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Microplastic exposure disparities in California communities through bottled water consumption

Samiksha Singh^{1,2*}, Andrew Gray¹, Mehdi Nemati³, Kurt Schwabe³ and Lingxiao Wang⁴

Abstract

Increasingly, governmental agencies are taking action in response to health concerns associated with microplastic exposure in drinking water. These efforts have focused primarily on municipal tap water rather than bottled water. This is concerning, given the surge in bottled water consumption in the U.S., a surge partially fueled by negative perceptions of tap water quality, especially among minority communities. Even though microplastics may not be the biggest health risk or primary reason for consumer choices around tap and bottled water, the rising concerns around microplastic exposure and impacts on human health are important to take into consideration. A systematic review was conducted to assess microplastic concentrations in various sources of drinking water, including bottled water and municipal tap water. To facilitate a more accurate comparison of microplastic concentrations between studies, we realigned the analyzed microplastic size classes between studies. Additionally, trends in California household-level bottled water purchases were analyzed using a nationwide dataset of bottled water transactions to determine the corresponding rates of microplastic exposure associated with these consumption patterns. Our results suggest that there is a sevenfold higher concentration of microplastics in bottled water compared to tap water globally. In comparison, studies conducted in the Global North have found a six times higher concentration of microplastics in bottled water compared to tap water, and seven times more microplastics in bottled water compared to tap water in the Global South. While income is found to be positively associated with bottled water purchases and increases in microplastic exposure in California, substantial disparities in exposure persist by ethnicity and race after controlling for income. Although microplastics may not be the primary health risk or the primary reason for consumer choices regarding tap and bottled water, the growing concerns about microplastic exposure and its impacts on human health are important to consider. Choices made by consumers regarding drinking water types, regardless of the reason for these choices, should be made with the best available information. Therefore, our results underscore the importance of addressing information disparities related to bottled water quality. This is particularly important within marginalized communities served by high-quality municipal drinking water, where misperceptions of tap water quality and limited information on bottled water quality contribute to the consumption of bottled water.

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Introduction

The ubiquitous nature of microplastics in all environmental compartments has resulted in growing concerns regarding human exposure through food and beverage consumption [1, 2]. Ingestion of microplastics has been linked to blockages and abrasions from the actual particle, the leaching of additives and toxic compounds sorbed onto the particle [3, 4], and their transport of persistent organic pollutants and pathogens [5]. Potential health impacts that have been identified from ingestion include oxidative stress, inflammation, immunological responses, and neurotoxicity, as well as preterm birth, low sperm counts, and endocrine disruption associated with the chemicals, plasticizers, and additives found on the particles [6, 7].

Concern over the potential health effects of microplastics has recently included ingestion from bottled water consumption [3, 8, 9], which is timely given the rise in bottled water consumption globally. In 2023, over 500 billion liters of bottled water were consumed, with a growth rate of 6% per year [10, 11]. The surge in bottled water consumption is driven by many factors, including taste, odor, convenience, and perceived quality [12]. In the U.S., the largest consumer of bottled water globally, with consumption growing from nearly 34 to 60 billion liters between 2010 and 2022 (11), mistrust in tap water has been found to increase bottled water sales [10, 13]. This is especially the case for minority groups who have been found to consume more bottled water per capita than non-minority groups [14, 15].

At a global level, the mistrust of tap water often stems from poor water quality due to contamination, the unreliability of tap water supply, and underdeveloped water treatment capabilities, especially in the Global South [16, 17]. In countries with highly developed municipal drinking water infrastructure, mistrust of municipal drinking water can result from high-profile cases of water quality violations leading to public health issues, such as in Flint Michigan [18] and the Louisiana Water Crises [19], both in the US. However, mistrust also has arisen from efforts to inform the public about municipal drinking water quality, even when quality is high. Research has shown that as consumers became aware of the quality of their drinking water and knowledgeable about water quality violations, they engaged in avoidance behavior, mainly in the form of increased bottled water consumption [20]. In the United States, the Environmental Protection Agency (EPA) is in charge of drinking water quality and requires regular monitoring of municipal water supplies against rigorous standards. This regulatory framework includes the 1996 Safe Drinking Water Act Amendments, which required public agencies to provide customers with annual water quality reports [21, 22]. These standards are far more stringent than those applied to bottled water,

which is regulated by the U.S. Food and Drug Administration (FDA) [23, 24]. Even though public drinking water supplies in the US are subject more stringent regulatory oversight and standards resulting in lower mean contamination levels and fewer water quality violations, mistrust of tap water relative to bottled water persists and contributes to increases in bottled water sales [15, 25].

This behavior may be exacerbated by the fact that these reporting requirements do not apply to bottled water. Drinking water is a differentiated good, and economics tells us that people make choices based on *differences* in price and perceived quality. While making information available regarding the quality of public drinking water supplies helps consumers understand the quality attributes of the public water system, a lack of similar information on bottled water undercuts the process of quality comparison in product choices. Such information asymmetries can lead to market failures and, consequently, inefficient outcomes both privately and socially.

To help address the information asymmetries surrounding drinking water quality and awareness of microplastics concentration, we compare concentrations of microplastics in tap water relative to bottled water. We obtained data through a systematic review of existing literature and realigned and standardized microplastic size classes across studies using a methodology outlined by Kooi and Koelmans (2019) [26], which enabled robust like-for-like comparisons. Our study is among the first to propose a correction factor for estimating microplastic concentrations across unstudied size ranges in drinking water matrices, providing a foundation for future research.

After illustrating how microplastic concentrations differ across drinking water types, we investigated the degree to which consumption of bottled water differs for communities of color by socioeconomic and demographic factors in California. Differences in microplastic exposure concentrations arising from differences in bottled water consumption were then identified. While the second part of our analysis provides evidence surrounding the degree to which high-income communities and communities of color have a greater reliance on bottled water, our analysis further extends the research to highlight microplastic exposure differences across such communities and the need for policy to reduce information asymmetries surrounding drinking water quality.

Data and methods

Literature review

A systematic literature search was conducted to identify studies that measured the differences in microplastic concentrations across drinking water types. The search was conducted using Google Scholar with a combination of the following keywords: “microplastics,” “drinking

water,” “bottled water,” and “tap water” for studies published up to 2025 (Fig. s1). In addition, the reference lists of the review papers were manually searched for additional publications. Altogether ($n=60$) studies were identified (Fig. 1).

Studies were excluded if they involved mechanical stress experiments ($n=4$), literature reviews ($n=5$), commentaries ($n=2$), or did not employ spectroscopic tools for microplastic identification ($n=5$). Eligible studies were required to report polymer-specific information validated through techniques such as Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy (RM), or pyrolysis gas chromatography/mass spectrometry (PyGC-MS). To ensure a robust dataset for statistical analysis, studies that reported some form of quality assurance/quality control (QA/QC) were included. In addition, supplementary information was examined to extract raw data on microplastic concentrations per sample when available; otherwise, individual sample concentrations were extrapolated from published figures using WebPlotDigitizer. As sample volumes varied considerably among studies, data were included if that concentrations were standardized and reported as particles per liter. When size classes were not explicitly reported, minimum detectable sizes were inferred based on instrumental limitations: 20 μm for studies using FTIR and 1 μm for studies using Raman for polymer identification.

These criteria resulted in a dataset comprised of studies of varying quality but sufficient scope to provide insights into microplastic concentrations at global scale and regional scales including both developing and developed countries over multiple years. Altogether ($n=44$) studies were used in the subsequent analyses (See GitHub repository for the complete dataset).

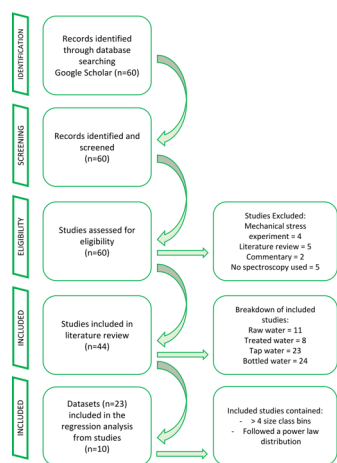


Fig. 1 PRISMA flow diagram of the data selection process for the literature review on microplastics in different drinking water types

Harmonizing microplastic concentrations

During the literature review process, it was evident that microplastics of different size ranges were reported across different studies. Therefore, to compare microplastic concentrations across different studies, the particle size distribution of each study was transformed to a common particle size range following the realignment method of Kooi and Koelmans (2019) [26] and Koelmans et al., (2020) [27]. The premise of this harmonization method is that microplastic concentrations within the measured size class can be translated into a default microplastic size range through a correction factor (CF). Microplastic size distributions usually follow a power law relationship (Eq. 1) with a negative slope because of the process of fragmentation, which produces exponentially larger populations of smaller particles:

$$y = bx^{-\alpha} \quad (1)$$

where x is the particle size in micrometers, y is the abundance of microplastics in percentage, and α and b are fitting parameters. A linear regression of log-transformed values was used to assess the values and statistical significance of alpha (α) (Kooi and Koelmans, 2019). Particles found within any size range can be translated into any other size range using a correction factor (CF):

$$CF = \frac{\int_{x_{1D}}^{x_{2D}} bx^{-a} dx}{\int_{x_{1M}}^{x_{2M}} bx^{-a} dx} = \frac{x_{2D}^{1-a} - x_{1D}^{1-a}}{x_{2M}^{1-a} - x_{1M}^{1-a}} \quad (2)$$

where x_{1D} , x_{2D} refer to the minimum and maximum default size range and x_{1M} and x_{2M} refer to the minimum and maximum measured size range within each study. The default size range for this study was 1–5000 μm because this is the most commonly reported size range for microplastics [28], and particles < 10 μm in size are more likely to cause potential health risks [29].

For a study to be included in the power law analysis, the results had to be presented in four or more size class bins within the microplastic range, i.e., between 1 μm and 5000 μm . Datasets ($n=23$) from 10 studies identified in the literature review matched these criteria (Table s2). The α for each study was determined by fitting a regression using Eq. 1 to the datasets (Fig. s2). The average α for all the studies was then computed. Following this computation, the correction factor (CF) was applied to each selected study ($n=44$) from the literature review and was calculated using the average α , the measured size ranges and corresponding microplastic concentration indicated in each study were transformed to the default size range (1–5000 μm) to allow for comparisons across studies using Eq. 2 (Table s2).

Comparison of microplastic concentrations

We compared the concentrations of (1–5000 μm) microplastics across four drinking water types: raw water (source water in a natural untreated state), treated water (included any public drinking water sample that was indicated as potable or final effluent in their studies conducted at drinking water facilities), tap water (public drinking water collected at the location of use transport through the distribution system), and bottled water. The average concentration and standard deviation of microplastics were calculated of each drinking water type globally and grouped according into the Global North and Global South. Global South studies were conducted in countries listed on the Group of 77 (G77). The G77 is a coalition of developing countries at the United Nations, established in 1964 to promote their collective economic interests, strengthen their negotiating power, and advance South-South cooperation.

A Shapiro-Wilk test for normality was performed on microplastic concentrations across different types of drinking water after the data were log-transformed. Differences in microplastic concentrations were then statistically analyzed using the non-parametric Mann-Whitney U Test to determine if there were significant differences in microplastic concentration between bottled and tap water, bottled and treated water, and treated and tap water for all studies globally, as well as across groupings of Global North and Global South. All statistical tests were performed using R statistical software version 4.1.0 (R Core Team, 2021).

Estimating factors associated with bottled water consumption

To understand how microplastic exposure from bottled water consumption may be increasing, thereby posing an increasing health risk to society, as well as to identify differences in microplastic concentrations from bottled water consumption by community characteristics, we use the NielsenIQ household-based and retail scanner data^{1,2}. The NielsenIQ data is a nationally representative panel recording all purchases by households intended for personal, in-home use. This dataset included a diverse sample of more than 40,000 annual nationally representative households from 52 U.S. markets and nine additional U.S. areas. Households voluntarily participate by scanning and transmitting store-bought (including

online) food and beverage purchases weekly for at least ten months annually³. The purchasing behavior of participant households is consistently tracked, including details such as shopping frequency, types and quantities of purchased products (both food and non-food), and corresponding prices. This dataset also includes comprehensive demographics at both the household and household head levels.

For our purposes, the dataset includes household-level purchases of bottled water in 54 of the 58 California counties (Fig. s3) with information on the price and quantity of bottled water purchased, allowing for the calculation of the price per liter (L) for bottled water purchased and the per capita bottled water consumption (L/person). We exclusively focus on California households that purchased bottled water or water filters between January 2006 and December 2019. We limit the data to December 2019 due to the impact of COVID-19 shutdowns on drinking water purchasing behavior (Nemati, 2020 [30] and 2022 [31]). Our analysis will be based on consumption data from 60,013 households in California, spanning from January 2006 to December 2019. Note that the national survey samples approximately 40,000 households each year, while the California data include 60,013 households that participated in the survey between 2006 and 2019. The household purchase data is aggregated on a monthly basis. The bottled water purchases are measured by ounces and corresponding dollar expenditures. Demographic information gathered included race and ethnicity categories for each household (e.g., Hispanic, Black, Asian, and White), age of participating individuals (defined as seniors, those aged 65 years or older), the presence of children within the household, and education (i.e., college educated or not). Additional variables include whether a household participates in the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC), which is run by the USDA and provides supplemental nutrition and other resources to lower-income households who are or are new parents or caregivers (USDA 2025) [32], or is located in a rural area.

A fixed-effects regression model with clustered standard errors at the household level was employed to estimate the factors associated with bottled water consumption in California. This approach was applied to the Nielsen household-based retail scanner data, which records purchases by households for in-home use at a national level (Table s3). Leveraging this extensive dataset of household-level transaction data enabled us to

¹ Researcher(s)' own analyses calculated (or derived) based in part on data from Nielsen Consumer LLC and marketing databases provided through the NielsenIQ Datasets at the Kilts Center for Marketing Data Center at The University of Chicago Booth School of Business.

² The conclusions drawn from the NielsenIQ data are those of the researcher(s) and do not reflect the views of NielsenIQ. NielsenIQ is not responsible for, had no role in, and was not involved in analyzing and preparing the results reported herein.

³ See here for more information on NielsenIQ datasets and the Retail Scanner Dataset which is used in this research: <https://www.chicagobooth.edu/research/kilts/research-data/nielseniq>.

incorporate various fixed effects and control for unobservable factors:

$$\ln Y_{it} = \alpha + \theta P_{it} + \beta X_{it} + \lambda_t + \phi_c + \vartheta_b + \epsilon_{it} \quad (3)$$

where the dependent variable, $\ln Y_{it}$, represents the natural log of per capita bottled water purchases by household i in year t . The vector P_{it} encompasses prices for bottled water per unit, as well as juice and soda prices per unit. The vector X_{it} includes essential demographic variables, such as ethnicity (Hispanic vs. non-Hispanics), race (White, Black, and Asian), age, presence of children at home, education level, cable access, participation in the WIC program, residing in rural areas, and income. To address potential biases that could arise from unobserved time-invariant characteristics of zip codes or counties that may impact bottled water sales, we incorporate zip code or county ϕ_c fixed effects, depending on the specification. This approach helps to eliminate confounding factors and enhances the accuracy of our estimates, particularly when considering factors like the quality of tap water, which can vary across geographic regions. Additionally, we include year dummies λ_t to control for common trends that affect all households in the sample concurrently, such as macroeconomic conditions like the 2010 economic downturn. The error term, ϵ_{it} , captures the combined impact of unobservable factors that might affect bottled water consumption but are not explicitly accounted for in our model. By incorporating fixed effects and controlling for various demographic and economic factors, our study aims to provide a comprehensive and robust analysis of the factors associated with bottled water consumption in California. Standard errors for all specifications are clustered at the household level to account for within-household serial correlation in the error term and produce consistent standard errors in the presence of such an association [33].

Microplastics exposure rates

Microplastic concentrations determined through a literature review and subsequent size class alignment were used to assess exposure to microplastics, dependent on rates of bottled water consumption in California, USA. The microplastic concentration used to determine these exposure rates was limited to studies conducted in the Global North (North American and Western European). This was done because global concentrations may not accurately represent microplastic concentrations in tap or bottled water in California. The Global North studies were specifically included based on the assumption of similar water treatment methods, water supply reliability, and plastic types used for bottled water packaging. Microplastic exposure levels were computed by multiplying the consumption data by the average microplastic

concentration for bottled water obtained from the literature review analysis. This resulted in a dataset containing two variables: bottled water consumption in liters/capita/day and microplastic exposure in particles/person/day. The data was then visualized using a cumulative frequency distribution curve of microplastic exposure in relation to bottled water consumption.

Method limitations

While the methods applied here provide valuable insights into microplastic concentrations in different drinking water types globally, they are subject to several limitations. First, there are no standardized protocols for microplastic extraction and quantification; therefore, the quality of included studies varied in terms of reporting and analytical approaches. It can also be assumed that identification and extraction techniques have improved over time, which may influence comparability across studies. In many cases, the lower size limits of microplastics analyzed were not explicitly reported, requiring inferences based on the capabilities of the polymer identification instruments used. Such inferences can influence the realignment approach and the resulting adjusted concentrations, as this method relies on information about the minimum size class investigated. Assumptions were also made regarding water treatment processes, supply reliability, cleanliness, and the types of plastics used for bottled water packaging, particularly when estimating exposure in California communities by drawing on data from the Global North. It is important to note that 1% of households in are classified as rural in California. These household using access their drinking water from other sources such as wells which are much more common in rural areas of California and throughout the US. We did not address these systems in this study, but they merit further investigation, given the significant proportion of our population served by such drinking water sources. Although microplastics may not be the primary factor influencing consumer choice, their concentrations provide a useful proxy for illustrating global differences in drinking water quality and the lack of transparency in available water quality information.

Results

Microplastic concentrations in drinking water

Microplastic size classes from all 44 studies were realigned to the range of 1–5000 μm using a correction factor based on a power function (Eq. 2) fitted to 23 particle size distributions from 10 studies (Table s2). The resulting mean and standard deviation of the exponent alpha (α) was 1.68 ± 0.54 ($n=23$). The goodness of fit varied between 0.68 and 0.99 (Eq. 1) (Table s2). The mean microplastic concentrations for drinking water ranged from 115 particle/L in the treated public drinking water

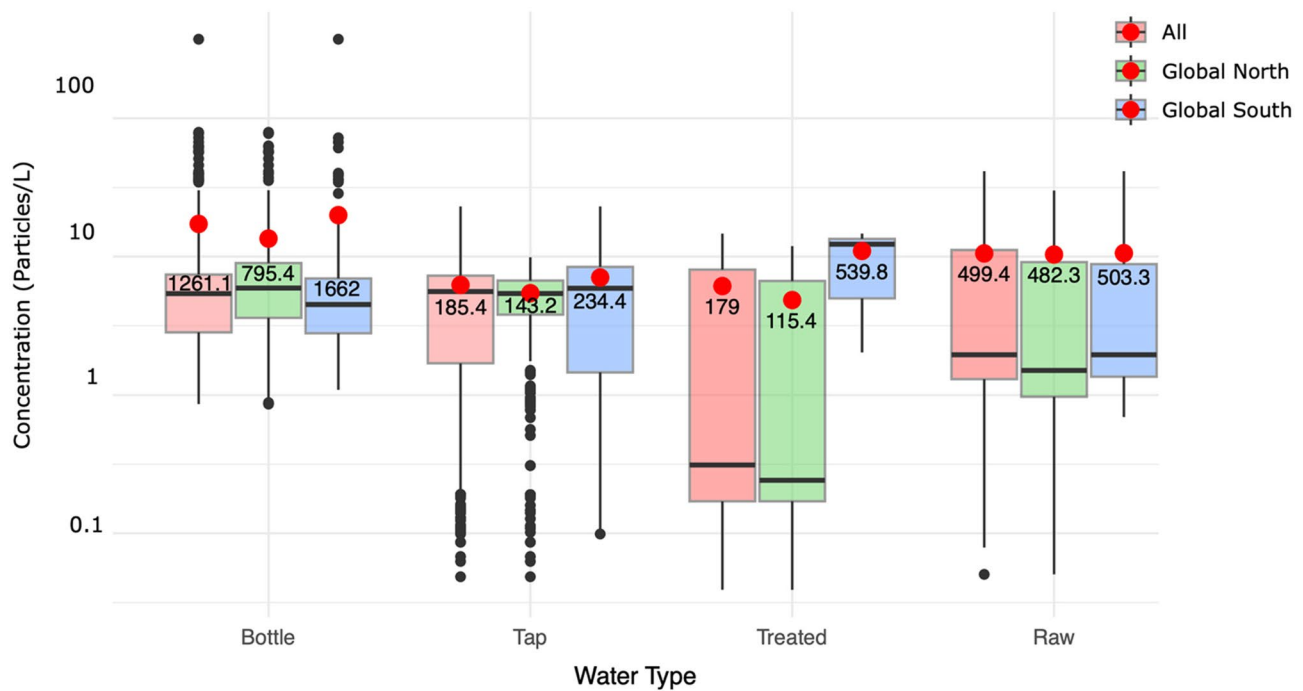


Fig. 2 Concentration boxplots across different water types (bottled, tap, treated, raw) and study location categories (All, Global North and Global South) in the realigned 1 μm to 5000 μm size range. Black dots represent outliers of individual samples, thick black lines represent the median concentration and red dots with labels represent the mean microplastic concentration of each water type

Table 1 Descriptive statistics for microplastic concentrations across water types and study locations

Water Type	n	Mean	Standard deviation	Geometric mean	Geometric standard deviation	Q1	Q3	IQR
Global								
Bottle	629	1261	16,799	128	4.66	41.9	257	215
Tap	413	185	228	53.8	11.7	16	248	232
Treated	20	179	281	4.37	52.6	0.21	301	300
Raw	97	499	1031	42.3	11.5	9.70	556	546
Global North								
Bottle	291	795	2651	159	4.92	66	369	303
Tap	222	143	96.8	57.9	9.80	73.1	213	140
Treated	17	115	195	2.16	45.5	0.21	210	210
Raw	18	482	953	23.3	29.8	5.58	447	441
Global South								
Bottle	338	1662	22,792	107	4.34	40.7	227	187
Tap	191	234	313	49.4	14.2	12	326	314
Treated	3	540	467	240	7.90	345	799	454
Raw	79	503	1053	48.4	8.85	10.5	511	501

of the Global North or 1167 particles/L in bottled water of the Global South (Fig. 2; Table 1). Average microplastic concentrations in bottled water was 6–7 times higher than tap water globally, in Global North, and in Global South, respectively (Fig. 2; Table 1). Because the data was not normally distributed and highly skewed, the raw data from all 44 studies was also log transformed and the geometric mean was calculated (see Table 1).

The log-transformed results illustrated an ~2x greater concentration in bottled as compared to tap water across all studies, as well as studies in the Global South and

Global North categories (Table 1). The concentration difference between tap and bottled water was significantly different ($p=0.001$) for studies in the Global North (Table 2.). In contrast, there was no significant difference in concentrations between tap and bottled water Globally or in countries from the Global South. In addition, there was a significant difference between treated and both tap and bottled water Globally as well as in countries in the Global North (Table 2.). However, no significant differences were found in microplastics concentration in tap, treated, and bottled water in the Global South (Table 2.).

Table 2. *P*-values from the Mann-Whitney U statistical test to determine significant differences in microplastic concentrations between different drinking water types

Water Type	All			Global North			Global South		
	Bottle	Tap	Treated	Bottle	Tap	Treated	Bottle	Tap	Treated
Bottle		0.066	0.004		0.0001	0.000		0.975	0.294
Tap	0.066		0.050	0.001		0.014	0.975		0.141
Treated	0.004	0.050		0.000	0.014		0.294	0.141	

Green cells indicate a significant difference in microplastic concentration between the two drinking water types

Table 3 Summary statistics of the data used in the fixed effects regression analysis

	Mean	Std. dev.	Min	Max
Annual consumption (Liters/person)	56.17	97.48	0.007	1938.53
Price Water (\$)	1.01	2.37	0.00	124.44
Price Juice (\$/liters)	2.03	1.01	0.00	32.80
Price Soda (\$/liters)	5.75	9.13	0.34	366.88
Ethnicity (Base = non-Hispanic)				
Hispanic (%)	16	36	0	1
Race (Base = White)				
Black (%)	10	30	0	1
Asian (%)	13	34	0	1
Senior (Yes if >= 65) (%)	28	45	0	1
Child (%)	24	43	0	1
Education (1 if >= college)	58	49	0	1
(%)				
Cable (%)	71	45	0	1
Household Size	2.49	1.36	1	9
WIC (%)	1	8	0	1
Rural (%)	1	9	0	1
Annual Household Income (\$)	69,844.65	36,170.58	2,500	200,000

The total number of observations was 60,013, spanning the years 2006 through 2019. The data included consumption, race, ethnicity, and other parameters, such as household size, presence of cable, enrollment in the WIC program, and residence in rural areas of California

Bottled water consumption: trends and drivers

Our analysis was based on consumption data on 60,013 households in California from January 2006 to December 2019 (Table 3). The average price for bottled water was approximately \$1.01/L (\$2019), which was 2–5 times less expensive than juice and soda. Individuals, on average, consumed 56.17 L of bottled water annually. To contextualize this consumption rate, it is equivalent to approximately 113 bottles of water per person per year (assuming 0.5 L bottles). About 40% of the sample population identified as non-white (Hispanic, Black, or Asian) (Table 3). Approximately 28% of the households included seniors aged 65 or older, 24% of the households included children, and 71% had access to cable. Around 58% of the households had members with at least a college education, about 1% of the households participated in the WIC program, and another 1% resided in rural areas.

Trends by ethnicity and income

Based on self-reported ethnicity data from the survey, approximately 16% of the sample identified as Hispanic (Table 3). Previous studies found that Hispanics tend to consume more bottled water than non-Hispanics due to a number of factors, including the mistrust of tap water [14, 34]. From 2006 to 2019, we found similar results, indicating that, on average, Hispanics consume more bottled water per person than non-Hispanics, although the trend reversed in the last few years (Fig. 3). Notably, during the economic downturn in 2010, there was a decrease in bottled water consumption overall, which aligns with findings from previous studies [35].

To explore the relationship between income and bottled water purchases, the sample data were categorized into three income terciles, representing the average annual household income of our sample: low (<\$21,250), middle (\$21,250–\$43,750), and high-income (>\$43,750) groups. Results suggest that households with higher incomes generally consume more bottled water relative to those with lower incomes (Fig. 4), contrary to other studies, which found that low-income groups consume more bottled water [13, 34, 36, 37]. Furthermore, average per-person bottled water consumption increased from 2010 to 2019, albeit minimally for middle- and high-income households, but significantly for low-income households (Fig. 4).

Drivers and associations

The results above indicate that bottled water consumption was positively related to income and higher among Hispanic households; however, this relationship did not account for potential interactions among income, ethnicity/race, and other confounding factors (e.g., education, age). To address this limitation, fixed effects regressions were employed to control for other observable (e.g., sales price) and time-invariant unobservable factors that may be correlated with bottled water consumption, as well as socioeconomic and demographic factors. As indicated earlier, our analysis focused on household-level bottled water purchases from 2006 to 2019, excluding 2020 due to significant changes in consumption trends resulting from the COVID-19 pandemic.

Individuals identifying as Hispanic exhibited consistently higher bottled water consumption—13.2% on

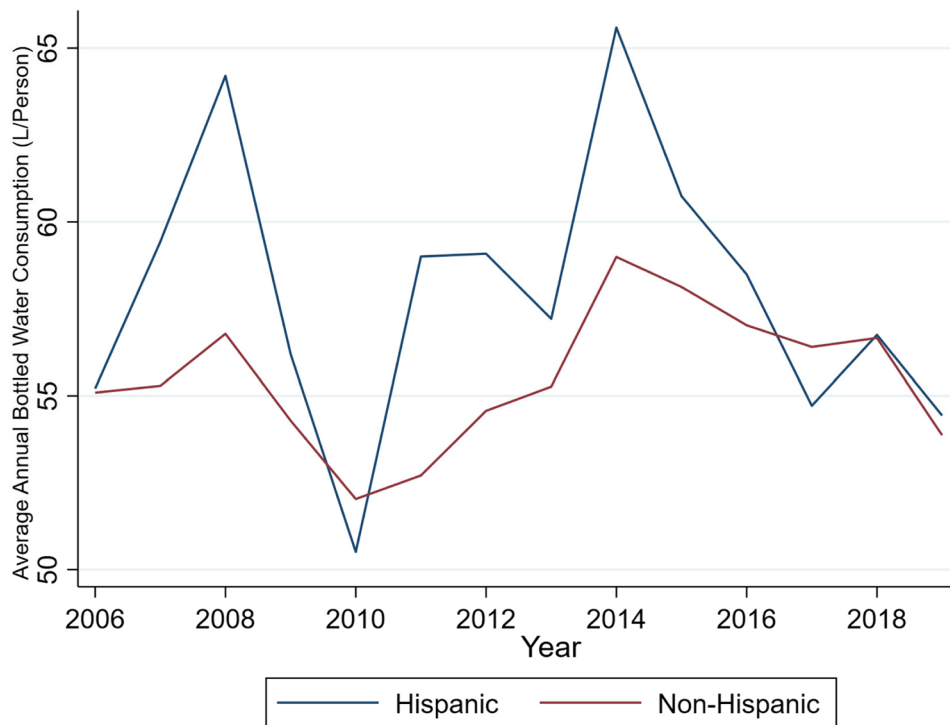


Fig. 3 Average annual per-person bottled water consumption by ethnicity comparing hispanic and non-hispanic populations in California (2006–2019)

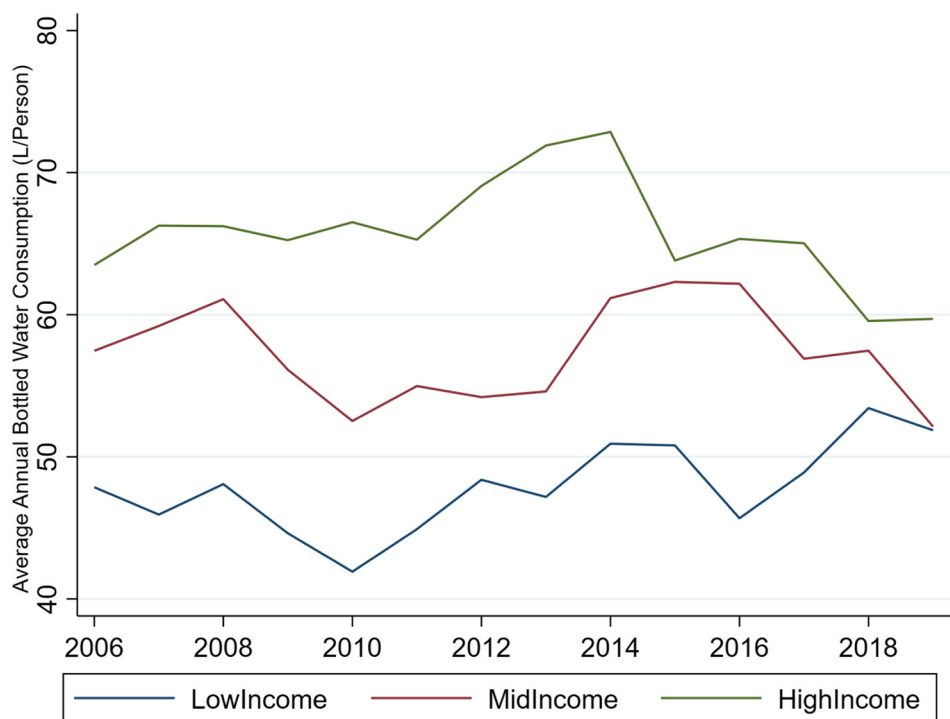


Fig. 4 Average per-person bottled water consumption by income group in California (2006–2019)

average—relative to non-Hispanics (Fig. 5). Compared to their White counterparts, Black individuals consumed more bottled water (36.1% more) while Asian individuals tended to consume slightly less (3.6% less). Our findings

reveal a positive association between income and bottled water consumption, indicating that high-income individuals consumed about 18.2% more, and low-income consumers about 18.1% less, than middle-income

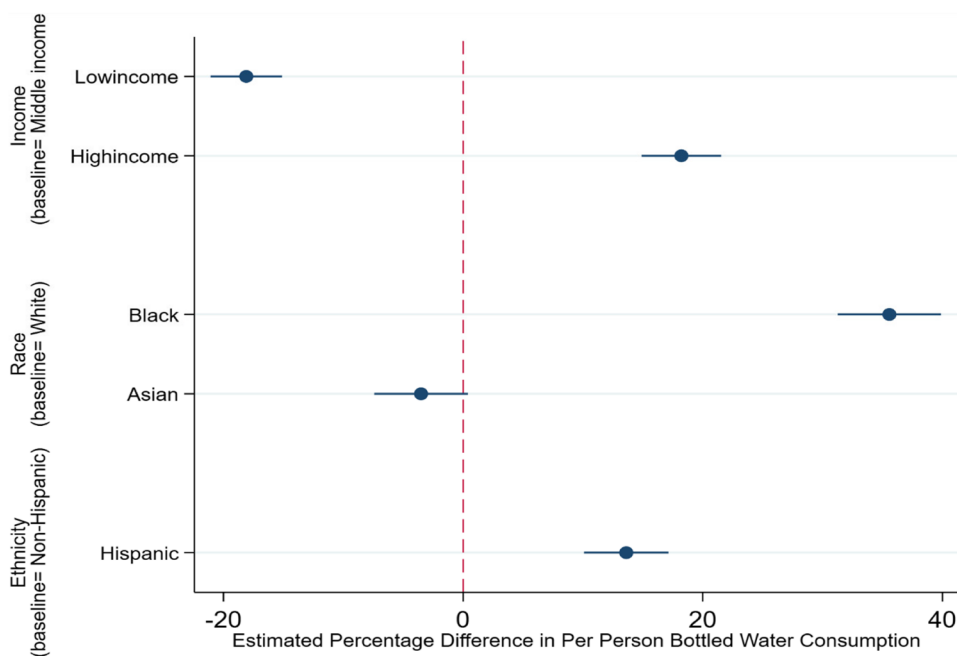


Fig. 5 Estimated changes in per-person bottled water consumption by ethnicity, race, and income group in California (2006–2019)

individuals, respectively (Fig. 5). The full estimation of results is presented in Table s3. Note that our econometric model specifies race/ethnicity and income as level effects rather than interaction terms. Accordingly, we assume that the slope between any race/ethnic cohort does not vary with income; instead, only the level effect changes according to the average income effect across income terciles.

Regarding the interpretation of the income term, our hypothesis is that it captures an “income effect” associated with bottled water purchases, which is consistent with economic theory: assuming bottled water is a normal good, higher income is expected to generate greater demand. At the same time, income may also reflect issues related to proximity to or access to clean drinking water. The race/ethnicity variables may similarly capture aspects of this, as well as cultural experiences and perceptions. Yet because we also include fixed effects at the zipcode and county level, any of these issues that were time invariant over our study period would be controlled for and, thus, would not be biasing our other estimated coefficients. Furthermore, a full untangling of these influences would require a more sophisticated model with additional explanatory variables. For the purposes of our analysis, however, we emphasize the contribution of showing that these differences emerge in the data, thereby justifying further investigation by researchers and consideration by policymakers.

The estimated bottled water price elasticity in this study was approximately 0.75%, indicating that a 10% price increase leads to a 7.5% decrease in bottled water

purchases (Table s3, Column 4). This low-price elasticity suggests that consumers are relatively insensitive to price changes when it comes to bottled water, a result that is consistent with previous studies [38, 39]. The cross-price elasticity of bottled water with other products, specifically juice and soda, as potential substitutes was also examined. Results reveal that as the prices of juice and soda increased by 10%, bottled water consumption increased by 6.1% and 4.9%, respectively, suggesting juice and soda are substitutes for bottled water, an outcome also consistent with previous studies [40].

Exposure to microplastics by Ethnic, Race, and income group

To evaluate differences in microplastic exposure from bottled water across racial, ethnic, and income groups, the results of our estimated microplastic concentrations in bottled water were applied to the differences in bottled water consumption. Bottled water consumption (liters/person/day) and its associated microplastic exposure (particles/person/day) in California were visualized using cumulative frequency distributions across racial and ethnic groups for each of the income terciles (Figs. 6 and 7).

Across each of the income terciles, the cumulative distribution for Black communities lies consistently below the cumulative distribution for White and Asian communities (Fig. 6). This indicates that black communities consume more bottled water and are therefore potentially more exposed to additional microplastics from these consumption differences relative to White communities, while Asian communities are least exposed to

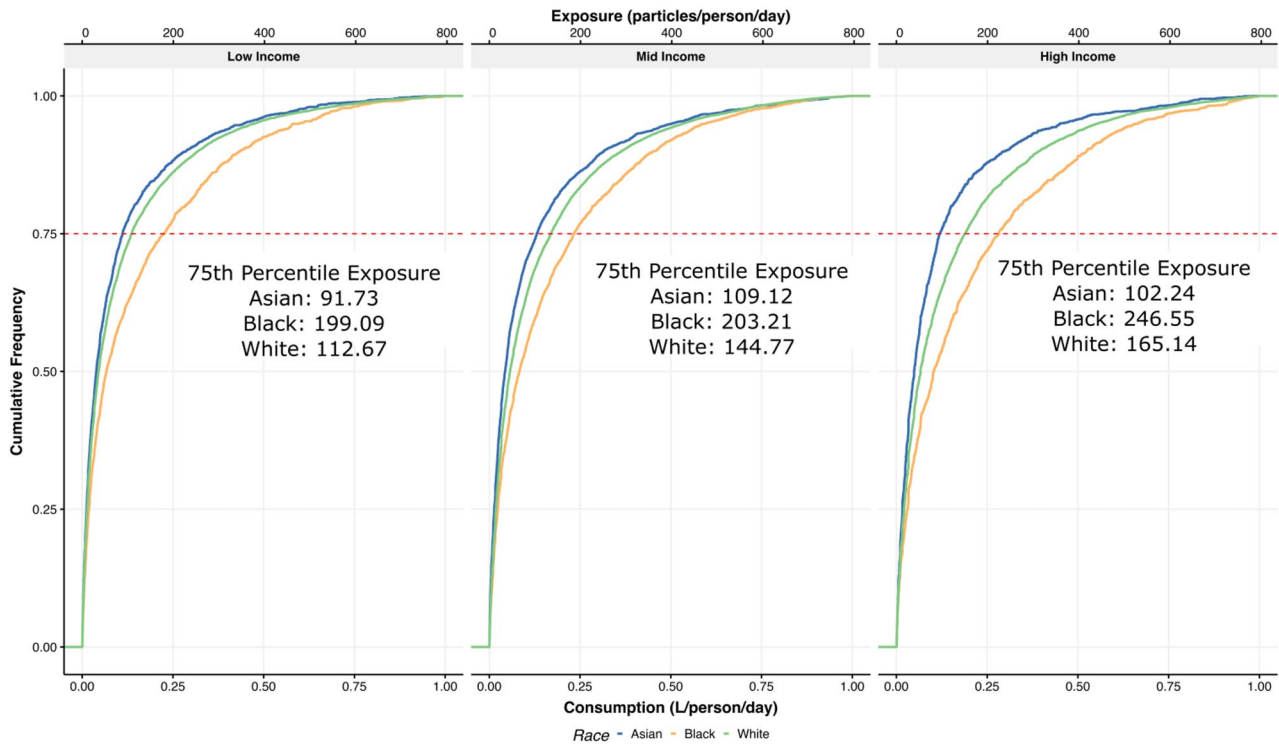


Fig. 6 Cumulative distribution of water bottle consumption and associated microplastic exposure per person per day across the low, mid, and high-income terciles for the sampled Asian, Black and White population in California

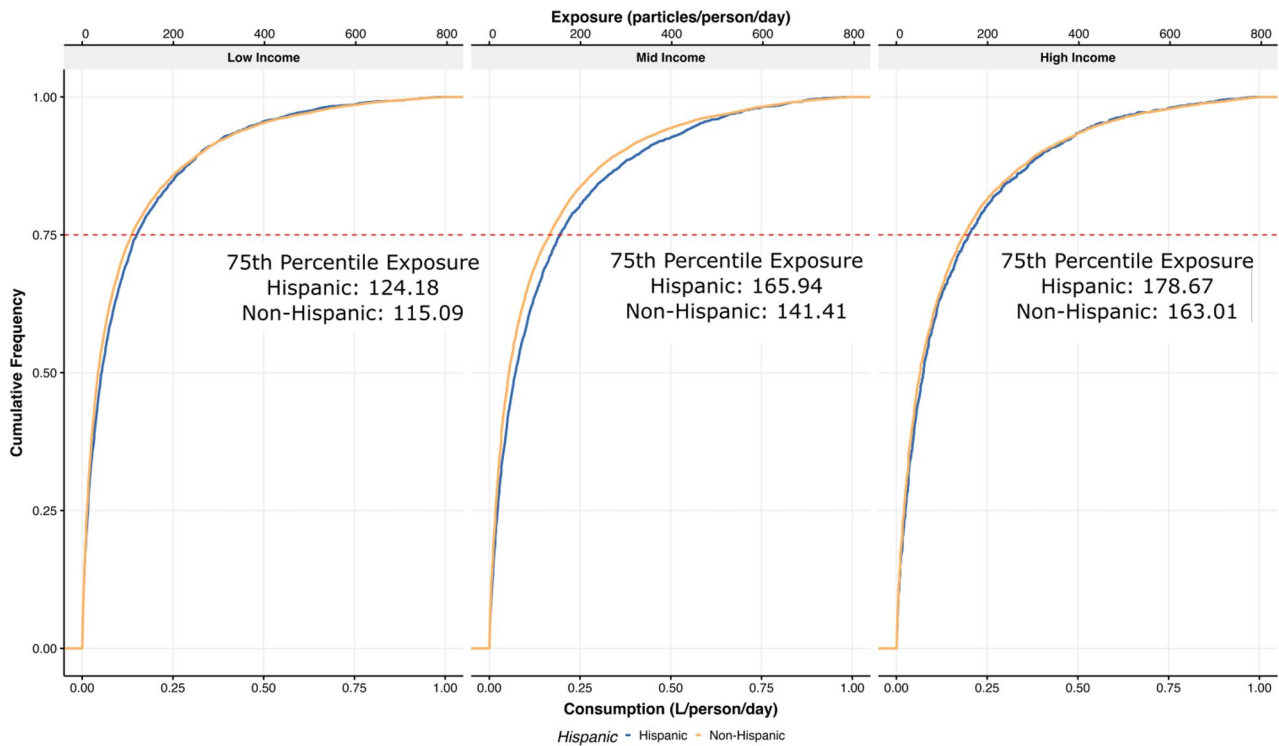


Fig. 7 Cumulative distribution of water bottle consumption and associated microplastic exposure per person per day across the low, mid, and high-income terciles for the sampled hispanic and non hispanic population in California

microplastics through bottled water consumption. At the 75th percentile of consumption, black communities are exposed to about 199 particles/person/day, 203 particles/person/day, and 247 particles/person/day of microplastics from the low, mid, and high income terciles, respectively (Fig. 6).

At the 75th percentile, Hispanic communities are exposed to approximately 124, 166, and 179 particles/person/day of microplastics from the low, mid, and high income terciles, respectively (Fig. 7). Microplastic exposure due to bottled water consumption ranges from 8 to 34% higher for Hispanic communities relative to non-Hispanic communities, and 30 to 77% higher for Black communities relative to White communities (Table s4).

Discussion

Global, federal, and state agencies increasingly recognize the potential threat posed by microplastics in the environment, particularly in terms of the human health effects associated with their consumption. The World Health Organization (WHO) has initiated a comprehensive assessment of microplastics in the environment, including their potential risk to human health through drinking water (WHO, [41]). The U.S. National Oceanic and Atmospheric Administration (NOAA) and Environmental Protection Agency (EPA), under a mandate from Congress, have acknowledged the growing body of evidence demonstrating the health effects of microplastics, evidence that points to microplastics inducing inflammation, dysregulating the immune and endocrine systems, increasing cancer risk, and affecting pregnancy outcomes [42, 43] (USEPA, 2024). At the state level, California, as mandated via the California Safe Drinking Water Act and Senate Bill No. 1422, is obligated to establish standardized methodologies for testing microplastics in drinking water, including public disclosure of the results [44, 45].

While regulatory efforts in monitoring, measuring, and reporting microplastics in drinking water are crucial first steps towards mitigating potential health effects, similar regulations are absent for bottled water. This discrepancy is concerning for three main reasons. First, microplastic concentrations vary across different types of drinking water. Our analysis suggests that on average, bottled water contains 6–7 times more microplastics than public supplies of tap water, with some variation between the Global South, and the Global North. We found averages in the hundreds to thousands of microplastics per liter of bottled water and tens to hundreds of microplastics per liter of public tap water. This aligns with previous research indicating up to 10,000 particles/L in bottled water [46], and tap water containing up to 1,000 particles/L [47, 48].

A second concern regarding the lack of regulatory oversight of microplastics in bottled water is the growing prominence of bottled water as the primary source of drinking water, and the potential health concerns associated with increased microplastic ingestion. For example, bottled water consumption is growing at a rate of 6% annually, with approximately 38% of Americans consuming bottled water as their primary drinking source [10, 49]. Consumers may choose bottled water over tap water for various reasons, including some actual water quality violations, taste, odor, and convenience. However, much of their consumption, especially in the Global North and the U.S. is based on perceived safety [14, 24, 50, 51]. These safety perceptions are primarily influenced by media and marketing that often emphasize the presumed purity, health benefits, and safety of bottled water [15, 52].

At the same time, mistrust in tap water in some highly developed countries is increasing, even though there has been a steady improvement in tap water quality overall [53]. In the U.S., this can be attributed to the standards for tap water set by the EPA, which are far more stringent than those for bottled water set by the FDA [15, 54]. So, while regulations are currently being developed to include microplastic concentrations in some public drinking water systems, no such information disclosure for bottled water is currently in development. Such asymmetric information will limit consumers' ability to make informed drinking water choices and, most likely, lead to the further overconsumption of bottled water and excess exposure to microplastics, *ceteris paribus*.

A third concern relates to understanding the differences in microplastic exposure amongst different populations as a result of bottled water consumption. Our findings indicate that across all income categories, higher bottled water consumption by Hispanic individuals relative to non-Hispanic communities results in an increase in microplastic exposure through drinking water of between 8% and 34% (Table s4). For Black communities, the study revealed microplastic exposure from bottled water consumption is even greater, with concentrations ranging from 30% to 77% higher compared to White communities (Table s4). The higher levels of bottled water consumption we find for Hispanic and Black communities, which leads to the higher levels of microplastic exposure, is consistent with previous research, which suggests choices are often influenced by concerns about tap water safety [13, 14, 54], and negative perceptions of tap water's taste, clarity, and purity, along with a fear of contamination [55–57].

While there are many pathways other than increased consumption of bottled water by which humans are exposed to microplastics [58], as well as many other contaminants and water quality violations that influence

consumer choice of bottle over tap water, highlighting disparities in microplastic exposure from enhanced bottled water consumption as a substitute for drinking water helps inform public health policy and private health choices. Furthermore, it is important to recognize that there are many cases of public water quality and supply failures globally, including vast systemic failures across broad regions, particularly in the Global South, that motivate choices to consume bottled water [16, 17]. However, in this study we have focused on the bottled water consumption in the context of households served by public drinking water supplies in California that are reliable in terms of supply and heavily regulated in terms of quality.

From a public health perspective, federal and state efforts to establish maximum contaminant levels (MCLs) and increase transparency regarding microplastics in tap water have been gaining momentum. Unfortunately, there is little evidence for public health agencies to draw upon regarding microplastic exposure in non-tap water substitutes for drinking water. Our research helps fill this gap by comparing microplastic concentrations in drinking water sources of bottled water and tap water. From a private health perspective, consumers make decisions about drinking water choices based on several criteria, including perceptions of water quality. The degree to which the surge in bottled water consumption as a substitute for tap water is driven by an uninformed understanding of the relative qualities of each indicates a market failure that can be corrected. One means to mitigate this market failure is to implement more stringent regulations and reporting requirements related to microplastic concentrations for bottled water companies. Without such requirements, ill-informed private decisions will lead to overconsumption of bottled water and unnecessary exposure to microplastics.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s43591-025-00150-9>.

Supplementary Material 1. References [59–100] are cited in the supplementary file as studies selected from the literature review for analysis.

Authors' contributions

****SS****: Obtained and analyzed the microplastic concentration data, the exposure rates data, produced all the microplastic-related figures, and was a major contributor to the writing of the manuscript. ****AG****: Co-supervised the project, assisted with project development, and contributed to writing, reviewing, and editing the manuscript. ****MN****: Obtained the Nielsen Homescan Dataset, analyzed the Nielsen Homescan database for bottled water consumption, and performed regression analysis. Analyzed the dataset and produced figures relating to this, and contributed to the writing and reviewing of the manuscript. ****KS****: Co-supervised the project, assisted with project development, and was a major contributor to the writing of the manuscript. ****LW****: Analyzed the Nielsen Homescan database for bottled water consumption and regression analysis.

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Data availability

The datasets generated and/or analyzed during the current study, related to microplastic concentration and exposure, are available in the [BottleWaterMP] repository at [<https://github.com/SamikshaSingh2506/BottledWaterMP>]. The data supporting the findings of this study, specifically the water bottle consumption data, are available from the authors; however, restrictions apply to their availability. These data were used under license for the current study and are therefore not publicly available.

Declarations

Ethics approval and consent to participate

The Nielsen Homescan Database was used for this research, and permission was provided to the University of California, Riverside, School of Public Policy to use it.

Competing interests

The authors declare no competing interests.

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