




Prevalence and health risks of microplastics in bottled water and beverages: A food safety concern

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ABSTRACT

Microplastics (MPs) have become a significant contaminant in the global food chain, with increasing evidence of their occurrence in bottled water and commercially packaged beverages. This review consolidates existing insights regarding the presence, polymer makeup, contamination routes, health effects, and strategies for reducing MPs in bottled water, soft drinks, teas, juices, and alcoholic beverages. Investigations indicate that concentrations fluctuate significantly, ranging from a handful to several hundred particles per litre, influenced by the type of beverage, the material of the packaging, and the method of analysis employed. The primary polymers detected include polyethylene terephthalate (PET), polypropylene (PP), and polyethylene (PE), primarily resulting from the degradation of bottles, bottling processes, and contaminated source water. Projected consumption levels indicate that children and regular users experience increased exposure, while findings of MPs in human tissues highlight worries regarding systemic bioaccumulation, inflammation, and oxidative stress. While advancements in technology like Raman spectroscopy, FTIR, and Py-GC-MS have enhanced detection capabilities, the lack of standardized methods hinders the comparability of data. Efforts to reduce impact should prioritize sustainable packaging materials, sophisticated filtration systems, regulatory standards, and consumer education to decrease exposure. This review highlights the presence of MP contamination in beverages as a significant food safety and public health concern. It emphasizes the need for standardized analytical methods, collaborative international policy efforts, and ongoing investigation into the long-term health implications for humans.

1. Introduction

Microplastics (MPs) (<5 mm) have become widespread contaminants in aquatic, terrestrial, and atmospheric environments. Their widespread presence arises from the extensive global utilisation of plastic materials and their inadequate degradability, leading to the buildup of enduring micro-sized debris within ecosystems [1,2]. The particles stem from both primary sources, including industrial abrasives and microbeads, as well as secondary sources that arise from the breakdown of larger plastic waste via mechanical, chemical, and biological processes. Due to their persistence and mobility, MPs have been identified in marine organisms, soils, air, and food chains, which raises considerable environmental and human health concerns [3,4].

The various routes of human exposure, particularly through the consumption of food and beverages, have garnered heightened interest from the scientific community and regulatory bodies alike. Bottled water

and commercially packaged beverages are significant sources of dietary MP intake, as they are regularly consumed by large populations across various age groups [5,6]. The increasing popularity of bottled water, frequently viewed as a more secure option compared to tap water, has unintentionally raised the risk of MP exposure. Numerous investigations have demonstrated the occurrence of MPs in bottled drinking water globally, with particle concentrations varying from a few to hundreds per litre, influenced by factors such as brand, packaging type, and the analytical methods employed [7,8].

MPs infiltrate beverages via various routes, such as the contamination of source water, the breakdown of plastic packaging, and the release of particles during the bottling and transportation processes [9,10]. Polyethylene terephthalate (PET) bottles and polypropylene caps exhibit a notable susceptibility to mechanical stress and degradation caused by temperature fluctuations, which results in the release of MP fragments into beverages during handling or storage [11,12].

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Furthermore, atmospheric deposition and airborne particles present in bottling facilities may also play a role in contamination [13]. The mechanisms underscore that MP contamination transcends being merely an environmental concern; it represents a significant challenge in the realms of beverage manufacturing and packaging safety.

The identification of MPs in drinks is not limited to bottled water. Investigations have indicated the presence of MPs in soft drinks, juices, teas, and alcoholic beverages, with identified polymer types encompassing PET, polyethylene (PE), polypropylene (PP), and polystyrene (PS) [14-17]. Contamination in tea-based beverages originates from both packaging and raw materials, with plastic teabags potentially releasing billions of microparticles during the brewing process [18,19]. This suggests that MP contamination is widespread across various beverage types, shaped by the materials used in packaging, the methods of production, and the regulatory frameworks in different regions.

The presence of MPs in beverages has sparked significant concerns regarding their possible biological impacts. Laboratory studies indicate that MPs have the potential to induce inflammation, oxidative stress, and cytotoxicity, and may act as carriers for hazardous chemicals and heavy metals [20-22]. Smaller particles, including nanoplastics, have the ability to traverse biological barriers like the intestinal epithelium, leading to systemic exposure [23]. Recent findings of MPs in human cardiac, pulmonary, and reproductive tissues [24-26] highlight their bioavailability and potential long-term risks. These findings emphasise the necessity of viewing MPs not just as environmental pollutants, but as new food contaminants that pose a risk to human health.

While significant advancements have been made in the identification of MPs across specific beverage categories, important knowledge gaps persist. Many studies concentrate on particular products or regions, resulting in a deficiency of comprehensive global analyses that incorporate contamination prevalence, polymer diversity, and health implications. Inconsistent sampling and analytical methodologies impede accurate comparisons across studies and complicate risk assessment [27]. Existing water treatment and bottling standards do not adequately address MPs, highlighting the necessity for revised regulations in food safety frameworks.

Recent studies have shown significant differences in the prevalence, analytical techniques, and contamination routes of MPs among various beverage types. Bottled water generally shows the highest and most variable concentrations of MPs, often ranging from a few to several hundred particles per litre, influenced by factors such as brand, packaging type, and analytical protocol [6,7]. Tea-based beverages exhibit significant variability, especially when contained in plastic teabags that may release billions of particles during the brewing process [18,19]. Juices and soft drinks typically exhibit moderate concentrations of MPs, primarily affected by the materials used in packaging and the carbonation methods employed [14,28]. Conversely, alcoholic beverages like beer and wine show a relatively lower yet steady level of contamination, mainly due to the filtration and packaging processes [16,17]. The analytical methods utilized in these beverage systems, specifically FTIR, Raman, and Py-GC-MS, exhibit varying sensitivities and detection limits, which account for the differences in reported concentrations. This comparison highlights the necessity for organized evaluations across different products to enhance our understanding of exposure risks and to standardize detection frameworks.

This review seeks to synthesise recent findings on the presence of MPs in bottled water and beverages, focussing on contamination pathways, polymer characteristics, human exposure, and mitigation strategies. This study distinguishes itself from prior reviews by encompassing a broader range of beverage categories, including soft drinks, teas, juices, and alcoholic beverages. It emphasises the technological, regulatory, and behavioral strategies required to mitigate contamination. The review aims to inform policy development and public health initiatives by presenting MP contamination as a critical food safety issue that necessitates coordinated global action.

2. Prevalence of MPs in bottled water and beverages

MPs have been increasingly documented in bottled water and various beverages worldwide. Concentrations differ significantly based on the type of beverage, the material used for packaging, and the practices employed in regional production. Bottled water continues to be the subject of extensive examination, consistently revealing quantifiable levels of MPs in both domestic and global brands [29,7,30]. Recent studies have broadened the scope of concern to include soft drinks, juices, carbonated beverages, teas, and even alcoholic drinks, indicating that contamination is not confined to drinking water alone [14,16,28,17,31]. The variation in results highlights the impact of different packaging materials, bottling conditions, and analytical techniques. This variability underscores the necessity for standardized monitoring frameworks to facilitate precise cross-comparison and thorough human exposure assessment from a food safety standpoint. Tables 1, 2, and 3 illustrate the presence of MPs in contaminated drinking water, soft drinks, carbonated beverages, alcoholic beverages, and tea-based beverages.

2.1. Physical characteristics of MPs in bottled water and beverages

MPs found in beverages exhibit a variety of shapes, sizes, and colors, indicating their numerous sources of contamination. In bottled water, MPs are frequently detected as fragments and fibers, exhibiting particle sizes that vary from 1 μm to several millimetres [29,7,30]. Soft drinks often include fibers, fragments, and thin films, typically ranging from 50 to 1000 μm , as documented in Turkey and Saudi Arabia [14,36]. Juices and various non-alcoholic drinks primarily consist of particles and fibers ranging from 1 to 1500 μm , often exhibiting colors like black, red, and green [28]. Tea-based beverages raise significant concerns, as highlighted by Kashfi et al. [19], who reported particle sizes ranging from 20 to 5000 μm in teabags. Additionally, Hernández et al. [18] demonstrated that a single plastic teabag can release billions of MP and nanoplastic particles. Alcoholic beverages, such as beer and wine, are similarly impacted, generally containing smaller fibers and fragments that are introduced during processing or packaging [16,17]. The morphological differences affect particle bioavailability and the associated health risks.

2.2. MP concentrations in bottled water and beverages

Concentrations of MPs in beverages differ markedly across product categories. In bottled water, values range from 7 MPs/L in Australian samples to 25 MPs/L in imported brands [30] and reach as high as 104 MPs/L in Saudi Arabia [29]. Similar contamination has been confirmed in Malaysia, India, and Iran [15,34,7]. Soft drinks display contamination ranging from 7.2 MPs/L in Tetra Pak-packaged products to 10.4 MPs/L in PET bottles in Turkey [14], with far higher levels of 113.75 MPs/L in Saudi Arabian brands [36]. In Iran, MPs were consistently detected in widely consumed non-alcoholic beverages [28].

Carbonated beverages often exhibit increased levels of contamination. According to the findings of Hassan et al. [37] in Bangladesh, the concentration of MPs was measured at 151 MPs/L in glass bottles, 134 MPs/L in cans, and 95 MPs/L in PET bottles. Similar values were noted in Brazil, with Alves et al. [38] documenting 18.3 MPs/L in plastic bottles and 150 MPs/L in aluminium cans. Juices and other non-alcoholic beverages generally exhibit moderate to high concentrations, with levels varying from 21.9 MPs/L in Iran [28] to exceeding 100 MPs/L in Saudi Arabia [36]. Tea products exhibit significant levels of contamination, with loose-leaf teas containing between 70 and 3472 MPs/g [31], plastic teabags emitting hundreds of particles per item [19], and in extreme instances, billions of particles being released during the brewing process [18]. Alcoholic beverages have been less extensively examined, yet they consistently demonstrate contamination: beers from 15 countries exhibited 20–80 MPs/mL [17], while French wines and lemonades revealed 8.2 and 45.2 MPs/L, respectively [16]. The findings

Table 1
Microplastics in contaminated drinking waters.

Source	Polymer	Size	Shape	Color	Concentration	MPs intake rate	Method of Detection	Country	Reference
Drinking water	Polypropylene (PP), Polyamide (PA), Polyethylene (PE)	1–6 mm	Fragments, Fibers, Foam	Violet, Blue, Green, Red, Black	1–3 MPs/item	N/A	Stereomicroscope, FTIR, and FESEM with EDS	India	Dileepan et al. [32]
Mineral water	Polypropylene (PP)	> 0.22 µm	Fragments	N/A	~10 MPs/mL	N/A	Bright-field microscopy, Raman spectroscopy	China	Li et al. [17]
Mineral bottled water	Ethylene vinyl acetate (EVA)	N/A	Fibers and Fragments	N/A	11.3 MPs/L	1505–2118 MP/mL/year.	Stereomicroscope and FTIR	Türkiye	Basaran et al. [15]
	Polyethylene terephthalate (PET), Polypropylene (PP), Polyamide (PA), Polyethylene (PE), Polystyrene (PS), Polymethylmethacrylate (PMMA)	77 µm	N/A	N/A	7 MPs/L (Australian bottled water) 25 MPs/L (Imported bottled water)	400 MPs/year (28.3 % of the Australian population)	FTIR	Australia	Samandra et al. [30]
Bottled Water	Polycarbonate (PC), Polyvinylchloride (PVC) Polyester (PES), Polyethylene terephthalate (PET), Polyethylene (PE), Polyamide (PA), Polystyrene (PS), Polypropylene (PP), Polysiloxane (SIL)	12.5–294 µm	Fragments, Fibers, Films	White/transparent	1.61 µg/L MPs (1.10–2.88 µg/L range)	4–18 ng kg ⁻¹ day ⁻¹ (adults)	Micro-FTIR	Spain	Gálvez-Blanca et al. [33]
	Polypropylene (PP), Polyethylene (PE), Polyethylene terephthalate (PET)	101–250 µm	Fragments, Fibers	Black, Blue, Red, Pink	104.36 MPs/L	4.77 MP/kg/day	FTIR, SEM, microscopy	Saudi Arabia	Ahmad et al. [29]
	Polyethylene terephthalate (PET), Polypropylene (PP)	100–300 µm	Fragments	N/A	11.7 MPs/L	0.068 and 0.19 particle/kg/day (Adults) 0.089 and 0.25 particle/kg/day (Children)	Optical Microscope, FTIR	Malaysia	Praveena et al. [7]
	Polyethylene terephthalate (PET), Polypropylene (PP), Polyethylene (PE)	1.1 µm	Fragments, Fibers	Black, Transparent/White	8.5 MPs/L	0.015 P/kg/bw/day (Adults) 0.065 P/kg/bw/day (Children)	Stereomicroscope, Hot Needle Test, FTIR, Raman spectroscopy	Iran	Makhdoumi et al.[34]

Here, FTIR = Fourier Transform Infrared Spectroscopy, FESEM = Field Emission Scanning Electron Microscopy, EDS = Energy Dispersive X-ray Spectroscopy, SEM = Scanning Electron Microscopy.

Table 2
Microplastics in contaminated soft drinks, carbonated and alcoholic beverages.

Source	Polymer	Size	Shape	Color	Concentration	MPs intake rate	Method of Detection	Country	Reference
Soft drinks	Polyamide (PA), Polyethylene terephthalate (PET), Polyethylene (PE)	50–100 µm	Fiber, Fragment, Flim	White/Transparent, Blue, Ash, Red, Black	7.2 MPs/L (Tetra Pak) 10.4 MPs/L (PET)	Adults: 0.002–0.006 MP/kg/bw/day Children: 0.006–0.018 MP/kg/bw/day	Stereomicroscope, FTIR	Türkiye	Altunışık [35]
	Polyethylene terephthalate (PET), Polyethylene (PE), Polypropylene (PP)	501–1000 µm	Fragments, Fibers	Black, Blue	113.75 MPs/L	0.36 MP/kg/day	FTIR, SEM, microscopy	Saudi Arabia	Ahmad et al. [36]
Non-alcoholic beverages	Polyethylene terephthalate (PET), Polyethylene (PE)	1–1500 µm	Fragments, Fibers	Black, Red, Green	21.90 MPs/L	N/A	Microscope, FTIR, SEM, EDS	Iran	Hoseinzadeh et al. [28]
Carbonated beverage (Glass bottles)	Polyethylene terephthalate (PET), Polypropylene (PP), High-density polyethylene (HDPE)	N/A	Fiber, Foam, Bead, Fragment	N/A	151MPs/L	855 MP/person/year	Stereomicroscope, FTIR, SEM	Bangladesh	Hassan et al. [37]
Carbonated beverages (PET bottles)					95MPs/L				
Carbonated beverages (Cans)					134 MPs/L				
Lemonade Cola	Polyester, Polyethylene (PE), Polypropylene (PP), Polyethylene-co-vinyl acetate (PEVA), Ethylene vinyl acetate (EVA)	30–500 µm	Fragments, Fragments, Fibers	N/A	45.2 MPs/L 31.4 MPs/L	N/A	Stereomicroscope, FTIR	France	Chaïb et al. [16]
Guarana Soda (Plastic & Can)	Polyethylene (PE), Polyethylene terephthalate (PET)	50–1360 µm	Fragments, Fibers, Flim	Blue, Black	18.3 MPs/L (Plastic bottle) 150 MPs/L (Aluminum Can)	N/A	Filtration, Stereomicroscope	Brazil	Alves et al. [38]
Lemon Soda Juice Drinks	Polyethylene terephthalate (PET), Polyethylene (PE), Polypropylene (PP)	450–820 µm 501–1000 µm	Fragments, Fragments, Fibers	Black, Blue	22.8 MPs/L 102.70 MPs/L	0.95 MP/kg/day	FTIR, SEM, Microscope	Saudi Arabia	Ahmad et al. [36]
Wine	Polyethylene (PE), Polyethylene terephthalate (PET)	20–5000 µm	Fragments, Fibers	Varied	8.2 MPs/L	N/A	Stereomicroscope, FTIR	France	Chaïb et al. [16]
Beer	Polystyrene (PS), Polypropylene (PP)	> 100 µm	Fibers, Fragments	N/A	20–80 MPs/mL	N/A	Vacuum filtration, Bright-field microscopy, Raman spectroscopy	15 countries (Including Denmark, Brazil,	Li et al. [17]

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Table 2 (continued)

Source	Polymer	Size	Shape	Color	Concentration	MPs intake rate	Method of Detection	Country	Reference
	Polyester, Polyethylene (PE), polypropylene (PP) Poly (ethylene-co-vinyl acetate) (PEVA) Ethylene vinyl acetate (EVA)	30–500 µm	Fragments, Fibers		82.9 MPs/L	N/A	Stereomicroscope, FTIR	Mexico, USA, China, etc.) France	Chaïb et al. [16]

Here, FTIR = Fourier Transform Infrared Spectroscopy, EDS = Energy Dispersive X-ray Spectroscopy, SEM = Scanning Electron Microscopy.

suggest that contamination is pervasive, impacting all sectors of the beverage industry rather than being confined to a single category. In addition to methodological variations, various environmental, technological, and behavioral elements can greatly impact the concentrations of MPs in different beverages. Higher temperatures during storage or transportation can speed up the degradation of polymers and lead to MP shedding from PET and PP packaging [52]. Similarly, extended storage time and ongoing mechanical stress due to handling or transport vibrations can elevate the rate of particle release. Climatic factors like humidity and UV exposure can exacerbate photooxidative degradation, especially in transparent bottles subjected to sunlight [53]. From a behavioral perspective, actions like reusing disposable bottles or exposing beverages to high temperatures further contribute to the leaching of MPs [54].

2.3. Polymer types and their presence in bottled water and beverages

The types of polymers most frequently reported in beverages reflect the dominance of plastic packaging in the food and beverage sector. PET, PP, and PE are the most common (as shown in Tables 1–3), being integral to bottles, caps, and packaging films [36,14,7]. Mineral waters may also contain polyamide (PA) and ethylene-vinyl acetate (EVA), linked to bottling and sealing processes [15]. Tea products often release nylon and polyester, especially from teabags [19,42,41]. Alcoholic beverages, meanwhile, have been found to contain PS and PE, introduced during brewing or packaging stages [16,17]. This diversity in polymer composition indicates multiple pathways of contamination, ranging from packaging breakdown and manufacturing processes to raw material and environmental inputs. The findings collectively indicate that microplastic contamination is widespread across various beverage types and packaging materials, highlighting the necessity of examining the sources and mechanisms of this contamination.

3. Pathways of MP contamination in bottled water and beverages

Understanding the origins of MPs within beverages is essential to designing effective control strategies. MP contamination in bottled water and beverages originates from various sources, which generally encompass packaging materials, the bottling and processing environment, and environmental contamination of source water. The interplay of these pathways frequently results in a range of contamination levels observed across different products and regions. Comprehending these sources is essential for developing focused mitigation strategies and guaranteeing food safety. Fig. 1 illustrates the origins of MP contamination in bottled water and beverages.

3.1. Packaging materials

Packaging materials represent a major factor in the issue of MP contamination. PET, PP, and PE bottles and caps are prevalent in the beverage industry, and their degradation throughout production, transport, and storage results in the release of MP fragments and fibers into beverages [7,10]. Sobhani et al. [12] illustrated that the straightforward action of opening and closing plastic bottles or packaging can produce quantifiable MP particles. Research indicates that an increase in recycled content within PET bottles could potentially enhance the release of non-intentionally added substances (NIAS), including acetaldehyde and benzene, thereby elevating the risk of MP shedding during usage [11]. The packaging of tea-based beverages presents unique challenges, particularly due to the fact that plastic teabags can release billions of particles into a single serving, as noted by Hernández et al. (2019) and Kashfi et al. [19]. The results unequivocally demonstrate that the selection of packaging significantly influences consumer exposure to MPs. The release rate of MP from packaging is significantly affected by various physicochemical factors. Increased temperatures during storage or transportation can hasten the oxidation of polymers and lead to chain scission, which in turn heightens the fragility of PET and PP surfaces [52]. UV radiation exposure facilitates photooxidative degradation, resulting in surface cracking and particle shedding [53]. Mechanical stress resulting from frequent bottle handling, vibrations during transportation, and compression during stacking can significantly enhance the detachment of MPs [55]. The interaction of heat, light, and mechanical wear works together, significantly increasing MP release during extended storage durations. Understanding these degradation dynamics is essential for enhancing packaging design, fine-tuning storage conditions, and minimizing consumer exposure to MPs.

3.2. Bottling and processing environment

The environment for bottling and processing represents a significant avenue of consideration. During the manufacturing process, equipment like filling machines, conveyor belts, and plastic linings may contribute to the introduction of MPs (Sharma, 2024a). Moreover, the processes involved in high-speed filling operations, along with friction from plastic piping and abrasion from mechanical seals or gaskets, can lead to the generation of plastic fragments that may inadvertently contaminate beverages. Thermal processes like pasteurisation or hot filling, which subject packaging to high temperatures, can hasten the degradation of polymers and the release of particles into the liquid [14,56]. Airborne MPs found in production facilities can potentially contaminate beverages during the bottling process [13]. The contributions related to production underscore the significance of industrial hygiene, equipment design, and controlled environments in mitigating contamination.

Table 3
Microplastic in contaminated tea-based beverage.

Source	Polymer	Size	Shape	Color	Concentration	MPs intake rate	Method of Detection	Country	Reference
Tea (Tea Bags)	Polyethylene (PE), Nylon, Polycarbonate (PC)	20–5000 μm	Fibers, Films	White/Transparent	Persian teabag: 412.32 MPs/item German teabag: 147.28 MPs/item	Adults: 810 MPs/person/day Children: 486 MPs/person/day	Optical microscope, Raman Spectroscopy	Iran and Germany	Kashfi et al. [19]
Tea (leaves)	Polyethylene terephthalate (PET), Polyethylene (PE), Polypropylene (PP)	251–500 μm	Fragments, Fibers	Black, Blue	675.71 MPs/item	15.06 MP/kg/day	FTIR, SEM, Microscope	Saudi Arabia	Ahmad et al. [36]
	Polyethylene (PE), Polyethylene terephthalate (PET)	> 100 μm	Fibers, Fragments	Yellow	200–500 MPs/g	N/A	Vacuum filtration, Bright-field microscopy, Raman spectroscopy	China	Li et al. [17]
	N/A	< 0.5–5000 μm	Fibers, Films	N/A	70–3472 MPs/kg	Children: 0.0538–0.09 67 MPs/kg body weight /day Adults: 0.0101–0.01 81 MPs/kg body weight /day	Optical microscope, SEM	China	Xing et al. [31]
Takeout bubble tea	Polyethylene (PE), Polyethylene terephthalate (PET)	< 5000 μm	Fibers, Fragments	N/A	2.2×10^5 – 3.3×10^8 MPs/kg	N/A	Fluorescence microscope, μ -Raman	China	Li et al. [39]
	Polyethylene terephthalate (PET), Polyethylene (PE) polypropylene (PP) Polystyrene (PS)	$\leq 500 \mu\text{m}$	Fibers, Fragments	N/A	< 10–730 MPs/L	N/A	Optical microscope, Raman spectroscopy	China	Bai et al. [40]
Empty plastic and non-plastic teabags	Nylon	0.4 μm –100 μm	Irregular		1.3×10^9 MPs/item		FTIR, NIR hyperspectral imaging	Ireland	Xu et al. [41]
Cold tea	Polystyrene (PS), Polytetrafluoroethylene, Polypropylene (PP), Polyvinylidene Fluoride, Polyethylene (PE)	$\leq 150 \mu\text{m}$	Films, Fragments, Fibers		42.1 MPs/L	6200 MPs/person/year	Optical microscope, Raman spectroscopy	Hong Kong	Lam et al. [42]
Tea (cellulosic Teabags)	Polyethylene Terephthalate (PET), Polyethylene (PE), Polypropylene (PP), Polystyrene (PS)	36–2228 μm	Fibers, Fragments	Black, Blue, Transparent/White	7.11 MPs/L	7.49 MPs/week	Stereomicroscope, PBN (2-Phenylbenzoxazole) method	Italy	Crosta et al. [43]
	Acrylonitrile Butadiene Styrene (ABS), Cellulose Acetate (CA), Ethylene-Vinyl Acetate (EVA), Polycarbonate (PC), Polyethylene (PE), Polyethylene Terephthalate (PET), Polytetrafluoroethylene (PTFE), Polyvinyl Chloride (PVC)	33–2180 μm	Fibers, Fragments, Films, Spherules	N/A	50–60 MPs/kg	N/A	Optical microscope, FTIR, SEM	Bangladesh	Afrin et al. [44]
Tea (plastic teabags/coffee bag)	Polyethylene (PE), Polypropylene (PP), Polyethylene Terephthalate (PET)	N/A	Fibers	N/A	35 %	N/A	Optical microscope, FTIR	Türkiye	Yurtsever [45]
	Polyamide (PA)	> 0.1 μm	N/A	N/A	N/A	N/A	SEM, STXM	Switzerland	Foetisch et al. [46]
	Polyamide (PA), Polypropylene (PP)	< 0.22 μm	N/A	N/A	3.02×10^{-7} g -1.96×10^{-6} g MP/g	N/A	DPV, SEM	China	Li et al. [39]
	Nylon, Polyethylene (PE), Polypropylene (PP), Polyethylene Terephthalate (PET)	> 2.7 μm	Fragments	N/A	80–1290 MP/item	N/A	Raman imaging, Py-GC/MS	China	Yue et al. [47]
Nylon, Polyethylene (PE), Polypropylene (PP), Polyethylene Terephthalate (PET)	< 840 μm	Fibers, fragments	N/A	N/A	N/A	Raman imaging	China	Mei et al. [48]	

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Table 3 (continued)

Source	Polymer	Size	Shape	Color	Concentration	MPs intake rate	Method of Detection	Country	Reference
	Nylon, Polyethylene Terephthalate (PET)	N/A	Linear, Spherical, Irregular	N/A	6–9 MP/item	N/A	FTIR, Raman imaging	China	Ouyang et al. [49]
Tea (biodegradable teabags)	Poly lactide (PLA)	0.1–0.4 μm	Spherules	N/A	8×10^6 MP/item	N/A	FTIR, SEM	Spain	Banaei et al. [50]
Bottled tea	Polyethylene (PE), Polypropylene (PP)	> 20 μm	N/A	N/A	< 1 MP/L	N/A	Optical microscope, FTIR	South Korea	Pham et al. [51]

Here, FTIR = Fourier Transform Infrared Spectroscopy, SEM = Scanning Electron Microscopy, SEM = Scanning Electron Microscopy, Scanning Transmission X-ray Microscopy, DPV = Differential Pulse Voltammetry, Py-GC/MS stands for Pyrolysis-Gas Chromatography-Mass Spectrometry.

3.3. Environmental contamination of source water

Environmental contamination of source water additionally exacerbates the presence of MPs in beverages. While bottled water is frequently promoted as coming from pure springs or groundwater, research indicates that these sources can already be contaminated with MPs due to factors such as runoff, wastewater inputs, and atmospheric deposition [3,57]. In certain areas, source water is found to contain remnants from agricultural plastic usage or urban plastic waste, which may evade standard water treatment processes and find their way into bottled products [58]. Contamination in tea and herbal infusions can begin at the cultivation stage and continue through drying and processing of raw materials. Notably, Xing et al. [31] found that the highest concentrations were present during the rolling stage of tea production.

4. Sensitivity of detection methods of MPs in bottled water and beverages

The detection and characterisation of MPs in bottled water and beverages present significant challenges, attributed to the complexity of beverage matrices and the limitations of current analytical techniques. Various methods have been utilized, each presenting unique benefits and limitations. The absence of standardized protocols among studies complicates cross-comparisons of prevalence data and impedes accurate exposure assessment. Table 4 provides a comparative overview of the analytical methods employed for detecting MPs in bottled water and beverages.

Spectroscopic techniques are the most commonly utilized methods. Fourier Transform Infrared Spectroscopy (FTIR) facilitates polymer identification through absorption spectra, rendering it effective for larger particles. However, its sensitivity diminishes for particles smaller than 5 μm , which may lead to an underestimation of exposure to nano- and sub-micron MPs [27]. Raman spectroscopy offers enhanced resolution and the capability to detect particles smaller than 1 μm , rendering it useful for analysing colored or complex matrices, including soft drinks and teas [59]. The primary limitation lies in the interference caused by fluorescence from dyes and additives, which may obscure the signal intensity. Nonetheless, Raman spectroscopy continues to be an exceptionally adaptable method for distinguishing between various polymer types within intricate beverage matrices like tea infusions and soft drinks.

Microscopy techniques yield crucial insights into morphological characteristics. Scanning Electron Microscopy (SEM), frequently paired with Energy Dispersive X-ray Spectroscopy (EDS), provides comprehensive surface characterisation and elemental analysis; however, it faces challenges with nanoparticles and necessitates extensive sample preparation [60]. Stereomicroscopy serves as a common initial screening method for assessing particle abundance and size. However, it falls short in resolution for smaller particles and frequently leads to overestimation caused by the misidentification of natural fibers.

Thermal analysis techniques, especially Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS), are being utilized more frequently for the analysis of beverages. The techniques employed break down plastics into recognisable chemical components, facilitating accurate identification of polymers even within intricate mixtures like tea infusions or juices [61]. Nonetheless, this technique is inherently destructive and fails to yield particle counts or morphological data, which restricts its application for exposure quantification.

Each of these methodologies poses distinct obstacles when implemented in the context of beverages. Carbonated beverages and fruit juices contain sugars, acids, and colors that complicate filtering and disrupt spectroscopic signals. Tea-based beverages provide significant challenges due to the presence of plant particles that could be erroneously identified as MPs. Pretreatment techniques, such as enzymatic digestion or oxidative cleaning, might enhance accuracy but may potentially compromise sensitive polymer types, resulting in false

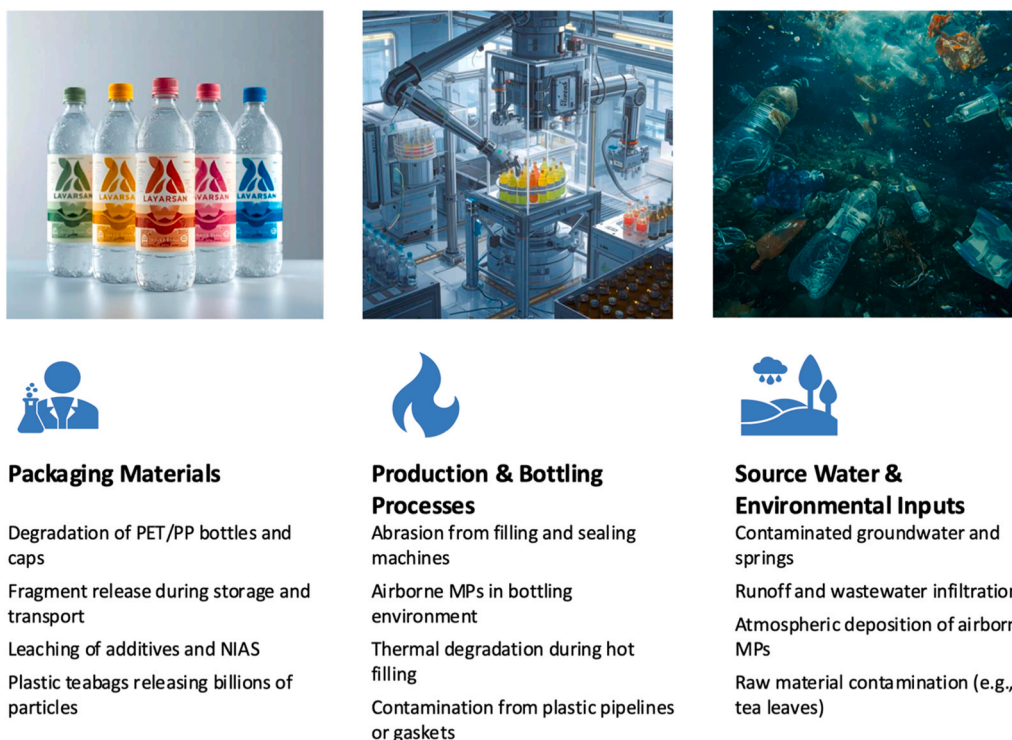


Fig. 1. Major sources of MP contamination in bottled water and beverages. The diagram illustrates the three primary pathways: (1) degradation of packaging materials such as PET and PP; (2) bottling and processing environments, where airborne MPs and frictional wear can introduce contaminants; and (3) source-water contamination through runoff or atmospheric deposition. These routes collectively explain the variability in MP levels observed across beverage types and regions.

Table 4

Comparative overview of analytical methods used for microplastic detection in bottled water and beverages.

Method	Detection Limit	Strengths	Weaknesses	Suitability for Beverages
FTIR (Fourier Transform Infrared Spectroscopy)	> 5 μm (limited for smaller particles)	Identifies common polymers; widely available	Misses smaller particles; matrix interference	Good for bottled water; less effective for juices/colored drinks
Raman Spectroscopy	< 1 μm (high sensitivity)	High resolution; effective in colored/complex matrices	Fluorescence interference; costly equipment	Useful for teas, juices, colored and carbonated drinks
SEM/EDS (Scanning Electron Microscopy + Energy Dispersive X-ray)	~1 μm (not effective for nanoparticles)	Detailed morphology and elemental composition	Labor-intensive; requires extensive sample prep	Good for detailed characterization in research settings
Stereomicroscopy	> 20 μm (low resolution)	Quick screening; estimates abundance/size	Prone to misidentification; lacks resolution	Initial screening of bottled water and soft drinks
Py-GC-MS (Pyrolysis-Gas Chromatography-Mass Spectrometry)	Polymer-specific; not particle size dependent	Accurate polymer ID in complex matrices	Destructive; no particle count or morphology data	Effective for teas, juices, and other complex beverages
Emerging (STXM, Hyperspectral Imaging, Microfluidics)	Sub-micron and nanoparticles (<1 μm)	Can detect nanoplastics; applicable in complex beverages	Not standardized; expensive; limited availability	Future potential for all beverages; not yet routine

negatives.

Even with considerable progress, nanoplastics (<1 μm) continue to be mostly undetectable through traditional FTIR and Raman methods [46,62]. Innovative techniques like scanning transmission X-ray microscopy (STXM), hyperspectral imaging, and microfluidic-based separation demonstrate potential for identifying smaller particles in intricate beverages [41,60]. However, these methods are costly, not yet standardized, and often limited to laboratory research settings. Future analytical frameworks should focus on (i) standardized sample pretreatment, (ii) multi-modal detection protocols that integrate spectroscopy, microscopy, and thermal analysis, and (iii) harmonised reporting units to enhance comparability across studies.

5. Mitigation strategies for MP contamination in bottled water and beverages

Having outlined the detection challenges and contamination pathways, this section focuses on practical and policy-based mitigation strategies to reduce MP contamination throughout the beverage supply chain. Mitigating MP contamination in bottled water and beverages necessitates a comprehensive strategy that integrates source reduction, technological advancement, regulatory measures, and consumer education. Although packing materials are the primary contributor, bottling techniques, supply water, and end-user handling also significantly influence the outcome. Consequently, mitigation efforts must be comprehensive, including the full production and consumption continuum. Fig. 2 illustrates the options for mitigating MP contamination in bottled water and beverages.

5.1. Source reduction and sustainable packaging

Minimising dependence on single-use plastics is the most straightforward approach to mitigate the release of MPs into beverages. The shift from PET and PP bottles to biodegradable polymers like polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based plastics has been suggested as a more environmentally friendly option [63]. Nonetheless, a thorough assessment of the durability and the risk of secondary pollution of these biopolymers in real-world scenarios is essential. Glass and metal containers serve as durable options, as they do not break down into MPs throughout their usage or recycling processes. The approaches of Life Cycle Assessment (LCA) highlight the critical need for beverage packaging design that prioritizes durability, recyclability, and a reduced environmental impact [64]. Regulatory precedents, including the European Union's Single-Use Plastics Directive [65] and national bans in Bangladesh and Rwanda [66], illustrate that interventions at the source can effectively diminish plastic leakage into the environment.

5.2. Technological innovations in filtration and treatment

Recent developments in water treatment technologies present significant opportunities for the reduction of MPs, applicable in both industrial and household settings. Membrane-based processes like nanofiltration and reverse osmosis (RO) demonstrate significant efficacy in eliminating MPs from source and process water, outperforming traditional micro- and ultrafiltration methods in terms of efficiency [67, 68]. Membrane bioreactors and dynamic membranes demonstrate significant potential in removing MPs from wastewater streams, suggesting possible applications in the beverage sector [69]. At the household level, the adoption of activated carbon filters and reverse osmosis systems is on the rise to reduce consumer exposure through tap water [70]. Nonetheless, these technologies incur significant costs, demand considerable energy, and could produce secondary waste, prompting enquiries regarding their viability on a large scale. In the beverage industry, the implementation of multi-stage treatment systems at bottling plants represents a vital measure for minimising MPs before the packaging process.

5.3. Policy and regulatory interventions

The lack of standardized guidelines for MPs in beverages represents a notable deficiency in food safety regulation. Establishing regulatory thresholds for acceptable MP levels is essential, akin to the current limits set for heavy metals or chemical contaminants. Global entities like the

WHO and EPA have the potential to serve as coordinators in the development of worldwide standards [71]. Economic policies, such as tax incentives and subsidies, have the potential to motivate companies to transition to sustainable packaging solutions. Extended Producer Responsibility (EPR) schemes, which have been implemented in various nations, transfer the responsibility of waste management from consumers to producers, encouraging advancements in eco-design [72]. Instances like the UK Plastic Packaging Tax, which imposes penalties on packaging containing less than 30 % recycled content, demonstrate how financial mechanisms can drive industrial transformation [73]. Enhanced oversight, documentation, and labelling standards are crucial for fostering transparency and accountability in the beverage sector.

5.4. Consumer awareness and behavioral change

Individuals are pivotal in influencing the demand for safer and more sustainable options. Public awareness campaigns, like the "Plastic Free July" initiative, have shown significant potential worldwide in decreasing reliance on single-use plastics [74]. Promoting the adoption of reusable bottles, implementing correct disposal methods, and utilising safe household water filtration systems can greatly minimise individual exposure to MPs. Programs that educate consumers about the presence of MPs in beverages and the related health risks can effectively influence preferences towards products packaged in glass or metal, as well as brands that implement MP-free practices. Knowledgeable consumers safeguard their interests while also influencing industries to embrace more sustainable technologies and packaging options.

6. Human exposure and health risks

The occurrence of MPs in bottled water and beverages signifies a direct route of dietary exposure for humans, alongside additional sources like seafood, salt, and ambient air. The absolute levels of MPs consumed through beverages might appear modest when compared to other dietary sources; however, their frequent intake and the prevalence of small-sized particles render this route especially significant for food safety considerations.

The estimated intake rates of MPs from beverages (Tables 1–3) show significant differences across various age groups, types of beverages, and geographical regions. In soft drinks, the estimated daily exposure for adults ranges from 0.002 to 0.006 MPs/kg bw/day, whereas children, owing to their higher fluid intake relative to body weight, may consume between 0.006 and 0.018 MPs/kg bw/day [14]. Some brands in Saudi Arabia have been documented to achieve exposures as high as



Fig. 2. Integrated mitigation framework for reducing MP contamination in beverages. Key strategies include source reduction through sustainable packaging, advanced filtration and treatment technologies, policy and regulatory interventions, and consumer behavior change. The schematic highlights the multi-level approach required from industry to individual actions to limit MP release and exposure.

0.36 MPs/kg bw/day [36]. Gálvez-Blanca et al. [33] estimated an intake of 4–18 ng/kg/day among adults for bottled water. Tea-based beverages can contribute significantly higher amounts: Kashfi et al. [19] calculated daily ingestion of 810 MPs per adult and 486 MPs per child from teabags alone. In Bangladesh, where the consumption of carbonated beverages is notably high, Hassan et al. [37] estimated an annual exposure of 855 MPs per person. The results highlight that beverages represent a significant source of MPs, especially among groups with elevated consumption of packaged drinks. Young children and infants seem to be especially at risk. Their beverage intake, when considered in relation to body weight, leads to estimated exposures through bottled water, juices, and soft drinks that are proportionally higher than those observed in adults [14]. Exposure during early life raises significant concerns due to the heightened sensitivity of the immune, neurological, and endocrine systems during development.

The properties of ingested MP particles, including size, shape, polymer composition, and surface chemistry, significantly affect their interactions with biological systems. Particles smaller than 10 µm raise significant concerns due to their ability to translocate across the gastrointestinal epithelium and enter systemic circulation [23]. Once internalised, MPs can serve as vehicles for heavy metals and hydrophobic organic pollutants, thus increasing toxicological risks [22,75]. Experimental studies show that MPs can alter gut microbiota, trigger inflammation, and damage tissue integrity, with long-term risks such as oxidative stress, potential carcinogenic effects, and endocrine disruption [20,21].

Recent findings in human biomonitoring provide additional insights into the widespread distribution of MPs. Qin et al. [24] discovered the presence of MPs in human endometrial tissue, noting a connection to reproductive toxicity and inflammation. Yang et al. [25] identified MPs in cardiac tissues and blood samples, thereby confirming their systemic bioavailability. Zhu et al. [26] documented the presence of MPs in lung, intestinal, and tonsil tissues, identifying polyvinyl chloride (PVC) as having the highest hazard index. Notably, female tissues showed greater MP burdens compared to male tissues, indicating potential differences in exposure or susceptibility based on sex [26]. Variations in occupational exposure, dietary choices, and drinking habits may affect exposure levels. Females typically show a greater body fat composition, which may aid in the retention of hydrophobic particles or related contaminants. Current epidemiological data are inadequate for determining specific dose–response thresholds; however, the consistent detection of tissue across various organs suggests extensive human exposure. The restricted elimination capacity for small MPs suggests that even minimal daily doses can result in cumulative body burdens over time. Long-term risk assessment necessitates the integration of chronic low-dose exposure models with *in vivo* biomarkers of oxidative and inflammatory responses. Despite growing evidence, the health risks associated with MPs in beverages are still not fully understood. Most toxicity data derive from *in vitro* and animal studies, which often employ concentrations considerably higher than those present in beverages. Human epidemiological data are insufficient, offering limited insights into dose–response interactions and long-term health effects. This information gap underscores the urgent need for standardized risk assessment systems that integrate quantitative intake estimates and mechanistic toxicology.

At present, proposing a tentative tolerable daily intake (t-TDI) for MPs is challenging, as investigations into the long-term and chronic health effects of human exposure are still in their infancy. The potential toxicity and harm are significantly influenced by factors such as the type of polymer, the size and shape of the particles, surface characteristics, and the presence of chemical additives. Due to this variety, it is not presently possible to establish a singular universal limit. Priority populations for intervention and monitoring include vulnerable groups such as infants, children, pregnant women, and individuals with high beverage consumption. Setting precise exposure thresholds and safety margins tailored to specific populations should be a primary objective in

upcoming regulatory and toxicological investigations.

7. Challenges and future directions

Despite the increasing body of evidence regarding mp contamination in bottled water and beverages, numerous significant challenges impede precise risk assessment and the implementation of effective mitigation strategies. The challenges can be categorised into three primary areas: analytical limitations, health risk uncertainties, and feasibility of proposed solutions.

A significant obstacle persists due to the absence of standardized analytical techniques for identifying MPs in beverages. The current methodologies, including FTIR, Raman spectroscopy, SEM, and Py-GC-MS, exhibit differences in sensitivity and selectivity, frequently yielding results that pose challenges for comparison across various studies. The challenge of reliably detecting nanoplastics (<1 µm) is a significant issue, given that these particles are likely to breach biological barriers and lead to systemic effects [60,76]. In beverages like teas, juices, or carbonated drinks, the presence of complex matrices complicates detection, resulting in the underestimation or misclassification of MPs [31]. There is an urgent need for standardized international protocols regarding sample preparation, measurement, and reporting to ensure the generation of reliable prevalence data and to facilitate informed regulatory decision-making.

The second challenge involves the ambiguities associated with risks to human health. Laboratory studies have shown inflammation, oxidative stress, endocrine disruption, and tissue damage resulting from MP exposure [20,21]. However, most of these experiments utilize concentrations that are significantly higher than those usually present in beverages. Studies on human biomonitoring have established the detection of MPs in cardiac, reproductive, and respiratory tissues [24–26], however, the causal relationships between beverage-derived MPs and chronic diseases have yet to be demonstrated. There is a lack of epidemiological studies, the dose–response relationships remain inadequately defined, and safe intake thresholds have yet to be determined. The absence of toxicological evidence hinders precise risk assessment and compromises regulatory readiness.

The third challenge pertains to the practical feasibility of mitigation strategies. Biodegradable polymers, including PLA and PHA, present alternatives to traditional plastics; however, their elevated costs, restricted durability, and propensity to fragment in environmental conditions hinder their scalability [63]. Advanced filtration techniques, such as nanofiltration and reverse osmosis, effectively eliminate MPs from source water; however, they are energy-intensive and produce secondary waste streams [67,68]. Policies like Extended Producer Responsibility (EPR) and plastic taxes incentivise sustainable packaging; however, their implementation is inconsistent across regions, especially in developing economies experiencing rapid growth in beverage consumption.

Future research and policy development should prioritize three key directions. The establishment of standardized, internationally recognised detection protocols will enable consistent monitoring and facilitate global comparisons. Investment in longitudinal human studies is essential to elucidate the long-term health effects of chronic MP exposure via beverages, particularly concerning vulnerable populations such as children and infants. Collaborative initiatives among governments, industry, and academia are essential to expedite the development and implementation of scalable alternatives to single-use plastics, underpinned by regulatory frameworks and economic incentives.

8. Conclusion

The presence of MPs in bottled water and beverages raises significant concerns regarding food safety and public health. Global investigations reveal the extensive occurrence of polymers like PET, PP, and PE, primarily stemming from packaging, manufacturing processes, and source

water. Projected consumption levels indicate that children and regular consumers encounter increased exposure risks. While there is evidence connecting MPs to inflammation and tissue accumulation, the health effects are still not clearly defined. To achieve effective mitigation, it is essential to implement sustainable packaging solutions, utilize advanced filtration technologies, establish regulatory limits, and enhance consumer awareness. Systematic international collaboration and uniform detection protocols are crucial for minimising exposure and guaranteeing the enduring safety of beverages.

CRedit authorship contribution statement

Saydur Rahman: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Writam Saha:** Writing – original draft, Visualization, Investigation, Data curation. **Tasnim Iqbal Maysha:** Writing – original draft, Data curation. **Promit Sarkar:** Writing – original draft, Data curation. **Tonni Rani Datta:** Writing – original draft, Data curation. **Samiha Rahman:** Writing – original draft, Data curation. **Rakhi Chacrabati:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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