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Microplastics and nanoplastics in drinking water and beverages: occurrence and human exposure

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Abstract

Microplastics (MPs) and nanoplastics have gained significant attention as emerging environmental pollutants due to their widespread presence and potential health risks. In recent years, these contaminants have been frequently detected in drinking water and various beverages, prompting concern about their sources and effects. This paper provides a comprehensive review of the occurrence of MPs in drinking water and beverages and exposure assessments. MP concentrations in drinking water vary significantly across countries and regions, influenced by diverse factors such as the efficiency of water treatment plants, the level of pollution in water sources, and the condition of transportation pipelines. Another critical aspect discussed in this review is the assessment of human exposure to MPs. Similarly, the daily intake of MPs shows significant variation across different countries and regions. Beyond the concentration of MPs in drinking water, an equally important factor is the quantity of water consumed, which can differ by as much as two orders of magnitude between studies. These variations in water consumption are a key focus of this article, as they greatly influence the estimation of human MP exposure. Furthermore, it discusses the limitations of current research, emphasizes gaps in understanding nanoplastics, and outlines potential future research directions.

Keywords: Microplastics, nanoplastics, tap water, bottled water, beverages, human exposure

INTRODUCTION

The study of microplastics (MPs) has gained increasing attention over the past two decades since the concept was first introduced by Thompson *et al.* in 2004[1,2]. MPs are defined as plastic particles that measure less than 5 mm in size, while nanoplastics are even smaller, with a diameter of less than 1 μm[3]. MPs are divided into two categories according to their sources: primary and secondary MPs. Primary MPs are intentionally manufactured in small sizes and directly discharged into the environment, such as plastic microbeads in facial cleansers. In contrast, secondary MPs are derived from the degradation of large plastics in the environment. These larger plastics break down into smaller particles, or MPs, through physical and chemical reactions, such as exposure to sunlight[1,4].

MPs are now widely recognized as pervasive environmental pollutants that exist in various ecosystems across the globe, from urban environments to the most remote corners of the planet[5-10]. Their widespread distribution has raised concerns about the potential impacts on ecosystems and human health[11,12]. The omnipresence of MPs in the environment eventually leads to human exposure. In recent years, numerous studies have reported the presence of MPs in the human body, signaling a growing public health concern. These particles have been found in human feces[13], the endometrium[14], the placenta[15,16], gallstones[17], bone marrow[18], and blood[19,20]. These findings highlight the extent of human exposure to these particles and raise critical questions about the possible health implications of long-term exposure to MPs and nanoplastics. For example, a recent study involving over 200 surgical patients found that nearly 60% had MPs or nanoplastics in a major artery. Those with detected plastics were 4.5 times more likely to experience cardiovascular issues, suggesting a link between plastic particles and heart health problems[20].

Human exposure to MPs is primarily through ingestion[21], inhalation[22], dermal contact[23], and maternal transfer[15]. For example, a study estimated that annual MP consumption through food ingestion ranges from 39,000 to 52,000 MP/year, depending on age and sex[24]. One of the most significant routes is through the consumption of liquids[24,25]. Drinking liquids, including tap water, bottled water, and beverages, have all been shown to contain MPs[26]. This is of particular concern because liquids are consumed in large quantities on a daily basis, increasing the likelihood of significant MP intake over time. Figure 1 shows the number of publications in recent years addressing the presence of MPs in tap water, bottled water, and beverages. The data are based on results from the Web of Science database using the search terms “microplastics”, “nanoplastics”, “tap water”, “bottled water”, and “beverages”. To date, over 100 studies have been conducted on the occurrence of MPs in tap water, bottled water, and beverages [Figure 1]. The research has consistently demonstrated the presence of MPs in these three types of drinking liquids, indicating that no matter the sources, drinking water and beverages may serve as a conduit for human exposure to micro- and nanoplastics. Given the widespread consumption of these liquids, understanding the factors contributing to MP contamination is crucial for assessing the risks they may pose to human health.

In recent years, several review studies that examine the occurrence of MPs and nanoplastics in drinking liquids, providing valuable insights into this emerging issue, have been published. For example, Maharjan (2024) and Menon *et al.* (2023) conducted comprehensive reviews on the presence of MPs in tap water[27,28]. Similarly, Dafne *et al.* (2024) and Shruti *et al.* (2021) reviewed the occurrence of micro- and nanoplastics in beverages[29,30], shedding light on the extent of contamination in popular drinks. In addition, Mandloi (2020) focused on the presence of nanoplastics in drinking water[31], while Belz *et al.* (2024) reviewed various analytical methods for detecting MPs in water[32].

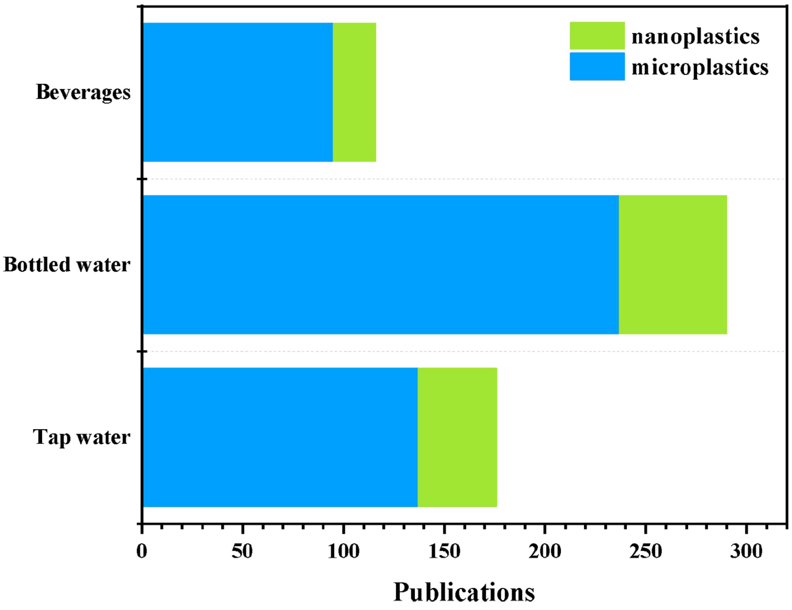

Figure 1. Publications from Web of Science until August 2024.

This review will focus on the occurrence and human exposure of micro- and nanoplastics in tap water, bottled water, and beverages, especially the parameters of daily consumption of different liquids, which are not discussed in the above reviews. It aims to highlight the importance of addressing MP contamination in drinking liquids, as well as the need for further research to better understand the implications for human health. The growing body of evidence points to the need for more awareness and action to mitigate the impact of MPs on both environmental and public health.

MPS AND NANOPLASTICS IN DRINKING WATER AND BEVERAGES

MPs in tap water

The presence of MPs in tap water has been widely confirmed by numerous studies conducted in various parts of the world[33-38]. MP contamination in tap water varies greatly between countries and even within regions of the same country. Figure 2 provides an illustration of the occurrence of MPs in tap water across different nations. According to the data, the concentration of MPs in tap water can range from 394 particles per liter, which is among the highest average concentrations, to as low as 0.012 particles per liter in certain regions of China [Figure 2]. These vast differences reflect not only geographical variability but also disparities in water management practices, the condition of infrastructure, and environmental pollution levels. Research on MP contamination in tap water has predominantly focused on Asia and Europe [Figure 2], where industrialization and urbanization contribute significantly to plastic waste generation.

The concentration of MPs in tap water varies widely among different countries, with reported values ranging from zero in Italy to as high as 61 particles per liter in the United States[39], and the global average has been reported at about five MP particles per liter[39]. Even within the same country, there can be significant variation in MP concentrations. For example, research conducted in 38 cities across China found that concentrations of MPs in tap water ranged from 0 to 1,247 particles per liter, with an average of 440 ± 275 particles per liter[40]. Such discrepancies can be attributed to factors such as the quality of source water, the efficiency of water treatment plants, and the condition of water distribution systems. The size distribution of MPs in tap water also varies, with smaller particles generally being more abundant. For

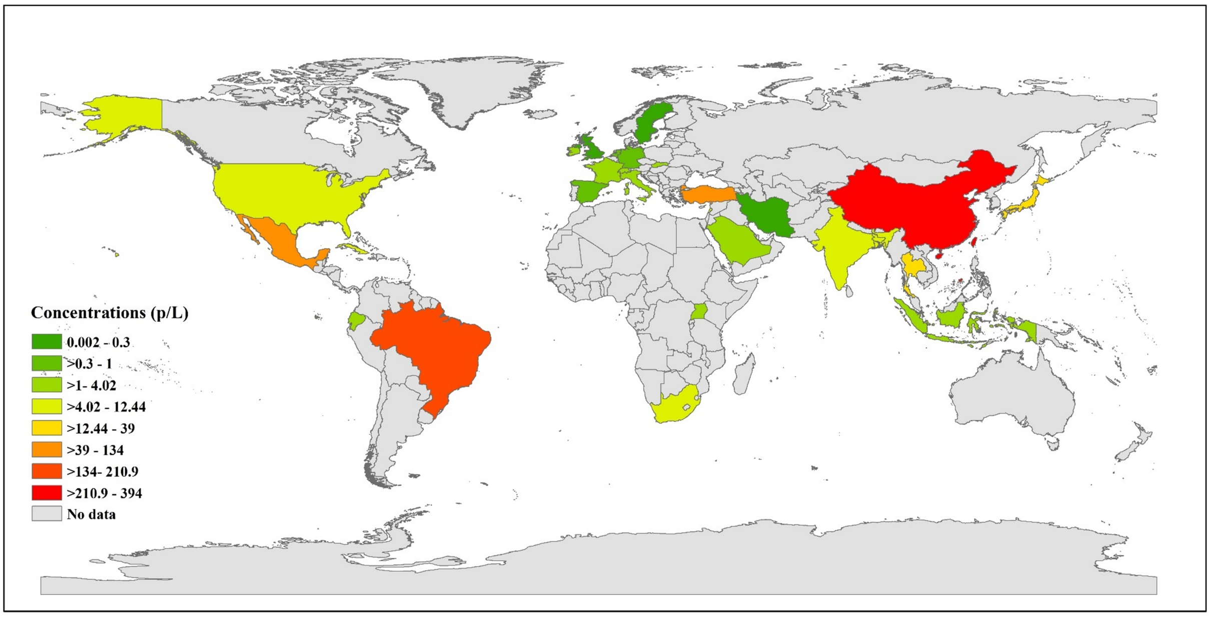

Figure 2. Mean particle concentrations of MPs in tap water in different countries. MPs: Microplastics.

instance, in Thailand, the concentration of MPs in the 6.3 to 53 μm size range was reported as 56 ± 14 particles per liter, while the concentration of larger MPs in the 53 to 300 μm range was only 21 ± 7 particles per liter[41]. This pattern of higher concentrations of smaller particles is common in most studies, highlighting the challenge of detecting and quantifying these tiny pollutants.

MP pollution in tap water can stem from two primary sources: the contamination of the water source itself and the transportation pipelines that deliver the water. For example, a study in the Netherlands found that a reservoir serving as a source of tap water contained MP concentrations as high as 81,249 particles per cubic meter[42]. In contrast, groundwater in the same study showed no detectable MP contamination[42]. Research from Iran discovered MP pollution in the water distribution pipelines of two different water treatment plants. The concentration of MPs in the effluent and faucet water from these plants ranged from 45 to 205 particles per cubic meter, indicating that the transport systems themselves drastically contribute to MP contamination[43].

Water treatment plants (WTPs) are designed to remove contaminants, and they do manage to remove a significant portion of MPs from tap water[44,45]. However, the efficiency of MP removal varies widely between plants. For example, in Qingdao, China, the average concentration of MPs in source water was 1.6 particles per liter, and it was reduced to 0.7 particles per liter after the treatment, which yielded a removal efficiency of about 56%[46]. WTPs in Shanghai reported removal rates of 72.7% to 83%[47], while a water treatment facility in Brazil achieved a removal efficiency of 68%[48]. A study has provided detailed quantitative evidence using pyrolysis gas chromatography to test water samples. MP concentrations in source water, settled water, filtered water, and effluent were found to be 9.632, 4.793, 2.238, and 0.772 μg/L, respectively[49]. On the contrary, some plants show poor efficiency in MP removal. In South Africa, one study found that there was no significant removal of MPs, with concentrations in the effluent similar to those in the source water (0.56 to 0.9 particles per liter)[50].

Despite the general success of water treatment plants in reducing MP concentrations, they are not foolproof. In some cases, they can even contribute to secondary contamination. A study in Switzerland found that the final concentration of MPs in water treatment plant effluent was 2 ± 2 particles per cubic meter, suggesting that some particles may be introduced during the treatment process[51]. Furthermore, while coagulation and sand filtration can remove a significant portion of MPs, advanced treatments such as ozone and granular activated carbon (GAC) filtration have proven even more effective. After ozone and GAC treatments, MP concentrations in water were reduced by 98%, from 38.2 ± 15.5 particles per cubic meter in source water to just 0.7 ± 1.2 particles per cubic meter[51]. Another study corroborated these findings, showing that MP particles larger than 20 microns were removed with an efficiency greater than 98%[35].

Transportation pipelines are a key source of MP contamination. In a study conducted in China, it was found that the concentration of MPs in tap water was higher than in the water plant's influent, indicating contamination during transportation through pipelines[52]. Polyvinyl chloride (PVC) is commonly used in water distribution systems, and studies have shown that PVC can be a significant source of MP contamination. In one study, the concentration of PVC MPs in tap water was significantly higher than in the water treatment plant's effluent, highlighting the role of pipelines in MP pollution[53]. Another study found that MP concentrations were higher in water samples taken from the middle of the transport pipelines compared to the water plant effluent, further reinforcing the conclusion that pipelines contribute to MP contamination[54]. In addition, other factors such as climate[55], population density[56], economic level[56], and industrial activity[57] will also affect the occurrence of MPs in tap water.

The issue of MP contamination in tap water is both widespread and multifaceted. While water treatment plants play a critical role in reducing the concentration of MPs, they are not entirely effective, and some plants perform better than others. Furthermore, the pipelines used to transport treated water can introduce new contaminants, particularly in regions that rely heavily on plastic materials like PVC in their infrastructure. The removal of MPs from tap water, especially the smaller particles, remains a significant challenge. As research continues to expand in this area, it is becoming clear that a combination of improved water treatment processes, better maintenance of water distribution systems, and more rigorous monitoring of MP concentrations are essential to mitigate the impact of these pervasive pollutants.

MPs in bottled water

MPs have also been consistently detected in bottled water, raising concerns about the safety and quality of this widely consumed product[58-62]. The concentration of MPs in bottled water varies considerably among different brands and countries. On average, the concentration ranges from 0.73 to as many as 54.2 million MP particles per liter [Figure 3]. One of the highest concentrations recorded comes from bottled water in Italy, where the MP load ranged between 3.16 million and the astounding 110 million particles per liter[62]. This unusually high concentration may, however, be attributed to the detection methods used in the study. The researchers employed scanning electron microscopy (SEM) for particle detection but did not identify the specific types of MPs, leading to the possibility of false positives in the data[62]. This example underscores the importance of using comprehensive methods that can identify the types and sources of MPs for more precise results.

In addition to the Italian samples, bottled water from Germany also displayed tremendous levels of MPs, with a maximum concentration of 35,346 particles per liter[61]. In a study conducted in Bangladesh, mineral water from ten different brands exhibited a lower range of MP contamination, where the concentration varies between 14 and 56 particles per liter, and the average was around 35 per liter[60]. These variations highlight not only geographical differences but also the influence of different manufacturing processes,

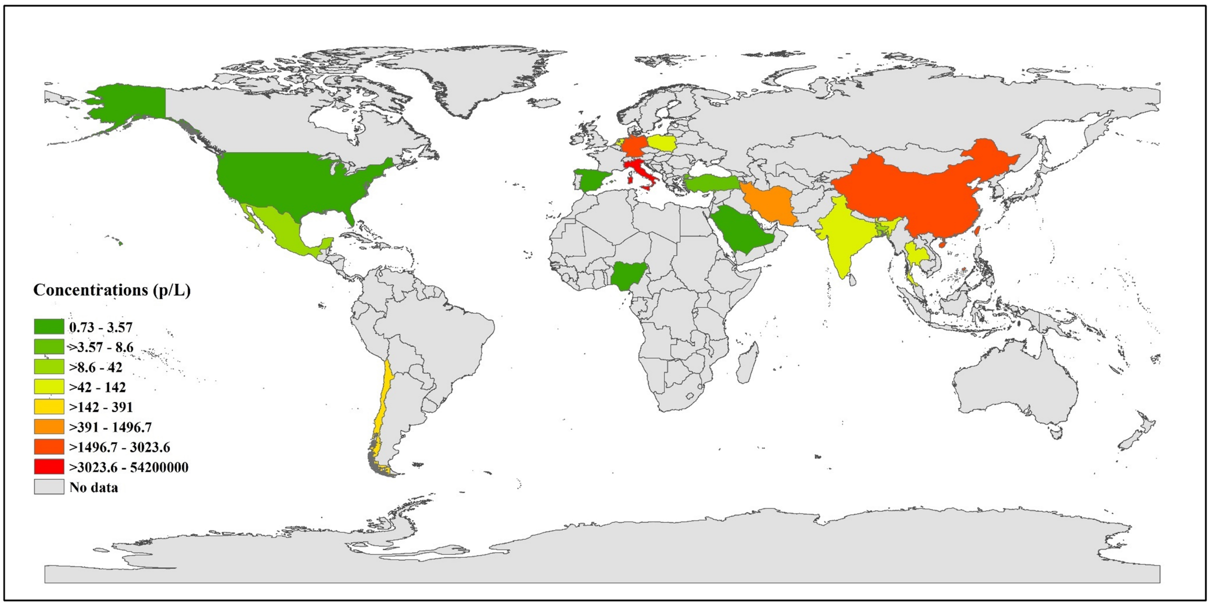

Figure 3. Mean particle concentrations of MPs in bottled water from different countries. MPs: Microplastics.

bottle materials, and environmental conditions.

A noteworthy study from Germany compared the concentration of MPs in water from plastic and glass bottles. While the water from glass bottles had relatively lower concentrations of MPs overall, one exception was noted, with a glass bottle sample containing up to 35,346 particles per liter. Interestingly, the study revealed that the concentration of MPs in glass bottles was generally similar to that in disposable polyethylene terephthalate (PET) bottles, and both were lower than that in reusable PET bottles[61]. However, a key difference emerged in the types of MPs found. In water from PET bottles - whether disposable or reusable - PET particles dominated, making up more than 70% of the detected MPs. In contrast, water from glass bottles showed a higher proportion of polyethylene (PE, 46%) and polypropylene (PP, 23%) plastic[61]. This pattern suggests that the type of packaging material plays an essential role in determining the composition of MPs in bottled water, potentially due to the degradation of these materials into smaller particles over time.

Findings from other regions provide additional insights into the presence of MPs in bottled water. For example, a study conducted in Thailand found that plastic bottled water had significantly higher concentrations of MPs (140 ± 19 particles per liter) than water in glass bottles (52 ± 4 particles per liter). The most prevalent types of MPs were PET and PE, mirroring results from the German study, where smaller MP particles were more frequently detected[63]. However, this study did not distinguish between the types of MPs in plastic versus glass bottles, leaving room for further investigation into how bottle materials may influence MP contamination.

Moreover, studies conducted in China have yielded different results. In bottled water from China, the primary particles detected were natural fibers rather than synthetic polymers. The main types of MPs identified in these water samples were PVC and PET[64,65]. The prevalence of PVC in Chinese bottled water samples is particularly noteworthy, as rather than PVC, PET and PE are more commonly reported in studies from other regions. This could be due to different packaging materials used in China or variations in water sources and treatment processes.

The bottles themselves - particularly plastic bottles - are recognized as a major source of MPs in bottled water[66]. Several studies have focused on the release of MPs from various types of water bottles, and the findings are striking. A study showed that reusable plastic bottles release an average of 118 ± 88 MP particles per liter, whereas disposable bottles release only 14 ± 14 particles per liter. In both cases, PET accounted for more than 50% of the MPs detected[67]. Glass bottles, often assumed to be free from MP contamination, are not innocent in the issue. In the same study, MPs were also detected in experiments involving glass bottles, with concentrations as high as 50 ± 52 particles per liter. The primary types of MPs released from glass bottles were PE (35%) and PET (33%), suggesting that even glass packaging, perhaps through interactions with caps or seals, can contribute to MP contamination[67].

These findings indicate that packaging materials play a critical role in MP contamination in bottled water. Plastic bottles, especially those made from PET, are a well-documented source of MPs. However, even glass bottles, which are often marketed as a more environmentally friendly alternative, also contribute to MP contamination, albeit to a lesser extent. The higher levels of MP release from reusable plastic bottles raise additional concerns, as these bottles are often used multiple times, increasing the likelihood of material degradation over time. To reduce the presence of MPs in bottled water, it is crucial to implement stricter standards for the production and use of plastic materials in packaging. Recycling practices and innovations in plastic alternatives could also play a pivotal role in mitigating the issue. Further research into how different materials release MPs under various conditions is necessary to promote better industry practices and regulatory policies. Additionally, the detection methods used in these studies must be standardized to ensure consistency and reliability in MP quantification, as the choice of detection technique can directly affect the reported concentrations of MPs.

MP contamination in bottled water is a global issue that varies significantly by region, type of packaging, and even by individual brands. The types and concentrations of MPs differ depending on whether the water is stored in plastic or glass bottles, with PET being the most commonly detected polymer in plastic bottles. Reusable plastic bottles tend to release more MPs compared to disposable ones, but even glass bottles can contribute to contamination. As consumers continue to rely on bottled water as a convenient drinking source, it is essential to understand the factors that contribute to MP contamination and work toward minimizing their presence in bottled water products.

MPs in beverages

There are various types of beverages consumed worldwide, which can be broadly categorized into non-alcoholic beverages (tea, soda, juice, *etc.*), alcoholic beverages (beer, wine, *etc.*), and dairy products (milk, infant formula, *etc.*). Across these categories, the presence of MPs has been detected in varying concentrations, raising concerns about the impact of plastic pollution on both consumer health and product safety.

In non-alcoholic beverages, studies have shown a wide range of MP concentrations, with some findings reporting up to 500,000 particles per kilogram or liter [Table 1]. For example, tea leaves from China exhibit some of the highest concentrations, ranging from 20,000 to 50,000 MP particles per kilogram[68]. The main types of MPs identified in tea are PP and PET. These particles likely enter the tea through the packaging process or the breakdown of plastic tea bags, which release MPs when steeped in hot water. Soda water, a popular non-alcoholic beverage, has also been found to contain MPs. In the United States, concentrations have ranged from 510 to 3,710 particles per liter, primarily composed of polyurethane (PU) acrylate varnish and PVC[69]. This contamination could be attributed to the plastic bottling process or the interaction of the soda with plastic caps and liners. Similarly, honey, another non-alcoholic product, has been shown to

Table 1. MPs in beverages from different countries

	Location	Drinks	Min	Max	Mean	Unit	Ref.
Soft drinks	Turkey	Honey	0	1,280	314 ± 353	p/kg	[70]
	Turkey	Traditional drinks	0	0.5		p/L	[86]
	Spain	Soft drinks			22.5 ± 18.7	p/L	[87]
	Spain	Other drinks			24.9 ± 27.3	p/L	[87]
	Italy	Soft drinks			9.94 ± 0.33	p/L	[82]
	Italy	Cold tea			7.11 ± 2.62	p/L	[82]
	South Korea	Honey	10	1,020		p/kg	[71]
	South Korea	Processed drinks	0	117.14		p/L	[71]
	Mexico	Soft drinks	0	7 ± 3.21	2.11 ± 1.29	p/L	[73]
	Mexico	Energy drinks	0	6 ± 1.53	0.75 ± 0.19	p/L	[73]
	Mexico	Cold tea	1 ± 0.57	6 ± 2	2.75 ± 1.31	p/L	[73]
	Turkey	Soft drinks	5	15	8.9	p/L	[88]
	China	Juice	-	-	30	p/L	[89]
	China	Tea	-	-	36.4	p/L	[89]
	China	Soft drinks	-	-	49.3	p/L	[89]
	China	Soda water	-	-	50.3	p/L	[89]
	China	Energy drinks	-	-	32.4	p/L	[89]
	USA	Soda water	510 ± 110	3,710 ± 1,110	1,660 ± 620	p/L	[69]
Alcohol drinks	China	Tea	200,000	500,000		p/kg	[68]
	Spain	Beer	22	281.8	95.5 ± 92	p/L	[87]
	Spain	Wine	4	283	56.7 ± 73.5	p/L	[87]
	South Korea	Beer	0	46		p/L	[71]
	Mexico	Beer	0	28 ± 2.59	1.08 ± 0.1	p/L	[73]
	USA	Beer	0	14.3	4.05	p/L	[39]
	China	Beer	20,000	80,000		p/L	[68]
	China	Baijiu	344	1,888	872	p/L	[72]
Milk	Turkey	Milk products	3	48	6 ± 5	p/L	[90]
	India	Milk products	164	512		p/L	[91]
	Europe	Milk powder	40	47,765		p/kg	[74]
	China	Formula	17,000	20,800	17,300	p/kg	[15]
	China	Infant mild powder	10 ± 10	110 ± 10	50 ± 30	p/kg	[92]
	Switzerland	Milk products	2,040	10,040	44 ± 24	p/L	[93]

MPs: Microplastics.

contain MPs. Studies from Türkiye and South Korea revealed concentrations as high as 1,280 and 1,020 particles per liter, respectively. The MPs found in these samples include materials such as ethylene-vinyl acetate (EVA), PE, PP, and Nylon-6[70,71]. The sources of contamination in honey could stem from plastic containers or beekeeping equipment, as well as environmental pollution affecting the flowers and bees involved in honey production.

In the case of alcoholic beverages, MP contamination has also been detected [Table 1]. For instance, Chinese beer exhibits some of the highest concentrations, with MP levels ranging from 20,000 to 80,000 particles per liter[68]. The MPs found in Chinese beer samples are predominantly polystyrene (PS) and PP. Another popular alcoholic beverage, Baijiu, a traditional Chinese spirit, was found to contain 1,888 particles per liter. The main MPs detected in Baijiu include cellulose, polyamide (PA), PET, PP, PVC, and PE[72]. These findings suggest that the brewing and bottling processes, along with the packaging materials, contribute significantly to MP contamination in alcoholic beverages. In contrast to Chinese beer and Baijiu, MP concentrations in alcoholic beverages from other regions tend to be lower [Table 1]. This may be due to differences in production methods, packaging materials, or regulations regarding the use of plastic in the beverage industry. For example, a study conducted in Mexico found that MPs in beer packaged in PET bottles were mainly PE and PP, further emphasizing the role of packaging in contaminating beverages[73].

Dairy products, including milk and infant formula, are not exempt from MP contamination. Studies have consistently detected MPs in dairy products, with concentrations ranging from 3 particles per liter to as high as 47,765 particles per kilogram [Table 1]. European dairy products have reported some of the highest concentrations, with the main MPs being PP, PE, PS, and PET[74]. These MPs could be introduced through packaging, as many dairy products are stored in plastic containers or cartons lined with plastic. In China, studies have revealed that infant formula is also a significant source of MP exposure. The highest concentration recorded in Chinese infant formula was 20,800 particles per kilogram, with an average concentration of 17,300 particles per kilogram[15]. The MPs detected in infant formula samples include PU, PET, polytetrafluoroethylene (PTFE), and chlorinated polyethylene (CPE). These findings are particularly concerning given the vulnerability of infants to environmental contaminants and their reliance on formula as a primary food source.

The sources of MP contamination in beverages are similar to those found in bottled water. Plastic packaging and containers are major contributors to MP contamination, as the degradation of these materials releases MP particles into the beverages. The production process itself can also introduce MPs. For example, beer packaged in PET bottles is more likely to be contaminated with MPs such as PE and PP due to the breakdown of the plastic during bottling, storage, or transportation[71]. Similar results have been found in other studies, such as research from Mexico, which showed that beer in plastic bottles had higher concentrations of MPs compared to other packaging types[73].

In addition to packaging and production processes, MPs can also be introduced into beverages through environmental contamination. For instance, tea leaves may be exposed to MPs in the soil or water used for irrigation[68], while honey can be contaminated by airborne MPs that settle on flowers[71]. Dairy products, especially milk, may become contaminated during the milking process or through the use of plastic equipment in dairies. Given the widespread presence of MPs in beverages, further research is necessary to understand the health implications of consuming these particles. While the concentrations of MPs in beverages vary depending on the type of drink, packaging material, and region, the fact remains that these contaminants are present in many of the products people consume on a daily basis.

The detection of MPs in a wide range of beverages, from non-alcoholic drinks like tea and soda to alcoholic beverages such as beer and Baijiu, as well as dairy products like milk and infant formula, points to the pervasive nature of plastic pollution. The primary sources of contamination include plastic packaging, production processes, and environmental exposure. With growing awareness of the potential health risks associated with MP consumption, it is imperative that industries explore alternative packaging materials and adopt stricter regulations to minimize MP contamination in beverages. Additionally, further studies are needed to assess the long-term impact of MP ingestion on human health and to develop strategies for reducing plastic pollution in the food and beverage supply chain.

Nanoplastics in drinking water and beverages

Compared to the extensive research on MPs, the study of nanoplastics in drinking water and beverages is still in its infancy. Nanoplastics pose unique challenges due to their smaller size and the difficulty in detecting and quantifying them. However, recent studies have begun to shed light on their presence in drinking water systems and bottled beverages, paving the way for more detailed investigations. A notable study from China utilized Pyr-GC/MS to analyze tap water for nanoplastic contamination. This study found that the concentration of nanoplastics, of particle size 58 to 255 nanometers, varied between 1.67 and 2.08 μg/L[75]. This discovery illustrates that nanoplastics are indeed present in drinking water. The use of sophisticated techniques such as Pyr-GC/MS has enabled researchers to detect these minuscule particles that were unnoticed in the past.

In Norway, a study analyzed bottled water sold in the country and found an average nanoplastic particle size of 88.2 nanometers after filtration through a 100-nanometer filter membrane. The study detected an abundance of 10^{11} nanoplastic particles per liter, with PET being the primary type of nanoplastic present[76]. This high abundance of nanoplastics suggests that bottled water may be more prone to nanoplastic contamination than previously recognized, especially as smaller particles might bypass conventional filtration methods used in the current production and packaging of bottled beverages. Similarly, a study from the United States detected an abundance of nanoplastics in commercially available bottled water. The concentration measured was $2.4 \pm 1.3 \times 10^5$ nanoplastic particles per liter, with the particle sizes ranging from 200 to 1,000 nanometers[77]. These ground-breaking findings indicate that the abundance of nanoplastics in bottled water can be higher than that of MPs, even though nanoplastics account for a smaller mass fraction. This difference is important because it suggests that while the overall quantity of nanoplastics might be high, their contribution to the total mass of plastic pollution is relatively low.

However, nanoplastics are harder to remove during water treatment compared to MPs. A study conducted in China showed that while the concentration of nanoplastics in the effluent of a water treatment plant was 0.04 μg/L, nanoplastics only accounted for 5.2% of the total plastic concentration in the treated water. In the source water, nanoplastics made up 3.2% of the total plastic concentration[49]. These findings suggest that conventional water treatment methods are less effective at removing nanoplastics compared to MPs, potentially leading to greater human exposure to these smaller particles through drinking water.

Although research on nanoplastics is still in its early stages, the available studies indicate that nanoplastics are present in both tap water and bottled beverages. Their higher abundance compared to MPs, despite their lower mass contribution, and their resistance to removal during water treatment, point to the need for further investigation into their potential health impacts and more effective filtration technologies. As the field of nanoplastic research grows, it will become increasingly important to develop standardized methods for their detection and regulation to safeguard public health.

HUMAN EXPOSURE

The human body can consume substantial amounts of MPs through drinking water, and research into exposure levels from various drinking liquids has expanded in recent years. Despite valuable insights provided by these studies, there are still inconsistencies in the methodologies used to estimate the exposure level, particularly when daily intake is to be calculated. Some studies rely on the direct concentration of MPs in liquids combined with the amount of liquid consumed, while others factor in population-specific variables, e.g., body weight. For ease of comparison across studies, one common method is to use the average concentration of MPs and the amount of liquid consumed to calculate daily intake[24]. This approach allows for a more standardized understanding of how much plastic humans potentially ingest through daily hydration.

The average daily intake of MPs from drinking tap water varies drastically from country to country. For example, studies have reported daily intake values ranging from 0 in Italy[39] to 1,787 MP particles in

China[47] [Figure 4A]. This vast range reflects regional differences in water quality and the concentration of MPs present in tap water. The global average daily intake of MPs from tap water is estimated to be around 185 particles per day, but there are substantial disparities among countries [Figure 4A]. Even within the same country, MP intake can vary dramatically. In China, for instance, one study reported a minimum daily intake of just 2.8 particles, while another found a maximum intake of 1,787 particles per day[47,78]. Similarly, in the UK, reported daily intake levels ranged from a low of 0.068 particles[33] to a high of 20.8 particles per day[39].

The primary driver behind these differences is the variation in the concentration of MPs in tap water across regions. Factors such as the sources of the water, the extent of plastic pollution in the surrounding environment, and the effectiveness of water treatment facilities all influence the levels of MPs present in drinking water. Another important factor contributing to these discrepancies is the variation in daily water consumption. Studies have shown that different populations consume different amounts of water daily, which affects the total intake of MPs. For example, most studies base their water consumption estimates on an average of 2 to 3 liters per day, but some report values evidently outside this range [Figure 4B]. A study in Bangladesh, for instance, used the World Health Organization's recommended daily water intake of 4.5 liters, leading to higher estimates of MP exposure[79]. On the lower end, a study in Hong Kong estimated daily water consumption to be just 0.869 liters, based on local statistical data[80]. These varying estimates of daily water intake introduce another layer of variability in assessments of MP exposure from tap water [Figure 4B]. In addition, the sources of the water consumption data used in studies differ. For example, the Chinese Nutrition Society (2016) recommends a daily water intake of 1.6 liters[40], while the Saudi Arabian Food and Nutrition Association recommends 1.8 liters[81]. Some studies rely on hypothetical assumptions, such as those conducted in Switzerland and the United Kingdom, which estimate daily water consumption at 1.5 liters[51] and 2.5 liters[33], respectively. These differences in water consumption assumptions influence the estimated daily MP intake and complicate direct comparisons between regions.

The daily average intake of MPs through bottled water is also of significant concern. Studies show that daily intake ranges from 0.13 to 1.08×10^8 MPs [Figure 4C], with an average intake of 279 particles per day (excluding extreme values from Italy). On the whole, the MP content of bottled water is higher than that of tap water, but it remains within the same order of magnitude. Just as in tap water, the concentration of MPs in bottled water varies significantly across brands and regions, leading to wide-ranging estimates of daily intake.

One major difference between bottled water and tap water studies is the substantial variability in daily consumption estimates. For instance, a study conducted in Bangladesh, which reported a high daily intake of tap water, also estimated bottled water consumption to be 4.5 liters per day, in line with WHO recommendations[60]. On the other hand, a study from Türkiye used a much lower daily consumption figure of 0.03 liters, based on data from the Türkiye Consumer Association[58]. A study from China estimated daily bottled water consumption to be 0.09 liters, based on annual consumption data[65]. The two orders of magnitude difference in bottled water consumption across these studies greatly influences the estimated daily MP intake from bottled water [Figure 4D]. This variability underscores the importance of using accurate, region-specific water consumption data when assessing MP exposure.

Assessing the intake of MPs through beverages other than water is more challenging due to the limited number of studies and the lack of consistent data on beverage consumption. Most research has not attempted to calculate daily MP intake from beverages, largely due to difficulties in obtaining reliable drinking quantity parameters. However, there are a few notable exceptions. A study from Türkiye assessed

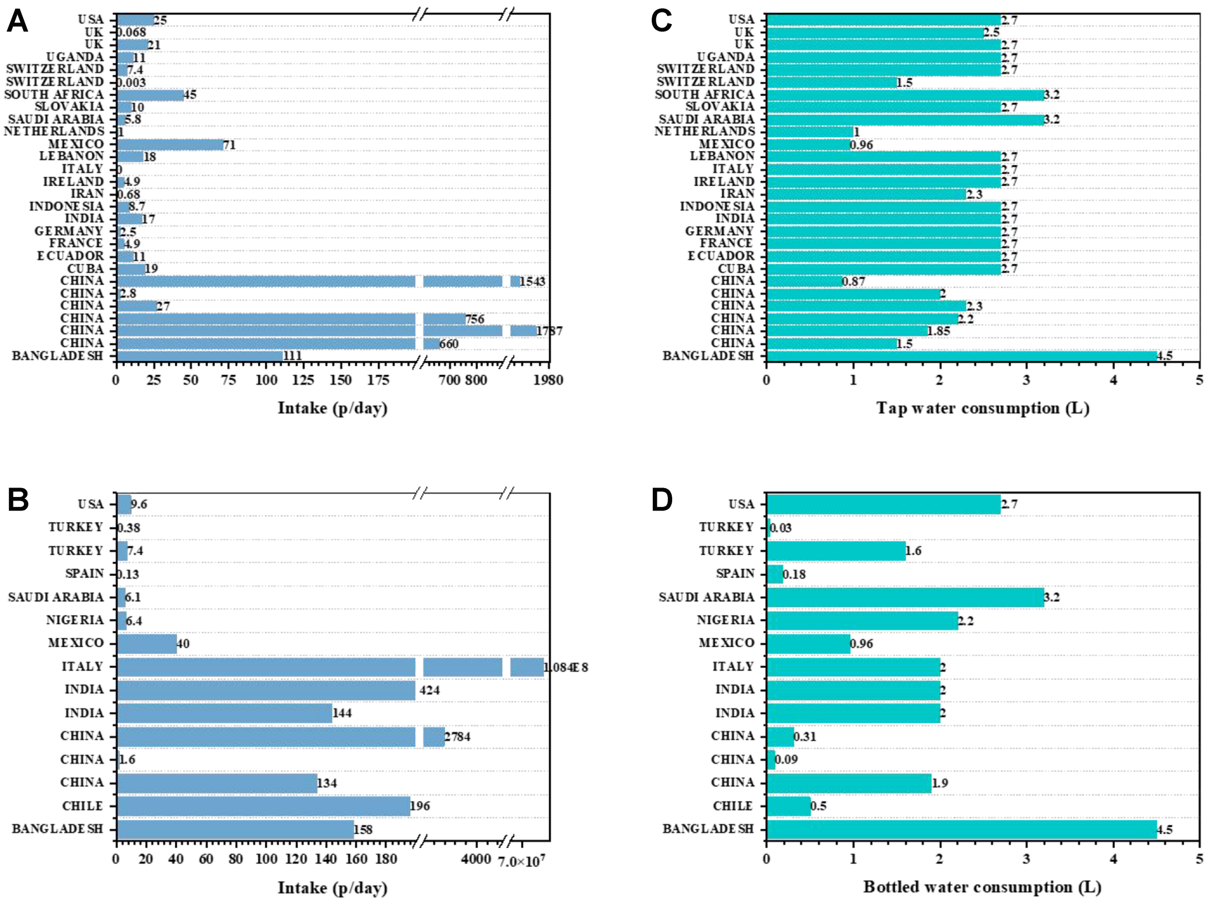

Figure 4. Daily MPs intake through (A) tap water and (B) bottled water and (C) tap water consumption and (D) bottled water consumption. MPs: Microplastics.

the intake of MPs through honey, reporting an average daily intake of 1.2 particles, with a daily honey consumption rate of 3.33 grams. These data were sourced from the United Nations Food and Agriculture Administration's 2019 report[70]. Another study in Italy estimated that the population consumed 8.1 MP particles per week through beverages, with a weekly beverage consumption of 0.4 liters. This estimate was based on a survey of college students[82].

Data on human exposure to nanoplastics through drinking water and beverages remain limited. Two studies have quantified the intake of nanoplastics through bottled water, reporting daily intakes of approximately 2.7×10^{11}[76] and 4.8×10^{5}[77] particles, assuming a daily drinking water intake of 2.2 liters. Compared to the daily intake of MPs through bottled water, the number of nanoplastics ingested is significantly higher. However, when analyzed by mass concentration, the nanoplastic levels are lower than those of MPs. The toxicity of plastic particles is strongly size-dependent, with smaller particles exhibiting greater toxic effects, particularly nanoplastics[83,84]. Research shows that PS nanoplastics with a diameter of 50 nm are more readily internalized by human epithelial cells than larger particles, such as those 500 nm in size, leading to inflammatory responses[83]. Currently, there are no reported studies on the ingestion of nanoplastics specifically through beverages.

The amount of liquid consumed is a critical parameter in evaluating human MP intake. As with water consumption, there are wide variations in beverage consumption patterns across different populations, and these variations have a direct impact on the accuracy of MP intake estimates. For example, people in economically disadvantaged areas may consume less bottled water and may rely more on locally sourced water, which could have higher or lower levels of MP contamination depending on the local environment. Additionally, people in different cultural contexts consume varying amounts of different types of beverages. A comprehensive survey by Guelinckx *et al.* (2015) investigated the daily intake of water, milk, hot drinks, and fruit juices in more than ten different countries. In China, for example, adult men consume an average of 0.98 liters of water, 0.11 liters of milk, 0.45 liters of hot drinks, 0.02 liters of fruit juice, and 0.09 liters of other liquids each day. In contrast, adult men in Japan consume only 0.27 liters of water but drink 0.74 liters of hot drinks daily[85]. These wide-ranging consumption patterns highlight the need for region-specific and culturally relevant data when assessing MP exposure through beverages. As seen from the wide variations in both water and beverage consumption across different studies, it is crucial to base liquid consumption parameters on the actual habits of the population under study. While various institutions and associations may have different recommendations for daily water and beverage intake, selecting values that reflect real-world consumption is essential for producing accurate estimates of MP intake. For example, the daily water consumption recommendations from the Chinese Nutrition Society (1.6 liters) and the Saudi Arabian Food and Nutrition Association (1.8 liters) reflect the typical water consumption habits of populations in those countries. However, in some regions, such as economically disadvantaged areas, individuals may consume significantly less bottled water or even tap water, relying instead on surface water, which may contain higher levels of contaminants, including MPs. Furthermore, different demographic groups, such as men versus women, or urban versus rural populations, often consume different quantities of liquids. Studies have shown that adult men generally consume more water and other beverages compared to women, and individuals in rural areas may have different beverage consumption habits compared to their urban counterparts.

The human body can consume significant amounts of MPs through drinking water, with exposure levels varying across countries and beverages. Daily intake estimates for MPs from tap water range widely, from 0 particles in Italy to 1,787 particles in China. These discrepancies are influenced by factors such as water quality, regional plastic pollution, water treatment efficiency, and differing assumptions about daily water consumption, which range from 0.869 liters in Hong Kong to 4.5 liters in Bangladesh. Similarly, MP intake from bottled water is higher on average than tap water but also varies significantly depending on regional consumption patterns and water quality. For example, estimates range from 0.03 liters of bottled water consumption per day in Türkiye to 4.5 liters in Bangladesh. For beverages other than water, MP exposure data are limited due to inconsistent methods and a lack of reliable consumption data. Exceptions include studies in Türkiye and Italy that provide estimates for MPs in honey and other beverages. The few studies on nanoplastic exposure indicate significantly higher particle counts than MPs, although their mass concentration is lower. Nanoplastics, particularly those smaller than 50 nm, are more readily internalized by human cells, raising concerns about their toxicity. Liquid consumption patterns, a key factor in determining MP exposure, vary widely across regions and cultures. Differences in beverage choices and economic factors further complicate accurate assessments. For example, populations in economically disadvantaged areas may rely on untreated surface water with higher contamination levels. Accurate exposure assessments require region-specific and culturally relevant data to reflect real-world consumption patterns. Establishing standardized methodologies and integrating demographic and environmental variables are essential to enhance the reliability of MP and nanoplastic exposure estimates globally.

CONCLUSIONS AND PERSPECTIVES

The concentration of MPs in tap water, bottled water, and beverages varies across different countries. While regional factors including pollution levels and water source quality play a role in these differences, the variability in sampling and testing methods also has a considerable impact on the results. MPs, being particulate pollutants, differ from traditional small molecule pollutants in that they have additional parameters, such as particle size and morphology, which need to be considered in studies. These parameters, particularly particle size, influence the concentration levels reported in different studies and contribute to discrepancies between findings.

Drinking liquids is essential as they provide the primary source of water for the human body, and as such, the ingestion of MPs and nanoplastics through this pathway is unavoidable. However, there are still gaps in our understanding of exposure to MPs from daily liquid consumption. One of the main issues lies in the selection of exposure parameters. Most studies rely on daily water intake as the sole factor for calculating exposure, but this approach introduces errors. In reality, people consume a wide variety of liquids - such as tea, coffee, juices, and sodas - throughout the day, so only focusing on water intake does not provide an accurate measure of overall exposure to MPs. A more comprehensive approach would involve using questionnaires and surveys to collect data on the full selections of liquids people drink, thereby improving the accuracy of exposure assessments.

In addition to the need for better exposure parameters, the potential risks associated with ingesting MPs via liquids must not be overlooked. Some studies have attempted to evaluate the risk by referring to the hazard values of different types of plastic materials. It provides a starting point but is insufficient for a full risk assessment. One major shortcoming is that most studies do not consider the size of the MP particles when assessing risk. Size matters because it determines the ways that MPs interact with the human body. Smaller particles, such as nanoplastics, have a greater ability to penetrate tissues, cross biological barriers, and potentially cause harm at the cellular level. Therefore, size must be included as a key variable in future risk assessments, especially when assessing the risks posed by nanoplastics.

In conclusion, substantial progress has been made in understanding the presence and effects of MPs in drinking liquids, but there are still significant gaps in knowledge, particularly concerning nanoplastics. Standardizing analytical methods and improving exposure parameters through comprehensive data collection are essential steps toward more accurate assessments of MP intake. Additionally, further innovation in detection technology is needed to study nanoplastics more effectively. Lastly, future risk assessments must consider not only the chemical composition of MPs but also their particle size, particularly those nanoplastics, which pose unique risks due to their small size and increased reactivity. By addressing these challenges, researchers will be better equipped to understand the full impact of MP and nanoplastic pollution on human health.

DECLARATIONS

Authors' contributions

Conceptualization, data analysis, writing - review and editing: Zhang J
Reviewing and editing: Liu Y, Zhao L, Peng C, Wang L

Availability of data and materials

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