



Microplastic Pollution and Risk Assessment in Packaged Teas in Türkiye

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Abstract This article presents the first-ever findings on the release of MPs (microplastics) from tea bags containing tea leaves into tea infusions in Türkiye. The study aimed to investigate the possible distribution and abundance of MPs in cup of tea bags and teapot tea bags of fifteen packaged tea brands in Türkiye using ATF/FTIR analysis. The results showed that MPs were found in all the analyzed tea brands. Surprisingly, the highest particle number was observed in the dry tea samples (removed from tea bags) belonging to all brands. Brands A and O had the highest abundance of MPs. All MP particles identified were fiber in shape, and four colors were identified, with a predominance of navy blue. Polyethylene terephthalate (PET) was the most abundant polymer type. The size of MPs varied from 33.65 µm to 1680.20 µm. The daily MP exposure by tea intake was analyzed for male and female groups, and the dietary exposure for males was greater than that for females. According to the

MP contamination factor values, a wide variety of MP contamination levels were determined, with a predominance of significant and very high levels of contamination. The mean polymer risk index was determined to be 10.80, indicating a low level of risk. Additionally, this study also provides information on the potential health effects of these harmful MPs. Considering that consuming tea is a significant way for individuals to come into contact with MPs, tea prepared with tea leaves packaged in tea bags could potentially have adverse effects on the health of consumers.

Keywords Contamination · Microplastic · Risk Assessment · Tea

1 Introduction

Plastic has been recognized as a key material with many applications since the early 20th century, leading to a rising demand and a substantial rise in production (Akanyange et al., 2022). Plastics are extensively utilized in the industrialized world because of their affordability, resistance to corrosion, convenience, stable physio-chemical properties, and insulating capabilities (Wang et al., 2023). The global production of plastic has increased over the last ten years, going from 280 million tons in 2011 to 367 million tons in 2020. Out of this volume, 40.5% is mostly used for plastic packaging (Plastics Europe, 2012; 2021). The projected plastic output for the year 2050

Highlights

1. The characterization of microplastics in tea was investigated for the first time in Türkiye.
2. Microplastics were detected in every brand.
3. All microplastic particles identified were fiber in shape.
4. PET was identified in a higher percentage.
5. Four colors were identified, with a predominance of navy blue.

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is estimated to reach 33 billion tons, as forecasted by Rochman et al. (2013). The plastic manufacturing sector, namely package production, is continuously growing, leading to an increase in the amount of plastic waste generated (Nagy & Kuti, 2016). Plastic-based food and beverage packaging materials are widely used in the food industry due to their ability to control temperature and atmosphere, lightweight nature, and ease of production and processing (Bott et al., 2014; Jadhav et al., 2021). Plastics, which have widespread applications, have a substantial detrimental impact on the environment (Gül et al., 2022; Talbot & Chang, 2022).

MPs are present in various habitats, including the atmosphere, as well as in the food and beverages we consume (Kadac-Czapska et al., 2022). Multiple studies have demonstrated the presence of plastics in various everyday food and drink items, such as bottled water (Akhbarizadeh, Dobaradaran, Schmidt, et al., 2020; Ibeto et al., 2021; Zhou et al., 2021), milk (Basaran et al., 2023; Kutralam-Muniasamy et al., 2020), tea (Afrin, Rahman, Akbor, et al., 2022; Kashfi et al., 2023; Shruti et al., 2020), table salt (Gündoğdu, 2018; Özçifçi et al., 2023), sugar (Afrin, Rahman, Hossain, et al., 2022; Liebezeit & Liebezeit, 2013), soft drinks (Shruti et al., 2020), fish (Karami et al., 2018), canned fish (Akhbarizadeh, Dobaradaran, Nabipour, et al., 2020), and fruits and vegetables (López et al., 2022; Oliveri Conti et al., 2020). Consequently, foods and beverages play a significant role in causing MP contamination in organisms (Zhang et al., 2020).

MP contamination arises when plastic particles are able to infiltrate food products during the manufacturing or packaging processes (Kedzierski et al., 2020). Plastic food packaging and containers are produced to store a wide range of meals and beverages (Geueke et al., 2018). Food-grade plastics have the potential to breakdown or release toxic compounds when exposed to temperatures above 40 °C (Bach et al., 2013). Within this particular framework, Hernandez et al. (2019) validate that a single tea bag disintegrates when exposed to the temperature used for brewing (95 °C) and releases around 11.6 billion MP particles into a single cup of tea. Individuals mostly consume MPs by ingesting them via food and drinks (Sewwandi et al., 2023). There is a growing concern about the level of interaction between MPs and people (Akhbarizadeh, Dobaradaran, Schmidt, et al.,

2020; Xu et al., 2021). A study conducted by Afrin, Rahman, Akbor, et al. (2022) revealed that a majority of tea drinkers, specifically ninety-six percent, have a preference for tea bags over loose leaf tea. It is crucial to identify the methods by which individuals come into contact with plastic residues in the environment in order to evaluate the health risks associated with MPs (Fadare et al., 2020). There has been a lack of extensive research on the exposure to MP through the intake of tea. Tea intake has been identified by Afrin, Rahman, Akbor, et al. (2022) and Kashfi et al. (2023) as a significant pathway for human exposure to MPs. The health concerns associated with packaged teas are a matter of great concern. Considering that teas are commonly consumed as commercial beverages without removing the tea bags in many countries, it is crucial to assess the risk and evaluate the extent to which tea bags contribute to MP pollution in Türkiye.

Utilizing index models to assess the pollution load and associated dangers of MP is crucial, as it aids in streamlining decision-making processes. Utilizing MP contamination factors (MPCF) offers a systematic method for monitoring and evaluating contamination levels across various samples (Enyoh et al., 2021). The Pollution Load Index (PLI) is a standardized method of monitoring and assessing pollution levels across various media, as described by Kabir et al. (2021). In order to enhance our understanding of MP pollution and its specific areas of concern, as well as our methods for pollution control and management, it is crucial to establish a pollution load index alongside polymeric and pollution risk assessments (Kabir et al., 2021). The MP pollution load index (MPLI) is a measure of the abundance of MPs in the teas being researched. It is used to evaluate the extent of pollution in the teas. The MPCF quantifies the degree of MP pollution in the analyzed teas relative to the existing background levels. The concentration or buildup of MPs in various teas was assessed using the MPCF. It is crucial to recognize that MPs might accumulate in teas differently based on the amounts of human activity involved, such as the packing process, transportation to markets, and storage conditions.

Due to its high consumption rate, tea has the potential to introduce a greater number of MPs into the human body. However, there has been limited research examining MPs in tea. These studies have focused on either empty tea bags (Hernandez et al., 2019; Kim et al., 2022; Mei et al., 2022; Xu

et al., 2021) or brewed bagged teas with tea leaves (Afrin, Rahman, Akbor, et al., 2022; Kashfi et al., 2023; Li et al., 2022). Afrin, Rahman, Akbor, et al. (2022) and Kashfi et al. (2023) examined the potential health risks associated with MPs; however, they did not assess the MP polymer risk index or pollution load index. Our country has only undertaken a single study on the composition of tea bags (Yurtsever, 2021). However, no prior research has examined the potential impact of Turkish-brewed bagged teas (including tea leaves) on MP contamination. Moreover, the quantity and quality of MPs in tea leaves (dry teas removed from tea bags) have not been determined. The quality and quantity of MPs in brewed bagged teas (with tea leaves) and their possible health risk assessment have not yet been evaluated in Türkiye. Therefore, aiming to fill the knowledge gap on the possible release of MPs through teabags sold in Türkiye which ranks fifth in the world in tea production and consumption, we simultaneously investigated the possible presence of MPs in tea bags, tea bags with tea leaves, and tea leaves for the first time. Hence, the main aims of this study were 1) to identify the number, size, shape, color, and type of MPs in the popular fifteen tea brands in Türkiye, 2) to determine MP exposure from tea consumption by estimating daily intake, 3) to detect MP polymer risk indices and the MP pollution load of tea, 4) to compare the abundance of MPs between both brands and tea types.

2 Materials and Methods

2.1 Sample Collection

This study was conducted to determine the presence of MPs in 15 samples of black tea packaged in individual plastic tea bags from various brands offered in the Turkish market. The research focused on 15 renowned tea brands that are available in various chain markets, local markets, grocery stores, and internet shopping portals in Türkiye. In April 2023, a total of 30 tea samples were bought from various grocery stores. Among these, 15 samples were cups of tea bags, and the remaining 15 samples were teapot tea bags. The brand names were concealed, and thus were labeled from A to O.

2.2 Sample Preparation and Extraction of MPs

Four distinct experimental setups were established to detect the presence of MP contamination in both tea bags used in cups and tea bags used in teapots. Initially, the tea bags were emptied in order to assess the release of particles. In accordance with Yurtsever's (2021) instructions, the tea bags were severed using steel scissors to extract the tea leaves. Before immersing, any attached string was likewise removed. The emptied tea bags were placed in a 250 mL glass beaker filled with 100 mL of boiled water (95 °C) and left to be steeped for 15 minutes. The reason why we chose the temperature of the water as 95 °C is that the temperature of the water used by consumers in the preparation of tea is close to the boiling point. After stepping, the water (the leachate) from the glass beaker was filtered through a filter paper (1.2 µm pore size, 47 mm Ø, GVS Filter Technology) by a vacuum filtration system (Isolab Laborgeräte GmbH, Eschau, Germany). Firstly, the filter paper was placed in a sterile petri dish with a cover. Subsequently, it was dried at room temperature and stored in a dark cabinet. In addition, in the event of any contamination, ultra-pure water was also subjected to filtration and stored in amber glass vials. In the second group, the cups of tea bag (i.e., with tea leaves; 2 g weight) were brewed in accordance with the brewing instructions (according to the widely adopted procedure) of the manufacturer. For this, the cup of tea bags was steeped at 95 °C for 3 min in a 250 mL glass beaker filled with 100 mL of boiled water, and the leachate was filtered. Then, the filter paper was kept at room temperature. In the third group, the samples in the second group were prepared by altering the brewing time. The cup of tea was brewed for 15 min. Subsequent stages were executed using the same methodology. Additionally, following the same techniques outlined for the first three groups, three blanks (ultra-pure water) were created and processed next to each batch. These blanks, which were containing only ultra-pure water, were carried out to account for background lab contamination from atmospheric deposition and ultra-pure water. The dry tea samples from the cup of tea bags (without bags) were digested using the wet digestion method in the last group. The wet digestion method for the dry tea sample was applied with some modifications (Li et al., 2022). For this, a 0.5 g dry tea sample was wet digested using 30% H₂O₂

(Merck Darmstadt, Germany). Each dry tea sample was placed in a 250 mL glass beaker with 100 mL of 30% H₂O₂. Glass beakers were hermetically sealed with aluminum foil and subjected to incubation in a water bath for a duration of 12 hours at a temperature of 65 °C using an automated shaker. This process was carried out to eliminate organic substances. Subsequently, the beakers were kept undisturbed at room temperature for a period of two days. Next, the leachate underwent filtration. The resulting filter paper was then placed inside a Petri dish, which was covered, and left at room temperature. Three blanks with no dry tea were run parallel to the samples during the sample preparation and digestion procedure in each batch. The blanks, which had a concentration of only 30% H₂O₂, were subsequently examined for potential contamination. To determine the maximum emission value, it was accepted that a cup of tea bags was used by people until the tea in the cup ran out (average 15 min.), and for the minimum range, a cup of tea bags was used by people in accordance with the procedure (average 3 min.). In addition, the whole experimental set, consisting of all four groups, was also carried out for teapot tea bags. Analyses were performed with three replicates. The beaker and filter device were rinsed with ultrapure water three times for each batch in all experimental sets. As a result, four different experimental groups were set up in the study. These are a) empty tea bag samples, b) intact tea bag samples (i.e., with tea leaves) for 3 minutes, c) intact tea bag samples (i.e., with tea leaves) for 15 minutes, and d) dry tea samples (dry teas removed from tea bags).

2.3 Quality Assurance (QA)

Prior to conducting analyses, all laboratory equipment was thoroughly cleansed using 96% ethanol (Merck Darmstadt, Germany) in order to limit the potential for contamination. Subsequently, all the equipment was thoroughly cleansed using ultra-pure water. The interior of the laminar flow cabinet and lab benches were sterilized using 96% ethanol. The samples were stored in a laminar flow cabinet throughout the whole duration of the experiment. The filters were meticulously transported to individual, airtight Petri dishes using metal tweezers. The experimenters wore lab coats and face masks made of 100% pure cotton throughout the entire trial.

2.4 Characterization of MPs

The filter papers were examined using a stereomicroscope. The particles believed to be MP were examined using a Leica S6D® stereomicroscope, and their photos were captured using a Leica EC3®-mounted camera (Leica Microsystems, Switzerland) that was connected to the microscope. The shape and color of MPs were assessed using a stereomicroscope, while the dimensions (lengths) of MPs were quantified using ImageJ software (<http://imagej.nih.gov/ij/>).

MPs from each filtered sample were further verified through the Attenuated Total Reflectance-Fourier Transform Infrared spectrometer (PerkinElmer Spektrum 100, ATR-FTIR) within the spectral range of 4000-650 cm⁻¹ by 24 repetitive scans at 2.0 cm⁻¹ resolution. In this process, the MP peaks that were saved in the device library were utilized, and the resulting data was then compared with these MP peaks.

2.5 Risk Assessment

2.5.1 Dietary Exposure

Individuals' MP exposure to cup of tea bag or teapot tea bag was calculated using Equation (1), adapted from Basaran et al. (2023).

$$EDI = T_a \times M_a / bw \quad (1)$$

where EDI is the estimated daily intake (MP particles/mL bw/day), T_a is the amount of consumed tea (mL/day) assumed to be 416.2 mL/day for females and 528.1 mL/day for males in Türkiye, M_a is the concentration of MP (MP particles/mL), bw is the body weight (kg) assumed to be 70.7 kg for females and 79.7 kg for males. Data on individuals' tea (black) consumption and body weight was obtained from a report generated in Türkiye (TBSA, Sağlık Bakanlığı Araştırmaları Genel Müdürlüğü, 2019).

2.5.2 MP Contamination Factors and Pollution Load Index

The following formulas (2) and (3) were used to calculate the MP contamination factors (MPCF) and MP pollution load index (MPLI) in tea (black), respectively (Enyoh et al., 2021). In respect to background

levels, the MPCF explains how much MP pollution was present in the tea under investigation. In the study of Basaran et al. (2023), MPCFs were assessed in four groups: low contamination ($MPCF < 1$; risk category I), moderate contamination ($1 \leq MPCF < 3$; risk category II), significant contamination ($3 \leq MPCF < 6$, risk category III), and very high contamination ($MPCF \geq 6$; risk category IV).

$$MPCF = \frac{MP_i}{MP_a} \tag{2}$$

$$MPLI = (MPCF_1 \times MPCF_2 \times MPCF_3 \times \dots \times MPCF_n)^{1/n} \tag{3}$$

The minimum reported average concentration of MPs (1.68 particles/kg) in processed foods is MP_a , where MP_i is the number of MPs in sample i and n is the total number of samples (Fadare et al., 2021). The criteria for the risk category regarding MP pollution load and contamination were calculated as defined by Basaran et al. (2023).

2.5.3 MP Polymer Risk Index

The following Eq (4) was used to calculate the polymeric risk index (pR_i).

$$pR_i = \sum \left(\frac{P_b}{P_t} \times R_c \right) \tag{4}$$

P_b is the number of each polymer of MPs detected in tea sample b , and P_t is the total number of various polymers of MPs determined in tea sample b . R_c is the chemical toxicity coefficient or risk score (Lithner et al., 2011). The risk category criteria for pR_i were taken from Basaran et al. (2023). pR_i values were assessed in five groups: low risk ($pR_i < 150$), medium risk ($150 < pR_i < 300$), considerable risk ($300 < pR_i < 600$), high risk ($600 < pR_i < 1200$), and very high risk ($pR_i > 1200$).

2.6 Software

The normality assumption of numeric variables was validated using the Kolmogorov-Smirnov test. Due to the lack of data normality, non-parametric tests (Kruskal-Wallis test or the Mann-Whitney U test)

were applied. When analyzing the data, defining statistics for numeric variables and the frequency distribution for categorical variables were given. Variation in MP concentration, the size and color of plastic particles, MP polymer type among brands / experiment sets was tested by the Kruskal-Wallis test. The concentrations, size and color of MPs, MP polymer type in the cup of tea bag and teapot tea bags / brewing time (3 min and 15 min) were compared through the Mann-Whitney test at 5% probability. IBM SPSS Statistics 22 software was used to perform the statistical analyses. Graphics were designed with R 4.3.1 (R Core Team, 2023; RStudio Team, 2020) using the "ggplot2 (Wickham, 2016)", "ggthemes (Wickham, 2016)", "ggalluvial (Brunson & Read, 2023)", "dplyr (Wickham et al., 2023)", and "scales (Wickham & Seidel, 2022)" packages. The designated graphical abstract was created by professional science icons of BioRender.com.

3 Results

3.1 Abundance of MPs

In the present study, a comprehensive investigation was conducted on a total of fifteen tea bag brands, which included both cup of tea bags and teapot tea bags. The findings revealed the presence of MPs in all of the samples. In Fig. 1a, the total number of MPs detected in the brands ($n=15$) is depicted. The total number of MP particles in each experiment batch ($n=120$) was expected in a 100 ml sample volume. MPs were found in all brands, which ranged in concentration from 3 to 33 items/single teabag, with an average of 5.77 ± 0.55 items/single teabag. On the other hand, a total of 258 MPs were found in all brands analyzed. MPs with the highest abundance were determined in brands A and O (33 items/single teabag). The Brands G and H were found to have the lowest MP abundance (3 items/single teabag). No significant variation in MP abundance was recorded between brands ($H=40.760$; $df=14$; $p < 0.01$). The total number of MPs was 258 for 120 experimental samples in the sample context of our study, and 2.15 per sample. According to experimental groups, the highest number of MPs was determined in dry tea samples of all tea brands, followed by empty tea bags

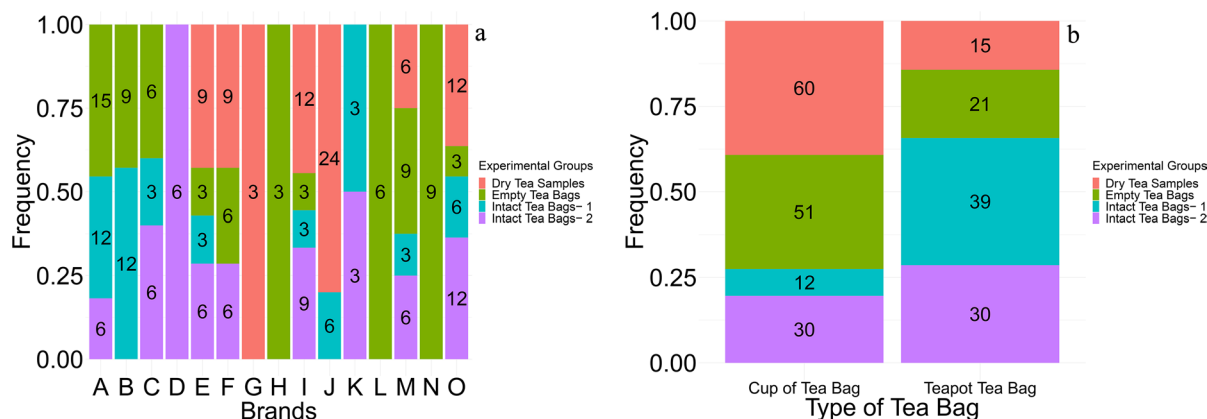


Fig. 1 Number of MP items/single teabag in tea brands (a), and type of tea bag (b) according to experimental groups

(Fig. 1a). 12 of 15 cups of tea bag (153 particles) and teapot tea bag (105 particles) brands had MPs. Cup of tea bag brands represented 59.3% of MPs-identified samples (Fig. 1b). When evaluating the type of tea, it was found that the highest amount of MP was in the dry tea samples, and the lowest amount of MP was in the intact tea bags-1, for cup of tea bag brands. The situation was exactly the opposite for teapot tea bag brands (Fig. 1b).

3.2 MP Characterization

Two hundred fifty-eight particle samples found in all samples were taken, and ATR-FTIR analysis was performed to determine polymer types (Fig. 2). The findings revealed seven different types of polymers (polypropylene (PP), ethylene vinyl acetate (EVA), polyethylene terephthalate (PET), NYLON-6 (NY6), polyvinyl alcohol (PVA), polyacrylonitrile (PAN) and polyamide (PA)) in brands. Various polymer types in different quantities were listed as follows: PET (60.47%) > EVA (12.79%) > PA (9.30%) > PVA (5.81%) > PAN=NY6 (4.65%) > PP (2.33%).

PET in 14 brands, EVA in 8 brands, PA in 2 brands, PVA in 4 brands, PAN in 2 brands, NY6 in 3 brands, and PP in 1 brand were found. The distribution of polymer types differed between brands. Significant differences were found between the polymer type frequencies of MPs in all brands ($H=67.074$, $df=14$, $p < 0.00$, Fig. 3a). Although a greater number of polymer types were determined in cup of tea bags (59.30%) than in the teapot tea bags samples, no statistically significant difference was observed in the

polymer types between the two groups ($U=7524.000$; $p > 0.05$; Fig. 3b). Moreover, we determined all polymer types, the dominant of which was PET in cup of tea bag brands. We detected other polymer types except PP in teapot tea bag brands. Overall, while all polymer types were detected in the experiments conducted with cup of tea bag brands, others were present except PP in the analyses conducted with teapot tea bag brands (Fig. 3b). Additionally, significant differences were determined in polymer types among brewing times ($U=1026.000$, $p < 0.05$). In terms of the experiment set, we observed a total of 6 and 5 polymer types in dry tea samples and intact tea bags-1 analyzed, respectively. It was followed by empty tea bags and intact tea bags-2 with four polymer types (Fig. 3c). The Kruskal-Wallis test demonstrated that the types of MP polymers used in each experiment set varied significantly ($H=45.633$, $df=7$, $p < 0.01$).

Four different colors were found in the MPs in the analyzed samples, namely navy blue (81.4%), followed by black (14%), turquoise (3.5%), and red (1.2%) (Fig. 4a). Navy blue colored particles were predominant in all brands except H and K, and red colored particles were detected only in brand O (Fig. 4b). While particles of all colors were observed in the teapot tea bag brands, red particles were excluded in the cup tea bag brands (Fig. 4c). There was a notable difference in color frequencies of MPs in terms of brands ($H=48.535$, $df=14$, $p < 0.01$) and experiment set ($H=21.897$, $df=7$, $p < 0.01$). However, there were no significant differences in terms of tea type (cup of tea bag and teapot tea bag, $U=7573.500$, $p > 0.05$) and brewing time ($U=1165.500$, $p > 0.05$).

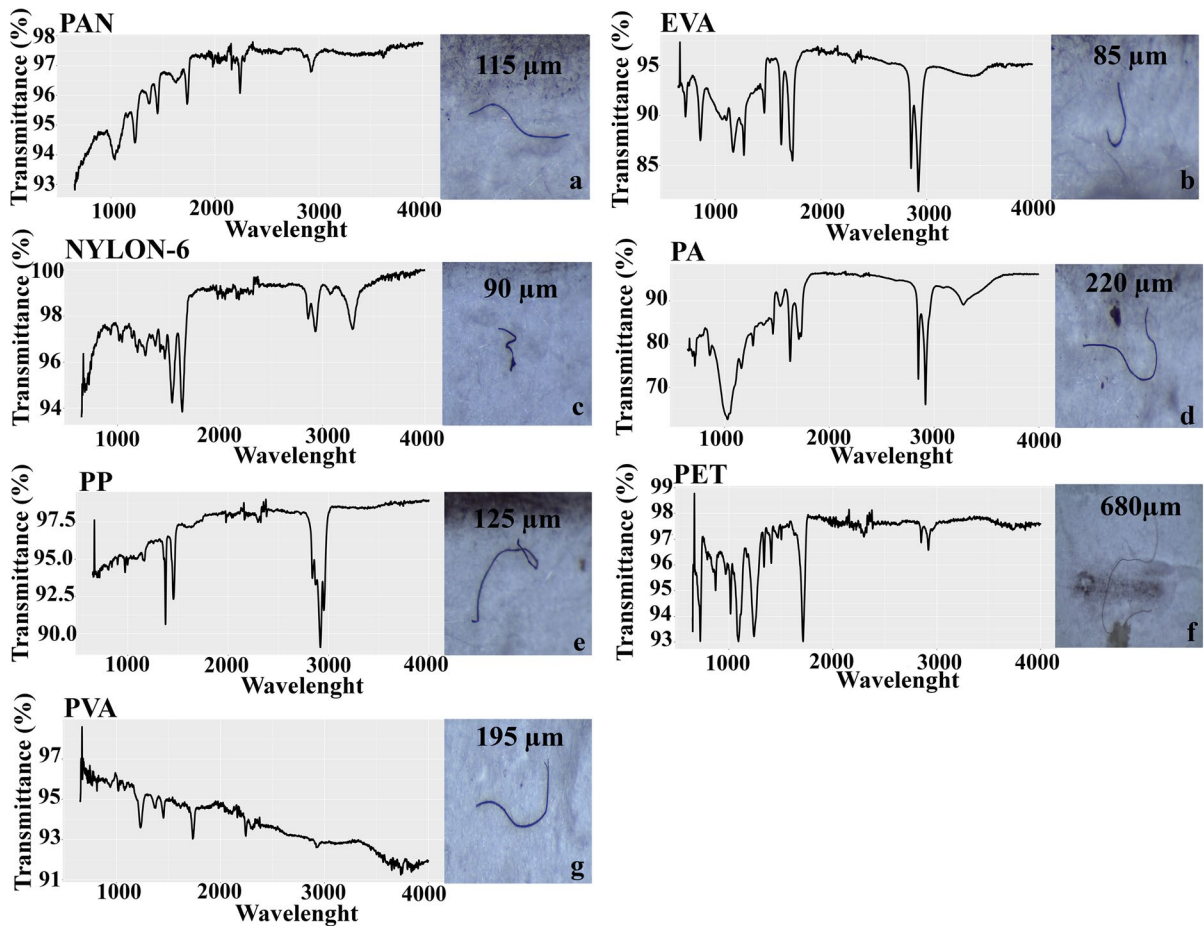


Fig. 2 FTIR spectra of MP samples. **a:** polyacrylonitrile, **b:** ethylene vinyl acetate, **c:** nylon-6, **d:** polyamide, **e:** polypropylene, **f:** polyethylene terephthalate, **g:** polyvinyl alcohol

The MPs observed had sizes ranging from 33.65 μm to 1680.20 μm , with an average size of 197.40 \pm 13.13 μm . The E and O brands had the highest mean MP size with 288.63 \pm 40.14 μm and 342.73 \pm 79.91 μm , respectively. The lowest mean size was found in G (35.54 \pm 1.90 μm) and H (91.27 \pm 1.27 μm). There was a significant difference between brands ($H=33.678$, $df=14$, $p < 0.01$). The sizes of MP detected in the examined brands were categorized into three groups: $< 500 \mu\text{m}$ (small size), 500-1000 μm (medium size), and $> 1000 \mu\text{m}$ (large size) (Chen, 2022). Ninety-three percent (240 particles) of MPs were shorter than 500 μm , followed by 500-1000 μm with 5.80% (15 particles) and $> 1000 \mu\text{m}$ with 1.2%

(3 particles). The average size of MPs in cup of tea bag brands is larger compared to those teapot tea bag brands ($U=6021.000$, $p < 0.01$, Fig. 5a). The size of samples brewed for 15 minutes was greater than the size of samples brewed for 3 minutes, based on brewing duration ($U=1278.000$, $p > 0.05$). In addition, there was no statistical difference among the experiment sets ($H=11.515$, $df=7$, $p > 0.05$, Fig. 5b).

The nodes in alluvial diagrams, which represent categorical data throughout, also showed linkages spanning from tea brands to polymer types (Fig. 6). According to the diagram, all MP particles (100%) were fiber shaped; fiber dominated at all brands.

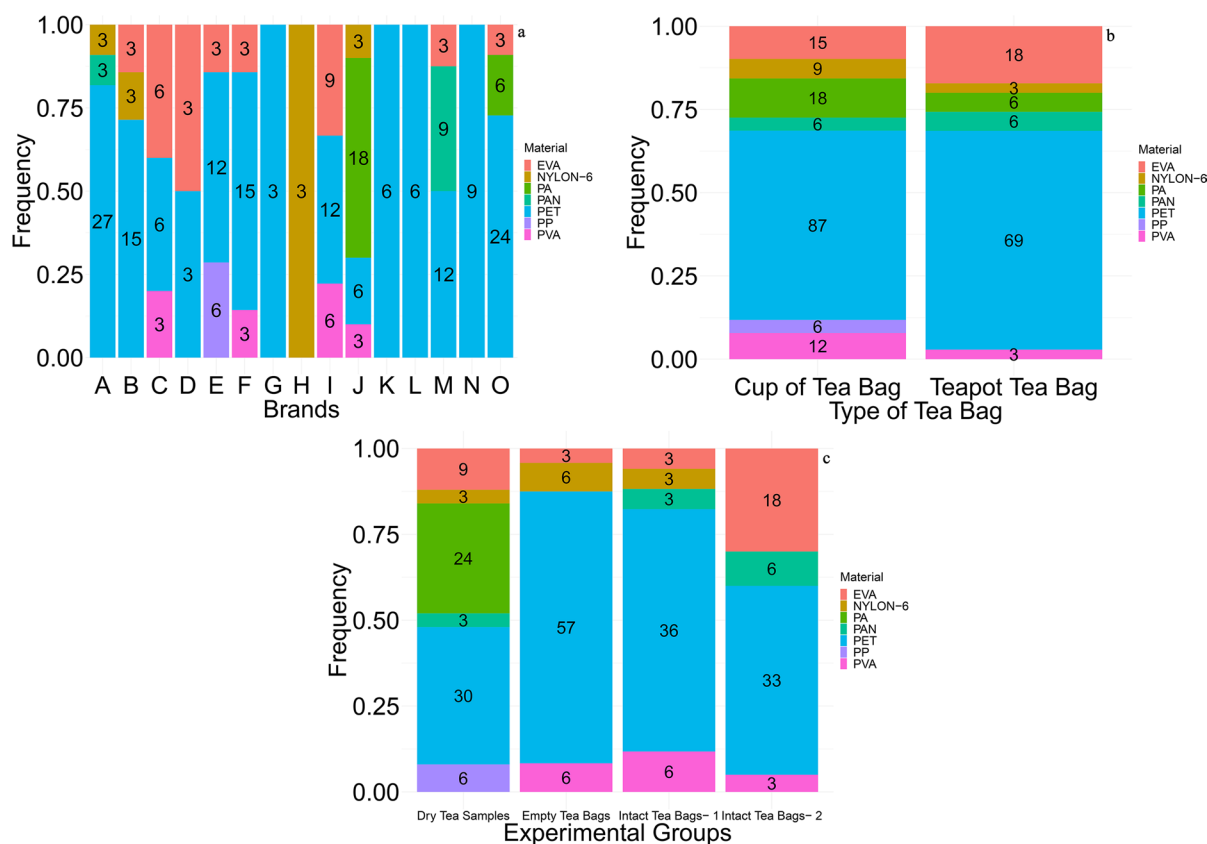


Fig. 3 Total number of MPs determined in tea brands (a), type of tea bag (b), and experimental groups (c)

3.3 Risk Assessment

3.3.1 Dietary Exposure

Tables 1 and 2 indicate the levels of individuals' MP exposure due to tea consumption (male and female). Males' daily MP exposure due to tea consumption ranged between 5.28 and 17.58 particles/mL/day for all tea brands. The daily MP exposure for female individuals varied from a minimum of 4.16 to a maximum of 13.85 particles/mL/day. According to tea types, the daily MP exposure of male and female individuals was 21.12 and 16.65 particles/mL/day for cup of tea bags, respectively. Similarly, for male and female individuals, the daily MP exposure due to tea consumption was calculated as 15.84 and 12.49 particles/mL/day in terms of teapot tea bags, respectively.

3.3.2 MPCF and MPLI

The MPCF and MPLI values of tea samples were calculated in the current study (Fig. 7). The mean MPCF values ranged from 1.79 to 19.64 for all tea brands. Brands G and H had a moderate level of contamination; Brands D, K, L, and N had a significant level of contamination; Brands A, B, C, E, F, I, J, M, and O had a very high level of contamination. The brands' increasing order of contamination was $G=H < D=K=L < N < C < B=E=F < M < I < J < A=O$ for MPCF. The mean highest MPCF was 19.64 (Brands A and O). The mean MPLI of all samples value was found to be 7.74, indicating a very high level of contamination (Risk Category IV).

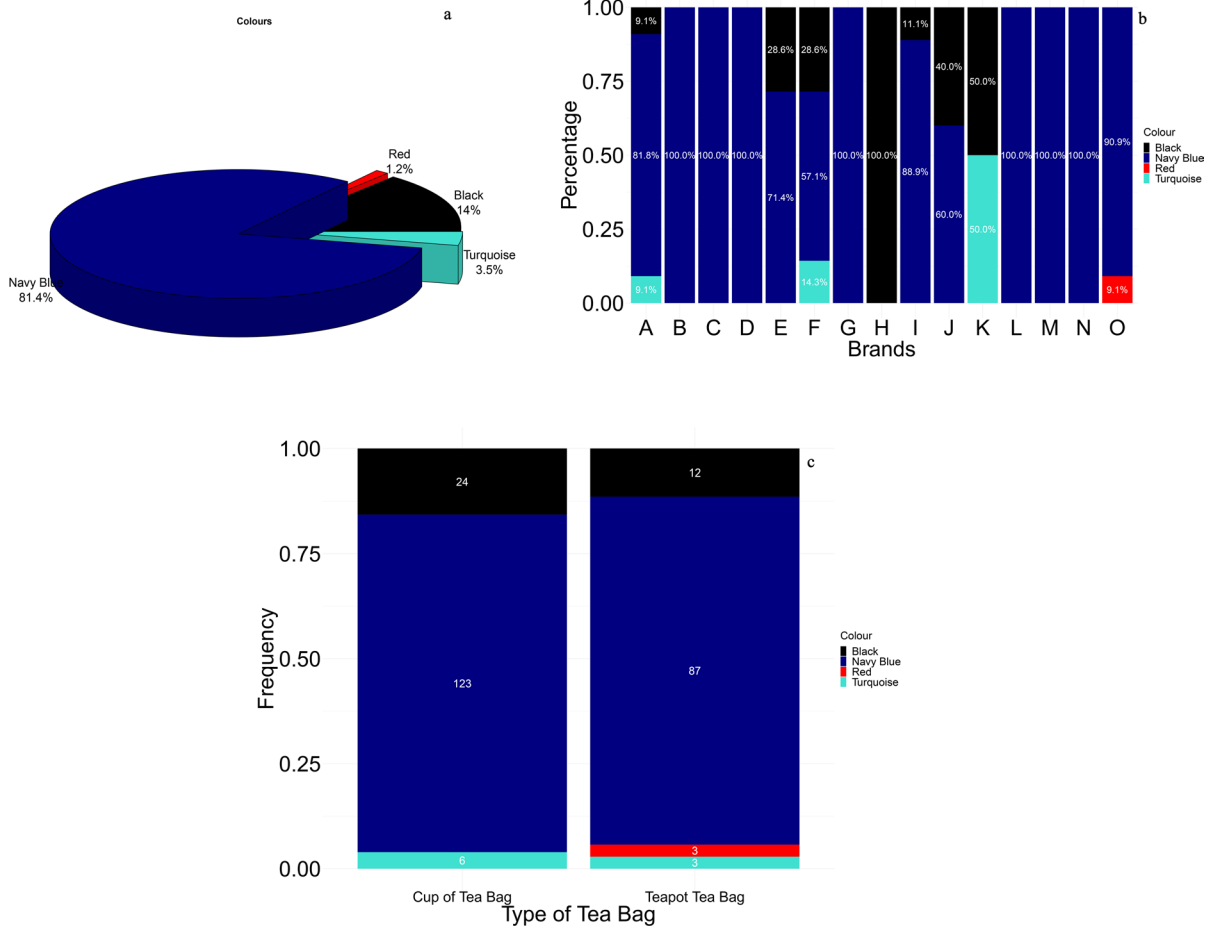


Fig. 4 Percentage of colors of MPs determined in tea samples (a), tea brands (b), and type of tea bag (c)

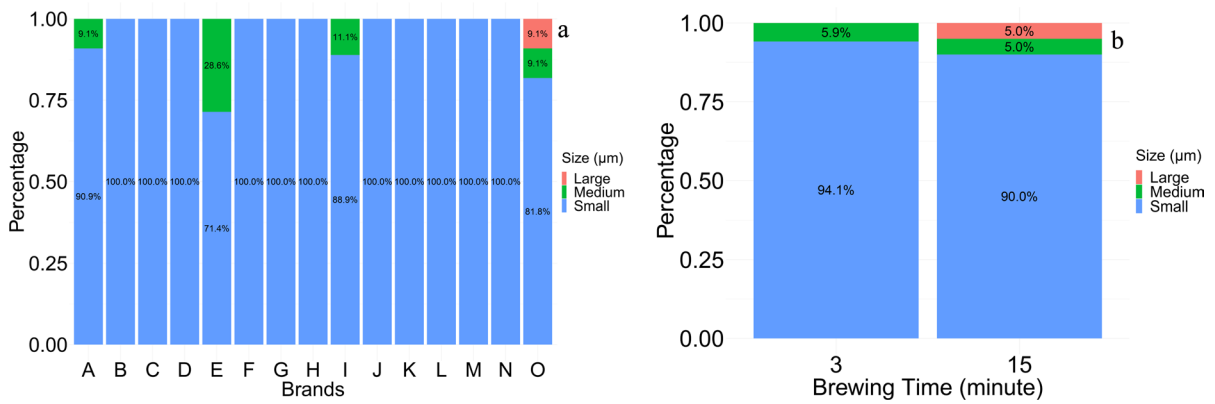


Fig. 5 Percentage of size of MPs determined in tea brands (a) and brewing time (b)

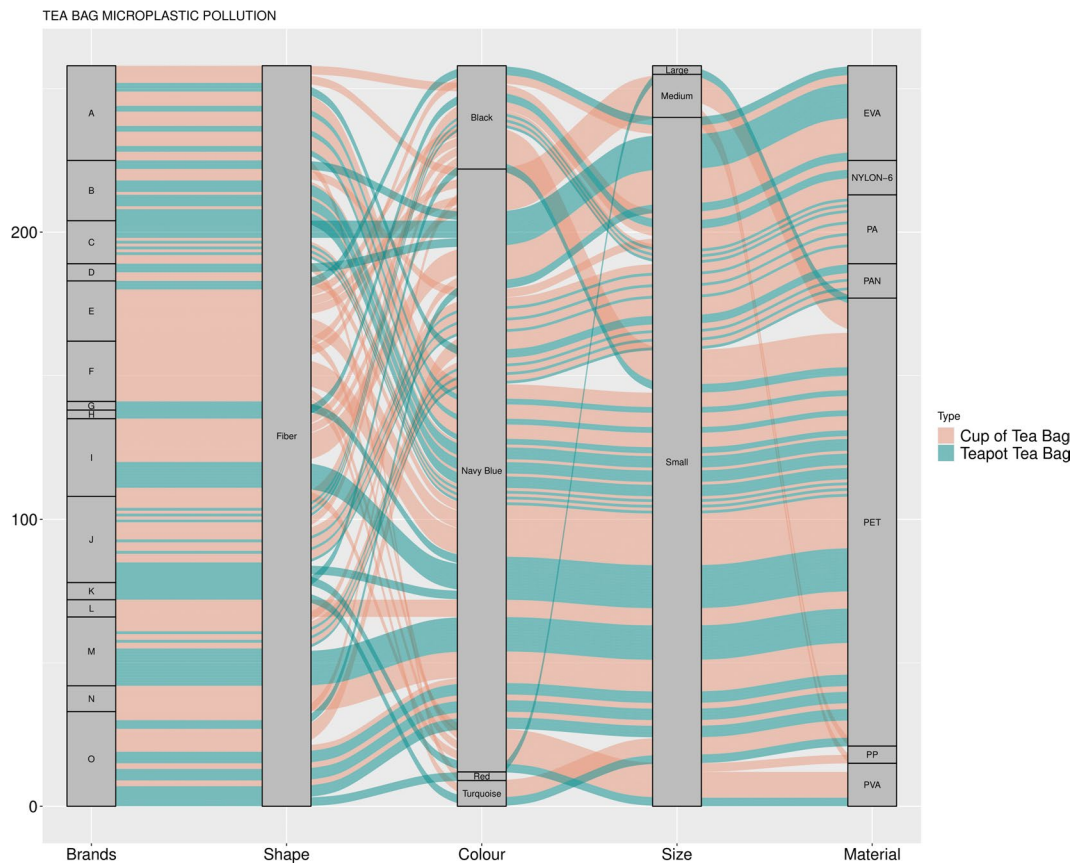


Fig. 6 The alluvial diagram shows the complexity of the relationships between tea brands and polymer types. Nodes in the flow represent the shape, color, and size of MPs

3.3.3 MP Polymer Risk Index

In the current study, the polymer risk index value was determined by considering the polymer types of MPs identified in tea samples (Fig. 8). The polymers were arranged in the following order, based on their degree of contribution to the MP polymer risk index: NY6 > PA > PAN > EVA > PET > PP = PVA. The polymer risk indexes of all tea brands ranged from 2.14 to 50. Brands H and E had the highest and lowest mean polymer risk indexes, respectively. All brands had a low-level MP polymer risk index. The mean polymer risk index was determined to be 10.80, indicating a low level of risk. The tea samples had a polymer risk index below 150.

4 Discussion

4.1 Abundance of MPs

A limited number of studies have been conducted on MPs in empty tea bags and brewed bagged teas (with tea leaves) around the world (Afrin, Rahman, Akbor, et al., 2022; Hernandez et al., 2019; Kashfi et al., 2023; Kim et al., 2022; Li et al., 2022; Mei et al., 2022; Xu et al., 2021). Any study originating from Türkiye has not been published yet, and such a study has been handled by our team for the first time. Thus, the current work is the first comprehensive study examining MPs in different tea brands including cup of tea bags and teapot tea bags in terms of different experimental sets.

Table 1 Estimated Daily Intake (EDI) values for male and female groups according to tea brands

Tea Brands	Groups	Body Weight (kg)	Consumption Amount (mL)	Daily exposure (particles/mL/day)	Exposure by body weight (particles/mL bw/day)
A	Male	79.7	528.1	11.61	0.146
	Female	70.7	416.2	9.15	0.129
B	Male	79.7	528.1	12.30	0.154
	Female	70.7	416.2	9.69	0.137
C	Male	79.7	528.1	6.60	0.082
	Female	70.7	416.2	5.20	0.073
D	Male	79.7	528.1	5.28	0.066
	Female	70.7	416.2	4.16	0.058
E	Male	79.7	528.1	7.39	0.092
	Female	70.7	416.2	5.82	0.082
F	Male	79.7	528.1	12.30	0.154
	Female	70.7	416.2	9.69	0.137
G	Male	79.7	528.1	5.28	0.066
	Female	70.7	416.2	4.16	0.058
H	Male	79.7	528.1	5.28	0.066
	Female	70.7	416.2	4.16	0.058
I	Male	79.7	528.1	9.50	0.119
	Female	70.7	416.2	7.49	0.105
J	Male	79.7	528.1	17.58	0.220
	Female	70.7	416.2	13.85	0.196
K	Male	79.7	528.1	5.28	0.066
	Female	70.7	416.2	4.16	0.058
L	Male	79.7	528.1	10.56	0.132
	Female	70.7	416.2	8.32	0.117
M	Male	79.7	528.1	8.44	0.106
	Female	70.7	416.2	6.65	0.094
N	Male	79.7	528.1	15.84	0.198
	Female	70.7	416.2	12.49	0.176
O	Male	79.7	528.1	8.29	0.104
	Female	70.7	416.2	6.53	0.092

Table 2 Estimated Daily Intake (EDI) values for male and female groups according to type of tea

Tea Types	Groups	Body Weight (kg)	Consumption Amount (mL)	Daily exposure (particles/mL/day)	Exposure by body weight (particles/mL bw/day)
Cup of Tea Bags	Male	79.7	528.1	21.12	0.27
	Female	70.7	416.2	16.65	0.24
Teapot Tea Bags	Male	79.7	528.1	15.84	0.20
	Female	70.7	416.2	12.49	0.18

Fig. 7 The mean MP pollution load index of tea samples

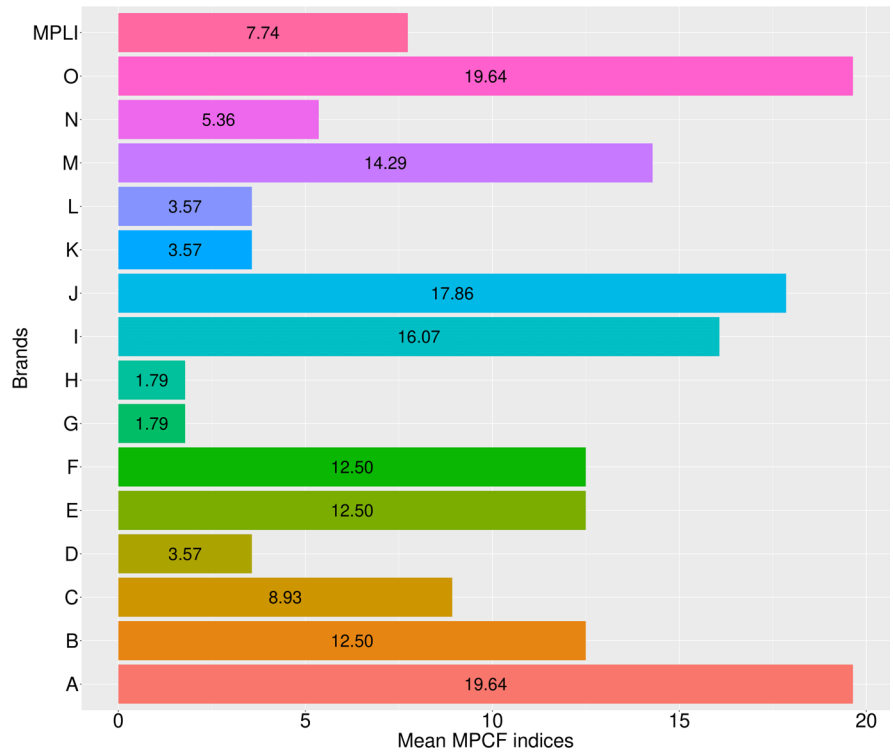
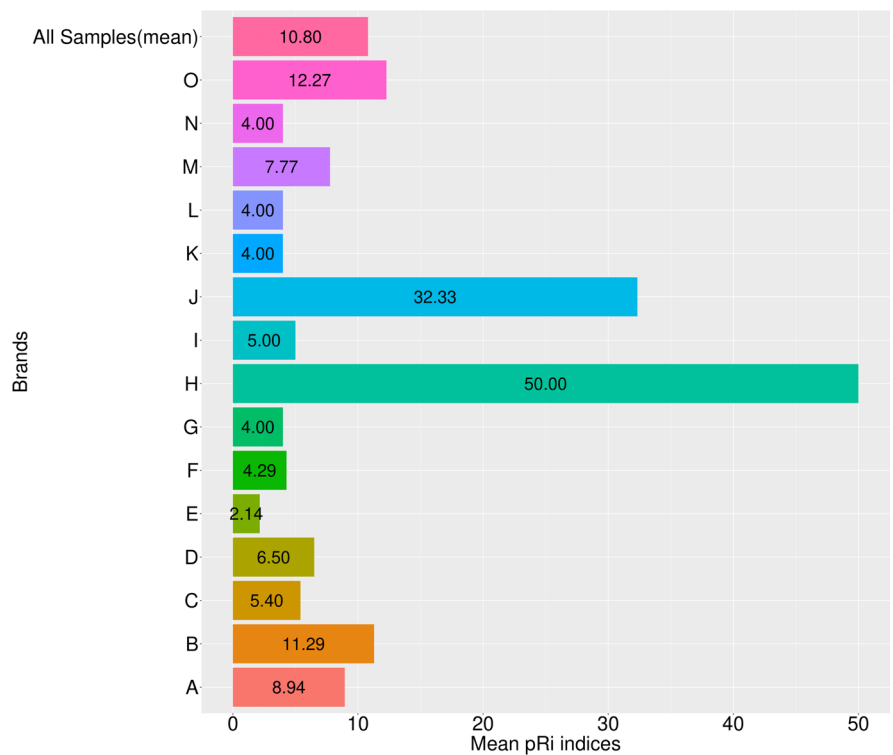


Fig. 8 The mean MP polymer risk index of tea samples



Firstly, MPs were found in the samples of all tea brands examined, which is consistent with the findings of the earlier studies into the MPs in different tea brands (Afrin, Rahman, Akbor, et al., 2022). A total of two hundred fifty-eight MPs were observed in all brands. Brands A and O had the most abundant concentration of MPs, with a value of 33 items/single teabag (Fig 1a). The lowest MP abundance was found in G and H brands, with a value of 3 items/single teabag. The difference among the MP abundance in brands can result from the amount of plastic used in the packaging of teabags and/or the characteristics of product packaging (Kashfi et al., 2023). Hernandez et al. (2019) reported that 3.1 billion nanoplastics and 11.6 billion MPs into tea infusion were released from a plastic tea bag. In another study, the average MP number in empty tea bag (without tea leaves) and intact tea bag (with tea leaves) was reported as 65 and 50 items/kg, respectively (Afrin, Rahman, Akbor, et al., 2022). The number of MPs found in different tea brands ranged from 55.6 to 1446.8 items/single tea bag (Kashfi et al., 2023). For tea leaves, the quantity of MPs detected varied between 200 and 500 items/g (Li et al., 2022). Shruti et al. (2020) concluded that the number of particles in beverages depended on the type of packaging material for food products.

As shown in Fig. 1c, although the number of MPs was similar between the experimental groups, the highest particle number was observed in the dry tea samples (removed from tea bags) belonging to all brands. However, empty tea bags also had the second highest MP number. Conformably, Afrin, Rahman, Akbor, et al. (2022) reported that numerous MPs were released even when teabags were uncut and concluded that this may be caused not only by tea bags but also by contamination of these products' exterior surfaces. Aside from its abundance in all experimental groups, the reason why the number of MPs in dry tea samples was dominant might be related to the way tea is collected and preserved or to fertilizers used.

MP was observed in different experimental samples from each brand, but it was not observed in the cup of tea bags (G, H, and K brands) and teapot tea bags (F, L, and N brands) of three different brands. In accordance with the conclusions of Xu et al. (2021), plastic was observed in five of the six brands tested in the research, and no plastic was observed in the sixth brand. In the study of Yurtsever (2021), eleven

tea brands were tested, and it was found that 4 of 11 teabags used in teacups included polyester, PE, and PP-PE blends. It can be because the plastic materials used for package teabags were different (Kashfi et al., 2023).

The main focus of this study is on empty tea bags, intact tea bags (with tea leaves), and tea leaves (dry teas removed from tea bags). Xing et al. (2023) reported that MPs can be found in tea plants due to exposure to plastic during processing and storage, as well as in the soil in which they are cultivated (Hernandez et al., 2019; Li et al., 2019; Li et al., 2022). In the present study, the most MP was identified in tea leaves, followed by empty tea bags. The following could be the reasons for higher MP levels in dry tea: a) the use of plastic sacks to store fertilizer applied to the soil in tea plantations; b) the use of plastic chamber tea picking scissors to collect fresh tea leaves from tea orchards; c) gathering the tea that has been picked in the tea garden and placing it into plastic sacks for transportation; d) the way in which fresh tea leaves are transported to collection depots; and e) the storage conditions and location of fresh tea leaves. Moreover, exposure to different sources such as atmospheric deposition and tools used during the processing stage may also constitute additional factors. The aforementioned reasons may result in MP contamination.

4.2 MP Characterization

The only MP morphotype identified in the study was fiber. The fact that fibers make up all MPs in different Turkish tea brands is in line with the former studies (Afrin, Rahman, Akbor, et al., 2022; Li et al., 2022; Xu et al., 2021). In addition, Akhbarizadeh, Dobaradaran, Nabipour, et al. (2020) stated that fibers were the most abundant shape of MPs. However, many studies (Busse et al., 2020; Hernandez et al., 2019) reveal that fragments are the most abundant type. Mei et al. (2022) reported that fragments and fibers were the most prevalent types of MPs. As highlighted by Acharya et al. (2021), Mishra et al. (2019) and Klein et al. (2018), especially textile garments release large amounts of fiber into the environment, and the fragmentation of plastics accelerates the formation of microfibers. Furthermore, synthetic fibers are widely found in fabrics, and atmospheric fiber shedding is

observed practically everywhere (Akhbarizadeh, Dobaradaran, Nabipour, et al., 2020).

The FTIR analysis conducted in this study revealed that all tea brands exhibited a diverse range of polymer types, as depicted in Fig. 2. The various MP concentrations in samples from fifteen different tea brands may result from different storage conditions and manufacturing processes (Bai et al., 2022). Afrin, Rahman, Akbor, et al. (2022) identified several types of MP polymers included in teabag samples, including PTFE, PETE, EVA, HDPE, CA, PC, PVC, ABS, and nylon. In a similar vein, Afrin, Rahman, Akbor, et al. (2022) proposed that many sources could have played a role in the contamination of the samples tested in Bangladesh with MPs. In various studies, the polymer types in empty plastic tea bags are as follows: Hernandez et al. (2019) reported that there were nylon and PET. Busse et al. (2020) stated that there were nylon, PET, and PP. Xu et al. (2021) reported that there were cellulose and PP in empty tea bags. Kim et al. (2022) reported that there was nylon in teabags. Kashfi et al. (2023) pointed out that there were nylon, PC, and PE in tea bags. As shown in Fig. 3c, MP was found in all experimental groups, and one type of polymer (60.47%) predominated among the MPs found in all experimental groups. Emmanouil et al. (2020) and Busse et al. (2020) confirmed that MP particles can pass from the components of tea bags to the beverages that are drunk. PET was the predominant material observed in all experimental groups, aligning with the results of previous studies conducted by Mei et al. (2022) and Li et al. (2022). One of the most significant and abundant polymers used as food contact materials is PET. Because of its excellent characteristics, such as being lightweight, flexible, resistant to high temperatures, and having low carbon dioxide permeability, it is widely used in many applications for packaging beverages and food (Tsochatzis et al., 2020). PET, one of the primary polymers used in food packaging, accounts for most of the world's need for plastic (Plastic Europe, 2021). Additionally, PET is the most prevalent type of polymer reported in Europe (Cera et al., 2020).

In this study, it was found that navy blue was the most common color in the majority of tea brands (Fig. 4b). The literature has determined the various dominant colors of MPs observed in tea bags. Afrin, Rahman, Akbor, et al. (2022) reported that the color blue was prevalent in intact tea bags, while the color

brown was dominant in empty tea bags. In most studies, transparent color was dominant (Hernandez et al., 2019; Kashfi et al., 2023; Li et al., 2022; Mei et al., 2022). However, some of the latest studies on teabags have not assessed the colors of MPs, as in the study by Xu et al. (2021). MPs can be distinguished by their color to determine where they were produced (Kashfi et al., 2023).

The dominant size of MPs was smaller than 500 μm in this study (Fig. 5a). The size data were similar to those identified in various studies (Afrin, Rahman, Akbor, et al., 2022; Kashfi et al., 2023). Moreover, Xu et al. (2021) reported that the dominant size range was 951–2496 μm . In different research (Mei et al., 2022) on teabags, researchers stated the dominant size of MPs ranged between 620 and 840 μm . In the present study, only a large particle (1680.20 μm) was found in the filtrate obtained by steeping the teapot tea bag of the O brand for 15 minutes. The teapot tea bag of the K brand displayed a small size of 33.65 μm . In this study, the majority of MPs were small particles. Larger-sized MPs can be broken down into smaller-sized particles due to water temperature (Zhou et al., 2023). Kwon et al. (2020) and Yang et al. (2022) reported that the toxicity of MPs was related to their size and that smaller particles would cause greater toxicity. Since the mentioned study used FTIR, it was less likely to see five-micron or lower-sized MPs.

4.3 Dietary Exposure to MPs

Based on the amount of food and drink consumed daily or annually, body weight, and MP content, it is possible to calculate the amount of MPs that humans consume (Cox et al., 2019; Zuccarello et al., 2019). Only two studies were found to calculate the daily exposure to MP for tea bags. Kashfi et al. (2023) identified MP exposure through tea consumption for various age groups, and children were indicated as having the highest exposure risk. The EDI values reported for adults, teens, and children were in the range of 1.04–27.27, 5.38–140.12, and 14.93–388.54, items/kg-BW/day, respectively. Afrin, Rahman, Akbor, et al. (2022) stated that a mean emission of 10.9 million grams of MPs/year was released from tea bags in Dhaka. In the current research, the EDI values of different sex groups (male and female) were between 0.058 and 0.22 items/kg-bw/day. The results showed that MP exposure through tea consumption varies

between males and females. Results further revealed a general higher intake of MPs for males than females. The fact that the calculated values are higher in males compared to females can be associated with the per capita consumption in males. MP exposure resulting from tea consumption may also differ according to the consumption habits of individuals. MP intake may increase significantly with increased consumption of tea prepared with tea bags. Higher MP exposure in this gender group is explained by the fact that males consume more tea than females. Factors that may affect the EDI include the quality of the drinking water supply, population trends and consumption patterns, storage conditions of the packaging, and the MP detection process (Akhbarizadeh, Dobaradaran, Schmidt, et al., 2020; Winkler et al., 2019). In addition, the frequency of packaged tea usage is a parameter that can affect EDI. Information on the risks of MPs to human health is still very unclear.

4.4 MP Polymer Risk Index (pR_i) and MP Pollution Load Index (MPLI)

No study identified the MP polymer risk index and the MP pollution load index for teas. The findings of this study were compared to previous research on MP contamination in food and beverages due to the absence of MPLI and pR_i calculations in prior investigations on tea samples. In a review, the MPLI value of milk was calculated to be 22.8 with a risk category III. According to Lin et al. (2022), bottled water, sugar, and table salt were classified as risk category II, while vinegar, beer, processed meat, honey, and canned fish were classified as risk category I. The polymer risk indexes of milk, bottled water, and beer were determined to be 337, 511, and 321, respectively. Based on these values, the risk level was classified as medium. The polymer risk indexes of beverage and table salt were calculated to be 823 and 766, respectively, and the risk level was classified as high. The risk level of honey and packaged meat were defined as very low and low, respectively (Lin et al., 2022). In the current study, the average MPLI of all samples was 7.74, and the level of contamination was very high (risk category IV). The index models made it easy to compare the levels of the MPs contamination in the different teas and provided concise information on the status of the MPs in the teas. The presence of harmful MP polymers significantly increases

the risk and level of MP contamination. The pollution load index is also affected by high levels of MPs (Enyoh et al., 2021). High levels of accumulation can lead to high risks.

5 Conclusion

This study is the first to establish the characteristics, including size, color, shape, and number of MPs found in various commercially packaged tea brands in Türkiye. Moreover, the MP polymer risk index, the MP pollution index, and MP exposure through tea consumption were also investigated. A 120 experimental samples from fifteen brands were analyzed for MP contamination, and a total of 258 MPs were determined in all samples analyzed. No MP was found in the cup of tea bags and teapot tea bags of some brands. PET was the most abundant polymer type identified by FTIR stereoscopy, and all MPs were fiber in the shape. Out of the four-color combinations, navy blue particles were the most prevalent. The highest exposure risk was determined to be for males based on the EDI values of MPs from tea intake prepared using teabags for different sex groups. The mean MP contamination values varied from 1.79 to 19.64, and polymer risk index values varied from 2.14 to 50 for all tea brands. The findings indicate that the use of plastic based bags for tea packaging may pose a risk to human health due to contamination from MP. Given the fact that there is only one study conducted on the MP pollution of tea bags in our country, the findings in the current study are important for future studies.

There are some limitations of our research that may impact the results of this study to a certain degree. Our findings may be influenced by certain restrictions, including the tea samples' packaging procedure, their transportation to the markets, and the storage conditions in the markets. Another limitation was the inability to detect MPs of smaller size and nanoscale particles. Furthermore, it is important to consider that Raman analysis is necessary in addition to FTIR analysis for the identification of smaller particles. It is possible that exposure to MPs may be higher than the calculated numbers. Furthermore, the evaluation of the MP polymer risk index and the MP pollution index was limited due to insufficient data on teas. There is currently no study reporting on tea in

the literature. The most popular and widely consumed tea brands in Türkiye were selected for this study; however, the findings do not represent all Turkish tea brands.

MP pollution in tea has not been properly investigated during the production process from tea soil to tea packaging. While the effects of MP contamination on human health are currently unknown, tea prepared using teabags containing tea leaves may pose a significant health risk to consumers. In this context, it is evident that further scientific research is required. Research on risk assessments will be crucial to formulating the regulations required for the production of safe food and public health. Considering the widespread consumption of tea worldwide, this study supports the necessity for further research on the effects of micro- and nano-plastics on human health. Further research on MPs' effects on human health is needed in order to identify the knowledge gaps in this field.

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Data Availability Data will be made available on request.

Declarations

Ethics Approval The authors have observed all the ethical issues throughout the experiment.

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

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