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Human Consumption of Microplastics

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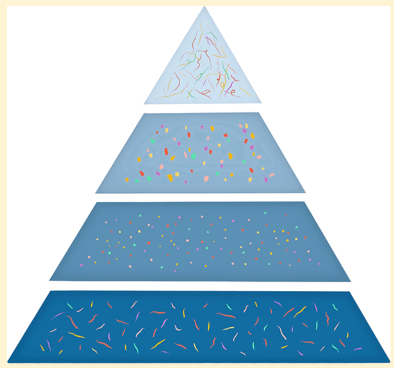
Supporting Information

ABSTRACT: Microplastics are ubiquitous across ecosystems, yet the exposure risk to humans is unresolved. Focusing on the American diet, we evaluated the number of microplastic particles in commonly consumed foods in relation to their recommended daily intake. The potential for microplastic inhalation and how the source of drinking water may affect microplastic consumption were also explored. Our analysis used 402 data points from 26 studies, which represents over 3600 processed samples. Evaluating approximately 15% of Americans' caloric intake, we estimate that annual microplastics consumption ranges from 39000 to 52000 particles depending on age and sex. These estimates increase to 74000 and 121000 when inhalation is considered. Additionally, individuals who meet their recommended water intake through only bottled sources may be ingesting an additional 90000 microplastics annually, compared to 4000 microplastics for those who consume only tap water. These estimates are subject to large amounts of variation; however, given methodological and data limitations, these values are likely underestimates.



INTRODUCTION

Microplastics are pervasive throughout marine and terrestrial ecosystems.[1−3] Current projections indicate that if unimpeded, 12 billion metric tons of plastic waste will be in landfills or the natural environment by 2050, compared to the 4.9 billion metric tons (60% of all plastics ever produced) found in 2015.[4] A growing body of evidence suggests that microplastics are being integrated into widely consumed food items via animals ingesting microplastics in the environment,[5] contamination during production,[6] and/or contamination by plastic packaging.[7] Microplastic particles (MPs) less than 130 μm in diameter have the potential to translocate into human tissues, trigger a localized immune response, and release constituent monomers, toxic chemicals added during plastic production, and pollutants absorbed from the environment, including heavy metals and persistent organic pollutants like PCBs and DDT.[8] Despite increasing evidence that microplastics contaminate a large variety of food and beverages, in addition to outdoor and indoor environments,[9] and the possibility of deleterious effects on human health following ingestion and/or inhalation,[10] an investigation into the cumulative human exposure to MPs has not occurred.

Here, we created a microplastics database, based on a thorough review of the literature, and used this in combination with U.S. dietary data to generate human exposure estimates. To do so, we analyzed the peer-reviewed literature to determine the concentration of microplastics present in commonly consumed items in combination with the recommended or reported consumption of these items by the American public as stated by the United States Department of Agriculture (U.S.D.A.), U.S. Department of Health and Human Services, World Health Organization (WHO), and the National Academies of Science, Engineering, and Medicine (Table S1, S2, and S3). Commonly consumed items included various sources of seafood, sugars, salts, honey, alcohol, as well as tap and bottled water. Other food groups (e.g., meat, grains, and vegetables) are not included in this analysis due to a lack of data on their microplastic content. The potential consumption of MPs through inhalation was evaluated using reported microplastic concentrations in air and the US Environmental Protection Agency's (EPA) reported respiration rates. Furthermore, we explored how the consumption of only bottled water may impact microplastic consumption relative to the consumption of only tap water and the current average American consumption of bottled water. We also determined how MP consumption might vary according to age and sex.

MATERIALS AND METHODS

Data Collection. A literature review was conducted to identify studies that determined the concentration of microplastic particles (MPs) within food and beverages consumed by Americans. Studies addressing the concentration of airborne

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MPs were also identified. For studies to be considered, they had to investigate items commonly consumed by humans and report MP concentration as exact values (total count in a single sample) or as a mean. One of the studies considering airborne plastics[11] did not provide a mean so the median values were extracted with the caveat that these are likely lower than means given the distribution of the data. In this instance, the study measured all particulates in the air of two apartments, an office, and outside of an office building and determined that only 33% of these particles were synthetic, petroleum-based polymers, so the median number reported was adjusted to 33% of the total. To ensure consistency, median values were also extracted from the second study addressing airborne plastics. For all studies, the type of MPs (e.g., fiber, bead) found was also noted, as well as the type of chemical method (if any) used to verify whether particles were plastic. Twenty-six studies were identified by this process, specifically investigating the following consumption groups: fish, shellfish, added sugars, salts, alcohol, water, and air (Table S1). Only studies assessing items that are commonly consumed by people were considered (e.g., whole fish, fish tissue, table salts, tap water, refined and raw sugars, etc.). All data were obtained from tables and text where possible; if necessary, the software GraphClick was used to retrieve data from figures.[12] A total of 402 data points, which represents over 3600 processed samples, were collected from the 26 studies where each data point represents the concentration of microplastics within a specific item presented within a study, commonly composed of multiple replicates (Table S1).

Recommended dietary intakes for Americans were determined using the Dietary Guidelines for Americans 2015−2020, eighth edition report, by the U.S. Department of Health and Human Services.[13] Average consumption was separated by sex and age: male adults, female adults, male children, and female children. Adults were considered to be 19 years of age or older. When consumption values were presented as ranges across an age group, as was the case with seafood, the mean of the range was used. During this process, we estimated caloric intake assuming a moderately active lifestyle (as this seemed to be the most widely applicable choice), which recommended calorie intakes of 1965, 2733, 1694, and 2133 for male children and adults, and female children and adults, respectively. Although it was noted that the difference between sedentary/moderate and moderate/active could be up to 400 calories per day depending on age, this decision only directly affected the recommended added sugar intake, which is 10% of consumed calories. To account for the amount of honey consumed by the American population, the per capita consumption of honey was subtracted from sugar consumption. The Department of Agriculture's National Agricultural Statistics Service Annual Honey Report estimates Americans consume 1.61 pounds of honey per year or 2.00 g per day. The amount of sugar remaining was then assumed to be made up of the other forms of sugar considered (e.g., refined).

To determine microplastics consumed via drinking water, separate calculations were made for 100% tap water, 100% bottled water, and a composite estimate of average current tap and bottled water consumption. For the composite estimate, the average per capita daily consumption of 0.436 L of bottled water was used, with the remaining recommended water consumption being made up by tap water; this was determined to be roughly 17% bottled water and 83% tap water, based on the amount of bottled water consumed per capita in the U.S. relative to the recommended water consumption.[14] Thus, in this instance, water was considered a combination of bottled and tapped sources based on the average per capita water consumption and The National Academy's recommended consumption of water for the age group and sex considered.[15]

As the only available data on microplastics in alcohol were concentrations within beer, the reported amount of per capita alcohol consumption by adult men and women was evaluated in terms of beer.[16−18] As the World Health Organization (2014) reports male and female per capita consumption of 13.6 and 4.9 L of alcohol, it was assumed this consumption was comprised entirely of beer. As the report lists beer as the most commonly consumed alcohol for both sexes, by a large margin, this is a reasonable assumption.[17]

Mean respiration rates for different age groups and sexes were obtained from the U.S. Environmental Protection Agency exposure factors handbook 2011, with values ranging from 3.4−19.3 m^3/day.[19] The age groups in this report were combined and averaged into the previously mentioned categories of male children and adults, and female children and adults; however, in this instance, adults were considered to be 22 years of age or older due to the preformed groupings.

Data Analysis. The literature review resulted in MP concentrations within commonly consumed items that could be separated into the following categories: air, alcohol, bottled water, honey, seafood, salt, sugar, and tap water. MP concentrations were converted, where necessary, to particles per gram, liter, or cubic meters, depending on whether the study focused on foods, liquids or air, respectively. At the study level, a mean concentration was determined from all the items within a single category (e.g., all the fish and bivalve values in the seafood category). As a result, in studies that evaluated the MP concentration within multiple items (e.g., bottled and tap water), each case was treated independently and the average for each item was determined. As the MP concentration across items was never pooled during the analysis, treating these cases as independent did not compromise our results.

The average intake of MPs associated with the daily consumption of each item was determined. The mean MP concentration for each study was determined within the various items (Table S1). Subsequently, the mean and associated standard deviation for each of the items was derived from the study means. Tap water and sugar were comprised of single studies. In these instances, the mean and standard deviation were determined within each study (as compared to across studies) using the five and 14 MP concentration values presented within the sugar and tap water studies, respectively. The number of MPs consumed for each age group and sex was then determined by multiplying each of the microplastic concentrations by the respective daily consumption value of each item (Table S1, S2, and S3).

The annual consumption of MP was determined. The mean MP concentration for each study was determined within the various items as outlined above (Table S1). In a similar fashion to the previously discussed mean and associated standard deviation calculations, the mean and variance for each of the items were derived from the study means. Again, tap water and sugar were comprised of single studies. The mean and variance for these items were determined within each study (as compared to across studies). The number of microplastics consumed annually by each age group and sex was determined by multiplying each of the microplastic concentrations by the respective annual consumption value of each item. To determine the average standard deviation for the annual

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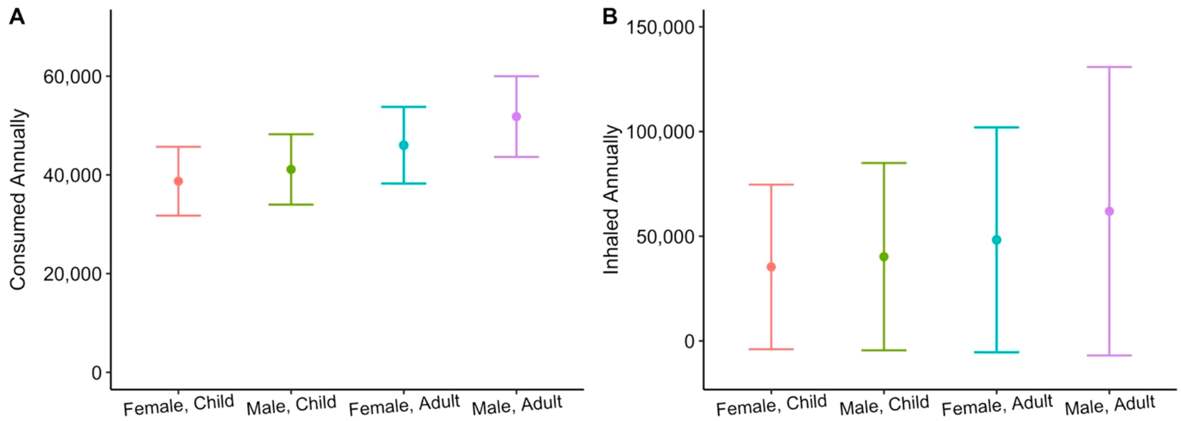

Figure 1. Total microplastic particle (MP) intake for female and male, children and adults from (A) annual consumption of commonly consumed items and (B) annual inhalation via respiration. Points and error bars represent the summation (total) and average standard deviation of all microplastics consumed.

Table 1. Daily and Annual Consumption and Inhalation of Microplastic Particles for Female and Male, Children and Adults[a]

	Daily		Annual		Total	
	Consumed	Inhaled	Consumed	Inhaled	Daily	Annually
Male Children	113	110	41106 ± 7124	40225 ± 44730	223	81331
Male Adults	142	170	51814 ± 8172	61928 ± 68865	312	121664
Female Children	106	97	38722 ± 6977	35338 ± 39296	203	74060
Female Adults	126	132	46013 ± 7755	48270 ± 53676	258	98305

[a]Points and error bars represent the summation (total) and average standard deviation of all microplastics consumed.

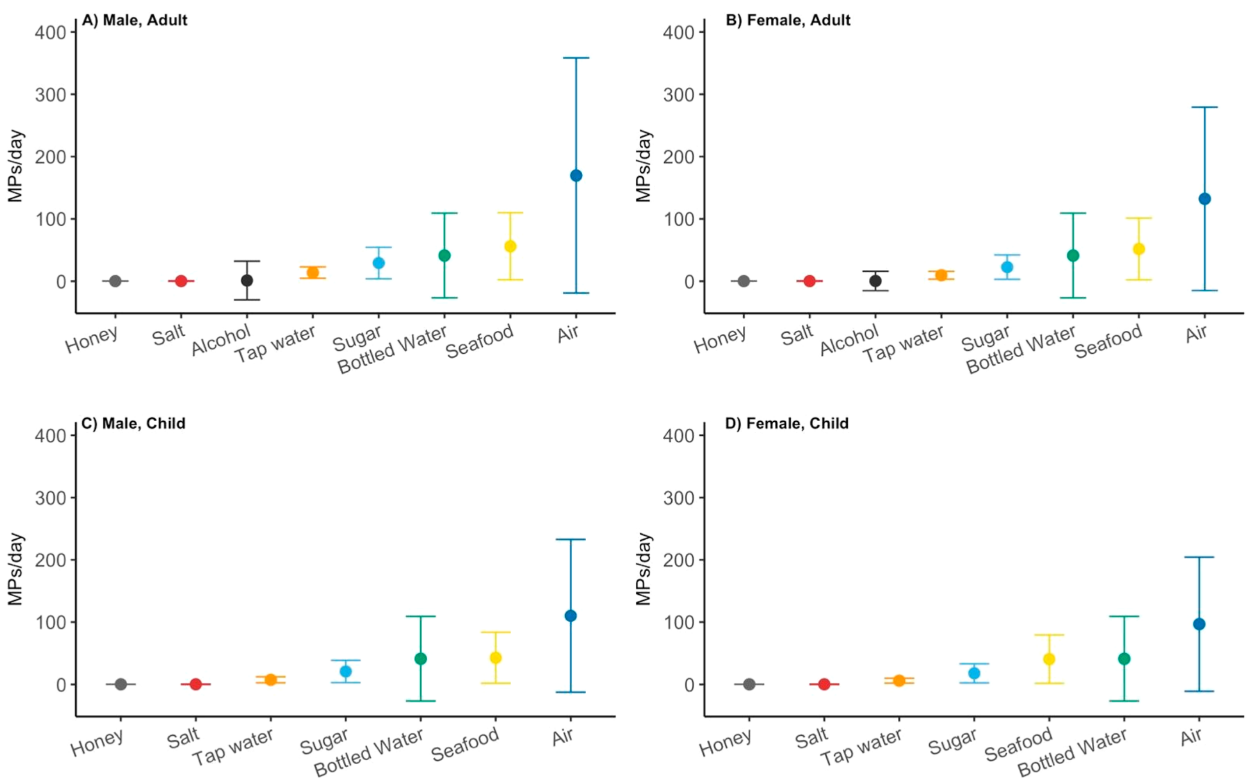

Figure 2. Mean and standard deviation of microplastic concentration within each source of ingested microplastic particles (MPs) including salt, alcohol (beer), seafood (fish, shellfish and crustaceans), added sugars (sugar and honey), water (bottled and tap), and air in (A) male adults, (B) female adults, (C) male children, and (D) female children.

consumption of MPs, the variances associated with each consumed item were averaged. The square root of the averaged variances was subsequently determined, which represents the averaged standard deviation and is an indication of the range of microplastics consumed when considering multiple sources and their associated variances.

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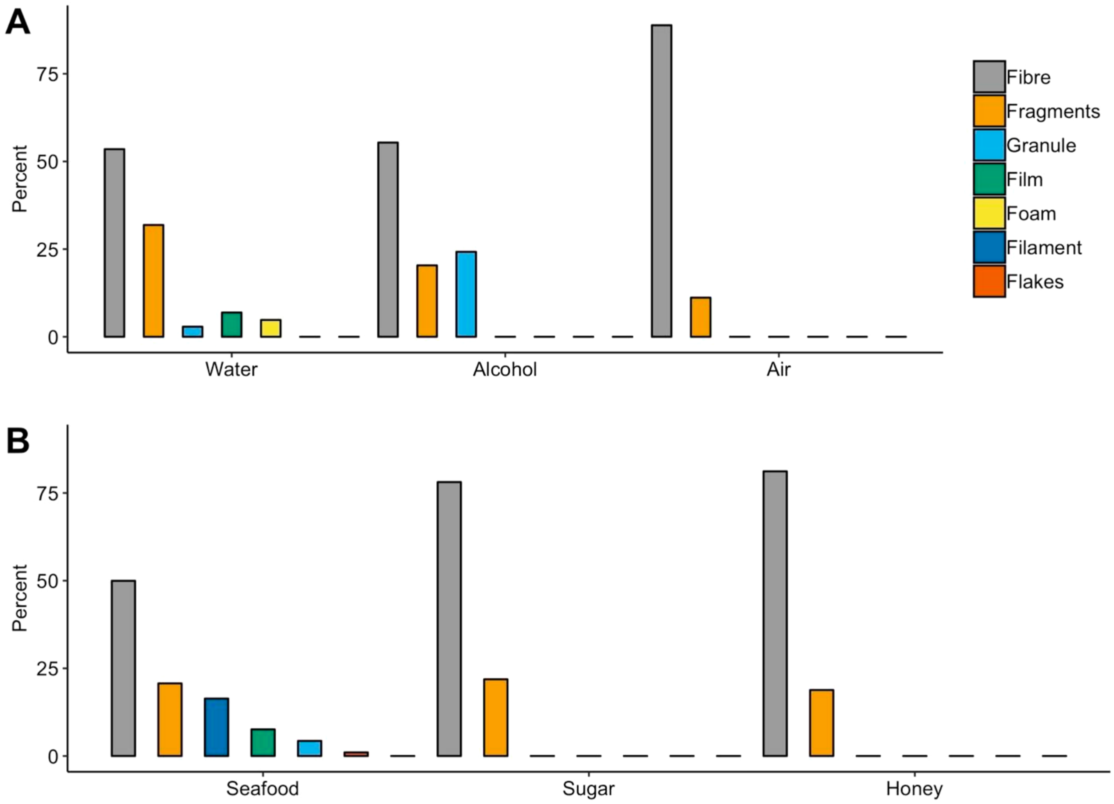

Figure 3. Average percent microplastic particle (MP) types including fibers, fragments, granules, film, foam, filaments, and flakes in (A) water, alcohol (beer), and indoor air and (B) seafood, salt, sugar, and honey.

Data Assumptions. Given the current state of knowledge surrounding the concentration of MPs within food items, various assumptions were made when conducting this research. In all cases, caution was taken to ensure that conservative estimates were used, which further increases the likelihood that our results are a substantial underestimate. In addition, we assumed that all demographic groups consumed all food items (except children and alcohol). Furthermore, our study focuses on recommended consumption, although people presumably deviate considerably from these suggestions. This would be especially true with drinking water and respiration, which is likely to greatly vary at the level of the individual. Inhalation of microplastics is based on two studies of air, which is a concern given the range of places people occupy throughout the day. Although a large majority of the average American's days are likely spent in their homes, at work, at school, or traveling between them, which were the air sources considered in these studies (albeit in different countries), an evaluation of a variety of outdoor and indoor air sources will be critical to solidify the risk that microplastic inhalation poses and reduce the variation surrounding these estimates.

■ RESULTS AND DISCUSSION

The items considered in this study were determined to have the following average microplastic concentrations: seafood = 1.48 MPs/g, sugar = 0.44 MPs/g, honey = 0.10 MPs/g, salt = 0.11 MPs/g, alcohol = 32.27 MPs/L, bottled water = 94.37 MPs/L, tap water = 4.23 MPs/L, and air = 9.80 MPs/m^3. Daily consumption of MPs by male children, male adults, female children, and female adults are estimated to be 113, 142, 106, and 126, respectively. Thus, annual consumption via food and beverages of MPs for these groups are roughly 41000, 52000, 39000, and 46000, respectively (Figure 1). Inhalation contributes an additional 110, 170, 97, and 132 MPs to daily consumption by the previously mentioned categories. Therefore, approximately 40000, 62000, 35000, and 48000 may be inhaled annually by the respective groups (Figure 1). The combination of ingestion and inhalation of MPs yields total annual exposure estimates of approximately 81000, 121000, 74000, and 98000 for male children, male adults, female children, and female adults, respectively (Table 1).

Our analysis accounts for approximately 15% of caloric intake. If the caloric value of 60 seafood species, ranging from tuna to mussels, including species not incorporated in our analysis, are averaged, the resulting value is 1.49 calories per gram of seafood. Therefore, the consumption of the recommended amount of seafood would account for roughly 5% of a moderately active individual's caloric intake. As such, our analysis combines the recommended consumption of seafood, 10% of the caloric intake through added sugars and honey, and the recommended consumptions of items with no caloric value including water and salt.

Microplastic ingestion levels varied extensively by item (Figure 2, Table S1). Similar consumption and inhalation rates, by proportion, led to relatively similar patterns in microplastic consumption according to age and sex. Air, bottled water, and seafood consumption accounted for the large majority of microplastic intake. Inhalation was subject to a large amount of variation due to studies reporting airborne MP concentrations of 2.09 and 17.75 MP per cubic meter of air (Table S1 and S2). The consumption of added sugars (including honey) contributed substantially less, but still a notable amount, of MPs to total consumption values (Figure 2). Salts, tap water, and alcohol contributed minimal amounts

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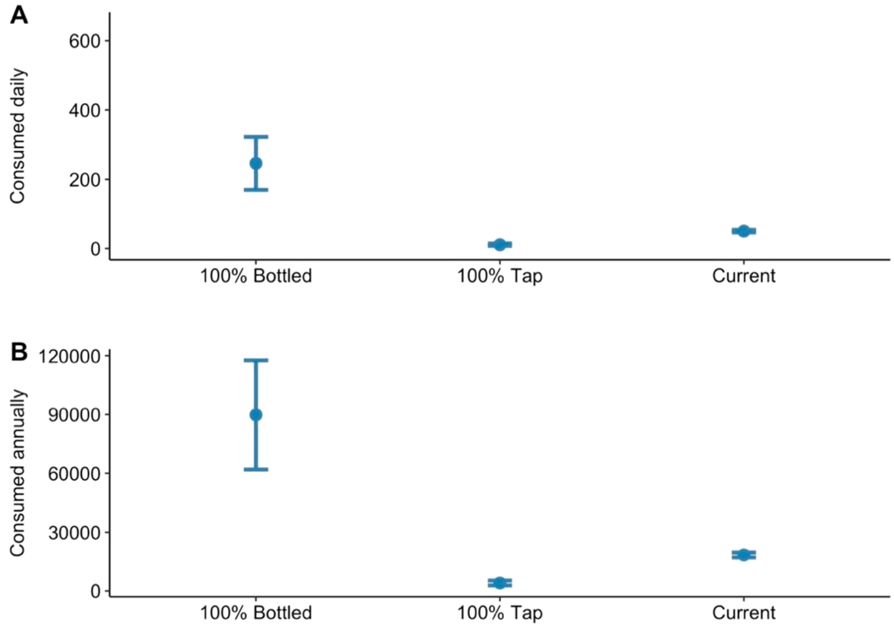

Figure 4. Microplastic particles (MPs) consumed from 100% bottled sources, 100% tap sources, and current average per capita consumption of bottled water with the remaining volume of recommended water consumption made up by tap water, averaged across the multiple age and sex categories and considered to determine the mean and standard deviation (A) daily and (B) annually.

of plastic to total consumption due to lower consumption by weight and volume. Salts had an average concentration of 0.11 MP per gram, while alcohol and tap water had an average concentration of 32 and 4.2 MP per liter, respectively, which resulted in less than 5 MPs consumed per day due to salt intake, less than 1 MP consumed per day from alcohol and less than 14 MPs per day from tap water. Regardless of the item, the vast majority of microplastic particles consumed were fibers (Figure 3A,B). Fragments were the second most commonly consumed type of microplastic particle. In the case of air, sugar, and honey, fragments and fibers were the only particles consumed.

The source of drinking water (bottled vs tap) led to a substantial amount of variation in microplastic consumption. On the basis of the assumption that people are consuming the average national per capita volume of bottled water and meeting their remaining water requirements via tap source, 48, 55, 47, and 51 MPs are consumed daily by male children, male adults, female children, and female adults, respectively (Figure 2). Microplastic consumption changed considerably depending on whether water requirements were met solely from tap water (4 particles/L) or from bottled water (94 particles/L). Drinking solely bottled water led to a daily microplastic intake of 205, 349, 174, and 255 particles for male children, male adults, female children, and female adults, respectively; the resulting average intake being 246 MPs per day (Figure 4A). Drinking only tap water, however, led to daily particle intakes of 9, 16, 8, and 11 for male children, male adults, female children, and female adults, respectively (Figure 4A). Annual intake of MPs via drinking water for male children, male adults, female children, and female adults can thus be estimated to be approximately 75000, 127000, 64000, and 93000 if bottled water is the only source or 3000, 6000, 3000, and 4000 if tap water is the only source (Figure 4B). Averaged across demographic groups, annual MP intake from drinking water was 90000 if only bottled water is consumed and 4000 if only tap water is consumed (Figure 4B); a 22-fold difference.

The trend for bottled water to contain vastly more microplastic than tap water is clear. However, ample variation surrounding the concentration of microplastics in different water sources exists. As evidenced by Mason et al.,[7] who reported substantially higher microplastic concentrations than those reported by others, this disparity may be a function of rapidly evolving methodologies. Mason et al.[7] employed Nile Red staining and automated image analysis to uniquely analyze particles as small as 6.5 μm, which is a smaller size of particle than most studies are able to detect. Thus, it may be possible that the numbers are more representative of the degree of contamination of bottled water.

Our findings indicate that American adults and children consuming the recommended or average amounts of the items that have been analyzed for MPs to date are exposed to between 81000 and 123000 MPs per year. These estimates substantially increase values previously provided by researchers who focused on single types of food or beverages (e.g., 123–4620 MPs/year from shellfish,[20] 5800 MPs/year from tap water, beer, and sea salt[16]). Drinking water, respiration, sugars, and seafood represent substantial vectors of MP consumption, with MP inhalation posing the largest risk to adults and drinking water the largest risk to children. Concerns exist surrounding whether inhaled MPs are actually ingested; however, unless coughed or sneezed out of the mouth or nasal openings, inhaled particles will either enter the digestive system via mucociliary clearing or remain trapped in the lungs, suggesting that most inhaled particles will be ingested.[8]

As microplastic research is still in its infancy, major limitations exist within the available literature that impose certain restrictions on the comparisons that can be made. Our study does not consider the large number of MPs that enter the human digestive system by simply settling onto food during meals[20] or the increases in microplastic content that occur during food preparation.[21] Initial estimates predict that 13731–68415 additional MPs could be ingested by humans per year based on particles settling out of the atmosphere

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during evening meals alone.[20] We also were not able to consider the ingestion of MPs via the consumption of many commonly consumed food items, including beef, poultry, dairy, grains, and vegetables, due to the lack of any studies investigating the contamination of these food groups by MPs. A further limitation is that the studies that quantified MP concentrations in added sugars (i.e., sugar and honey) did not make use of spectroscopic or thermal analysis to verify visually identified particles as plastic (Figure S1). Thus, although added sugars appear to represent a notable source of MPs for human ingestion, these numbers are likely overestimates. In addition, the concentration estimates for MPs in air are taken from only two studies. Further investigation of MP concentrations in both indoor and outdoor air needs to be undertaken to quantify the degree of risk of human MP intake via respiration.

Seafood contamination by microplastics represents a large proportion of the work done related to human consumption of microplastics to date (14 of the 26 studies analyzed by this study). However, despite our finding that seafood is one of the top three contributors to human consumption of microplastics based on current knowledge, its role as a vector for microplastic consumption relative to other food items may still be unresolved. This is especially true when the relatively low annual consumption of seafood in many urbanized populations is considered, which is well below the recommended intakes considered in this analysis (e.g., 281 g/week recommended for U.S. males aged 19−30 compared to 125 g/week actual intake).[13] Alternatively, certain parts of the world consume a much greater dietary proportion of seafood, with highest estimates of 104.2 g/day in Japan in 2010.[22] If our data are representative, Japanese seafood consumption represents a potential daily consumption of 154 MP. For these regions, seafood may in fact represent a considerable food vector for microplastic exposure. However, under either circumstance, data on microplastic consumption via other proteins sources (e.g., poultry or beef) are lacking, which makes the relative exposure risk posed by seafood consumption difficult to discern. Initial findings into this topic have indicated that chickens raised in home gardens have 62.5 and 10.9 microplastic particles within their gizzards and crops, respectively.[23] This result indicates that poultry, either as chicken gizzards if eaten directly or potentially via consuming other body parts which may also contain MPs, could represent a substantial microplastic exposure source.

Our estimates of American consumption of microplastics are likely drastic underestimates overall. Our current analysis indicated that meeting approximately 15% of a person's caloric intake is associated with the consumption of up to 52000 microplastics annually. Extrapolating the number of microplastics consumed with the remaining 85% of calories is not possible; however, if our findings are remotely representative, annual microplastic consumption could exceed several hundred thousand. Many major food groups (e.g., poultry, beef, dairy, grains, vegetables) have not been assessed for microplastic content by any researchers to date. Furthermore, we have not considered the degree to which food items sold in large amounts of plastic packaging are contaminated with microplastics, which could be high based on findings from bottled water.[7] As a result, any recommendations to reduce or avoid certain food groups to minimize MP exposure would currently be unfounded.

Although the effects of consuming MPs on human health are largely unknown, potential pathways for harm have been suggested.[8,24] Once MPs are in the gut, they can release constituent monomers as well as additives and absorbed toxins, which can cause physiological harm ranging from oxidative stress to carcinogenic behavior.[25] The MPs can further penetrate the human body via cellular uptake in the lungs or gut as well as by paracellular transport in the gut.[8] The degree of uptake will vary according to the shape, size, solubility, and surface chemistry of MPs. Particles on the scale of a few microns or less may be directly taken up by cells in the lungs or gut, while particles up to 10 μm may be taken up by specialized cells in the Peyer's patch of the ileum.[26] Particles as large as 130 μm can enter tissue through paracellular transport in the form of persorption, although the rate of particle transfer to blood over 24 h may be as low as 0.002%.[27] Given the data limitations surrounding the size classes of microplastic particles present in consumed items, it is still unclear to what extent our estimate of human consumption of MPs poses a risk to human health.

Our results suggest that avoiding the consumption of bottled water might effectively reduce exposure to MPs. However, this does not address the fact that the prevalence of plastic within ecosystems is increasing. These data suggest that microplastics will continue to be found in the majority, if not all, items intended for human consumption. Future work needs to be conducted to thoroughly investigate the contamination of other food groups, especially products like grains, vegetables, beef, and poultry, which represent major sources of nutrition globally. In addition, more studies using more recently developed methods should be carried out on food items such as alcohol and added sugars, where the existing data is somewhat questionable due to outdated methods. New data will allow for updates to our estimates of human consumption of MPs and eventually allow scientists to estimate the potential risk to humans of microplastic ingestion. If the precautionary principle were to be followed, the most effective way to reduce human consumption of microplastics will likely be to reduce the production and use of plastics.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b01517.

Polymer identification methods, details of studies included in the analysis, source information on the dietary recommended intake of each food group used to determine human microplastic consumption (PDF)

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K.C., G.C., H.D., J.D., F.J., and S.D. conceived the idea for this piece. K.C., H.D., and G.C. designed the research and conducted the data collection and analysis under the supervision of J.D., F.J., and S.D. K.C., G.C., H.D., J.D., F.J., and S.D. wrote the manuscript.

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Notes

The authors declare no competing financial interest.

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