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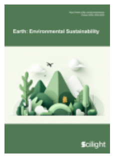

Article

Evaluation of Microplastic Contamination in Table Sugar: What Does Sugar Have Besides Its Sweetness?

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Highlights

- Microplastics are present in sugar sold in sachets
- Samples from all 24 assessed countries were contaminated: 100% contamination rate
- Polymers found were PU, PET, and PE
- Table sugar represents a worrisome pathway for MPs intake by humans

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Abstract: This study evaluates microplastic (MPs) contamination in table sugar packaged in sachets consumed in 24 countries, 18 from Europe, five from America, and one in Asia, emphasizing the ubiquity of MPs in food products. The samples were obtained in a sampling effort involving several people. 100 samples of 3 g of sugar were analyzed (3 replicates each) in a stereoscope with and attached camera, revealing a 100% contamination rate, with 3977 MPs particles identified. Filaments (56.63%) predominated over fragments (43.37%), with blue and black particles being the most frequent. Polymer analysis using Raman spectroscopy identified polyurethane (PU—predominant), polyethylene terephthalate (PET) and polyethylene (PE) as the main types of MPs. Considering estimated dietary intake (EDI) values calculated by $EDI = (SgC \times MPp)/SM$, Brazil and the USA ranked as the countries with the highest levels of total MPs intake. These findings highlight sugar as an important pathway for dietary exposure to MPs, raising critical concerns about the risks to human health and food safety. Regulatory interventions and improved processing protocols are imperative to mitigate MP contamination in sugar and other widely consumed processed foods.

Keywords: microplastic ingestion; table sugar; food hazard; human health; raman spectroscopy

1. Introduction

The global demand for plastics has increased substantially in various sectors over recent decades, resulting in a corresponding rise in plastic waste production. After use, most plastics accumulate as waste in various environmental, compartments, both terrestrial and aquatic, representing a toxic legacy for the future that is difficult to remove, since pollution and its impacts are cumulative [1,2].

In the environment, larger fragments of plastic are degraded by different routes and mechanisms [3,4], by thermal, mechanical, chemical, hydrolysis, and photodegradation [5], turning plastic waste into smaller particles, known as secondary microplastics (MPs). Primary MPs are produced in microscopic sizes and include plastic pellets, microspheres, and even powders used in personal and home care products and cosmetics [6]. In this scenario, the problem of plastic pollution scales massively since MPs are more easily dispersed, reaching other areas, providing a continuous increase in MPs contamination [7] Matavos-Aramyan, 2024. Once in the environment, different groups of organisms are exposed to these micromaterials, promoting impacts in different taxa, as already described [8–13].

In recent years, many studies have been carried out on the distribution and environmental behavior of MPs in terrestrial [14,15], marine [16–19], and freshwater systems [20]. In addition, several studies have shown that MPs act as carriers of toxic pollutants [21] such as heavy metals [22] Tang et al., 2020, polycyclic aromatic hydrocarbons (PAHs) [23], polychlorinated biphenyls (PCBs) [24], dichlorodiphenyltrichloroethane (DDT) [25], and polybrominated diphenyl ethers (PBDEs) [26].

Due to the growing awareness of plastic pollution and the risks to human health, the World Health Organization has begun to encourage studies into the impact of MPs on human health [27]. Microplastic particles can be transported to human tissues, giving rise to local immune responses *per se*, or by the release of potentially toxic chemicals added during their production or from other pollutants absorbed from the environment. Humans can ingest MPs by eating aquatic organisms contaminated especially marine shellfish [28,29].

Apart from digestion, the main routes by which MPs enter the human body are inhalation and dermal contact. According to [30], a person ingests around 39,000 to 52,000 MPs per year. Several studies have indicated high levels of MPs pollution in agricultural or industrial food products [31–34].

MPs can also break through biological barriers, especially in the lungs or intestines, or via paracellular transport in the intestines, penetrating human tissues [35,36]. The degree of absorption varies according to the intrinsic characteristics of the MPs. Another critical way in which humans absorb MPs is via respiration since MPs are inhalable particles [37–39].

Studies have shown the presence of MPs in human feces [40], in the placenta [30,41], lungs [42,43], blood vessels [43], heart tissue [44] and bone marrow, brain and testicular tissue [45].

MPs contamination has already been described in various beverages and human foods, including commercial mollusks [46,47], shrimps [48], fishes [49], tap water [50,51], bottled water [52–54], milk [55,56], beer [57–59], tea [32], soft drinks, energy drinks [60], vinegar [61], salt [62–64], honey [5], milk powder [65], flour [66], fruit and vegetables [31], rice [66], and sugar [67]. According to [68], these food items are among the main sources of dietary intake of MPs.

However, due to the ubiquity of MPs, the sources of human contamination by MPs may include many other foods that have not yet been reported, or have been insufficiently studied. Therefore, there is a need to expand studies on human contamination in dietary items. Among the various types of food that need further study, sugar stands out.

Sugar is a natural carbohydrate found in fruits and vegetables that gives them a sweet taste. Sugar is produced commercially from sugar cane (*Saccharum* spp.) and sugar beet (*Beta vulgaris*), and its average global production in 2022/2023 reached around 181,912 million tons [69]. Sugar is the main commercial commodity, being produced in many countries around the world, where Brazil is the largest producer, followed by India, the European Union, and Thailand [70,71].

Although sugar consumption is an important factor in human exposure to MPs, this topic has not yet been widely studied. In the literature, few studies have investigated the presence of MPs in sugar [5,67,72].

At the same time, sugar consumption is growing all over the world, either in its pure form or as an additive in different products, such as drinks, cookies, sweets and confectionery, and many ultra-processed foods. Therefore, studies dedicated to the identification and characterization of MPs in sugar are necessary and imminent, especially in countries with high levels of production and consumption of this commodity.

Sugar is an important source of energy and is mainly consumed in the form of solid crystals. Its production process involves different stages and operations [73–76], resulting in raw sugar and refined sugar. High temperatures and various chemicals are involved throughout its production [77]. In summary, sugar production includes the stages of extracting the juice from the cane, clarifying and boiling the juice, crystallization, centrifugation, and drying. All of these stages are susceptible to contamination by MPs dispersed in industrial environments or present in the machinery used. After drying, the sugar can be packaged in different quantities, usually 50 kg or 1200 kg big bags for sale. Depending on the use of the sugar, different quantities can be packaged, from packages available to the direct consumer, with a few kilos, to "table sugars", which are small sachets with around 3 to 5 g of sugar for individual use, available on the tables of cafeterias and restaurants around the world.

Studies on the contamination of sugar by microplastics are still limited. [5] analyzed five samples of sugar and honey in Germany. [72] analyzed 19 samples of various brands and types of sugar in Adapazarı, Turkey. Microplastics were detected in every sugar sample examined, with a minimum concentration of 11,724 microplastics per kilogram and a maximum concentration of 53,464 ± 9622 microplastics per kilogram. The study by [67] investigated microplastics in commercial sugar and salt from Iran using just four samples.

In conclusion, sugar is one of the most important commodities contributing to the economy of many people and its consumption is increasing all over the world, either in its pure form or as additives to many food products. However, the presence of microplastics in sugar has received little attention, given the small number of studies as shown above.

Thus, considering that sugar is one of the most important foods in all countries, this study aimed to assess the contamination of table sugar by microplastics and correlate this contamination with the countries where these products are being consumed, contributing to the analysis of this important route of human contamination by microplastics.

2. Material and Methods

2.1. Sampling and Filtration

Our partners and associates traveling or working abroad in different countries have gathered samples of table sugar and kindly sent them to our study group. This is an approach called Citizen Science, where members of the public actively participate in the construction of science as an attempt to involve society in the processes of scientific research, narrowing the gap between them, making science accessible and more sensible.

In total, samples were obtained from 24 countries. All volunteers who contributed to the collection of samples were instructed to collect at least three of the same brand of table sugar, which were analyzed as replicates. Before being processed in the laboratory, all the sachets were carefully assessed to ensure that they were well preserved, free of any stains that might indicate a change in quality, and fully sealed, guaranteeing no external contamination by MPs. It is important to note that the samples were collected in restaurants, cafeterias, and commercial establishments. Consequently, information on the origin and production of table sugar was not taken into account in this study, with emphasis only on the country where it was being consumed.

All sachets were photographed for identification, and each brand received an ID (S1, S2, S3… S100) so the samples were anonymized for ethical reasons. We will refer to each brand as one sample with three replicates (Table S1, Supplementary Material). After identification, we sampled 3 g of sugar from each sachet using a glass petri dish and an analytical scale, this procedure was made three times for each sample, creating replicates (for samples that had exactly 3 g of sugar, the whole sachet was considered a replicate, for those with more than 3 g, sugar content was homogenized and subsampled to match 3 g). The 3 g of sugar was transferred to a glass beaker, and 50 mL of filtered deionized water was added to dissolve the sugar. Beakers were agitated for 2 to 5 min with a glass cane until the formation of a homogenous solution. The beaker was left to rest for 30 min covered with aluminum foil to prevent atmospheric contamination. The final solution was filtered with a qualitative filter paper 80 g with the aid of a glass funnel. The filter paper was then transferred to a petri dish, maintained at 60 °C until completely dry to avoid the growth of fungi (which can compromise the samples), and then stored for further analysis.

2.2. Microplastic Counting and Measuring

Petri dishes were analyzed using a stereoscope Leica™ S8AP0 with an attached camera MC170HD. The filter paper was humidified with drops of filtered deionized water before counting because microplastic particles are too light and can fly away if dried. Sorting and quantification of plastic particles were done on a Leica™ S8AP0 stereomicroscope with an attached MC170 HD camera. Types (filaments and fragments) and colors (Blue, red, green, black, transparent, purple, multicolor). The chemical composition of the polymers was determined using the Raman spectroscopy technique. We used microplastic definition as particles between 1 µm and 5 mm [78,79], any particles bigger than that were considered mesoplastic and so discarded from the analysis. Random microplastic particles were measured (~12% of the total particles) using the Leica Application LAS v4.9, where the length of filaments and perimeter of fragments were measured.

2.3. Raman Spectroscopy

At least 34 samples of microplastics of each color were selected from the samples with the highest and lowest amounts of microplastics (S2, from Spain; S5, from Brazil; S18, from UAE; S19 and S26, from USA). The surfaces of the microplastics were also characterized by microspectroscopy Raman, using a WITec Raman-AFM Microscope combination alpha300 (Oxford Instruments-WITec, Ulm, Germany). Raman's Data acquisition was performed using the integrated Control FIVE 5.2 software and based on the Project FIVE 5.2 software package (WITec software—Germany, v. 5.2.). The acquisition of Raman spectra was conducted with a 532 nm laser, a 20× visible microscope objective (Zeiss EC Epiplan 20×/0.4), a 200 µm confocal hole, and a G1:600 grooves/mm BLZ = 500 nm grating with a spectral resolution of 1 cm^{-1}. The acquisition time was 0.5 s with 30 accumulations in the air under ambient conditions (T = 293 K).

2.4. Statistical Analysis

We used the software GraphPad Prism 9.3.0 to perform all statistical analyses. Values were significant when $p < 0.05$. Normality and homoscedasticity were tested using the Shapiro-Wilk and Levene tests, respectively. Data were transformed if abnormal, and in case of persistent abnormality, respective non-parametric tests were applied.

We used data on sugar consumption per country in 2022 from the Food and Agriculture Organization of the United Nations (FAO), an organization of the World Health Organization (WHO), to estimate microplastic ingestion for each country based on the findings of this study. To calculate the Estimated Dietary Intake (*EDI*) of microplastics, we used the following formula:

$$EDI = \frac{(SgC \times MPp)}{SM}$$

The formula comprises the variables Sugar Consumption (*SgC*/whether *Per Capita* or *Total* consumption), Microplastic Particles (*MPp*) found in this study, and Sample Mass (SM/in this study, is a fixed variable, i.e., 3 g). The final value of EDI is presented in MP g^{-1} $year^{-1}$. We underscore that this extrapolation does not accurately reflect the actual microplastic ingestion and do not recommend using it as an exact measurement for comparisons, only as an approximation that highlights the significant quantity of plastic consumed.

To compare the types of microplastic, filaments and fragments, we used the T-test. We used Krustal-Wallis to test the difference between the quantity of microplastic regarding the color among both filaments and fragments, between the countries, and between regions. We performed ANOVA to compare the differences between the samples individually and between the microplastics combined data with sugar consumption from the WHO. For both tests, the multiple comparisons test were performed afterwards to verify specific differences.

2.5. Quality Control Measures

The quality of the sachets and their selection for the study is described in the methodology. During all procedures, the researchers wore cotton lab coats and gloves. The benches were sanitized with paper and 70% alcohol. All vials were washed with filtered deionized water. During the weighing of the samples, the scales were cleaned between samples. The beakers containing the sugar solution remained covered with aluminum foil. During the stereomicroscope analysis, Petri dishes covered with damp filter paper were kept close to the equipment in order to capture possible MPs in the laboratory atmosphere. These plates were also analyzed under the stereomicroscope. All liquids used in processing were filtered using a 10 µm metal mesh and were analyzed for MP presence. There were no MPs particles in the liquids utilized.

3. Results

In total, 3977 microplastic particles were found among the 100 table sugar samples (300 replicates), distributed between 2252 filaments (56.63%) and 1725 fragments (43.37%) (Figure 1). The T-test showed significant difference between the two types of MPs (Figure 2). All samples had microplastic present, and the quantity ranged from 4 particles to 312. A table with all the MP content can be found in Supplementary Material (Table S1).

Blue was the predominant color for both filaments and fragments, followed by black. The other colors appeared in a notably smaller filament frequency and a less pronounced difference for fragments (Figure 3). The Kruskal-Wallis test showed a significant difference between colors for both types ($p < 0.05$).

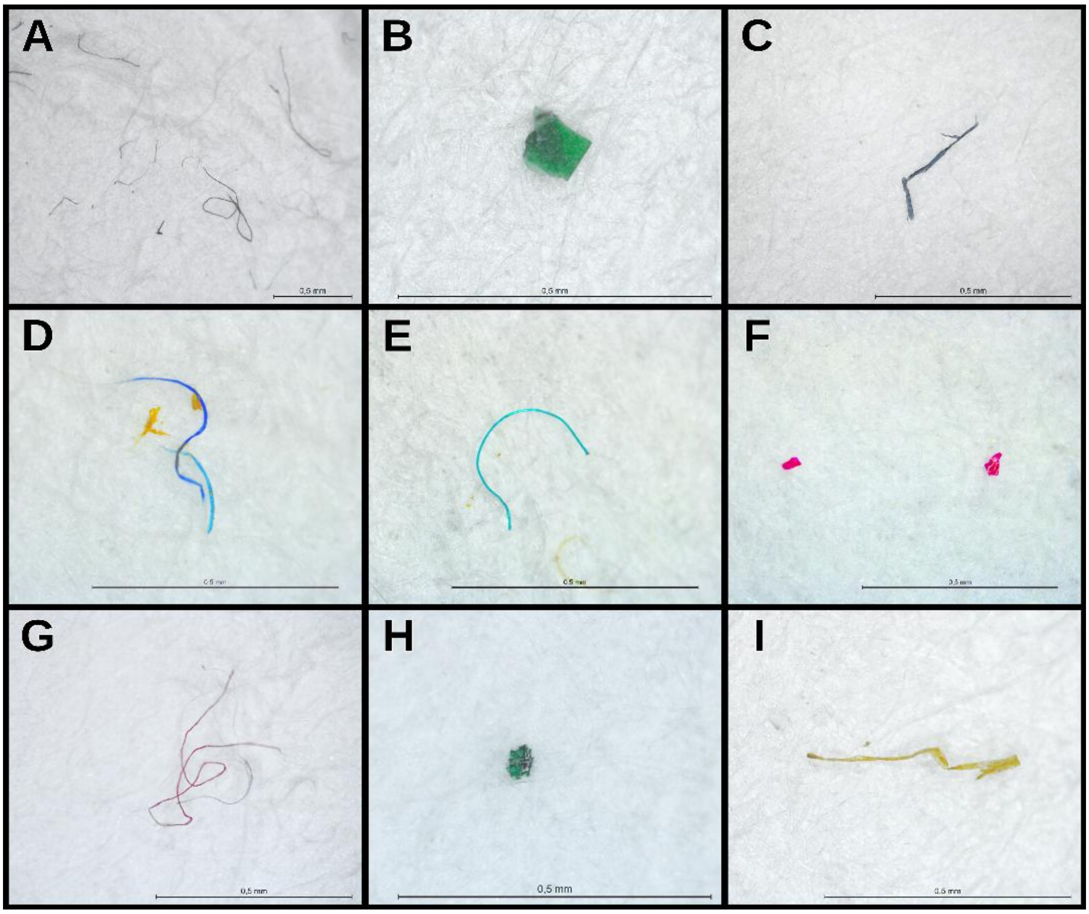

Figure 1. Images of microplastic particles found in this study. (**A**) Various filaments. (**B**) A green fragment. (**C**) A Blue filament. (**D**) A blue filament with at least two tons of blue. (**E**) A green filament. (**F**) Two red fragments. (**G**) A red filament. (**H**) A multicolor fragment. (**I**) A yellow filament.

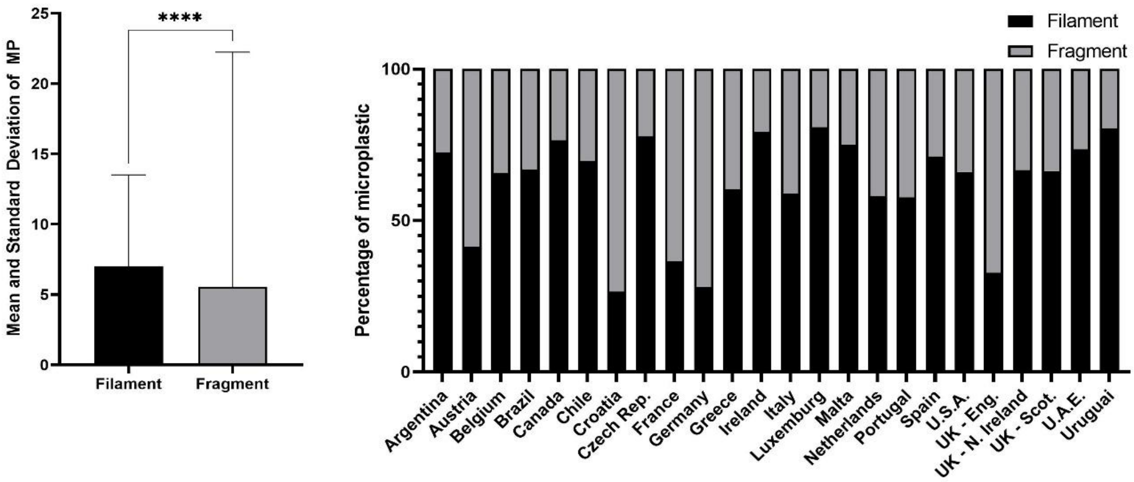

Figure 2. Mean and Standard Deviation of microplastic sorted by type (filament and fragment) and country. The significance of the T-test is showed as (****).

Regarding the individual samples, the highest values for microplastic presence were found in sample 87 from England, followed by sample 11 from Brazil, and sample 33 from Germany. The ANOVA test showed a significant difference between samples ($p < 0.05$) and the multiple comparisons test pointed for the differences to be, mostly, between sample 87 and the other samples (Figure 4).

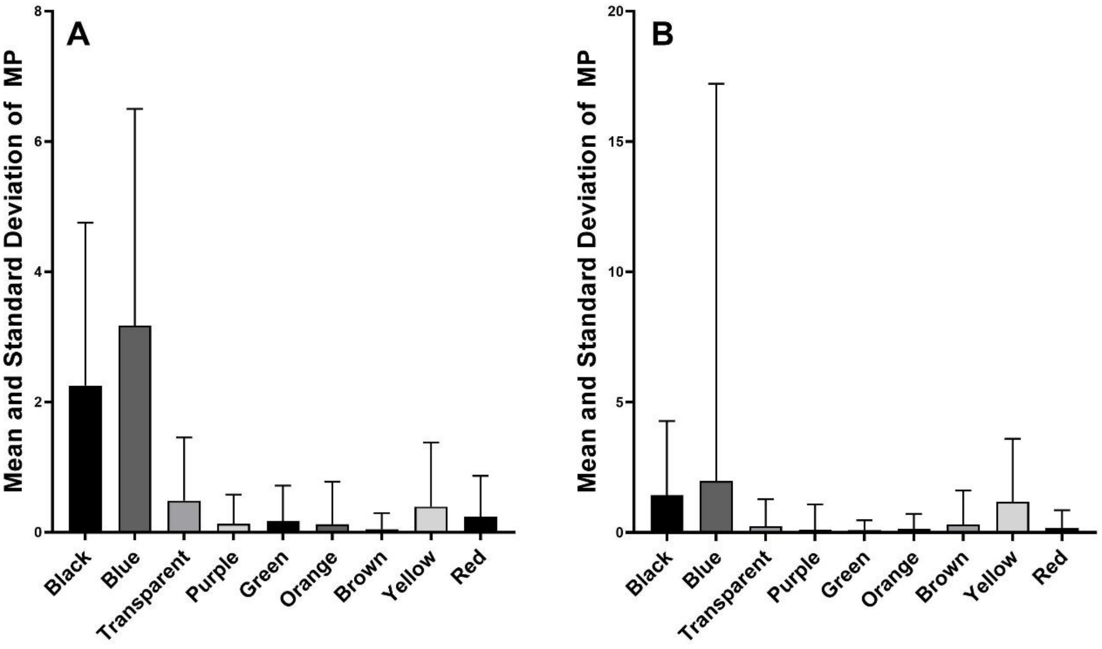

Figure 3. Mean and Standard Deviation of Microplastic. (**A**) Filaments sorted by color. (**B**) Fragments sorted by color.

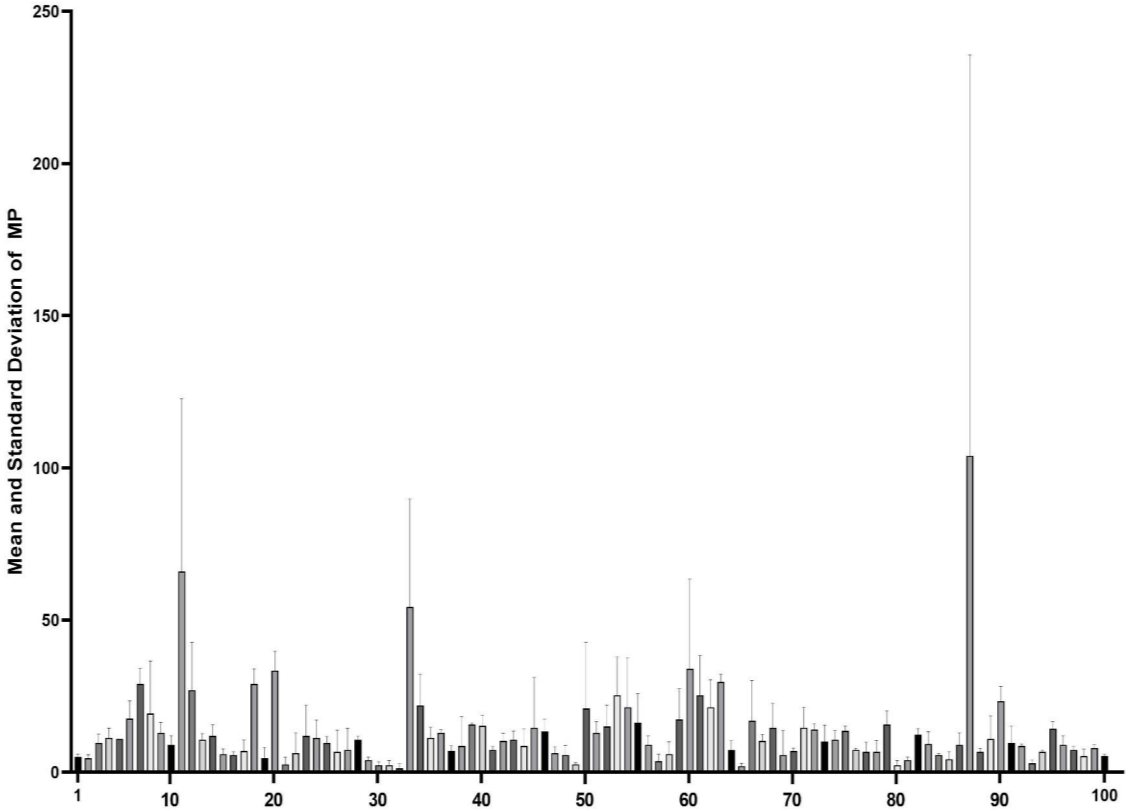

Figure 4. Mean and standard Deviation of microplastic in each sample (1 to 100). Different bar colors are used just to differentiate the sampling sites.

The map in Figure 5A shows the MP/g relation in each country, where Brazil presents the highest value with a pronounced margin. When comparing the amount of microplastic found in samples according to the respective country of origin (Figure 5B), countries that presented the highest numbers for total of microplastic were Spain (691), England (573), Brazil (543), and Croatia (264). On the other hand, countries with the smallest quantity of microplastic were Argentina (29), Luxemburg (26), Austria (29), and Malta (44). The highest mean of microplastic presence was found in Brazil, Northern Ireland, and England. The Kruskal-Wallis test showed significant difference in MPs presence between countries ($p < 0.05$). However, the multiple comparisons test was unable to point out these differences specifically. When sorting these samples according to regions (South America, North America, West Europe, and East Europe), the Kruskal-Wallis test showed no significant difference (Figure 5C).

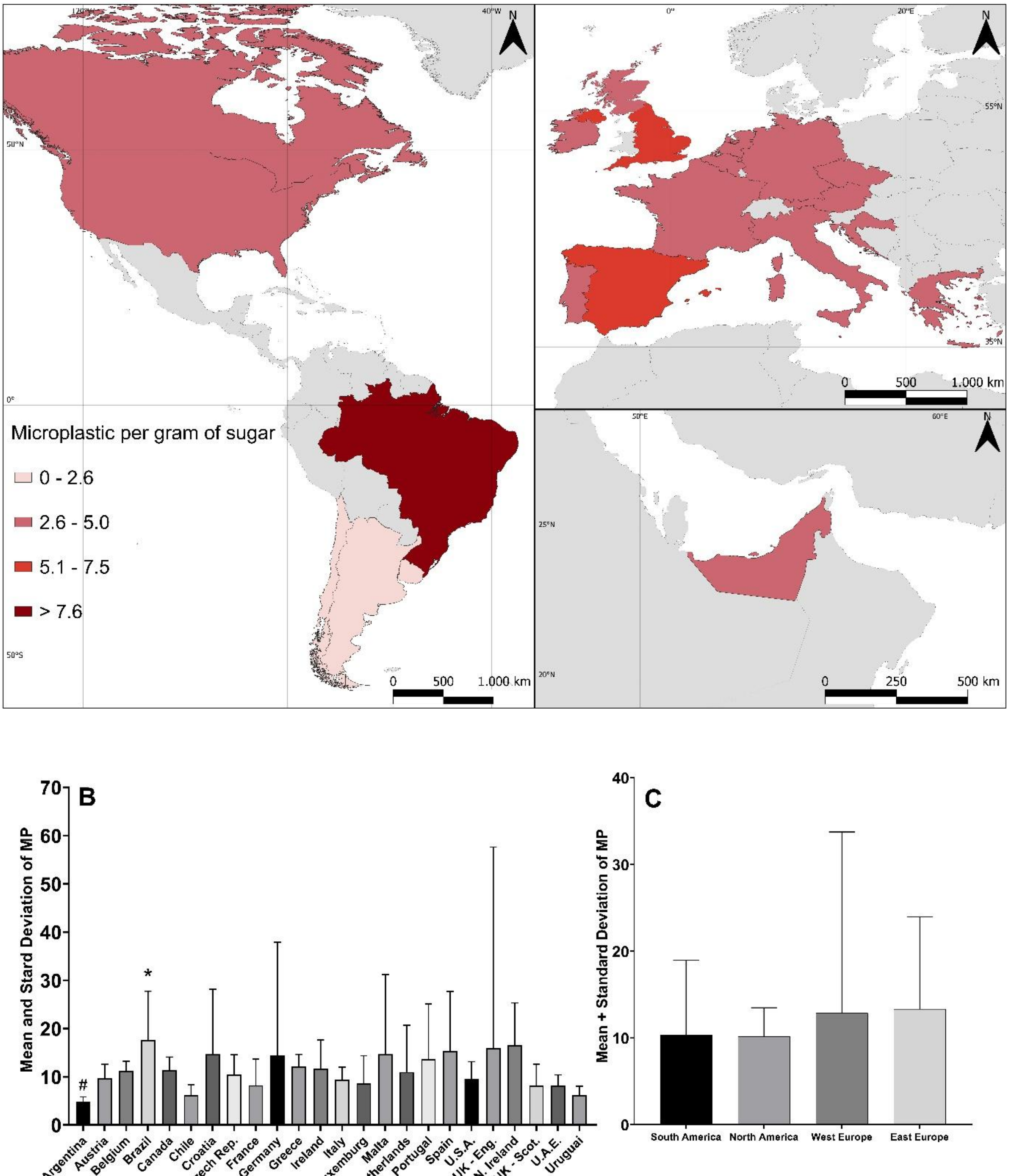

Figure 5. Microplastic data found in this study. (**A**) Map of the countries with analyzed samples of table sugar showing the gradient of microplastic (MP) particles per gram of sugar. (**B**) Mean and standard deviation of MP sorted by country. (**C**) Mean and standard deviation of MP sorted by region.

Combining our results with data from the World Health Organization for Sugar Consumption in each country for the year 2022, extrapolating roughly, the Estimated Dietary Intake (EDI) per capita in countries can be seen in Figure 6A. Luxemburg, Malta, Ireland, Croatia, and Brazil exhibited the highest values of MP/*Per Capita*.

However, the total EDI in each country as a whole (Figure 6B) shows a difference scenario where the U.S.A. (7.2×10^{13} particles) and Brazil (6.9×10^{13} particles) lead the list by a pronounced margin, followed by Germany (2×10^{13} particles) and the United Kingdom (1.4×10^{13} particles).

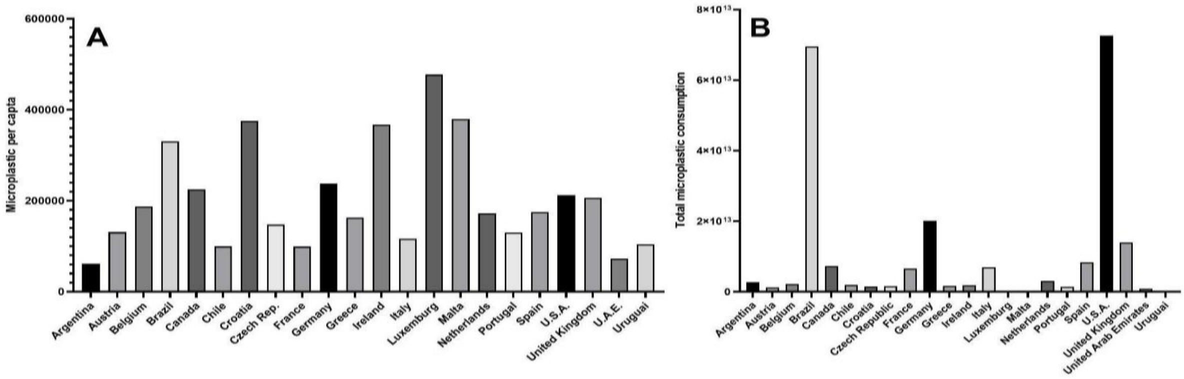

Figure 6. Mean and standard deviation of microplastic and total plastic consumption extrapolation. (**A**) Potential consumption of microplastic particles per capita by country. (**B**) Potential microplastic particle consumption in total by country.

Regarding the size of microplastic found in this study, the length of filaments varied from 0.33 mm to 1.9 mm with a mean of ~0.24 mm. For fragments, the perimeter ranged from 0.105 to 0.25 mm with a mean of ~0.17 mm (Figure 7).

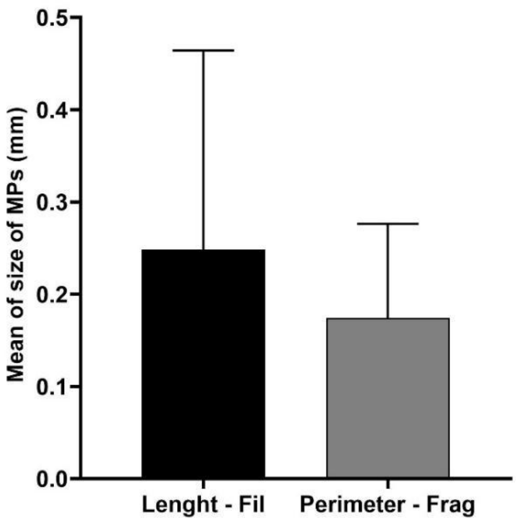

Figure 7. Mean and standard deviation of microplastic size in millimeters. Length of filaments and perimeter of fragments.

When looking into the chemical composition of the microplastics, the Raman spectroscopy analysis showed three different types of polymers. From the 34 analyzed microplastics, 23 spectrums were clear and precise for chemical characterization. Of these 23, 11 were black, 10 were blue, one was red, and one was green. Fourteen (14) of the samples were polyurethane, six were Polyethylene Terephthalate (PET), and three were Polyethylene (PE) (Figure 8).

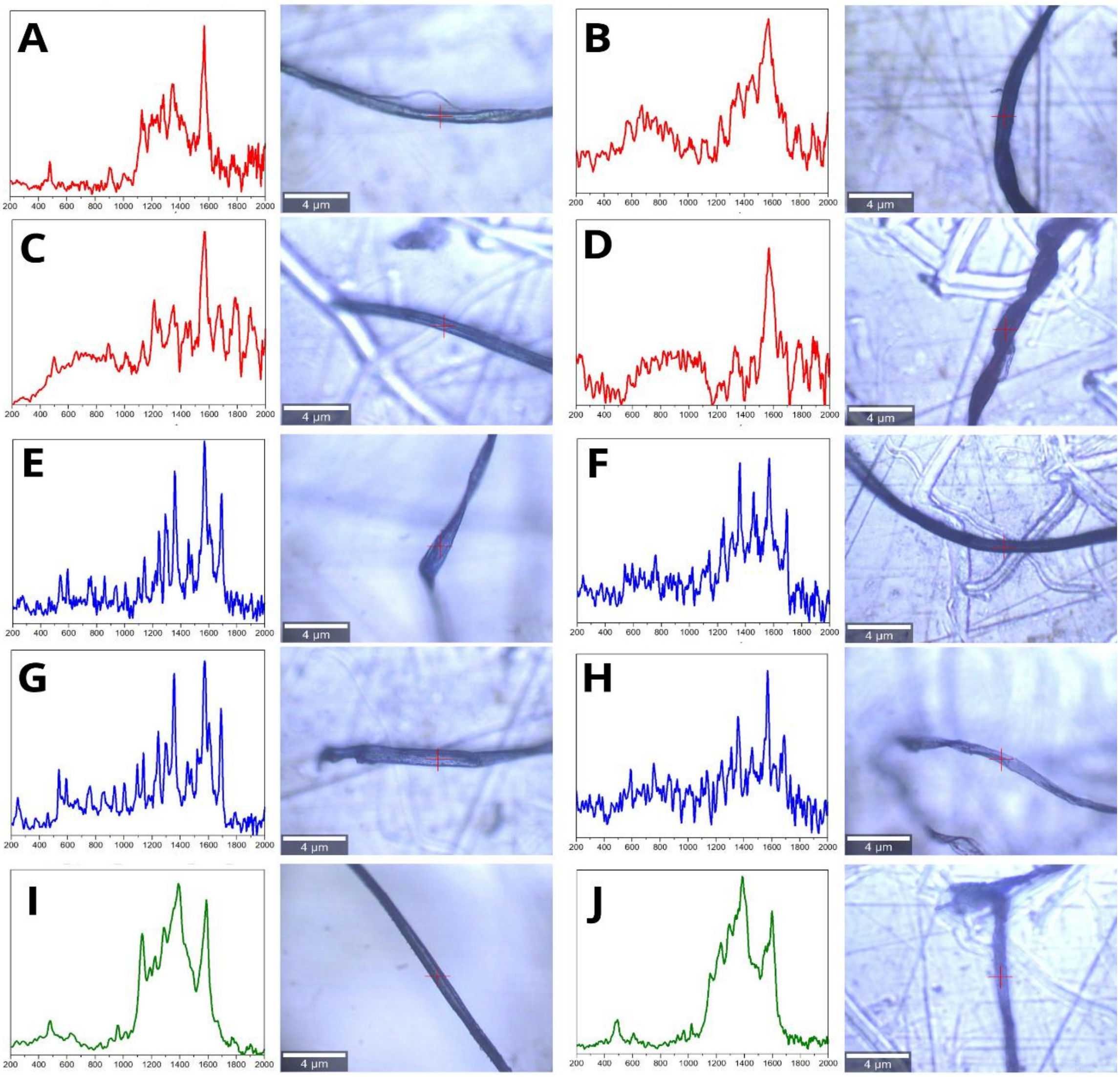

Figure 8. Raman spectrum of microplastics. (**A**–**D**) Polyurethane/PU. (**E**–**H**) Polyethylene Terephthalate/PET. (**I**,**J**) Polyethylene/PE. The X-axis represents the Raman shift ranging from 200 to 2000 cm^{-1}.

4. Discussion

The present study can be considered the most extensive research on microplastics in processed sugar, covering 100 samples in triplicates obtained from 24 countries and pointing to worrying results, since all the samples analyzed showed microplastics, i.e., a 100% contamination rate in all countries.

This result is very worrying, given that sugar is the most consumed food, both in its basic form and added to various foods [43]. The contamination of sugar by microplastics is confirmed as a major threat to the human food chain, due to the adverse effects of microplastics on human health that are already known [80].

Literature data indicates few studies on the presence of MPs in sugar, but our results corroborate the findings of [5]. The number of filaments was higher than the number of fragments, however, the difference was not pronounced, as is common in other studies on microplastic contamination, especially for assessments of environmental matrices [17,18,47]. However, [63] showed a different database regarding the types of microplastics, where they found 75% fragments, 21% film, and 4% fibers.

It is possible that microplastic particles are being introduced between the sugar crystals during stages sugar processing, such as, purification, refinement, drying, and packaging, from industrial equipment and from other additional sources such as plastic debris, gloves and clothing worn by workers. Some authors [5,73] have already pointed out the complex protocols for processing sugar cane into sugar crystals and the various possibilities for MPs to enter during these processes, such as MPs particles present in the industrial environment and produced by machinery. Another possibility pointed out by the same authors and considered to be the most critical is the drying process, in which large dryers are used to eliminate moisture in the sugar and, without proper air filtration, may be adding MPs to the sugar.

Consumption of sugar can intensify the problem associated with microplastic pollution. Some studies show that microplastics can pose several health risks, ranging from inflammation, oxidative stress, tissue damage [81,82], adverse effects on male fertility and sperm quality [83], and reproductive problems [10,84]. It can lead to various other health problems, including heart disease [85], cancer [86], and autoimmune disorders [87].

In our study, the highest values of MP/g were found in Brazil, followed by Northern Ireland, England and Spain, demonstrating that the quality of sugar consumed in different countries may not vary, regardless of the economic level or even regulatory policies related to food safety in different countries. Our results suggest that the awareness of microplastic contamination in food, like sugar, is still poorly implemented in public management and is not a priority of monitoring programs that should draw a threshold of the maximum MPs presence in edible products. However, the delimitation of this threshold is still not reachable due to the knowledge gap about the extension of microplastic impacts on human health.

Regarding microplastic colors, we found a predominance of blue particles, followed by black. However, other studies of MPs in commercial sugar, like [63] that showed black as the predominant color (29.2%) followed by shades of blue-grey (25%) [67]. observed a predominance of the color white. In environmental studies, this predominance of black and blue appears constantly, discussing the popularity of these colors for use in industry machinery and clothes, a hypothesis we believe to be the case for sugar contamination by MPs.

A study by [60] investigated the presence of microplastic in beverages from Mexican supermarkets. They found a predominance of blue fibers and filaments in cold tea, soft drinks, energy drinks, and beer [88] investigated several beverages, including water, energy drinks, mineral water, and cold tea in Turkey and found similar results: predominance of blue filaments and fibers. These results are aligned with the data found in our investigations.

Most MPs particles in this study were bright-colored in opposition to the opaque ones found in environmental studies. In the environment, plastic structures are susceptible to weathering, where variation in the pigmentation tone can be an indicator of older particles. This suggests that plastic input on sugar packed in sachets comes from the processing, where the machinery is potentially generating microplastics while processing the sugar. The MPs' input could also come from the storage of sugar before being packed. Despite this research having no data to prove these inferences, this is another alert for MPs, and plastics in general, regulations that encourage companies to review their protocols and include steps for microplastic filtering or monitoring.

Polymer types found in this study via Raman spectroscopy were PU, PET, and PE, where PU was predominant. Polyurethane is a versatile polymer and is often used in insulation, furniture, adhesives, and coatings, especially applied to industrial use, which could be the reason it was the predominant form of polymer. In addition, PET and PE are also used in industrial applications such as containers, construction materials, and piping (MIT Course on *Introduction to Solid State Chemistry*). These applications of each polymer can be related to the presence of MPs in table sugar for both the machinery during the processing of sugar and the packaging. The Raman Spectroscopy technique is widely used in microplastic studies to precisely assess the chemical composition of plastic samples and is one of the most accurate methods to chemically characterize MPs samples [30,59,89–93]. In addition, Raman Spectroscopy has been used in several of our studies regarding MPs contamination [17,18,47,94].

Despite the small number of samples analyzed (34 samples), we believe that these data are relevant and contribute to the identification of possible routes of contamination of samples by MPs. Certainly, a new study, including a larger number of samples and even other analytical techniques, could contribute to a better understanding of the possible routes of contamination of sugar by MPs.

On the other hand, other authors [72] identified a wide variety of polymers, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyester (PES), polyamide (PA), polystyrene (PS), acrylic derivatives, polydimethylsiloxane, as well as additives, pigments, and dyes. It is worth noting that [72] analyzed commercial sugar, those sold by supermarkets in larger amounts, and we investigated the presence of MP in table sugar, which goes through a slightly different protocol of processing. This could explain why they found so many polymers that were different from the ones found in this study [67] found only two types of polymer, PE and PP. According to these authors, PE is used mainly as a raw material in plastic bags and the fabrication of numerous products.

However, the plastic problem goes further than the polymer type. The polymeric chain represents just a piece of the complex structure that modern plastics have, most of their composition includes chemical additives such as catalysts that give plastics their shape, color, and enhanced resistance and performance. In addition, the polymeric chain alone is supposed to be chemically inert and have no physiological interactions. A report from [95] showed that from more than 16.000 known chemicals, less than 6% are globally regulated. The report also underscores that 66% of chemicals have no hazard data. These chemicals are persistent, bioaccumulative, and highly mobile, especially throughout the water column of aquatics environments. Among the numerous risks to human health, additive chemicals can disrupt the endocrine and reproductive systems and have the potential to induce carcinogenic or mutagenic reactions. Despite microplastics being small, the amount of these pollutants ingested by humans every year combined with the increased surface of contact provided by plastic fragmentation, concerning concentrations of these chemicals being released inside the human body are potentially already happening. This reinforces the need for regulations that force companies to specify the additives included in the formulation of plastic products and packages they sell since there is no information about these chemicals disclosed on the packages today.

In this scenario, cooking ingredients with added sugar contaminated with microplastics could magnify the problems cited above. The heat of the cooking process can promote migration (transference of substances from packaging to food) of chemical compounds (present in the plastic composition or adsorbed by them in the processing of sugar) a process already shown to happen for bigger plastic materials [95]. Migration could also be happening by exposure of the sachet bags to heat, as they tend to stay on the establishments' tables for long periods.

According to our estimations based on the WHO database for sugar consumption, the Estimated Dietary Intake (EDI) *per capita* potentially reached between 60.000 particles and 477.000 in one year (2022). In contraposition, [30] showed that a person ingests around 39–52 thousand MPs/year. Our data for the lowest value of EDI *per capita* was higher than the highest estimation of [30]. It is worth noting that our data is based purely on values of sugar consumption. This disparity suggests that the knowledge gap about microplastic intake by humans is bigger than speculated since MPs has been proven to be present in other food types.

The total EDI by each country shows another perspective on microplastic intake. Brazil and the United States were the most affected by a prominent margin from Germany, the third highest, and the other countries. This data underscores the need for food policies that increase awareness of high sugar consumption, not only due to microplastic intake but also because sugar is harmful. High-sugar diets have been shown to pose a risk for cardiovascular disease [96–99], diabetes [100–102], and obesity [103,104]. Microplastic presence in table sugar adds another risk to human health, as well as consuming other processed sugar and sugar-sweetened beverages like soft drinks, cereals, cookies, cakes, bread, soups, and multiple processed food items.

When looking at the mean of MPs sorted by each country, despite presenting no statistical difference, the highest values were found in samples from Brazil and the smallest from Argentina. We hypothesized that countries would present a numeric and visual difference more pronounced than the actual data, whereas countries with different levels of development presented similar values for MPs contamination in table sugar. As discussed above, this underscores the need to increase public awareness about MP contamination in food and beverages. The difference in the mean of microplastic between regions also had no pronounced difference. However, East and West Europe had the highest values.

Microplastics are usually categorized as particles between 1 µm to 5 mm. The sizes of particles registered in this study ranged from 0.33 to 1.9 mm for filaments and from 0.105 to 0.25 mm for fragments. Recent studies have shown that microplastics are small enough to enter the blood system by crossing biological barriers such as lung cells [39] and the intestine, potentially moving to other organs [102]. Although the size range found in this study did not fall into the size scale shown to potentially cross the cellular barrier of the human digestive tract, the prolonged presence of microplastic particles in the intestine fosters the interaction of these synthetic particles with the gastrointestinal microbiome. This interaction can reduce the size scale of these particles making them small enough to disrupt the cellular barrier while also changing the composition of the microbiota [105,106].

Given the discussion above, monitoring steps should be added to the protocols of sugar processing. Among the possible measures to mitigate MPs contamination, the industrial environment where sugar is processed should have air filters capable of withdrawing microplastics from the atmosphere, which would also guarantee the employees' safety. The machinery should be routinely assessed for MPs presence and production since most parts are made of plastic and the friction of machine motion could generate MPs. Ideally, the final product of processed sugar should always be assessed for MP's presence before packaging and distribution, ensuring no microplastic contamination in the marketed packages of sugar.

5. Conclusions

Microplastics are present in all samples of table sugar analyzed from the 24 countries. This underscores the ubiquity of microplastics. The difference in the number of microplastics between countries was not pronounced, although the presence of MPs in sugar combined with high rates of sugar consumption is an urgent matter to be addressed by both developed and developing countries.

The presence of microplastics in table sugar represents another threat to human health, as it may serve as another pathway for MP ingestion. This opens another question for future studies since we analyzed only a small percentage of processed sugar products: are all processed sugar-sweetened foods contaminated with microplastic? Where and when is this contamination coming from?

The production of plastics necessitates urgent regulation, particularly concerning the use of chemical additives. The adverse effects of plastic, along with its associated risks to both human and environmental health, are increasingly evident. It is imperative that we prioritize efforts to address these challenges before they become irreparable.

These results serve as an important milestone for the study of food contamination by MPs and subsidize future studies addressing the gaps in the presence of MPs in other foods, directing the necessary care in the production process up to the marketing of food. It is hoped that these results contribute to the different segments of food production and quality control, reducing environmental problems and the transfer of microplastics via the diet, and increasing public awareness about food contamination with MPs.

6. Authors' Suggestions for a Sustainable Management of Microplastics in Sugar Production

To address the widespread contamination of sugar by microplastics effectively, it is essential to adopt sustainable management strategies across the entire sugar production chain. This includes implementing preventive measures such as improved air filtration systems in processing facilities, regular maintenance and replacement of plastic components in industrial machinery, and the use of alternative materials less prone to microplastic generation. Additionally, establishing standardized protocols for monitoring and reporting MPs contamination in sugar products can support transparency and consumer safety. Encouraging the sugar industry to adopt eco-friendly practices—such as biodegradable packaging, closed-loop production systems, and employee training programs focused on microplastic risk mitigation—can further reduce contamination. These actions, aligned with national and international food safety guidelines, would contribute to a more sustainable and health-conscious sugar industry, while also addressing growing environmental and public health concerns related to plastic pollution.

Supplementary Materials

The additional data and information can be downloaded at https://media.sciltp.com/articles/others/2508131500242669/SupplementaryMaterial.xlsx.

Author Contributions

J.M.S.: Writing—review & editing, Writing—original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. G.Z.D.: Visualization, Validation, Methodology, Investigation, Formal analysis. S.P.P.B.: Visualization, Validation, Methodology, Investigation, Formal analysis. B.L.F.: Visualization, Validation, Methodology, Investigation, Formal analysis. K.M.M.: Visualization, Validation, Methodology, Investigation, Formal analysis. M.M.A.: Visualization, Validation, Methodology, Investigation, Formal analysis. E.A.: Visualization, Validation, Methodology, Investigation, Formal analysis. R.S.: Visualization, Validation, Methodology, Investigation, Formal analysis. A.A.L.M.: Visualization, Validation, Methodology, Investigation, Spectroscopy Raman analysis. E.R.Y.O.: Visualization, Validation, Methodology, Investigation, Spectroscopy Raman analysis. M.B.d.C.: Writing—review & editing, Writing original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflict of interest.

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