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Microplastic contamination in ice cream: Occurrence, exposure assessment, and potential health risks

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ABSTRACT

This cross-sectional study evaluated micro- and nanoplastics (MNPs) contamination in 39 ice cream samples from multiple brands and price categories in Türkiye. Samples were purchased in Kastamonu/Merkez during June–August 2024 and analyzed in triplicate (117 filters). Microscopy identified 75 particles in total: filaments 56 %, fragments 29 %, films 15 %. Attenuated Total Reflectance–Fourier Transform Infrared Spectroscopy (ATR-FTIR) confirmed synthetic polymers ≥ 20 µm—predominantly polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyethylene (PE), and polyvinyl stearate (PVS)—indicating multiple entry points across processing and packaging. Estimated Daily Intake (EDI) ranged 0.34–2.05 particles mL^{-1} kg-BW^{-1} day^{-1} (124.1–748.25 particles mL^{-1} kg-BW^{-1} year-^{1}) and varied by brand/price strata without statistically significant differences ($p > 0.05$). Although the analytical window excluded particles < 20 µm, findings provide first evidence of MNPs in ice cream in Türkiye. To the best of our knowledge, this study combines a stratified market design (brands × price tiers) with polymer confirmation by ATR-FTIR (≥20 µm) and deterministic, consumption-based exposure estimates. Controls include HACCP monitoring of contact surfaces, routine filtration/piping maintenance, and careful packaging-polymer choice. Broader farm-to-fork surveillance, validated recovery studies, and toxicological testing are needed to refine exposure and risk estimates and guide risk management and policy.

1. Introduction

The widespread use of plastics is driven by their functional versatility, durability, and cost-effectiveness. Since the mid-20th century, global production has grown from ~1.5 million tons in 1950 to > 350 million tons by 2019, with projections approaching ~1.1 billion tons by 2050 (Geyer, 2020; Houssini et al., 2025; Wright et al., 2013). This expansion has amplified the environmental burden of plastic waste mismanagement. Through abiotic and biotic processes (photodegradation, mechanical abrasion, and microbial action), bulk plastics fragment into smaller debris that can persist and disperse across ecosystems. Common polymers implicated include polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyvinyl chloride (PVC), which are widely used in consumer packaging and industrial applications (Barbeş et al., 2014; Harris and Walker, 2010; Rochman et al., 2013). Size-based terminology typically distinguishes macro-, meso-, micro-, and nano-plastics (Iheanacho et al., 2023).

While early research centered on aquatic systems, accumulating evidence shows that terrestrial matrices-especially soils-act as major reservoirs for micro- and nanoplastics (MNPs), with documented occurrences worldwide (Corradini et al., 2019; Fuller and Gautam, 2016; Rillig, 2012; Scheurer and Bigalke, 2018; Wang et al., 2019; Yang et al., 2018). Consequently, emerging studies suggest translocation from contaminated soils to forage crops and subsequent entry into livestock, raising concerns for animal-derived foods (Khan et al., 2024; Lwanga et al., 2022). Against this backdrop, dairy products warrant particular attention due to high consumption and extensive contact with polymeric materials throughout milking, processing, and packaging. For instance, Basaran et al. (2023) detected PP, polyurethane (PU), nylon, and polyethylene terephthalate (PET) in packaged milk, with the profile

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indicating that processing equipment-beyond packaging- may contribute to contamination.

Human exposure to MNPs occurs via ingestion and inhalation, with particles that can interact with the gastrointestinal epithelia and undergo transformations that may modulate bioactivity (Jadhav et al., 2021; Waring et al., 2018). Although long-term health outcomes remain uncertain, associations have been reported with inflammatory responses, endocrine perturbation, respiratory impairment, cardiovascular dysfunction, and gastrointestinal disturbances (Garrido Gamarro and Costanzo, 2022; H. Tan et al., 2020; Yu et al., 2022). Milk and dairy products are among the most widely consumed food sources worldwide (Mohammadpour et al., 2024). Notably, ice cream is among the most popular frozen dairy desserts, consumed worldwide, and is produced in numerous varieties with different formulations and presentations (Nalbone et al., 2022). Despite the centrality of dairy in human diets (FAO, 2021; Mohammadpour et al., 2025), data on MNPs in this group are limited (Diaz-Basantes et al., 2020; Kutralam-Muniasamy et al., 2020). Reported concentrations in milk products vary by geography and product type (e.g., 150 particles across 23 samples in Mexico; 164–427 particles L^{-1} across 16 brands in India) (Kiruba et al., 2022; Kutralam-Muniasamy et al., 2020). Notably, ice cream, a widely consumed processed dairy product, remains under investigation, particularly in Türkiye.

Available reports indicate that Türkiye's annual ice cream production is approximately 460 million liters, while per-capita consumption has been reported at roughly 4–4.2 liters in recent years. Consumption is strongly seasonal, with intake concentrating in summer; this seasonal clustering can yield relatively higher exposure in children (i.e., intake per unit body weight) during periods of increased total consumption (Arslaner and Salik, 2020). Accordingly, this study systematically investigated the presence of MNPs in commercial ice creams in Türkiye by characterizing particle abundance, color, morphology, size, and polymer type, and by estimating dietary exposure based on national consumption estimates. Although our analytical window focuses on the finished product, we interpret the results within a supply-chain perspective, acknowledging plausible upstream contributors (e.g., raw-milk collection and transport equipment) alongside processing and packaging-related sources. To our knowledge, this work is among the first in Türkiye to combine a stratified sampling design with ATR-FTIR–confirmed polymer identification (≥20 μm) and consumption-based exposure estimates, thereby informing actionable control points under HACCP/ISO 22000 from farm collection and plant reception through to packaging.

2. Materials and methods

2.1. Sample collection

Packaged ice creams were purchased in their original containers from retail outlets in Kastamonu/Merkez, Türkiye, between June and August, 2024. Three nationally distributed brands (A-C) were sampled across four prices categories; in addition, an unpackaged product from a local producer (D) was obtained (Table 1). For each packaged item, we recorded the container volume (mL), cup materials and recycling code (e.g., PP [5], PS [6], and PET [1]), lid type, laminate information where available, and declared shelf life. For the unpackaged product, vendor container type, time to analysis, and serving conditions were documented. All samples were transported under cold chain and processed immediately upon receipt. This study quantified MNPs in finished commercial ice cream products using a market-basket sampling design. Raw milk and intermediate processing streams (e.g., standardized mix and post-pasteurization product) were not sampled. Accordingly, potential upstream inputs from farm collection, transport, and plant reception are discussed as plausible pathways based on processing knowledge and the observed polymer profiles, rather than as source-attributed measurements. The final dataset comprised 39 unique products, each analyzed in triplicate (total 117 technical replicates).

All equipment and materials used for sampling, sample preparation, and analysis were carefully selected to be plastic-free, to minimize the risk of external contamination. Prior to use, all solvents and reagents were screened for MNP contamination to ensure the integrity of the procedure. The glassware was rigorously cleaned by sequential rinsing with filtered distilled water, acetone, and ethanol, followed by a final rinse with distilled water. The filters (Filter-Lab, MFV3/047) were precombusted at 300°C for 5 h to eliminate potential residual contaminants. All procedures were carried out under a laminar flow cabinet to

Table 1
Sampling frame and packaging characteristics ice creams by brand and price tier.

Brand	Price ($)	Number of samples	Recorded container volume (mL),	Cup materials	Recycling code	Lid type	Laminate information	Shelf life
A	0.50–1	3	30	PP	5	Heat-sealed film	Yes	February 2026
	1.1–2	3	65	PP	5	Heat-sealed film	Yes	
	2.1–3	3	500	PP	5	Snap-on overcap	No	
	3.1–4	3	1000	PP	5	Snap-on overcap	No	
B	0.50–1	3	30	PP	5	Heat-sealed film	Yes	February 2026
	1.1–2	3	65	PP	5	Heat-sealed film	Yes	
	2.1–3	3	500	PP	5	Snap-on overcap	No	
	3.1–4	3	1000	PP	5	Snap-on overcap	No	
C	0.50–1	3	30	PP	5	Heat-sealed film	Yes	February 2026
	1.1–2	3	65	PP	5	Heat-sealed film	Yes	
	2.1–3	3	500	PP	5	Snap-on overcap	No	
	3.1–4	3	1000	PP	5	Snap-on overcap	No	
D	3	3	250	PP	5	Open	NA	NI

NA: Not Available, NI: No Information, PP: polypropylene reduce airborne particle interference. Laboratory surfaces were wiped with ethanol before sample handling, and the personnel wore nitrile gloves and cotton laboratory coats throughout the process.

2.2. Chemicals and reagents

TRIS-HCl buffer (400 mM tris base, pH 8 (HCl) (Sigma-Aldrich, T5941, CAS: 1185–53–11, USA)

Sodium dodecyl sulphate (SDS) (Sigma-Aldrich, L3771, CAS: 151–21–3, USA)

Proteinase K (Bioshop, PRK403, CAS: 39450–01–6, Canada)

5 mM $CaCl_2$ (Sigma-Aldrich, C4901, CAS: 10043–52–4, USA)

All liquids were pre-screened for background by filtration over pre-combusted filters.

2.3. Instruments and Software

Compound microscope with digital camera (Leica Microsystems, DM500, Wetzlar, Germany); ATR-FTIR Spectrum Two (PerkinElmer Inc., Waltham, MA, USA); laminar flow cabinet (MSC-IIA-C159 Meti-Safe, Ankara, Türkiye); vacuum filtration unit with glass components (NST-G2000/AS20, İstanbul, Türkiye) and glass-fiber filters (FilterLab, MFV3/047, Barcelona, Spain); image analysis ImageJ (National Institutes of Health, Bethesda, MD, USA); statistics IBM SPSS v23 (IBM Corp., Armonk, NY, USA).

2.4. Sample preparation and polymer identification

A dairy matrix-adapted enzymatic digestion (Proteinase-K + SDS) was selected to minimize polymer alteration and pigment loss. Oxidative digesters (e.g., Fenton) and aggressive density separations were not employed to avoid polymer damage and color leaching biases in a lipid/protein-rich matrix. Post-digestion, residues were vacuum-filtered and inspected at 10 × and 40 × magnifications. Putative MNPs were sized in ImageJ and classified morphologically (filament, fragment, film). ATR-FTIR spectra were collected 600–4000 cm^{-1} , 32 scans, 4 cm^{-1} resolution. Due to spatial resolution, polymer identification was restricted to particles ≥ 20 µm. Operational definitions: nanoplastics < 1 µm; microplastics 1 µm–5 mm; optical detection in this workflow effectively covered ≥ 10–20 µm.

2.5. Quality Assurance / Quality Control (QA/QC)

To assess and minimize background contamination, all steps were conducted under a plastic-reduced workflow (glassware, pre-combusted glass-fiber filters, cotton laboratory coats, laminar flow). Procedural blanks (all reagents, no sample) and airborne blanks (open filters during handling) were run with each batch; no particles were detected in any blank (procedural blanks, n = 10]; [air blanks, n = 10). Accordingly, sample counts are reported per mL without blank correction. We note that polymer-specific spike-recovery and LOD/LOQ experiments were not performed in this dataset; this limitation is explicitly stated, and such validation is planned for subsequent work.

2.6. Method

Ice cream samples transported under cold chain conditions in their original packaging were thawed at room temperature and transferred into glass containers. Each sample was labeled and processed at the Food Hygiene and Technology Laboratory, Faculty of Veterinary Medicine, Selçuk University (Konya, Türkiye). All procedures were performed in triplicate. Following homogenization, 1 mL each sample was transferred into sterile glass tubes, and 15 mL of TRIS-HCl buffer (400 mM Tris-base, pH 8.0, containing 0.5 % SDS) was added. The samples were incubated in a water bath at 60°C for 1 h. Subsequently, 100 µL of Proteinase K and 1 mL of 5 mM $CaCl_2$ were added, followed by incubation at 50°C for an additional 2 h.

After enzymatic digestion, the samples were agitated in a rotary incubator at 450 rpm for 20 min, followed by a secondary thermal treatment at 60°C for an additional 20 min to ensure complete enzymatic activity. The digested samples were vacuum-filtered through pre-cleaned glass fiber membrane filters (Filter-Lab, MFV3/047).

Retained particles on the filters were examined using a Leica DM500 compound light microscope at 10x and 40 x magnifications. Visual identification was performed based on morphological characteristics, such as size, color, and shape, following the modified criteria of Hidalgo-Ruz et al. (2012). The particle sizes were measured using the ImageJ software, according to the method described by Cabansag et al., 2021.

Suspected particles were analyzed using attenuated total reflectance Fourier-transform infrared (ATR-FTIR) spectroscopy (PerkinElmer Spectrum Two, USA) at the Department of Chemical Engineering, Ondokuz Mayıs University (Samsun, Türkiye). Spectra were acquired in the 600–4000 cm^{-1} range with 32 scans per sample, at a resolution of 4 cm^{-1} in absorption mode. Particles smaller than 20 µm were excluded from the ATR-FTIR analysis due to the known spatial resolution limitations of the method. Polymer identification was performed exclusively on particles ≥ 20 µm, in accordance with established analytical capabilities of ATR-FTIR spectroscopy.

2.7. Estimation of microplastic exposure via deterministic model

Microplastic exposure through ice cream consumption was estimated using a deterministic model adapted from Basaran et al. (2023). The estimated daily intake (EDI) was calculated using the following formula:

$$EDI = \frac{M_a \times M_c}{BW} \quad (1)$$

EDI: Estimated daily intake (particles kg BW^{-1} day^{-1}),
Ma: Amount of ice cream consumed (mL day^{-1}),
Mc: Microplastic concentration in the sample (particle mL^{-1})
BW: Body weight (kg).

2.8. Microplastic Contamination Factor (MCF) and Pollution Load Index (MPLI)

The Microplastic Contamination Factor (MCF) and Pollution Load Index (MPLI) were calculated following the methodology proposed by Christian et al. (2022). The MCF for each individual sample was determined using the following equation:

$$MCFi = \frac{\text{MPi}}{MPi} \quad (2)$$

MPi: Microplastic concentration in sample i (particles/kg)

MPb: Baseline microplastic concentration in processed foods (1.68 particles/kg, as reported by Lin et al. (2022).

The Pollution Load Index (MPLI) was subsequently calculated as the geometric mean of the individual MCF values across all analyzed samples:

$$MPLI = \left(\prod_{i=1}^{n} MCF_i\right)^{\frac{1}{n}} \quad (3)$$

Where n denotes the total number of samples analyzed.

Risk classification threshold for MCF and MPLI values were adopted according to the criteria proposed by Ibeto et al. (2023) and Christian et al. (2022), as presented in Table 2.

2.9. Statistical analysis

The effects of brand and price category on the microplastic concentrations in the ice cream samples were analyzed using two-way ANOVA. Prior to hypothesis testing, descriptive statistics and the Shapiro-Wilk

Table 2
Risk category assessment.

MCF	Contamination level
MCF < 1	Low
1 ≤ MCF < 3	Medium
3 ≤ MCF < 6	Significant
MCF ≥ 6	Very high

MCF: Microplastic contamination factors

test were performed separately for each group to evaluate the normality assumption. A two-way ANOVA was conducted to test for statistically significant main effects of brand and price category, as well as their interaction ($p < 0.05$). All statistical analyses were performed using IBM SPSS Statistics, version 23.

3. Results

3.1. Determination of micro- and nanoplastic particles

MNP contamination was assessed in 39 ice cream samples representing various commercial brands and price categories. Prior to filtration, the optical properties of the glass microfiber filters were examined under a light microscope equipped with a digital camera to prevent the misidentification of background artifacts. Following sample filtration, the retained particles were analyzed microscopically to characterize their key features, including color, morphology, particle count, and length (Fig. 1).

A total of 75 MNP particles were identified in all the analyzed samples. The most frequently observed morphologies were filament (n = 42), irregular fragments (n = 22), and thin films (n = 11) (Tables 3 and 4). The particles exhibited a broad color spectrum, including black, green, red, blue, white, transparent, yellow, and purple, indicating diverse sources of origin and notable compositional heterogeneity.

Results from the two-way ANOVA revealed no statistically significant differences in MNP concentrations among ice cream samples from different brands ($p = 0.988$; Table 5), indicating a relatively consistent level of contamination across companies. Additional analyses were performed to assess whether price categories within each brand affected microplastic levels. Although minor variations were observed across different price tiers, these differences were not statistically significant ($p = 0.667$), suggesting that product price is not a reliable indicator of MNP content.

The interaction effect between brand and price category was also examined to assess whether the influence of pricing on MNP concentrations varied across brands. Although this interaction was not statistically significant ($p = 0.167$), the observed partial eta squared value ($\eta^2 = 0.296$) indicated a moderate effect size. While not conclusive, this suggests that the interaction may be practically meaningful, and that a larger sample size could potentially yield statistically significant results.

Collectively, these findings underscore the need for further employing larger datasets to clarify whether brand identity or pricing structure significantly influences MNP contamination in ice cream products. Future studies that incorporate broader sampling framework,

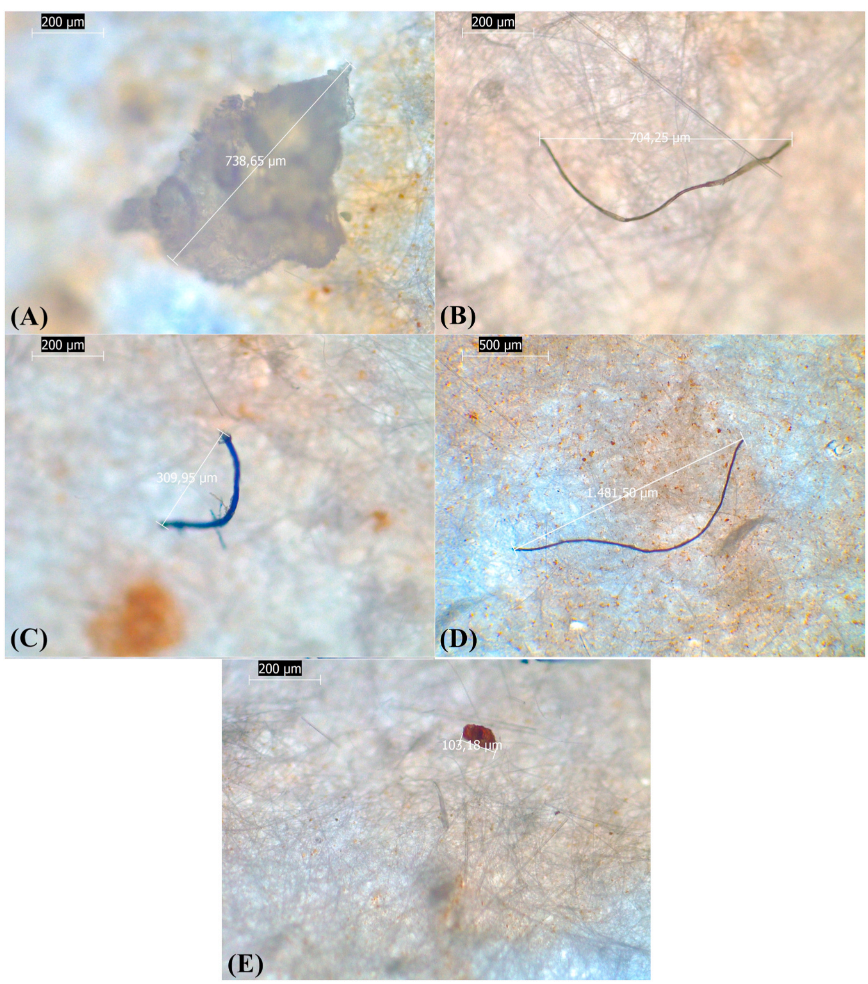

Fig. 1. Image and dimensions of microplastics under binocular biological microscope. A: PET-738.65 μm, B: PE-704.25 μm, C: PS-309.95 μm, D: PP-1481.50 μm, E: PVC-103.18 μm.

Table 3
Colors, shapes, and numbers of different plastics detected.

Brand	Price Range ($)	Color	Fragment	Filament	Film	Particle Count
A	0.50–1	ND	ND	ND	ND	ND
A	1.1–2	Black-Green	ND	6	ND	6
A	2.1–3	Red-Black-White	1	8	2	11
A	3.1–4	Blue-White-Black	ND	4	3	7
B	0.50–1	Black-Red-White	1	5	3	9
B	1.1–2	Transparent	1	1	ND	2
B	2.1–3	Red-Blue-Yellow	1	4	1	6
B	3.1–4	Black-Blue-Transparent-Yellow	2	4	ND	6
C	0.50–1	Transparent-Black-Yellow-Purple-Blue-Red	10	1	1	12
C	1.1–2	Red-Transparent-Blue	2	2	ND	4
C	2.1–3	Black-Transparent	2	3	ND	5
C	3.1–4	Black-Red-Green	2	2	ND	4
D	3	Blue-Transparent-Black	ND	2	1	3
Total			22	42	11	75

ND: Not detected

Table 4
Size Distribution of MNPs.

Brand	Price Range ($)	Total Number of Particles	Size Distribution of MNPs in Samples (μm)	
			Range (mean ± SD)	Median
A	1.1–2	6	476.616–1146.994 859.183 ± 306.872	980.768
A	2.1–3	11	124.051–680.191 332.751 ± 233.091	166.57
A	3.1–4	7	71.047–1330.383 590.140 ± 532.519	471.572
B	0.50–1	9	95.257–3600.986 1270.402 ± 1187.113	1660.888
B	1.1–2	2	732.348–1863.656 1298.002 ± 799.955	1298.002
B	2.1–3	6	101.425–2225.339 770.723 ± 792.347	608.994
B	3.1–4	6	445.471–461.581 420.588 ± 57.616	445.471
C	0.50–1	12	23.287–512.514 128.822 ± 147.880	65.856
C	1.1–2	4	42.433–1075.028 446.507 ± 462.736	334.285
C	2.1–3	4	42.385–650.387 362.602 ± 275.211	378.818
C	3.1–4	4	37.500–151.297 539.682 ± 726.258	264.965
D	3	3	110.952–352.792 271.418 ± 138.972	350.51

Table 5
Two-way ANOVA results for MNP levels by company, price category, and their interaction (F, p-value, partial η^2).

Source	F	p-value	Partial η^2
Firm	0.043	0.988	0.005
Price	0.529	0.667	0.062
Firm x Price	1.685	0.168	0.296
Model Significance	0.997	0.480	0.333

variations in production methods, and geographic sourcing are warranted to gain deeper insights into the underlying drivers of MNPs occurrence in processed foods.

The polymer identification of the detected MNP particles was performed using ATR-FTIR spectroscopy. In accordance with the method's spatial resolution limitations, only particles ≥ 20 μm in size were subjected to polymer analysis. The results revealed that the most frequently identified polymer types were polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyethylene (PE), and polyvinyl stearate (PVS). These polymers are widely used in food packaging, industrial components, and storage materials, suggesting multiple potential entry points for contamination within the production and distribution chains. The representative ATR-FTIR spectra of the identified polymers are shown in Fig. 2.

3.2. Dietary exposure estimation

Türkiye's annual ice cream output is approximately 460,000,000 L based on national production statistics; reported per-capita consumption is ~4–4.2 L and shows pronounced summer seasonality. (Arslaner & Salik, 2020). Ice cream is particularly popular among children and adolescents, especially during the summer months, raising concerns about early-life exposure to MNPs due to frequent intake. Dietary exposure levels were estimated using the deterministic model described in 2.4. The daily intake of ice cream was assumed to be 12.6 g, and the average body weight was 73.7 kg, based on national demographic statistics. Microplastic exposure levels were calculated using Eq. 1. The results, stratified by brand and price category, are presented in Table 6.

As shown in Table 6, the estimated daily and annual MNPs exposure levels from ice cream consumption were quantified across different brands and price categories. For context, Yadav et al., (2022) reported average daily MNP exposure levels of 382 particles from drinking water, 594 particles from inhaled air, and 1036 particles from food sources. These comparisons highlight the cumulative nature of MNPs exposure through multiple environmental and dietary pathways. Although the levels detected in ice cream represent a relatively small proportion of total daily intake, their significance becomes more pronounced when considered alongside habitual consumption patterns – particularly among children and other high-consumption populations. The observed variability in exposure estimates across samples aligns with previous studies, reflecting the combined influence of food intake behaviors and environmental contamination levels on individual MP burden.

3.3. Microplastic contamination factors and pollution load index

The calculated Microplastic Contamination Factors (MCF) and Microplastic Pollution Load Index (MPLI) values for the analyzed ice cream samples are summarized in Table 7. These indices provide a standardized framework for assessing the extent of MP contamination across different sample groups. While most samples fell within the low to moderate contamination range, notable variations were observed among brands and price categories, reflecting heterogeneity in contamination sources and production practices.

The results indicate a measurable level of MNPs contamination across all ice cream samples. Considering the multifaceted nature of ice cream production, potential contamination pathways may originate from upstream sources – such as animal feed and auxiliary raw

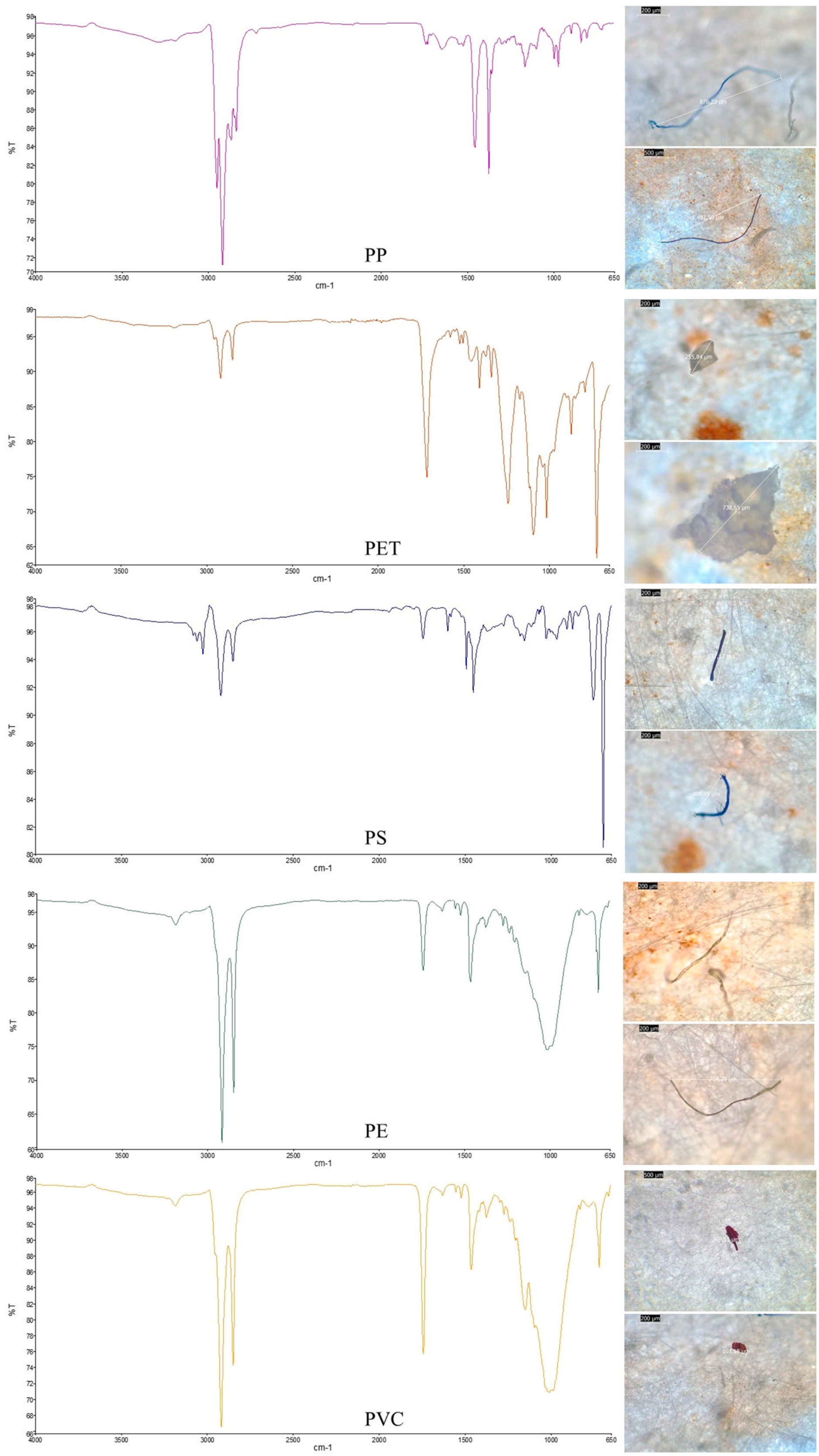

Fig. 2. ATR-FTIR typing results.

Table 6
Daily and annual plastic exposure due to ice cream consumption.

Brand	Price Range ($)	Amount of Exposure (Daily) (particle/mL^{-1} BW^{-1}/day^{-1})	Exposure Amount (Annually) (particle/mL^{-1} BW^{-1}/$annually^{-1}$)
A	0.50-1	ND	ND
A	1.1-2	1.03	375.95
A	2.1-3	1.89	689.85
A	3.1-4	1.2	438
B	0.50-1	1.5	547.5
B	1.1-2	0.34	124.1
B	2.1-3	1.03	375.95
B	3.1-4	1.03	375.95
C	0.50-1	2.05	748.25
C	1.1-2	0.7	255.5
C	2.1-3	0.85	310.25
C	3.1-4	0.7	255.5
D	3	0.5	182.5

: Estimated microplastic exposure amount green: Low; red: High,
ND: Not detected

Estimated microplastic exposure amount green: Low; red: High, ND: Not detected

Table 7
Results of microplastic contamination amounts and microplastic pollution load index.

Brand	Price Range ($)	Particle Number	MCF	Contamination Level	MPLI
A	0.50-1	ND	ND	-	-
A	1.1-2	6	3,57	Significant	1.033
A	2.1-3	11	6,54	Very high	1.049
A	3.1-4	7	4,16	Significant	1.037
B	0.50-1	9	5,35	Significant	1.043
B	1.1-2	2	1,19	Medium	1.004
B	2.1-3	6	3,57	Significant	1.033
B	3.1-4	6	3,57	Significant	1.033
C	0.50-1	12	7,14	Very high	1.051
C	1.1-2	4	2,38	Medium	1.022
C	2.1-3	5	2,97	Medium	1.028
C	3.1-4	4	2,38	Medium	1.022
D	3	3	1,78	Medium	1.014

MCF: microplastic contamination factors, MPLI: microplastic pollution load index

: Microplastic contamination rates by brands and price. Green: Low; Red: High;
ND: Not detected

MCF: microplastic contamination factors, MPLI: microplastic pollution load index
Microplastic contamination rates by brands and price. Green: Low; Red: High; ND: Not detected

ingredients – and extend to downstream factors including industrial equipment and packaging. Polymer characterization revealed a predominance of PP, a material widely employed in food-grade packaging, implicating packaging-related migration as a key contributor. The additional detection of PS, PE, and PVS across multiple samples further supports the hypothesis that contamination may occur at various stages along the production and supply chain. These observations underscore the urgent need for targeted mitigation strategies and regulatory oversight to reduce microplastic migration in processed dairy products.

4. Discussion

This study represents the first systematic investigation of MNP contamination in ice cream—a widely consumed dairy product with high seasonal intake, particularly among children. Across 39 samples spanning multiple brands and four price categories, we identified 75 particles in 117 replicates; diverse polymer types, morphologies, and colors were consistently observed, with 84.6 % of sample categories (11/13) containing $\geq$ 3 MNPs, one (7.7 %) containing two, and one (7.7 %) testing negative (Table 3). Within our analytical window (optical screening $\geq$10–20 µm; ATR-FTIR confirmation $\geq$20 µm), we interpret the observed polymer and size profiles from a supply-chain perspective, considering both upstream (raw milk collection and transport) and downstream (processing and packaging) stages as plausible contributors. This framing highlights the study's contribution relative to prior dairy reports and supports the identification of practical HACCP/ISO 22000 control points across the chain, from farm collection and plant reception through to filling and packaging.

Potential contributions before ice cream mix preparation cannot be quantified in the present study, as raw milk and in-process streams were not sampled. Nevertheless, microplastics have been reported in milk and dairy matrices, and PET/PE/PP are frequently observed among dominant polymers, which may reflect a combination of packaging- and process-contact inputs (Visentin et al., 2025). At farm, collection, and transport stages, elastomeric food-contact materials (e.g., hoses, gaskets, seals) are widely used; under mechanical wear and cleaning/thermal stress, these materials may represent plausible pathways for particle introduction (Kühne et al., 2021). In addition, multi-node investigations in fermented-dairy production lines (e.g., ayran) have shown that MPs can be detected across ingredients, processing steps, and packaging materials, supporting the view that both equipment interfaces and packaging may contribute to the final product burden (Buyukunal et al., 2023). Accordingly, we discuss upstream stages as plausible pathways—not source-attributed measurements—and frame them as potential HACCP/ISO 22000 attention points (e.g., hygienic design, material selection, and preventive maintenance of hoses/valves/seals) to minimize baseline loading before standardization and downstream packaging.

To date, no study has specifically examined MNP contamination in ice cream on a global scale, positioning the present study as a pioneering contribution to this critical research gap. Despite the lack of direct investigations, multiple potential contamination pathways can be inferred by considering the complexity of dairy supply chains and the industrial production of ice cream in Türkiye. Starting from milk collection, plastic pipes, valves, and tanker transport systems introduce notable contamination risks, particularly through mechanical abrasion and residual cleaning agents such as detergents and water additives. Rubber-based components may also leach synthetic particles into the milk matrix of the dairy products. In the production phase, auxiliary ingredients – including sweeteners, emulsifiers, chocolate or fruit inclusions – as well as direct contact with plastic packaging materials may further elevate the MNP burden. Additionally, on-farm practices involving synthetic gloves, milking equipment, and sanitation agents may contribute to early-stage contamination, potentially leading to MNP transfer into raw milk. These cumulative inputs across the production continuum underline the urgent need for integrated monitoring protocols and contamination control measures at both the farm and processing levels (Da Costa Filho et al., 2021).

An often under-recognized yet significant source of MNP infiltration in dairy processing is the filtration system itself. Mechanical stress and chemical degradation of filter seals, gaskets, and membrane components can lead to polymer leaching directly into the milk stream. In commercial practice, ultrafiltration is routinely applied to reduce microbial load and remove suspended solids before downstream processing such as ice cream production (Kumar et al., 2013; Tomasula & Bonnaillie, 2015). However, if filtration units are not properly maintained or replaced at recommended intervals, biofouling and mineral scaling may compromise membrane integrity. These structural alterations can increase pore size and allow polymeric debris to bypass the filtration barrier, ultimately contributing to MNP contamination of the final product (Maliwan and Hu, 2025; Yadav and Morison, 2010). This mechanistic vulnerability reinforces the need for rigorous equipment monitoring and preventive maintenance within dairy production facilities.

The polymeric profile of the detected MNPs provides valuable insights into their likely origins within the food processing and packaging continuum. Notably, sulfone-based polymers – widely used in the fabrication of ultrafiltration and microfiltration membranes due to their high hydrolytic resistance, broad pH tolerance, and mechanical robustness – have been implicated as potential contributors to contamination during dairy processing (Nady, 2016; X. Tan and Rodrigue, 2019). In addition, the identification of propylene-ethylene copolymers, which are routinely employed as sealing materials in closed-loop air and fluid transmission systems (Kühne et al., 2021), supports the hypothesis of contamination via gaskets, valves or processing conduits. These polymers were also confirmed as the primary constituents of packaging material used across all sampled ice cream products, reinforcing the dual role both processing equipment and packaging as plausible contamination sources.

The size of MNP particles plays a crucial role in determining their uptake efficiency across gastrointestinal, alveolar, and dermal epithelia. Empirical evidence indicates that over 90 % of ingested MNPs larger than 150 µm are excreted feces, while particles of this size can still cross the gastrointestinal barrier under conditions (Prietl et al., 2014). Notably, particles smaller than 10 µm have been reported to penetrate the alveolar epithelium following inhalation (Li et al., 2022), and those under 0.1 µm may even traverse highly selective physiological barriers such as the blood-brain barrier and placenta. Through endocytosis and phagocytosis, particles as small as 2.5 µm can gain access to systemic circulation (Kannan and Vimalkumar, 2021).

Although the MNPs detected in the current study were primarily larger in size, their potential for fragmentation into smaller particles during digestion or processing cannot be overlooked. These secondary fragments may pose an increased risk of systemic absorption and tissue accumulation. In addition to their physical effects, MNPs serve as vectors for environmental pollutants. Their high surface-area-to-volume ratio enables them to adsorb a broad spectrum of chemical contaminants, including endocrine-disrupting compounds such as bisphenol A, phthalates, and brominated flame retardants (Vethaak and Leslie, 2016). Thus, risk assessment efforts should consider both the intrinsic properties of MNPs and the potential for co-exposure to hazardous adsorbed compounds that may amplify toxicological outcomes.

To contextualize these findings, we briefly evaluate the analytical workflow regarding performance, cost, and suitability for routine dairy surveillance. The enzymatic protocol used here is cost-efficient and scalable for dairy matrices: it preserves polymer integrity while reducing lipid/protein interference, requires standard wet-chemistry equipment, and allows microscopy-guided targeted ATR-FTIR confirmation of $\geq$ 20 µm. Although more sophisticated pipelines (e.g., µ-Raman; FPA-µ-FTIR; Nile-Red imaging) may extend size coverage and throughput, they impose higher costs and can be hindered by fluorescence and pigment artifacts in complex foods. Thus, our workflow represents a pragmatic balance between analytical fidelity and routine surveillance feasibility in dairy products.

In this study, MNPs were observed in various colors, including black, blue, yellow, green, red, purple, transparent, and white. Although visual color serves as a preliminary indicator for distinguishing plastic types, it is not a definitive proxy for polymer identification. This is because synthetic pigments and color additives are often introduced during polymer manufacturing, resulting in overlapping color profiles across different polymer types (Azari et al., 2024; Lusher et al., 2020). Moreover, the visual appearance of MNPs under microscopy may be influence by pigment residues and additives derived from packaging materials, rather than the inherent characteristic of the base polymer (Oßmann et al., 2018). Therefore, FTIR spectroscopy remains essential for accurate polymer identification, as it enables compositional verification beyond superficial morphological characteristics.

The risk assessment conducted in this study was based exclusively on the quantitative detection of microplastic particles in the final food matrix – ice cream. This evaluation reflects the potential number of particles available for ingestion but does not account for their biological fate within the gastrointestinal tract. Parameters such as fecal elimination rates, intestinal absorption efficiency, or systemic translocation were not included in the current model (Dris et al., 2016). Nonetheless, the existing literature suggests that particles smaller than 1.5 µm may traverse the intestinal barrier via the paracellular pathway or transcytosis, while larger particles can still be internalized through endocytosis and phagocytosis (EFSA, 2016; Hwang et al., 2020; Kannan and Vimalkumar, 2021). It is also important to note that this study did not investigate the potential for chemical or microbiological contaminants absorbed onto the surface of MNPs, which may exacerbate health risks. Although scientific interest in this area is growing, the toxicokinetic, bioavailability, and long-term health implications of dietary MNP exposure remain insufficiently characterized. Notably, several studies have demonstrated that particles as large as 20 µm may cross biological membranes, accumulate in various tissues, and elicit cytotoxic and immunological responses via ingestion or inhalation (Kannan and Vimalkumar, 2021).

In the present study, 39 ice cream samples were analyzed, with three technical replicates per sample, yielding a total of 117 filters. Across these replicates, 75 MNP particles exhibiting diverse colors, shapes, and sizes were identified. Filaments constituted the most prevalent morphological category (n = 42, 56 %), followed by irregular fragments (n = 22, 29.3 %) and thin films (n = 11, 14.6 %). ATR-FTIR spectroscopic analysis revealed that PP was the most frequently identified polymer, although PS, PE, and PVS were also detected. According to the dietary exposure assessment, an average individual may ingest up to 750 MNP particles per year solely through ice cream consumption (Table 6). Furthermore, brand- and price-stratified analyses indicated that contamination risks ranged from moderate to very high, as reflected in the MCF and MPLI values (Table 7).

Given the findings of this study, the potential health implications of MNP ingestion through ice cream consumption warrant serious consideration – particularly for vulnerable populations such as children. According to Cox et al. (2019), the estimated annual MNP intake in humans ranges from 74,000 to 121,000 particles, influenced by factors such as age, body size, and dietary habits. These exposures are attributed to various sources, including sea salt (37–1000 particles/year), tap water (up to 4000), and shellfish (up to 11,000). More concerning, Pironti et al., (2021) reported that infants and children may ingest up to 1.58 million MNP particles annually, with regional estimates ranging from 14,600 to over 4.5 million particles – potentially up to 3000 times higher than adult levels. This stark discrepancy underscores the disproportionate exposure burden faced by younger individuals. Given their lower body weight and higher relative intake of sweetened dairy products, children are particularly susceptible to elevated MNP exposure per kilogram of body weight, especially through frequent consumption of low-cost, high-volume ice cream products.

Kutralam-Muniasamy et al. (2020) identified an average of 6.5 MNP particles (> 11 µm) in 23 milk samples, with variable colors – findings consistent with our results. Similarly, Zipak et al., 2022, in a systematic survey of 12 stages of yogurt production, reported 171 MNP particles, with particularly high contamination levels in raw milk and packaging materials. These observations suggest that plastic particles originated from both raw inputs and processing environments may persist through to the final product. Supporting this, our analysis revealed PP – commonly used in food packaging – as the most frequently detected polymer, indicating potential leaching during storage or handling.

In a recent study on yogurt, Ling et al. (2024) found PS, PP, and PE to be the most abundant polymers, which is consistent with the distribution observed in our ice cream samples. Da Costa Filho et al. (2021) employed Raman spectroscopy to detect PE, PES, PP, PTFE, and PS (≥ 5 µm) in raw farm milk, with concentrations ranging from 204 to 1004 particles per 100 mL – substantially higher than in most commercial products, potentially due to upstream contamination sources. Chakraborty et al. (2024) reported MNP levels of 279.47 ± 134.26 particles/kg in powdered milk and 182.27 ± 55.13 particles/L in fluid milk samples from Bangladesh, with PE being the dominant polymer. A high pollution load index was also noted, reinforcing concerns regarding the scale of contamination in dairy products.

In a study, Basaran et al. (2023) detected 264 plastic particles in 14 commercial milk brands. Ethylene vinyl acetate (EVA) was the most common polymer, followed by nylon, PE, PU, and PP. Interestingly, while packaging was PE-based, PE was not detected in the final product – indicating that processing stages may pose a more significant contamination risk than packaging itself.

These collective findings align with the hypothesis that thermal and mechanical stress during processing – such as pasteurization and sterilization – may promote the release of MNPs from food-contact surfaces. Ranjan et al., 2021, for instance, demonstrated that single-use paper cups released detectable amounts of MNPs into hot water within just 15 min, underscoring the influence of temperature on leaching behavior. When the current literature is viewed in conjunction with our findings, it becomes evident that the type, quantity, and morphology of MNPs detected in dairy products are influence by multiple variables – including raw material integrity, processing conditions, and packaging composition. In our study, PP and PE were among the most dominant polymer types, suggesting converging contamination pathways across different dairy product categories. These considerations motivate future work using a multi-node sampling design (raw milk → intermediate streams → finished product) to enable source apportionment with recovery-validated analytical methods.

5. Limitations and future directions

This study provides the first evidence of MNPs in commercial ice cream in Türkiye, yet several constraints should be noted. The sampling frame was modest and stratified by brand, price, and one unpackaged product to represent market segments rather than maximize sample size; each product was analyzed in triplicate (39 products; 117 technical replicates). Our analytical window enabled microscopy at ~10–20 µm with ATR-FTIR confirmation ≥ 20 µm, leaving particles < 20 µm largely uncharacterized. Although we used a plastic-free workflow with procedural/air blanks, we did not perform polymer-specific spike-recovery or establish method-level LOD/LOQ, and we conducted deterministic (average-intake) exposure estimates without toxicological assays. We also did not sample raw milk or intermediate streams; therefore, any discussion of upstream contributions is presented as process-informed interpretation rather than source-attributed measurement. Future studies should adopt chain-wide, multi-node sampling (e.g., farm bulk tank → tanker discharge → plant reception → standardized mix → finished product) to enable source apportionment. Methodological robustness could be strengthened by polymer-specific spike–recovery experiments with defined LOD/LOQ, inter-laboratory comparability checks, extension of particle identification below 20 μm (e.g., μ-Raman or FPA-μ-FTIR), and probabilistic exposure modeling stratified by age group and season. Source-oriented studies on equipment wear and packaging (polymer codes, holding times) and formal integration of MNP monitoring into HACCP/ISO 22000—via packaging logs and preventive-maintenance checkpoints—are likewise recommended to translate exposure into actionable risk reduction.

6. Conclusion

This study provides the first systematic evidence of micro- and nanoplastics in commercially available ice creams in Türkiye across multiple brands and price categories, with diverse morphologies and polymers (predominantly PP, alongside PE, PS, and PVS), indicating various entry points along the dairy supply chain. Beyond packaging and in-plant equipment, raw-milk collection and transport are plausible early sources. Translating surveillance into action requires embedding MNPs as a defined hazard within HACCP/ISO 22000, from farm to filler, supported by asset-level maintenance for liners/seals/membranes, as well as reception-bay audits and product-level packaging trace logs (including polymer code, lid/laminate, and holding time). Proportionate controls include preventive maintenance and sanitary design of high-wear components (such as membranes, gaskets, valves, and fillers), verification of seal integrity, minimization of mechanical agitation during storage/transport, and procurement/validation of lower-shedding food-contact materials through migration/abrasion testing under realistic time–temperature profiles. For quality programs, periodic contamination logs and targeted screening of high-consumption, high-moisture products (e.g., summer ice creams) can focus resources where exposure is highest—delivering measurable risk reduction while sustaining product quality and consumer confidence.

CRediT authorship contribution statement

Yasin Akkemik: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Data curation, Conceptualization. **Kemal Kaan Tekinşen:** Writing – review & editing, Supervision, Resources, Project administration. **Veysel Doğan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Sedat Gökmen:** Writing – review & editing, Writing – original draft, Methodology, Data curation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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