, and regulation. The elevated MPRI in tap water underscores that contamination severity cannot be assessed by particle abundance alone, as polymer hazard identity plays a decisive role in risk outcomes. Infants are more vulnerable than adults due to higher intake to BW ratio advocating targeted exposure-reduction guidance. This baseline evidence on MPs contamination highlights monitoring, quality standards and packaging safety regulations which mostly do not exist, especially in developing countries.

Key Words: Water, Plastic, pollution, Pet bottles, Health risk, Microplastics

Graphical Abstract



Introduction

Microplastics (MPs) are plastic particles smaller than 5 mm that are either intentionally manufactured to incorporate into consumer products such as exfoliating scrubs, toothpaste, and body washes, where they serve as abrasives or texturizing agents, or they formed through the mechanical, physicochemical, or biological breakdown of larger plastic items and stay in the environment (Ashrafy *et al.*, 2023). MPs have also been detected worldwide in natural waterbodies, treated wastewater, tap water and even in bottled water (Oßmann et al., 2018a; Zuccarello et al., 2019). Contamination sources could be environmental deposition, addition during packaging processes, including abrasion from PET bottle walls, caps, and machinery. Commonly packaging is considered as a key contributor to microplastic presence in PET bottles, however, behavior of disposable plastics used for hot and cold conditions remains incompletely

understood (Janairo, 2021) especially region-specific data particularly for emerging markets such as Pakistan remain scarce. On the other hand, the ubiquitous occurrence of MPs across diverse environments, persistence nature, their chemical composition poses significant risks to all aquatic and terrestrial ecosystems (Haque and Fan, 2023).This widespread distribution has facilitated their entry into human food chain (Dong *et al.*, 2021). Senathirajah et al., (2021) estimated that humans consume between 0.1 and 5 g of microplastics each week through food and drinking water. Once ingested, these particles can migrate to organs such as the liver, kidneys, and gastrointestinal tract, where they may disrupt energy and lipid metabolism or trigger oxidative stress responses (Senathirajah et al., 2021; Huang et al., 2024).

Food contamination by MPs is not only from environmental exposure but also from food additives (Eze *et al.*, 2024) and packaging materials (Udovicki et al., (2022). Furthermore, variations in processing, transportation, and storage conditions can alter the extent of contamination (Kataria et al., 2024). Hernandez et al. (2019) reported that steeping plastic teabags in hot water at 95 °C resulted in the release of approximately 11.6 billion micro and 3.1 billion nano plastics (<100 nm) particles into the leachate. Similar findings have been documented in infant feeding bottles, where exposure to hot water and reuse produced hundreds of thousands of microplastic particles in the liquid (Zhao et al., 2025). The pronounced influence of elevated temperature and aging on MPs release is linked to the degradation behavior of polymers under thermal or hydrolytic stress. High temperatures accelerate chain scission reactions, which weaken polymer integrity, promote surface cracking, and ultimately lead to fragmentation into smaller particles (Hernandez et al., 2019; Singh & Sharma, 2008). Disposable plastics often release MPs under heat stress (Zhou *et al.*, 2020; Janairo, 2021). Reuse, aging, and exposure to high temperatures accelerate polymer degradation, producing more particles than storage at low temperatures. In addition to particles, additives such

as plasticizers, stabilizers, and antioxidants migrate into water during heating (Zhou et al., 2019) these include dibutyl phthalate, Irgafos 168 OXO, alkanes, and benzene derivatives (Luo et al., 2020). Despite these findings, systematic comparisons of bottled water under different conditions remain limited. Given global reliance on bottled water, assessing microplastic and chemical release across single-use, reused, and aged bottles is essential for tracing contamination sources and evaluating health risks.

This study hypothesizes that drinking water sources are at the risk of MPs contamination in Pakistan like rest of the world with significant spatial variability in abundance and characteristics differences depending upon the use, age, while storage conditions especially temperature play significant role in alleviating the risk levels. The human exposure to MPs contamination from water was assessed along with estimated daily intake to develop scientific evidence regarding public health safety and regulatory frameworks as currently no quality standards or threshold exist for this contamination at national level and few at global level.

1. Materials and Methods

2.1. Tap water and Bottled water samples collection.

Tap water and bottled water samples (1 L each) were collected from ten cities in Pakistan. Pet bottled water samples were collected from local markets, with details of the sampled brands and packaging materials provided in Table S1. Tap water samples were collected at the household level from locations supplied by the government-operated Water and Sanitation Agency (WASA). Before collection, the tap was allowed to run for 2–3 min to minimize the influence of stagnant water within the household plumbing system. Each sample consisted of one litre of water and was collected in pre-cleaned containers for subsequent microplastic analysis (Table 1).

Table-1: The sampling sites and their demographic and environmental status

City	Population (million)	Temperature (°C)	Waste generation (tons/day)
Bahawalpur (n=29)	1.2	44.4	~500
Attock (n=20)	1.8	~40–42	~300–400
Gujranwala (20)	3.0	~42–44	~1,000
Islamabad (n=21)	3.4	~40–43	~400–600
Rawalpindi (n=24)	2.8	~44–46	~600–700
Rahim Yar Khan (n=24)	2.8	~44–46	~600–700
D.G. Khan (n=20)	3.0	~44–45	~500–600
Multan (n=2)	2.2	~45–47	~1,000
Faisalabad (n=20)	4.0	45.5	~1,200–1,500
Lahore (n=25)	15.2	41	>6,000

2.2 Simulation of Storage Conditions

To evaluate the effect of temperature during storage and transportation on MPs release in bottled water, new water bottled were kept under controlled temperature conditions at 4 °C, 25 °C and 35 °C for three days representing, refrigeration, room temperature and sun exposure situations during storage. In addition, water bottles were tested after prolonged storage periods of seven days (7D), six months (6M), and twelve months (12M) to assess the effect of long-term storage.

2.3 Sample Preparation and Analysis

One Liter of each sample was transferred into a 2 L glass beaker, and 180 g of NaCl was added to prepare a saturated solution. The mixture was heated at 90 °C for 30 minutes with continuous stirring, then transferred into a separatory funnel. The mixture was left overnight for sedimentation, after which the dense lower phase was drained and the floating phase containing MPs was retained and treated with 100 mL of 30% H_2O_2 overnight to remove organic matter and pigments. The material was filtered under vacuum using 0.45 µm pore size cellulose membrane filters. Finally, membranes were transferred to clean petri dishes with stainless steel tweezers, dried at room temperature for 24 hours, and used for MPs identification and characterization (Shruti *et al.*, 2020).

2.3 Microplastic Isolation, Identification and Quantification

After filtration, the filter papers were immediately stored in clean glass petri dishes and examined by using Stereotype and hot needle test was performed to confirm the presence of plastic particles (Rafique *et al.*, 2020). Click or tap here to enter text. A heated needle or metal point was applied to particles to confirm the presence of plastics, which melt upon contact, while non-plastic particles either remained unchanged or burned to ash. Twenty samples from each type were assessed, and visual characteristics such as size, colour, and shape were recorded. Microplastics were categorized by colour (white, black, blue), shape (fibres/elongated, pellets, fragments), and size ranges (0.045–0.1 mm, 0.1–0.3 mm, 0.3–1.0 mm, and 1–5 mm). Size, shape, and colour were determined using a stereomicroscope. Polymer identification was conducted with a Fourier Transform Infrared (FTIR) spectrometer (Nicolet 380, Thermo Fisher Scientific, USA) equipped with a diamond Attenuated Total Reflectance (ATR) accessory, operating over a spectral range of 4000–400 cm^{-1}. Spectra were acquired in absorbance mode with 64 scans per sample at a resolution of 4 cm^{-1}, and polymer identification was validated against reference spectra using OMNIC software version 9.1, applying a ≥90% library match threshold to ensure reliable classification.

2.4. Dietary exposure

The daily intake of microplastics per person from drinking water ($C_{MP,DW}$) was estimated using a probabilistic exposure model.

$$C_{MP,DW} = \left(1 - f_{abs} \cdot f_{a,n}\right) \cdot \sum_{i=1}^{n} (Ir_i \cdot C_i) \quad (1)$$

Here, is i represents the two types of drinking water considered: bottled and tap. Ci is the microplastic concentration (particles/L), and Iri is the daily ingestion rate (L/capita/day). A total daily consumption of 2.0 L was assumed, distributed as 1.14 L bottled water and 0.86 L tap water. based on WHO (Zhu et al., 2024; Prole et al., 2026).

2.5. MPs contamination factor (MCF)

MCF was used to determine the pollution level in individual samples by comparing the measured value with the background value reported in previous studies (Basaran et al., 2023; Binelli et al., 2025; Enyoh et al., 2021).

$$\text{MCF}\ \frac{P_i}{P_\beta} \quad (2)$$

Where P_i is the number of MPs in the sample, and P_β is the minimum average MPs concentration in liquids (1.68 particles/kg) (Lin *et al.*, (2022))

Contamination levels were classified as: MCF < 1 = Low 1–3 = Moderate 3–6 = Considerable 6 = Very high (Chakraborty *et al.*, 2024)

2.6. MPs pollution load index (MPLI)

MPLI provides an integrated assessment of pollution status across multiple samples and calculated following Basaran et al., (2023) and Binelli et al., (2025) and given below in eq-3.

$$\text{MPLI} = (\text{MCF}_1 \times \text{MCF}_2 \times \text{MCF}_3 \cdots\cdots\cdots \times \text{MCF}_n)^{1/n} \quad (3)$$

Where *n* is the number of sampling points.

Pollution levels were categorized as: MPLI < 1 = Baseline level, MPLI > 1 = Polluted (Chakraborty *et al.*, 2024)

2.6. MPs polymer risk index (MPRI)

MPRI is used to evaluate the chemical toxicity of MPs polymers using hazard scores index as described by Lithner et al., (2011)and given below in eq-4. Polymeric risk categories were defined as: < 10 = Low, 10–100 = Moderate, 101–1000 = Considerable ,1001–10000 = High, 10000 = Very high (Chakraborty *et al.*, 2024)

$$\text{MPRI} = \frac{P_a}{P_t} \times R_s \quad (4)$$

Where P_a is the number of each polymer type identified in a water sample, P_t is the total number of different polymer types, and R_s is the chemical toxicity coefficient of each polymer. Click or tap here to enter text.

2.6 Quality assurance and quality control

All glassware was meticulously rinsed between trials using ultrapure water that had been passed through a 5 µm stainless steel filter to reduce background contamination during sample preparation. The glassware was cleaned and then wrapped in aluminum foil. To further lower the possibility of contamination. Every experimental method was carried out in a sterile bench setting.

2.7 Statistical Analysis

The mean ± standard deviation (SD) of three replicate measurements was used to report microplastic concentrations in both tap water and bottled water. One-way ANOVA was applied, and a p-value of less than 0.05 was considered statistically significant.

3. Results

3.1 Abundance of MPs in Tap water and bottled water

MP concentrations in household tap water varied notably across Pakistani cities, ranging from 22 to 85 MPs L^{-1} with minimum in in Bahawalpur and highest in Lahore (Figure-3.1a). Intermediate values were observed in Attock, Gujranwala, Islamabad, Rawalpindi, and Multan (34–65 MPs/L). These results reveal clear spatial variability, with higher contamination in urban centres linked to increased plastic use and wastewater discharge.

Microplastic (MP) concentrations varied among the thirty bottled water samples (Figure-3.1b). The lowest mean concentrations were observed in BW1 and BW2 (≈15 ± 2 MPs L^{-1}), followed by BW21, BW22, BW28, and BW29 (≈23 ± 3–7 MPs L^{-1}) and BW6 (≈25 ± 5 MPs L^{-1}). Moderate contamination was recorded in BW7, BW13, BW15, BW17, and BW30 (≈33–34 ± 4–6 MPs L^{-1}),

while BW3–BW5, BW8–BW9, and BW14 showed concentrations of 44–45 MPs L^{-1}. Higher concentrations were observed in BW16, BW18, BW19, and BW24 (≈54–55 MPs L^{-1}), with BW25 reaching approximately 65 ± 9 MPs L^{-1}. The highest MP concentrations occurred in BW10–BW12 and BW26–BW27, ranging from 76 to 87 MPs L^{-1}, with BW12 showing the maximum level (≈87 ± 8 MPs L^{-1}). Overall, the substantial variation among bottled water samples indicates differences in contamination levels that may be associated with packaging materials, bottling practices, handling, and storage conditions.

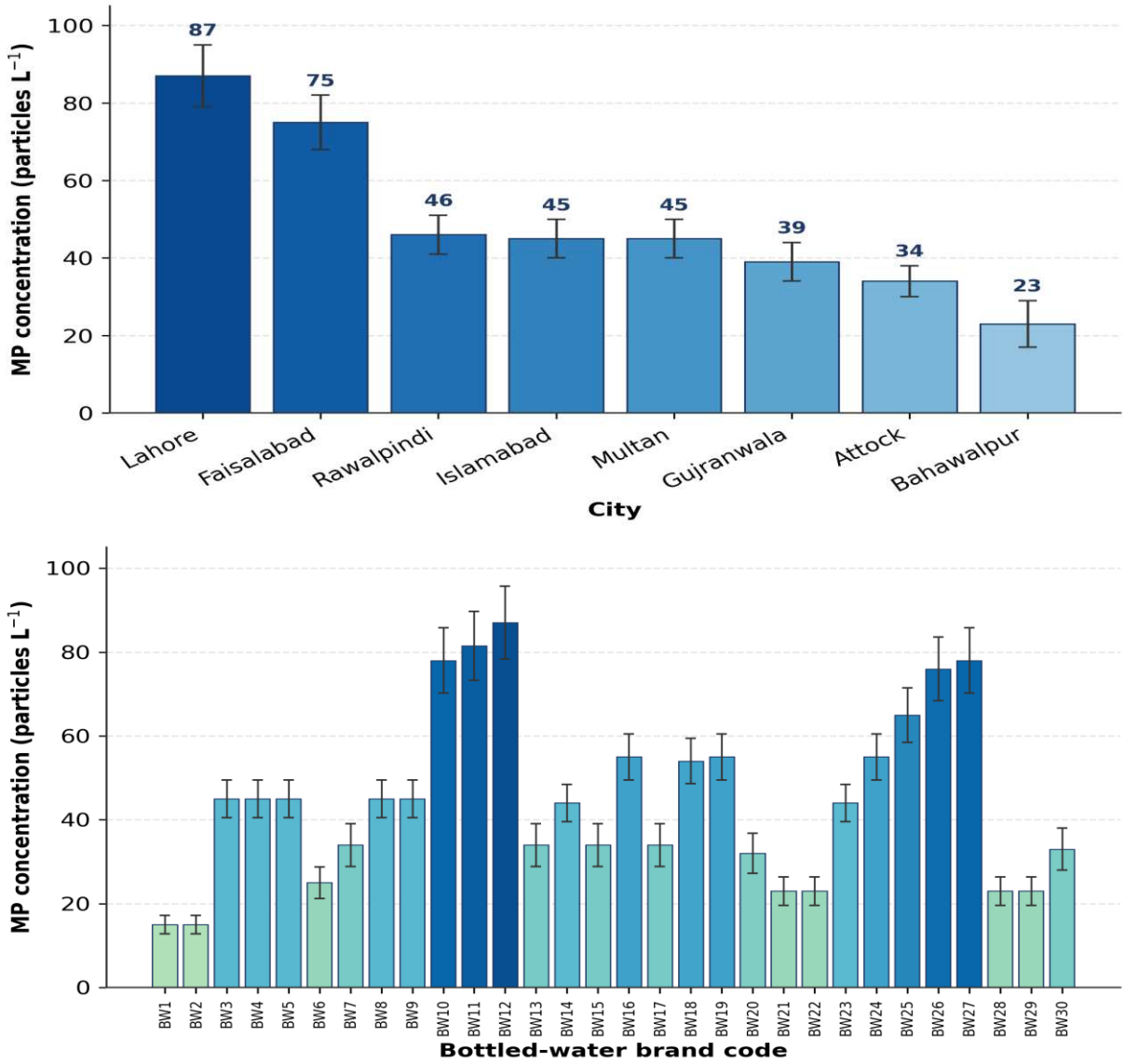


Figure 3.1 Abundance of MPs in Tap water and bottled water brands across Pakistan

3.3 Characteristic of MPs of water samples

Drinking water samples were found having MPs of diverse particle morphologies (Figure-3.2). Tap water samples exhibited a higher proportion of fragments (55%) alongside a substantial fibre contribution (35%), indicating more diverse sources and degradation pathways (Figure 3.3a). In bottled water samples, MPs fragments were the dominant shape (60%), while fibres and pellets contributed equally (20% each).

Colour distribution was more varied compared to bottled water (Figure 3.3b), with blue particles slightly dominant (34%), followed by equal proportions of white and black (23% each), and a notable presence of red particles (20%). Colour analysis revealed black particles as most abundant (44%), followed by blue (33%) and white (23%), with no red particles detected.

Size analysis (Figure 3.3c) showed larger particles (1–5 mm) as the most abundant fraction (38%), with equal contributions from 1–0.3 mm and 0.1–0.045 mm (25% each), while the 0.3–0.1 mm fraction was least represented (12%). Size distribution was skewed toward the smallest fraction (0.1–0.045 mm), accounting for 50% of particles, with decreasing proportions in 0.3–0.1 mm (20.02%), 1–5 mm (18%), and 1–0.3 mm (12.10%).

Polymer composition differed markedly, eight different polymers of MP were observed in water samples using (ATR-FTIR) spectroscopy (Figure-3.3d), with polyurethane (PU, 34%) and acrylonitrile butadiene styrene (ABS, 18%) dominating, both associated with higher toxicity scores, while PET, PS, and PP were comparatively less abundant. Polymer composition was characterized by a predominance of polyethylene terephthalate (PET, 33.1%), polystyrene (PS, 29.6%), and polypropylene (PP, 11.7%), while high-hazard polymers such as polyurethane (PU) and acrylonitrile butadiene styrene (ABS) were detected only in minor amounts (1.8% each).

Bottled water samples were dominated by PET (≈30%) and HDPE (≈25%), followed by moderate proportions of PP, PE, and PS, while minor fractions of Nylon, ABS, and PU were detected.

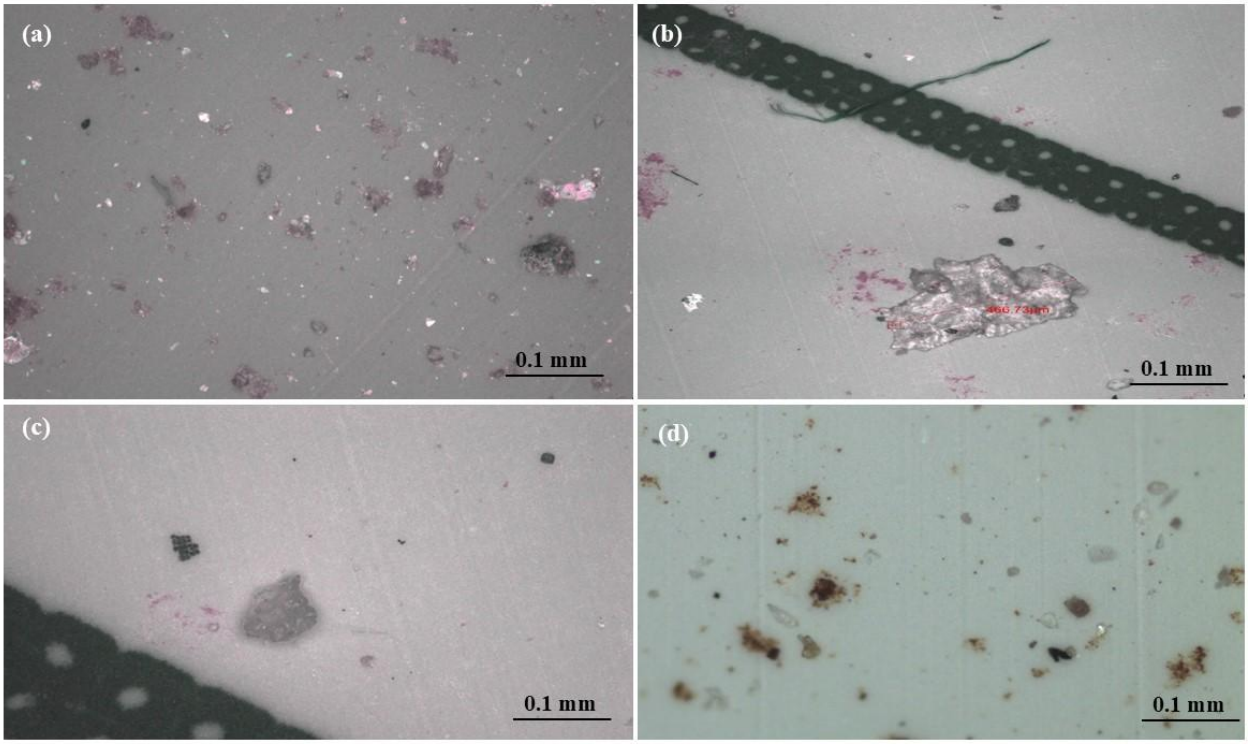


Figure 3.2. Microscopic images of microplastics detected in water samples showing different particle morphologies and sizes: (a) irregular fragments, (b) fibrous and fragmented particles, (c) irregular/fragmented particles, and (d) mixed particulate matter containing suspected microplastic particles.

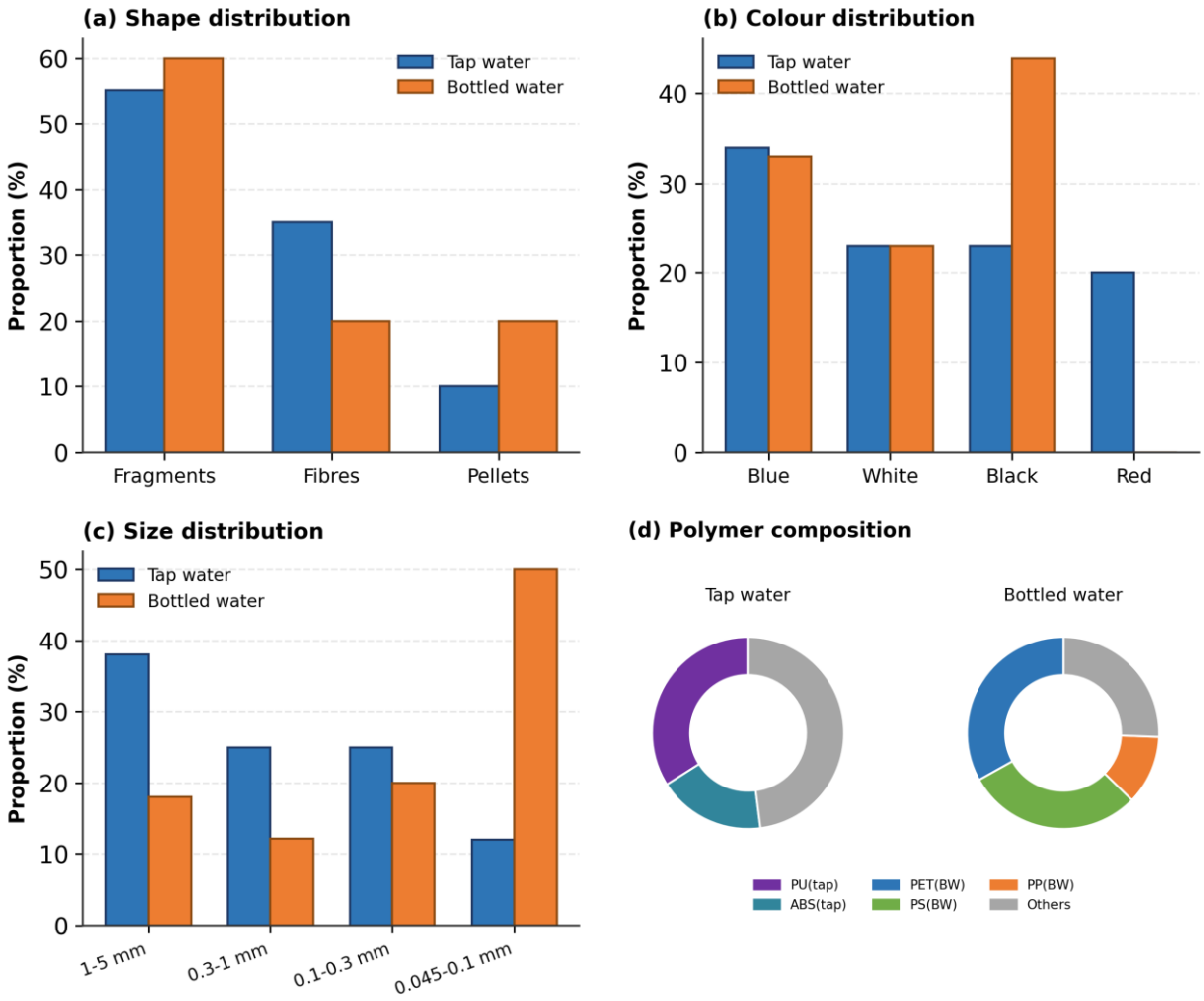


Figure 3.3 Microplastic Characteristics; Shape Distribution (a), Color Distribution (b), Size Distribution (c), Polymer Composition (d) in Tap and Bottled Water Samples:

3.4 Effect of Bottle use Type, Temperature, and Storage Conditions on Microplastic Levels in Bottled Water

The results show the effect of temperature and storage duration on MPs release in bottled water, while temperature had a strong and variable influence on MPs levels in pet bottled drinking water (Figure 3.4a). At refrigerated conditions (4°C), MPs count was moderate (~14,000 MPs/L) and levels decreased to nearly zero at room temperature (25°C), however, at elevated temperature (35°C), MPs levels increased substantially to approximately 51,000 MPs/L, indicating the

influence of higher temperatures on MPs release and confirming the importance of optimized storage conditions to limit the MPs contamination. MPs concentrations in bottled water also increased steadily with longer storage times. As shown in Fig. 3.4b, samples stored for 7 days (BW-7D) contained low MPs level, averaging below 1000 items/L, while bottles stored for 6 months (BW-6M) exhibited a sharp rise, with concentrations exceeding 3000 items/L. The highest contamination was observed in bottles stored for 12 months (BW-12M), where MPs count approached 7000 items/L.

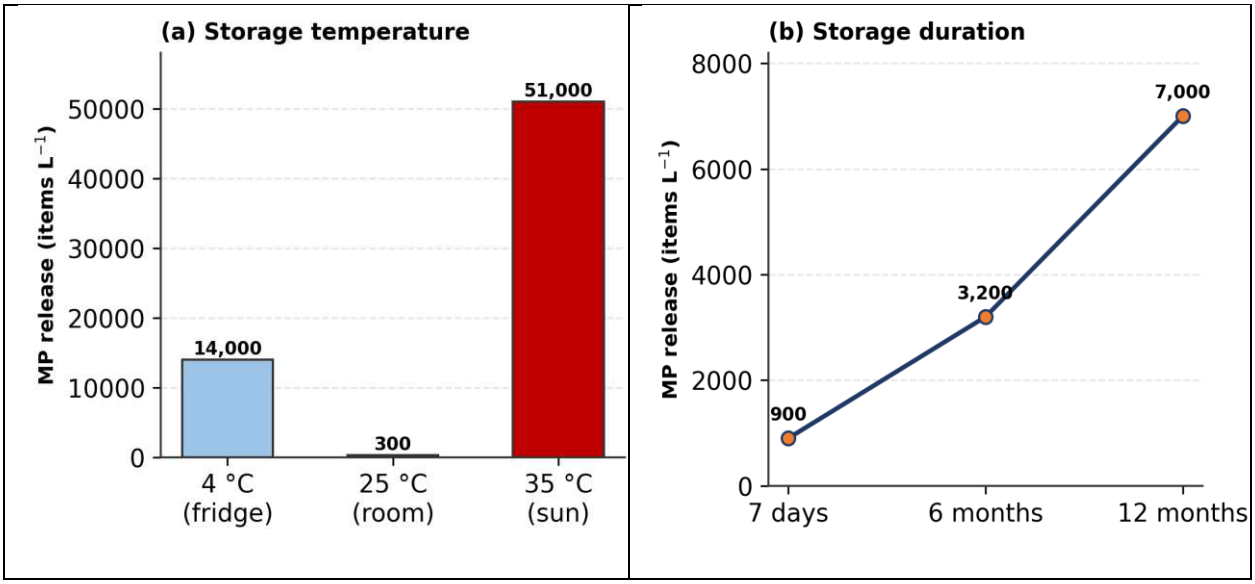


Figure 3.4 Microplastic Concentration in Bottled Water under Different Temperature Conditions (a) and Storage duration (b)

3.5. Dietary exposure

The estimated MPs intake varied between bottled and tap water, with consistently higher values observed in bottled water (Table-2). For adults, bottled water contributed 0.97 particles kg^{-1} day^{-1}, correspondingly upto 26,583 particles kg^{-1} over a lifetime, whereas tap water intake was lower at 0.44 particles kg^{-1} day^{-1} and 12,045 particles kg^{-1} lifetime. Infants exhibited markedly greater exposure, with bottled water yielding 8.70 particles kg^{-1} day^{-1} compared to 3.92

particles kg^{-1} day^{-1} from tap water. Overall, bottled water consistently resulted in higher MPs intake than tap water, and infants were disproportionately affected, highlighting both the influence of water source.

Table-2: Estimated Daily Intake (EDI) of Microplastics

Water Type	Adult			Infant		
	Daily	Yearly	Lifetime	Daily	Yearly	Lifetime
Bottled Water	0.97	354	26,583	8.70	3,176	238,163
Tap Water	0.44	159	12,045	3.92	1,431	107,430

3.6 MPs pollution and polymeric risk assessment

3.6.1 MPs contamination factor (MCF)

The Microplastic Pollution Load Index (MPLI) indicated substantial microplastic contamination in both bottled and tap water (Table-3). For bottled water, the MPLI was 24.03, with sample-level MCF values ranging from 8.93 to 51.79; all 30 bottled-water samples were classified as having very high contamination (MCF ≥ 6). The highest MCF was recorded for BW12 (51.79; 87 MP/L), followed by BW11 (48.51; 81.5 MP/L), whereas BW1 and BW2 showed the lowest MCF (8.93; 15 MP/L). Tap water exhibited a higher MPLI of 27.11, with MCF values ranging from 13.69 to 51.79, and all sampling locations were also classified as having very high contamination. City-wise, contamination followed the order Lahore (87 MP/L; MCF = 51.79) > Faisalabad (75; 44.64) > Rawalpindi (46; 27.38) > Islamabad = Multan (45; 26.79) > Gujranwala (39; 23.21) > Attock (34; 20.24) > Bahawalpur (23; 13.69). Overall, the combined MPLI across all 38 sampling points was 24.65, confirming widespread microplastic pollution in the investigated bottled and tap-water samples (Table S3-4).

Table-3 Microplastic Contamination Factor (MCF) and Pollution Load Index (MPLI) in Bottled and Tap Water Samples

Water type	MCF range	MPLI	Status
Bottled water	8.93–51.79	24.03	Polluted
Tap water	13.69–51.79	27.11	Polluted
Combined	8.93–51.79	24.65	Polluted

3.6.2 MPs polymeric risk index (MPRI)

The Microplastic Polymer Risk Index (MPRI) also showed a substantial variation between bottled water and tap water samples, although both sources are under high-risk category (101-1000) of MPRI (Figure-3.5). Bottled water exhibited an MPRI value of approximately 266.1, primarily contributed by PET and PS polymers. In contrast, tap water demonstrated a significantly higher MPRI value of ~3696, The graphical representation clearly highlights this sharp increase, with tap water showing a markedly elevated risk compared to bottled water. This heightened MPRI is mainly driven by the high proportion of polyurethane (PU) and acrylonitrile butadiene styrene (ABS), both of which possess extremely high hazard scores.

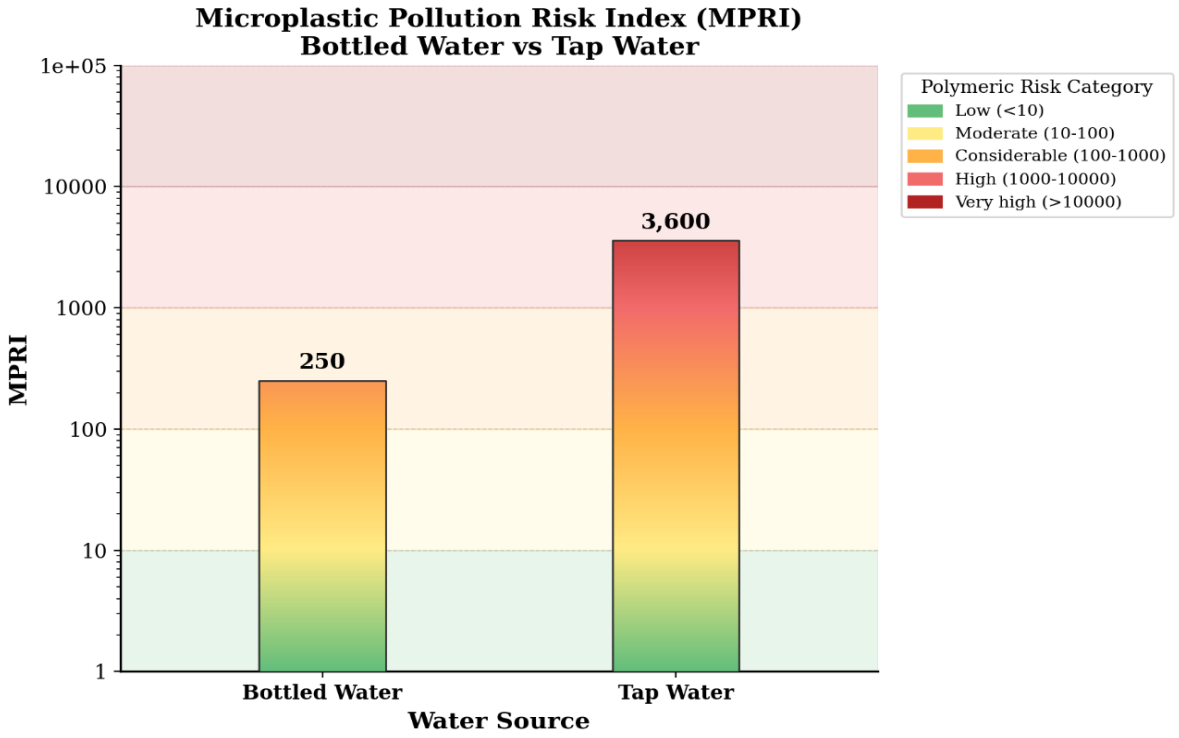


Figure 3.5 Comparison of Microplastic Polymer Risk Index (MPRI) in Bottled and Tap Water

4. Discussion

4.1 Tap water

Microplastic contamination observed in tap water samples from most of the major cities of Pakistan ranging from 22 ± 3 to 85 ± 6 MPs L^{-1} highlighting the existence and variability in the problem across the country and same was observed when compared with other countries (Table-4). However, overall, levels remained low compared to reports from other regions around the globe, for instance around 243–684 MPs/L in European supplies (Pivokonsky *et al.*, 2018). These variation in MP concentrations arises not only from human activity and location but also from methodological differences. Sample preparation, identification techniques, chemical characterization, particle size ranges and QA/QC practices vary widely, creating inconsistencies in data.

Polyurethane (PU) found as the dominant polymer in water samples due to contamination from untreated industrial effluents from textile, aging of pipeline network, coatings and urban waste mismanagement (Chophel et al., 2026). Click or tap here to enter text.

Table-4: Occurrence, Characteristics, and Analytical Methods of Microplastics Detected in Drinking Water from Different Countries

Country	Methods	Concentration (MPs/L)	Shapes	Colours	Reference
Turkey	Microscopy, SEM-EDS, ATR-FTIR	10–390 (188)	Fibers, fragments	Red, pink, blue, black, transparent	Buyukunal et al., (2023)
Iraq	Stereomicroscopy, FTIR	2394	Fibers, fragments	Transparent (48%), black, blue, red	Sultan et al., (2023)
China	Visual ID (Rose Bengal)	0–8.6 (2.18)	Fibers (98.7%)	Black, blue, transparent	Lam et al., (2020)
Bangladesh	Microscopy, FTIR	10–74 (35)	Fibers (96%)	Transparent (64%), violet, green, blue	Hossain et al., (2024)
S. Africa	Microscopy, SEM, Raman, WPO	4.7–31 (14)	Fibers (77–86%)	Black, green, blue, transparent	Ramaremisa et al., (2024)
Brazil	Fluorescence microscopy, Nile Red	4–31 (a14)	Fibers (77–86%)	Black, green, blue, transparent, red	Pratesi et al., (2021)
China	FTIR, AFM-IR, TEM, XPS	10–74 (35)	Fibers (96%)	Transparent (64%), coloured	Li et al., ((2022))

300

301 **4.2 Bottled water and factor effecting the abundance of MPs.**

302 Microplastics were also observed in PET water bottles from various national and international
303 brands as reported globally. MPs in bottled water were predominantly fragmented, white, black
304 and blue in color, reflecting diverse sources, largely shed from bottle materials degradation (Pan
305 *et al.*, 2023) as well as atmospheric deposition during processing (Al-Mansoori *et al.*, 2025).
306 Polymer diversity raises concern: HDPE, PE, and PS align with bottle and cap materials, as PET
307 and HDPE are widely documented as bottled materials (Yang et al., 2024), but the detection of PU,
308 ABS and nylon indicates direct contamination beyond packaging possibly from source water or
309 during manufacturing processes (Al-Mansoori, 2026)Since bottled water in Pakistan is mostly
310 from groundwater sources, as there are already emerging evidence suggesting MPs contamination
311 in groundwater through adjacent industrial settings (Samandra *et al.*, (2022)) and recharge form
312 agriculture/irrigation water, untreated wastewater application, surface runoff and river/canal water
313 especially in urban areas (Cao *et al.*, 2021; Ullah *et al.*, 2025). MPs abundance in soil may also
314 contribute to groundwater contamination (Zia *et al.*, 2025). Where, fiber shaped MPs are released
315 from domestic washing machines (Gambino *et al.*, (2022)), while regional differences are evident
316 for example, bottled water samples from Thailand contained 62.8% fibres and 37.2% fragments.
317 Overall, the dominance of PU, ABS, and nylon underscores the urgent need for source
318 identification and policy interventions to limit polymer release, strengthen quality control, and
319 safeguard public health.

320 **4.3 Potential sources and release mechanisms of microplastics in bottled water**

321 Temperature fluctuations exerted the strongest influence on microplastic (MP) release from bottled
322 water systems. Shifting bottles from ambient (25 °C) to cooler (4 °C) or warmer (35 °C) conditions

sharply elevated contamination, reaching ~14,000 and ~51,000 items/L, respectively. These findings are consistent with evidence that thermal stress accelerates polymer chain scission, additive migration, and surface degradation (Hee, Weston and Suratman, (2022)). At elevated temperatures, fibers became dominant, reflecting thermal degradation, though microbial or ionic interactions may also contribute. HDPE and PS were the primary polymers shed, with particle sizes of 0.1–0.045 mm, indicating both fragmentation and fresh release from packaging (Pivato *et al.*, (2022); Zhu, Kang, *et al.*, 2024). PET, the main bottled water polymer, resists heat better than PE and PS, but UV aging still causes cracks and MP release. Everyday handling, twisting, squeezing, shaking, or freezing, accelerates shedding, especially in heat-weakened materials(Winkler *et al.*, 2019).

In contrast, long-term storage promoted progressive fragmentation and microbial colonization. Extended storage intensified contamination (3000 MPs items/L), detected after 12 months, consistent with embrittlement, cracking, and biofilm colonization associated with PET aging (Zhou *et al.*, 2023). Fragmented particles (~90%) dominated, underscoring reduced durability of plastics over time. Polymer characterization revealed PS and HDPE as dominant, often appearing as white fragments, while ABS and PU remained constant across storage durations, suggesting external sources rather than packaging-derived release. Microbial growth and biofilm formation within bottled water altered polymer surfaces and facilitated mechanical fragmentation, though microbial effects were secondary compared to UV- and aging-induced degradation, given PET's high resistance to biodegradation (Kataria et al., 2024; Yadav et al., 2025). Surface morphology changes, particularly irregularities induced by UV exposure, enhanced abrasion and fragmentation, explaining the significantly higher MP release observed in aged samples compared to freshly stored bottle (Winkler et al., 2019). Taken together, these findings show a multifactorial pathway:

heat triggers MP release, storage drives fragmentation and colonization, and polymer type shapes persistence, highlighting the need for safer packaging and storage practices.

4.4 Polymer Toxicity

Microplastic (MP) pollution poses serious risks to both ecosystems and human health. All samples in this study were classified as polluted (MPLI > 1, MFC > 1). Bottled water showed higher maximum contamination, yet tap water was consistently more hazardous, with a far greater risk index (~3696 vs. ~266) due to high-risk polymers such as PU and ABS compared to lower-hazard PET and HDPE. Moreover, EDI values showed that Adults consumed ~0.97 particles kg^{-1} day^{-1} (~26,583 lifetime) compared to ~0.44 particles kg^{-1} day^{-1} (~12,045 lifetime) from tap water. Where, Infants were disproportionately exposed, with bottled water yielding ~8.70 particles kg^{-1} day^{-1} versus ~3.92 from tap water. However, showed the serious concern as this potential hazard to hazardous polymer is high in Pakistan drinking water. ABS releases carcinogenic styrene and acrylonitrile, PU exposes humans to asthma-inducing isocyanates and VOCs, and nylon sheds endocrine-disrupting microplastics that accumulate in organs (Luo et al., 2025). These findings highlight a dual concern: bottled water increases exposure levels, while tap water introduces more hazardous polymers. Together, they emphasize the urgent need for safer packaging, improved water infrastructure, and stronger regulations to mitigate human health risks.

4. Conclusion

This national-scale survey confirms that microplastic (MP) contamination is pervasive in both tap and bottled drinking water across Pakistan, with all 38 sampling sources classified as polluted (MCF > 1; MPLI > 1). However, the risk profile of the two sources diverges sharply once hazard, not just abundance, is considered. Bottled water delivered the higher particle intake (EDI 0.97 particles kg^{-1} day^{-1} for adults; 8.70 particles kg^{-1} day^{-1} for infants), driven largely by lower-hazard

polymers (PET, PS) released through packaging degradation, storage, and temperature stress. Tap water, in contrast, carried a substantially greater polymeric risk (MPRI ≈ 3,696 versus 266 for bottled water), because its MP load was dominated by high-toxicity polymers, polyurethane (PU) and acrylonitrile butadiene styrene (ABS), most plausibly sourced from aging distribution infrastructure, industrial effluent, and urban runoff. Infants, who ingest more water relative to body weight, are disproportionately exposed under both pathways. These findings point to a dual and largely uncoupled hazard: exposure risk is concentrated in bottled water, while chemical/toxicological risk is concentrated in tap water. Reducing overall public health burden therefore requires source-specific interventions rather than a single generic response — packaging and cold-chain controls for bottled water, and pipe/infrastructure and industrial-discharge controls for tap water. The results also suggest that government should extend extended-producer-responsibility obligations to PET/HDPE bottle manufacturers alongside continued toxicological research on PU and ABS leachates, is essential to translate these exposure and hazard findings into enforceable public health protection.

Disclosures and Declarations

Authors Contribution: All authors contributed to the study conception and design. Material preparation, data collection, data analysis performed by Amna Zia, Amna Zulfiqar. The first draft of the manuscript was written by Amna Zia and finalized by Zulfiqar Ahmad Saqibs and Mukesh Goel. All authors read and approved the final manuscript.

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