Forensic Science International 364 (2024) 112246

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

Presence of microplastics in human stomachs

Sait Özsoy [a,b,*], Sedat Gündogdu [c], Sermet Sezigen [d], Esra Tasalp [a], Durmuş Arinc Ikiz [b], Ahmet Erkan Kideys [e]

[a] Department of Forensic Medicine, Gulhane School of Medicine, University of Health Sciences, Ankara, Turkey
[b] Council of Forensic Medicine, Ankara Branch, Ankara, Turkey
[c] Faculty of Fisheries, Department of Basic Sciences, Cukurova University, Adana, Turkey
[d] Department of Medical CBRN Defense, University of Health Sciences, Ankara, Turkey
[e] Institute of Marine Sciences, Middle East Technical University, Erdemli, Mersin 33731, Turkey

ARTICLE INFO

Keywords:
Microplastics
Human exposure
Plastic pollution
Food
Autopsy
Gastrointestinal tract

ABSTRACT

This study presents the first definitive confirmation of microplastic presence in the human stomach, based on samples from 26 cadavers. 97 microplastic particles were extracted from stomach contents, across all 26 individuals, revealing a universal prevalence of microplastics in the cadavers. Morphological analysis of the extracted particles unveiled distinct shapes, with fibers constituting the majority (52.04 %), followed by fragments (39.80 %) and films (8.16 %). The average quantity of microplastics per individual was calculated to be 9.4 ± 10.4 particles, with an estimated daily intake of microplastics at 32.2 particles per day. These figures are lower than estimates derived from both daily microplastic consumption alone and notably, those calculated from stool analyses. Our study also suggests that the breakdown or transformation of microplastics cannot be ruled out during their passage through the digestive tract. Although the number of microplastics in stomach contents reported in this study was even lower than the daily microplastic intake rates reported in the literature, it provides conclusive evidence for the presence of microplastics in the human stomach and provides important preliminary data in terms of the risks that may arise for human health.

1. Introduction

The escalating production demand and subsequent environmental leakage make plastic pollution a paramount global issue, directly impacting human health as well. By the end of 2019, global plastic production was close to 10 billion tons [1]. Of this total, roughly 10 % underwent recycling, and 14 % underwent incineration, leaving the remaining 76 % in landfills, dumps, or dispersed in the natural environment [2]. A staggering 22 % of all plastics produced globally is estimated to be mismanaged, contributing to environmental leakage [1].

While a significant quantity of plastics is intentionally produced as microplastics for various sectors, the inevitable breakdown of macroplastics into microplastics or nanoplastics is a growing concern. Microplastics (MPs) are defined as plastic particles with sizes ranging from 1 μm to 5 mm [3]. Nanoplastics is used for plastic particles at the nanometer dimension, covering 1–1000 nm (i.e. = <1 μm). Considering a specific weight of 1, the 22 million tons of plastics, previously calculated and reported to have leaked into the environment for the sole year of 2019 [1], results in a staggering outcome—approximately 5×10^26 micro-particles when hypothetically broken down to a size of 100 μm in diameter, posing a significant impact on the world's ecosystems and eventually to human. To put this into perspective, it is noteworthy that the estimated number of individual live insects at any given time is significantly lower, approximately only 10×10^18 [4].

Whether in the form of macro-, micro-, or nanoplastics, these materials can inadvertently be ingested by a large number of aquatic or terrestrial animals. Consequently, they have been discovered in the stomach contents of a diverse array of terrestrial and aquatic organisms, ranging from earthworms and birds to zooplankton, fish, shellfish, turtles, dolphins, and whales [5–9].

Micro- or nano plastics also traverse the food web, reaching higher organisms, including humans. Therefore, plastic pollution is recognized not only as a significant environmental threat but also as a critical concern for human health. Recently, heightened attention has been directed towards the matter of human exposure to microplastics, driven by mounting concerns about its potential risks. The measurement of

* Corresponding author at: Department of Forensic Medicine, Gulhane School of Medicine, University of Health Sciences, Ankara, Turkey.
E-mail addresses: ozsoysmd@gmail.com, sait.ozsoy@sbu.edu.tr (S. Özsoy), sgundogdu@cu.edu.tr (S. Gündogdu), sermet.sezigen@sbu.edu.tr (S. Sezigen), esra.tasalp@sbu.edu.tr (E. Tasalp), arinc33@hotmail.com (D.A. Ikiz), kideys@metu.edu.tr (A.E. Kideys).

https://doi.org/10.1016/j.forsciint.2024.112246
Received 6 August 2024; Received in revised form 30 September 2024; Accepted 6 October 2024
Available online 9 October 2024

toxic chemicals in the human body, verification of exposure levels, and the implementation of public health protection measures are crucial. However, conducting a risk assessment for micro/nanoplastics is challenging due to the scarcity of data on both toxicological hazards and human exposure [10–12].

The exposure of humans to plastics, particularly those less than 10 μm in size, has become a prominent concern in this context. Studies conducted to date have primarily assessed human exposure to microplastics through inhalation [13], ingestion, and dermal contact [14]. Human exposure levels to microplastics vary according to age, sex, diet, and lifestyle [15].

Among these routes, ingestion, particularly through the consumption of food, stands out as a prevalent pathway for human exposure to microplastics. Numerous reports have highlighted the presence of microplastics in a wide variety of food items [16]. The research findings suggest a pervasive presence of microplastics across a diverse range of human-consumed food, beverage items, and plastic food packaging [15]. Notable examples include table salts [17], meat products [18], sushi seaweed (nori) [19], rice [20], vegetables, and fruits [21], mussels [22], fish [6,23], and various beverage products [24].

When inhaled, microplastics, depending on their size, may permeate various organs or tissues by entering the bloodstream through the lungs. Similarly, plastic particles taken up in the intestine could also be transported throughout the body via the bloodstream. The translocation of microplastics through either intestinal absorption or epidermal infiltration, and nanoplastics through blood circulation, has been extensively documented in fish [25,26]. Hence, the growing number of studies revealing the presence of plastic particles in various human organs is not surprising. The widespread presence of microplastics has been detected in human blood [12] lungs [27], saliva [28], sputum [29], placenta [30], stool [31–33], liver [34], and urine [35].

The World Health Organization [13] underscores the imperative for enhanced estimations regarding the exposure of the general population to micro/nanoplastics and its co-pollutants through both inhalation and dietary pathways. This data is crucial for understanding the relationship between the human exposure dose of microplastics and their toxic biological effects. The toxic effects of microplastics mainly depend on the physicochemical properties of the particle, the co-existence of organic pollutants, heavy metals that are adsorbed by the particles, and exposed cell types. Potential toxicity mechanism of microplastics includes oxidative stress due to increased intracellular reactive oxygen species (ROS), induced inflammatory response, and disruption of the energy homeostasis and metabolism which could lead to cytotoxicity, genotoxicity, metabolic disorders, and even carcinogenicity [15,36,37].

Recent studies have demonstrated adverse health effects due to the presence of micro/nanoplastics in humans. The study conducted by Yan et al. presents findings that indicate a positive correlation between the severity of inflammatory bowel disease (IBD) and the concentration of faecal microplastics [33]. Laboratory tests have demonstrated that microplastics can induce harm to human cells, triggering allergic reactions and even cell death [38]. Nanoplastics have been found to interact with the brain's naturally occurring protein; α-synuclein and resulting in alterations associated with both Parkinson's disease and certain forms of dementia [39]. A potential link between colorectal cancer and microplastic exposure levels has been proposed, based on the analysis of both tumoral colon tissues (TCT) and non-tumoral colon tissues (N-TCT) from patients diagnosed with colorectal adenocarcinoma [40].

Although micro/nano plastics have been identified in various human tissues, organs, fluids (such as blood and milk), and faeces excretion, to our best knowledge, no studies have specifically detected microplastics within human stomach content despite the human gastrointestinal system the primary target of toxic effects of ingested microplastics [37]. While numerous studies have demonstrated the presence of microplastics in a diverse range of food and beverages, their existence and behaviour in the highly acidic (pH = 1.5–2) environment of the human stomach remain unexplored, constituting the primary objectives of the current study.

2. Material and methods

2.1. Sample collection

In this study, microplastic samples were procured from the stomachs of 26 cadavers, with individuals having empty stomachs or gastrointestinal injuries systematically excluded from the study. Details pertaining to the cadavers used for microplastic sampling from the stomach are summarized in Table 1. Authorization for microplastic sampling from the cadavers' stomachs was granted by the Scientific Research Committee of the Presidency of the Forensic Medicine Institute of Istanbul, Turkiye.

Before sample collection, metal equipment was rinsed with distilled water and pre-filtered acetone. Chemically resistant, amber-coloured glass laboratory bottles (100 mL) with aluminium screw caps were also rinsed twice with pre-filtered acetone. After drying, empty bottles, screw caps, and metal equipment's were covered with aluminium foil

Table 1
Cadaver information used for microplastic sampling extracted from the stomach.

Cadaver Code	Sex	Age (y)	BMI (kg/cm^2)	Cause of death*	Toxicology*	PMI (min)
1	M	60	29	CAD	Cardiac medications	1140
2	M	63	16	Methanol intox.	Methanol	150
3	M	30	24	Hanging	Ethanol, Meth, MDMA	600
4	M	65	36	CAD	Cardiac medications	105
5	F	24	24	Hanging	Antidepressants	910
6	F	50	38	CAD	Ethanol	815
7	F	58	23	CAD	Antidiabetics	105
8	M	37	23	Gunshot wound	NONE	200
9	M	41	21	Hanging	NSAID	400
10	F	72	46	CAD	Antidiabetics	672
11	M	39	23	CAD	Cardiac medications	210
12	F	68	26	CA	Cardiac medications, Ethanol	1260
13	M	32	24	Traffic accident	NONE	235
14	M	24	25	Drug intoxication	MDMA	240
15	M	54	17	Pneumonia	Antiepileptics	365
16	M	58	30	Traffic accident	Cardiac medications	215
17	M	57	29	CAD	Cardiac medications	630
18	M	37	21	Hanging	Antipsychotics	510
19	M	58	27	CAD	Cardiac medications	190
20	M	61	29	Fall from height	Antidepressants	710
21	M	26	23	Hanging	Ethanol, antidepressants	725
22	M	45	20	Fall from height	Antidepressants	1050
23	M	53	23	CAD	NONE	404
24	M	18	27	CAD	NONE	750
25	M	45	34	CAD	NONE	485
26	F	43	24	Pneumonia	NSAID	825

* PMI: Postmortem Interval (time of death); M: Male; F: Female; CAD: Coronary artery disease; CA: Endometrial cancer; BMI: Body mass index; Toxicological examination results of the cases: Meth: Methamphetamine; NSAID: Non-steroidal anti-inflammatory drugs; MDMA: 3,4-metilenedioksi- N-metilamfetamin.

until the sampling.

During the autopsy, the stomach was removed and dissected from the pylorus. A 50 mL of stomach-duodenum content from each case was transferred into a separate, amber-coloured glass bottle, uniquely coded with a numeric identifier. The bottle was covered with a new layer of aluminium foil before sealing with a screw cap.

All sampling procedures were meticulously executed within a Biosafety Level Two (BSL-2) autopsy laboratory, featuring state-of-the-art HEPA filters and a dedicated aeration system. The sampling was carried out by the autopsy team, using personal protective equipment (PPE).

2.2. Stomach content digestion and filtration

Microplastics extraction from the samples was carried out by the methodology employed by Gündogdu and Kösker [41]. In detail, the sample from each individual was placed in a pre-cleaned beaker and the beakers were then covered with aluminium foils against airborne contamination. For the digestion of organic material, a solution of 30 % KOH: NaClO was used. This solution was a mixture of 700 mL of microfiltered water, 150 mL of saturated KOH solution (1.120 g/L), and 150 mL of NaClO containing 14 % active chlorine [41]. Afterwards, 250 mL of the solution was added to each beaker containing the sample. The beakers were then covered with aluminium foil and kept on a hot plate at 50 °C for one week until the organic material was fully digested. After completely dissolving the organic materials, the solution was transferred to a separation funnel and 500 mL (5 M 1.6 g/mL density) NaI solution was added to the samples. After waiting for one day for the density separation, all settled material was removed and the supernatant was transferred to a separate sterile beaker and filtered through a GF/C filter paper with a pore size of 0.45 μm. Finally, the filter papers were put in clean Petri dishes for microscopic and spectroscopic analysis.

2.3. Chemical characterization of particles using μ-Raman analysis

MP-like particles on the filter paper were initially counted under a microscope and all counted particles were analysed for chemical composition using a Renishaw InVia Qontor confocal Raman microscopy system (Renishaw Plc, New Mills, Wotton-under-Edge Gloucestershire, UK) with 532 nm and 785 nm lasers. The particles were examined under a Leica microscope at 50x magnification. Two cumulative readings were taken with a spectral range between 300 and 3200, an exposure of 10 seconds, and grating settings varying from 600 l/mm to 1200 l/mm. The obtained spectra were compared to those in the ST-Japan microplastics library. The ratio of MP-positive results from polymer identification to the total presence of microplastics was used as a correction factor.

2.4. Quality assurance and contamination control measures

To ensure the prevention of potential contamination during the study, all equipment underwent a rigorous cleaning process involving three washes with MilliQ distilled water, followed by pre-filtered acetone before usage. The cleaned equipment was stored in a closed cabinet (Class-4, Esco Technologies Inc.) throughout the study. To eliminate the possibility of contamination, solutions, and solvents used in the analytical processes were filtered through GF/C Whatman filter paper with a pore size of 0.45 μm, utilising a vacuum pump from Millipore. All analyses were conducted inside an enclosed laminar flow cabinet, and sample containers were consistently covered with aluminium foil during waiting periods. Work surfaces were thoroughly cleaned with acetone before and after each use. Microscopic examination was carried out using a microscope (SZX16, Olympus Co.), placed in a closed cabinet. All analyses were conducted while wearing cotton laboratory clothing.

All procedures employed in the actual sampling were also applied to a dummy sample set. To ascertain if there was any microplastic contamination from the surgical environment, the same method used for stomach contents was performed on dummy samples in four replicates. To simulate laboratory contamination, a dummy sample set ($n = 3$) was produced, as recommended by Dawson et al. [42]. Ultrapure water (water for injection, using Aqua-Nova distillation unit, Sweden) was added to pre-cleaned sterile sample bottles, and the stomach content sampling process was imitated. The filter papers were then also analysed by μ-Raman and the spectral profiles of the particles were investigated.

2.5. Statistical analysis

In this study, the normality of microplastic counts was assessed using the Shapiro-Wilk test, a widely accepted method for evaluating conformity to a normal distribution. Subsequently, to explore potential differences between males and females, the Mann-Whitney U test was employed. This non-parametric test is particularly suitable for comparing two independent groups, making it robust even in cases where the assumption of normality is not met. The statistical analyses were conducted using the Scipy stats module in Python, providing a comprehensive approach to both distributional assessment and group comparison.

3. Results

3.1. Demographic composition of cadavers

The study comprised 20 male (76.9 %) and 6 female (23.1 %) individuals. The median age was 46.8 years ranging from 18 to 72 years. Among the participants, 14 individuals (53.8 %) had normal weights (body mass index (BMI) ranging from 18.5 to 24.9), while 12 individuals (46.2 %) were classified as obese (BMI $\geqslant$ 30).

Autopsies were performed within a timeframe of 105 minutes to 1140 minutes after the death, with a mean duration of 534.6 minutes. The causes of death varied, with atherosclerotic coronary artery disease identified in 11 individuals (42.3 %), hanging in 5 individuals (19.2 %), major trauma in 4 individuals (15.4 %), and infection and cancer each accounting for 3 individuals (11.5 %). Additionally, drug abuse was reported in 2 individuals (7.6 %), and firearm injury in 1 individual (3.8 %) respectively.

Post-mortem toxicological analysis revealed the presence of antihypertensive and antidiabetic drugs in 9 individuals (34.6 %), and antidepressant drugs in 6 individuals (23.1 %). There was no chemical detected in 5 individuals (19.2 %). (Table 1).

3.2. Quality assurance and contamination control measures

In the microscopic analysis of control samples from the surgical environment examined, 14 particles (3.5 particles/replicate) with a size of 60–300 microns were detected. However, despite utilizing Raman analysis, no specific spectrum could be obtained from any of these particle's indicative of synthetic polymers. Consequently, it can be concluded that there is no apparent contamination from the surgical environment in this study.

In evaluating potential contamination from the microplastics laboratory, three control samples were scrutinized under a microscope. The findings indicated that there were 7, 2, and 4 particles detected in each respective sample, with an average length of 254 ± 125.2 μm (Table 2). We subjected all the particles to Raman analysis, revealing that only a total of three transparent fibers in the three Petri dishes exhibited peaks characteristic of cellulose, with no other synthetic plastic polymers detected. Additionally, a hot needle test was conducted on the particles, and they did not exhibit any plastic-like behaviour, such as shrinkage or melting when exposed to heat.

Table 2
Details of particles obtained from dummy sample analysis to measure laboratory contamination.

Dummy sample number	Shape	Colour	Size (μm)	Raman result
Sample−1	Fragment	Black	65,00	No peak
	Fiber	Transparent	120,00	Cellulose
	Fiber	Transparent	368,00	Cellulose
	Fiber	Transparent	274,00	Cellulose
	Fiber	Brown	94,00	No peak
	Fiber	Black	254,00	No peak
	Fragment	Black	169,00	No peak
Sample−2	Fragment	Green	74,00	No peak
	Fiber	Black	157,00	No peak
Sample−3	Fiber	Black	829,00	No peak
	Fragment	Cream	467,00	No peak
	Fiber	Black	148,00	No peak
	Fiber	Transparent	58,00	No peak

3.3. Particle characterization of microplastics via μ-Raman

A comprehensive Raman analysis was performed on 36 microplastic-like particles (out of 97 total), constituting 37 % of all particles (Fig. 1). This analysis led to the identification of 8 synthetic polymers and cellulose. Predominantly detected particles included Polyethylene (PE, 30.5 %), Polypropylene (PP, 13.9 %), Polymethyl methacrylate (PMMA, 13.9 %), Nylon-6 (Polyamide, 11.1 %), Polyethylene terephthalate (PET)/Polyester (11.1 %). Notably, cellulose, representing only 2.8 % of the particles was the sole microplastic in our contamination tests. Consequently, no adjustments were made to the average value, as such deductions would have had a negligible impact on the overall result.

3.4. Microplastics found in the stomachs

A total of 97 microplastic particles were extracted from the stomach contents of all 26 individuals (Fig. 2). Remarkably, microplastics were identified in the stomachs of all 26 cadavers. The observed range of microplastics in each sample varied from 1 to 14 particles. When assessing the overall gastric content, the total number of microplastics ranged from 1 to 39 particles per individual. The calculated average quantity of microplastics per individual was determined to be 9.4 ± 10.4 particles (Table 3).

The Shapiro-Wilk normality test value of 0.76 ($P < 0.05$) indicated that the data is non-parametrically distributed. Correlation analyses revealed no significant trends between the quantity of microplastics in the stomach and body mass index (BMI, $r^2 = 00002$), age ($r^2 = 0.02$), or post-mortem interval (PMI, $r^2 = 0.05$). However, while no statistical gender-based differences were evident in the Man-Whitney U analyses (46.5, $P < 0.05$), the average count of microplastics in females (7.1 ± 6.9 particles, n = 6) was approximately 30 % higher than that observed in males (10.2 ± 10.3, n = 20).

3.5. Morphology and length distributions of microplastics extracted

The morphology analysis of the extracted particles revealed distinct shapes, with fiber comprising the majority (52.04 %), followed by fragment (39.80 %), and film (8.16 %) (Table 3). Additionally, upon examining the colour pattern exhibited by the particles, it was discerned that there were 8 different colour variations. Notably, the prevailing colours were blue (38.8 %), black (24.5 %), transparent (11.2 %) and red (11.2 %).

The length of the extracted microplastics was found to be 802.1 ± 858.6 μm on average, with a minimum size of 51.53 μm and a maximum size of 4789.1 μm. After examining the different shapes, it was found that the fibers were 1196.6 ± 907.1 μm, the films were 635.6 ± 310.8 μm and the fragments were 330.4 ± 261.4 μm. For all microplastic types, there is an apparent skewness (i.e. the lack of symmetry) and kurtosis towards the left as seen for the total values in Fig. 3.

4. Discussion

This study utilizing samples from 26 cadavers marks the first confirmation of microplastics' presence in the human stomach, aligning with expectations. Recent studies have already shown that microplastics were observed almost in all stool samples; for example, Schwabl et al. (2019) found microplastics in the faeces of all eight healthy volunteers aged 33–65 years from Europe and Asia [31]. Zhang et al. found in faecal samples 23 (95.8 %) participants out of twenty-four participants tested positive for microplastics 18–25 years were recruited from Beijing, China [32]. Similarly, Yan et al. found microplastics in the faeces of all 102 individuals from Nanjing, China [33]. In our study, despite the consistent identification of microplastics in all individuals, the average count of 9.4 particles per individual revealed a broad range of values between 1 and 39 particles per individual and associated a notable standard deviation of 10.4. This is also not surprising as there was a high heterogeneity among the individuals in terms of age, gender, body mass index (BMI), health conditions, as well as the causes of death and post-mortem intervals (PMI) from which stomach samples were derived.

The transit time of food through the stomach varies based on factors such as the type and quantity of nourishment. Liquids typically exit the stomach more rapidly, while solid foods tend to have a longer residence time. As reported by Lee et al., the transit time of solid food in the human digestive system is characterised by the following intervals: gastric emptying (2–5 h), small bowel transit (2–6 h), colonic transit (10–59 h),

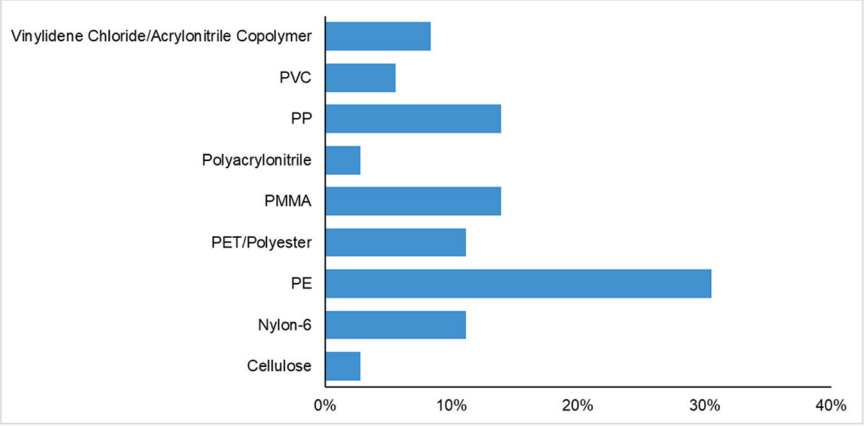

Fig. 1. Percentage distribution of polymer types identified by Raman analysis, encompassing 39 MP-like particles out of a total of 97 microplastics extracted from cadavers.

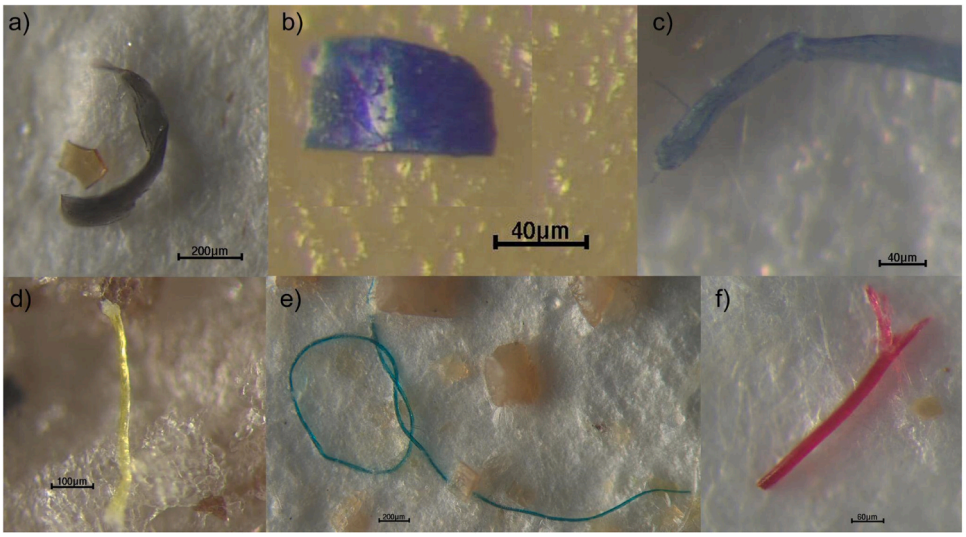

Fig. 2. Photos showing various types and shapes of microplastics extracted from the stomachs of cadavers. a) film and fragment, b) fragment, c) film, d) fiber, e) fiber, and f) fiber.

Table 3
The number of different types of microplastics (MPs) extracted from cadaver stomachs.

Cadaver Code	Total Gastric Content (mL)	Type of MPs			Total number of MPs in the sample	Total number of MPs in each cadaver
		Fiber	Film	Fragment		
1	100	9	0	5	14	28
2	100	3	0	1	4	8
3	100	0	0	1	1	2
4	100	0	0	2	2	4
5	150	2	0	0	2	6
6	50	0	0	2	2	2
7	250	0	0	2	2	10
8	100	1	1	0	2	4
9	100	2	0	1	3	6
10	50	1	0	0	1	1
11	200	0	0	1	1	4
12	75	12	0	1	13	19.5
13	100	1	0	0	1	2
14	75	1	0	0	1	1.5
15	100	1	0	0	1	2
16	300	1	1	1	3	18
17	500	0	0	3	3	30
18	150	9	2	2	13	39
19	50	3	0	2	5	5
20	75	1	0	2	3	4.5
21	50	2	1	9	12	12
22	100	0	0	1	1	2
23	50	0	0	1	1	1
24	150	0	1	1	2	6
25	400	0	2	1	3	24
26	200	1	0	0	1	4
Total	**3675**	**50**	**8**	**39**	**97**	**245.5**
Average	**141.3**	**1.9**	**0.3**	**1.5**	**3.7**	**9.4**
SD	111.3	3.1	0.6	1.9	4.2	10.4
Median					2	4.8

and whole gut transit (10–73 h) [43]. Given a presumed transit time of an average of 3.5 h and a feeding period of 12 hours for humans, the estimated average daily intake of microplastics could be calculated as approximately 9.4 microplastic particles multiplied by the ratio of the feeding period to the gastric transit time, resulting in an approximate value of 32.2 microplastic particles per day.

Regrettably, there is no existing study for a direct comparison with our observed values. However, indirect comparisons could be possible.

In a comprehensive evaluation, Cox et al. analysed 26 published studies on human microplastic uptake through consumption, encompassing over 3600 processed samples and accounting for approximately 15 % of Americans' caloric intake [44]. Their estimation, including microplastics less than 50 µm, suggests that daily microplastic consumption varies from 107 to 142 particles, depending on age and sex. Notably, our finding of 32.2 microplastics per individual per day, for microplastics >50 µm, is considerably lower than the indirect estimations calculated by Cox et al. [44]. It is noteworthy to mention that Cox et al. proposed even higher values (247 microplastics daily) for individuals who exclusively rely on bottled water to meet their recommended water intake [44].

On one hand, the detection of a high number of microplastics (median value of 41 particles/10 mL) in human sputum, ranging between 20 and 500 µm in size, confirms a significant exposure of the human digestive system to these pollutants [29]. On the other hand, several studies have documented the presence of microplastics in the spool of healthy individuals. Schwabl et al. reported an average concentration of 9.4 items/g, [31] and Zhang et al. reported 8.9 particles/g wet weight in human faeces [32]. Yan et al. recorded an average of 28.0 particles/g dry weight of stool for healthy individuals and 41.8 particles/g dry weight of stool for patients with IBD [33]. Considering that more than 70 % of stool is composed of water, Yan et al. value for healthy individuals in terms of wet weight (8.4 items/g wet weight) is likely to align within a similar range as the results of the previous two studies [33].

It is important to emphasize that the concentration of microplastics detected in faeces in these studies is not a direct equivalent to their concentration in the stomach, as reported in this study. On average, individuals expel around 30 millilitres of stool for every five kilograms of body weight per day [45]. For an individual weighing approximately 70 kg, this results in roughly half a kilogram of faeces daily. Considering the microplastic particles values found by Schwabl et al., Zhang et al. and Yan et al., the total amount of microplastics in the stool of healthy individuals with an average weight of 70 kg would be approximately range between 7 ×500 = 3500–9.4 ×500 = 4700 microplastics in the entire stool per day [31–33]. These values significantly exceed both our daily value calculated from the stomach content and estimations based on daily consumption.

One potential reason for the higher values calculated through consumption or observed in faeces could be the minimum size of microplastics studied between our study and the literature. In our study, the size range of microplastics was 51.5–4789.1 µm. While the size ranges in

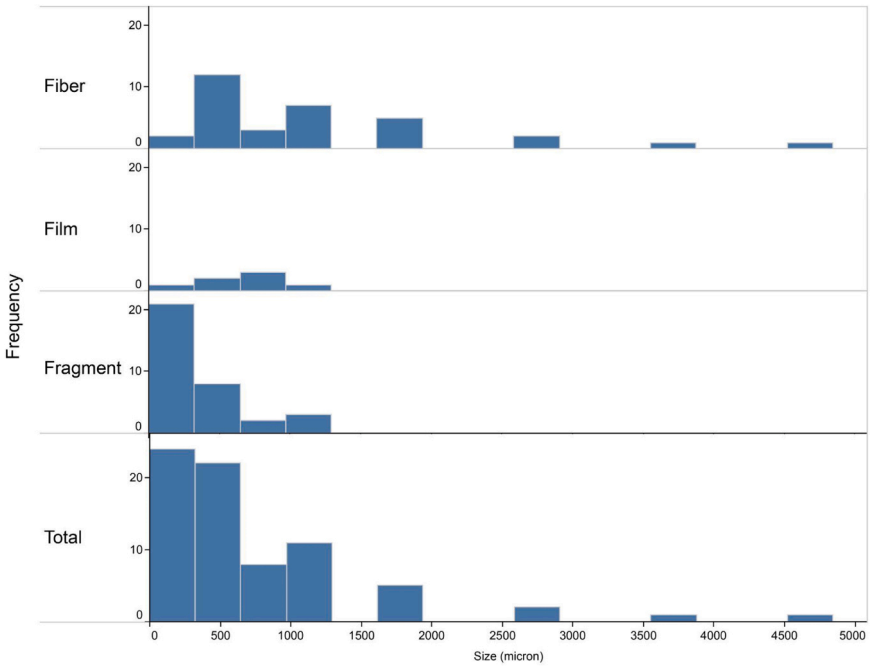

Fig. 3. The length frequency distribution of the 96 microplastics extracted from the cadavers.

studies reviewed by Cox et al. could vary considerably, some reported sizes as low as 10 μm, which is much smaller than our minimum size [44]. Zhang et al. reported a size range of 20–800 μm, encompassing relatively smaller microplastics in faeces [32]. Schwabl et al. identified faecal microplastic particles within the size range of 50–500 μm in their study [31]. Yan et al. reported a detected size range of 1.7–393.8 μm for microplastics in faeces from both healthy and IBD participants [33]. They noted that in both groups, over 97.5 % of microplastics were smaller than 300 μm, with about half being less than 50 μm in the faeces. Since we could not successfully analyse microplastics less than 50 μm in size, our concentration values may be substantially underestimated. Qian et al. recent study provides a compelling example supporting this suggestion [46]. They have very recently demonstrated that the actual concentrations of micro/nanoplastics in regular bottled water are two to three orders of magnitude higher (reaching an average of 24000 particles per liter) than previously reported results, which primarily focused on large microplastics at the level of 105 particles per liter. The pronounced skewness (i.e. the lack of symmetry) value of 1.58 and left kurtosis (heavy-tailed distribution having more outliers) value of 1.56, prominently favouring smaller sizes in our frequency distribution (refer to Fig. 3), is indicative of the abundance of smaller-sized microplastics in the human stomach in this study.

Furthermore, it is important to consider the prospect of decomposition or fragmentation of microplastics throughout their transit within the human digestive system, potentially contributing to an increased prevalence of faecal matter. The absence of larger particles (>800 μm) in the studies mentioned above is noteworthy, especially when contrasted with our findings, which revealed the presence of fibers measuring up to almost 5 mm. Such disparities may hint at a process involving chemical and/or mechanical breakdown of fibers, resulting in elevated levels of microplastics in stool samples. Adding to this, the stomach presents a highly acidic environment with a pH range of 1.5–3.5, primarily attributed to the presence of hydrochloric acid. Notably, a few studies have demonstrated the degradation of various forms of fibers in high hydrochloric acid environments, especially under elevated temperatures [47,48].

The potential breakdown of microplastics into smaller particles raises concerns about heightened risks, as they could have a higher possibility be absorbed along the intestinal tract, facilitating their entry into the circulatory system and various organs within the human body.

The study highlights that the observation of microplastics in the highly acidic environment of cadavers, as depicted in Fig. 2, does not conclusively indicate their degradation. Considering this, the authors recommend a more comprehensive approach to the analysis by advocating for the quantification of microplastics, along with an examination of their size distribution, throughout the entire digestive system—from the mouth to the anus. This proposed investigation could provide a more thorough understanding of whether microplastics undergo breakdown or transformation during their passage through the digestive tract.

Upon entry into the body through ingestion, the fate of foreign substances hinges on their ability to traverse biological barriers and distribute within the organism. Studies in mice indicate that certain particles can be transported to the liver via the circulatory system, recirculated through bile to the small intestine, and ultimately excreted in faeces [49]. According to WHO, data suggest that microparticles (>150 μm) are less likely to be absorbed, with absorption increasing as particle size decreases, particularly through oral exposure [13]. Nanoparticles (<1 μm), including the nano-sized fraction, are deemed more likely to be absorbed, though the characterization and quantification of uptake remain limited.

The gastrointestinal tract poses significant physiological barriers to particle absorption and systemic bioavailability. Mucus, a selectively permeable hydrogel known as mucin, serves as a crucial physical barrier against particle diffusion across epithelial tissues. Lai et al. demonstrated the rapid penetration of large polymer nanoparticles up to 500 nm through physiological human cervicovaginal mucus [50]. In addition to mucus, other sites of particle uptake, contingent on size, include enterocytes, intestinal macrophages, the epithelium of Peyer's patches, and the villus tips [51].

Yoo et al. propose an upper limit for endocytosis at around 500 nm, while particles exceeding this size are absorbed by intestinal macrophages [52]. Uptake of particles exceeding 1 μm is primarily attributed to specialize "microfold cells" in Peyer's patches [44,51,53]. Translocation and absorption of microparticles measuring less than 10 μm across microfold cells have been observed, involving active phagocytic transport from the gut lumen. These particles then migrate to the blood via mesentery nodes and the thoracic lymph duct [54]. Additionally, larger microplastics can undergo translocation through villous uptake, a

process known as "persorption" [55]. This passive absorption occurs for microparticles ranging from 5 to 150 μm, traversing the intestinal mucosa through gaps resulting from mechanical kneading of the single-layered intestinal epithelium. Volkheimer's experiments, conducted in both animals and humans, demonstrated the detection of starch particles up to 130 μm in diameter in the bloodstream following ingestion [56,57].

Cox et al. highlight the limited understanding of the effects of consuming microplastics on human health [44]. Once microplastics enter the gastrointestinal tract, there is the potential for the release of constituent monomers, additives, and absorbed toxins, posing a spectrum of physiological risks, ranging from oxidative stress to potential carcinogenic behaviour [58].

Li et al. proposes that as microplastics traverse the gastrointestinal tract, their interaction with the physiological processes of the body, particularly in the colon and rectum, may compromise the effectiveness of the protective colonic mucus layer, consequently elevating the risk of colorectal cancer [59]. Aligning with this hypothesis, Cetin et al. conducted a ground-breaking study that explored the presence of microplastics in both tumoral colon tissues (TCT) and non-tumoral colon tissues (N-TCT) of patients diagnosed with colorectal adenocarcinoma [40]. Notably, colon tissue (C group) samples from individuals without colorectal cancer were examined for the first time in this context. The findings revealed a significantly higher number of microplastics extracted from the TCT group compared to both the N-TCT and C groups. Cetin et al. study identified three specific microplastic polymers; polyethylene (PE), polymethyl methacrylate (otherwise known as acrylic glass, PMMA), and nylon (polyamide) in the spectra of the extracted microplastics [40].

Consistent with the findings of Cetin et al. our study also revealed the dominance of these three polymers, along with polypropylene, in the analysed samples [40]. Notably, the total number of polymers identified in our study, nine in total, was fewer than that reported by Yan et al., who identified 15 types of microplastics in faeces. In their study, polyethylene terephthalate constituted 22.3–34.0 %, and polyamide comprised 8.9–12.4 % of the detected microplastics [33]. Similarly, Zhang et al. noted the presence of eight types of microplastics in faeces, with polypropylene (PP) being the most abundant, followed by polyethylene terephthalate (PET), polystyrene (PS), PE, polyvinyl chloride (PVC), polycarbonate (PC), polyamide (PA), and polyurethane (PU) [32].

Interestingly, Yan et al. observed primary shapes such as sheets for polyethylene terephthalate and fibers for polyamide [33]. In contrast, our study found that fibers constituted more than half of the microplastics, followed by fragments, which aligns with findings from various Turkish environmental samples. For instance, Güven et al. reported 70 % fiber content in marine fish samples [6], while Gündogdu found 70 % fiber content in Turkish table salts [17], and Tutaroglu et al. reported 61.7 % fiber content in solid *Spirulina* products [60].

Furthermore, the prevailing blue colour (38.8 %) observed in this study was also dominant in Turkish environmental samples. Aydın et al. reported that in 25 studies conducted on various Turkish environmental samples, the most reported microplastic colour was blue [16].

The pervasive presence of microplastic particles across diverse environmental elements such as air, water, soil, organisms, food, and beverages underscore the extensive exposure of humans which may cause different toxic effects on specific organ systems. Despite being in the nascent stages, studies on microplastic-induced toxic effects in humans are becoming increasingly crucial, given the continual surge in plastics production. This upward trajectory suggests a probable escalation in the levels of microplastics and nanoplastics in human tissues and vital organs over time. The accumulation of knowledge on the levels and effects of microplastics and nanoplastics in various human tissues is crucial for understanding the significance of these contaminants for human health.

CRediT authorship contribution statement

Ahmet Erkan Kideys: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Durmus Arinc Ikiz:** Writing – original draft, Methodology, Data curation, Conceptualization. **Esra Taşalp:** Writing – original draft, Visualization, Methodology, Data curation. **Sermet Sezigen:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Data curation, Conceptualization. **Sedat Gündogdu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Sait Özsoy:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Data curation, Conceptualization.

Ethical approval/Consent for publication

Permissions were obtained from the Council of Forensic Medicine Scientific Ethics Committee (Ethics No: 2021/1053).

Funding

The authors have no relevant financial or non-financial interests to disclose.

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.

Data Availability

The data that support the findings of this study are included in this published article and available from the corresponding author, upon reasonable request.

References

[1] OECD (2022). Overview and policy highlights. In Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options. OECD Publishing, Paris, ⟨https://doi.org/10.1787/f9c3a6c4-en⟩.
[2] R. Geyer, Production, use, and fate of synthetic polymers, in: Trevor M. Letcher (Ed.), Plastic Waste and Recycling, Academic Press, 2020, pp. 13–32, https://doi.org/10.1016/B978-0-12-817880-5.00002-5.
[3] Arthur, C., Baker, J., & Bamford, H. (2009). Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris. Sept. 9–11, 2008. NOAA Technical Memorandum NOS-OR&R-30.
[4] Smithsonian (1996) Numbers of Insects (Species and Individuals). ⟨https://www.si.edu/spotlight/buginfo/bugnos⟩. (Accesses 27 June 2024).
[5] M. Cole, P. Lindeque, C. Halsband, T.S. Galloway, Microplastics as contaminants in the marine environment: A review, Mar. Pollut. Bull. 62 (2011) 2588–2597, https://doi.org/10.1016/j.marpolbul.2011.09.025.
[6] O. Güven, K. Gökdağ, B. Jovanović, A.E. Kideys, Microplastic litter composition of the Turkish territorial waters of the Mediterranean Sea, and its occurrence in the gastrointestinal tract of fish, Environ. Pollut. 223 (2017) 286–294, https://doi.org/10.1016/j.envpol.2017.01.025.
[7] A.L. Lusher, G. Hernandez-Milian, S. Berrow, E. Rogan, I. O'Connor, Incidence of marine debris in cetaceans stranded and bycaught in Ireland: recent findings and a review of historical knowledge, Environ. Pollut. 232 (2018) 467–476, https://doi.org/10.1016/j.envpol.2017.09.070.
[8] L. Svetlichny, M. Isinibilir, T. Mykitchak, K.M. Eryalçın, E.E. Türkeri, E. Yuksel, A. E. Kideys, Microplastic consumption and physiological response in Acartia clausi and Centropages typicus: Possible roles of feeding mechanisms, Reg. Stud. Mar. Sci. 43 (2021) 101650, https://doi.org/10.1016/j.rsma.2021.101650.
[9] P.K. Rose, S. Yadav, N. Kataria, K.S. Khoo, Microplastics and nanoplastics in the terrestrial food chain: Uptake, translocation, trophic transfer, ecotoxicology, and human health risk, TrAC Trends Anal. Chem. 167 (2023), https://doi.org/10.1016/j.trac.2023.117249.
[10] H.A. Leslie, M.H. Depledge, Where is the evidence that human exposure to microplastics is safe? Environ. Int. 142 (2020) 105807.

[11] A.D. Vethaak, J. Legler, Microplastics and human health, Science 371 (6530) (2021) 672–674.
[12] H.A. Leslie, M.J. Van Velzen, S.H. Brandsma, A.D. Vethaak, J.J. Garcia-Vallejo, M. H. Lamoree, Discovery and quantification of plastic particle pollution in human blood, Environ. Int. 163 (2022) 107199.
[13] WHO, (2022). Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health. Geneva: World Health Organization; 2022. Licence: CC BY- NC-SA 3.0 IGO.
[14] R. Gautam, J. Jo, M. Acharya, A. Maharjan, D. Lee, P.B. KC, Y. Heo, Evaluation of potential toxicity of polyethylene microplastics on human derived cell lines, Sci. Total Environ. 838 (2022) 156089.
[15] N. Ali, J. Katsouli, E.L. Marczylo, T.W. Gant, S. Wright, de la S.J. Bernardino, The potential impacts of micro-and-nano plastics on various organ systems in humans, EBioMedicine 99 (2024) 104901, https://doi.org/10.1016/j.ebiom.2023.104901.
[16] I. Aydın, Y. Terzi, S. Gündoğdu, Ü. Aytan, R.C. Öztürk, M. Atamanalp, G. Alak, N. Sivri, C. Akarsu, A.A. Atıcı, O. Güven, L. Bat, E. Kılıç, A. Öztekin, A. Uçar, V. Z. Sönmez, S. Paslı, A.E. Kıdeyş, Microplastic Pollution in Turkish Aquatic Ecosystems: Sources, Characteristics, Implications, and Mitigation Strategies, Turk. J. Fish. Aquat. Sci. (2023) 12.
[17] S. Gündoğdu, Contamination of table salts from Turkey with microplastics, Food Addit. Contam. Part A 35 (5) (2018) 1006–1014.
[18] M. Kedzierski, B. Lechat, O. Sire, G. Le Maguer, V. Le Tilly, S. Bruzaud, Microplastic contamination of packaged meat: Occurrence and associated risks, Food Packag. Shelf Life 24 (2020) 100489, https://doi.org/10.1016/j.fpsl.2020.100489.
[19] Q. Li, Z. Feng, T. Zhang, C. Ma, H. Shi, Microplastics in the commercial seaweed nori, J. Hazard. Mater. 388 (2020) 122060, https://doi.org/10.1016/j.jhazmat.2020.122060.
[20] C. Dessì, E.D. Okoffo, J.W. O'Brien, M. Gallen, S. Samanipour, S. Kaserzon, C. Rauert, X. Wang, K.V. Thomas, Plastics contamination of store-bought rice, J. Hazard. Mater. 416 (2021) 125778, https://doi.org/10.1016/j.jhazmat.2021.125778.
[21] G.O. Conti, M. Ferrante, M. Banni, C. Favara, I. Nicolosi, A. Cristaldi, M. Fiore, P. Zuccarello, Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population, Environ. Res. 187 (2020) 109677, https://doi.org/10.1016/j.envres.2020.109677.
[22] S. Gündoğdu, Microplastic intake of Unio mancus Lamarck 1819 collected from Ataturk Dam Lake, Türkiye, Turk. J. Zool. 47 (2023) 268–278, https://doi.org/10.55730/1300-0179.3140.
[23] S. Gündoğdu, C. Çevik, N. Temiz Ataş, Occurrence of microplastics in the gastrointestinal tracts of some edible fish speciealong the Turkish coast, Turk. J. Zool. 44 (2020) 312–323, https://doi.org/10.3906/zoo-2003-49.
[24] V.C. Shruti, F. Pérez-Guevara, I. Elizalde-Martínez, G. Kutralam-Muniasamy, First study of its kind on the microplastic contamination of soft drinks, cold tea and energy drinks - Future research and environmental considerations, Sci. Total Environ. 726 (2020) 138580, https://doi.org/10.1016/j.scitotenv.2020.138580.
[25] C. Ma, Q. Chen, J. Li, B. Li, W. Liang, L. Su, H. Shi, Distribution and translocation of micro- and nanoplastics in fish, Crit. Rev. Toxicol. 51 (9) (2021) 740–753, https://doi.org/10.1080/10408444.2021.2024495.
[26] N.J. Clark, F.R. Khan, D.M. Mitrano, D. Boyle, R.C. Thompson, Demonstrating the translocation of nanoplastics across the fish intestine using palladium-doped polystyrene in a salmon gut-sac, Environ. Int 159 (2022) 106994, https://doi.org/10.1016/j.envint.2021.106994.
[27] L.C. Jenner, J.M. Rotchell, R.T. Bennett, M. Cowen, V. Tentzeris, Sadofsky, L. R, Detection of microplastics in human lung tissue using μFTIR spectroscopy, Sci. Total Environ. 831 (2022) 154907, https://doi.org/10.1016/j.scitotenv.2022.154907.
[28] C. Baeza-Martínez, S. Olmos, M. González-Pleiter, J. López-Castellanos, E. García-Pachón, M. Masiá-Canuto, L. Hernández-Blasco, J. Bayo, First evidence of microplastics isolated in European citizens' lower airway, J. Hazard. Mater. 438 (2022) 129439, https://doi.org/10.1016/j.jhazmat.2022.129439.
[29] S. Huang, X. Huang, R. Bi, Q. Guo, X. Yu, Q. Zeng, Z. Huang, T. Liu, H. Wu, Y. Chen, J. Xu, Y. Wu, P. Guo, Detection and analysis of microplastics in human sputum, Environ. Sci. Technol. 56 (4) (2022) 2476–2486, https://doi.org/10.1021/acs.est.1c03859.
[30] L. Zhu, J. Zhu, R. Zuo, Q. Xu, Y. Qian, L. An, Identification of microplastics in human placenta using laser direct infrared spectroscopy, Sci. Total Environ. 856 (2023) 159060, https://doi.org/10.1016/j.scitotenv.2022.159060.
[31] P. Schwabl, S. Koppel, P. Konigshofer, T. Bucsics, M. Trauner, T. Reiberger, B. Liebmann, Detection of various microplastics in human stool: A prospective case series, Ann. Intern. Med. 171 (2019) 453–457, https://doi.org/10.7326/M19-0618.
[32] N. Zhang, Y.B. Li, H.R. He, J.F. Zhang, G.S. Ma, You are what you eat: Microplastics in the feces of young men living in Beijing, Sci. Total Environ. 767 (2021) 144345, https://doi.org/10.1016/j.scitotenv.2020.144345.
[33] Z. Yan, Y. Liu, T. Zhang, F. Zhang, H. Ren, Y. Zhang, Analysis of Microplastics in Human Feces Reveals a Correlation between Fecal Microplastics and Inflammatory Bowel Disease Status, Environ. Sci. Technol. 56 (1) (2022) 414–421, https://doi.org/10.1021/acs.est.1c03924.
[34] T. Horvatits, M. Tamminga, B. Liu, M. Sebode, A. Carambia, L. Fischer, K. Püschel, S. Huber, E.K. Fischer, Microplastics detected in cirrhotic liver tissue, EBioMedicine (2022) 104147, https://doi.org/10.1016/j.ebiom.2022.104147.
[35] C. Pironti, V. Notarstefano, M. Ricciardi, O. Motta, E. Giorgini, L. Montano, First evidence of microplastics in human urine: A preliminary study of intake in the human body, Toxics 11 (1) (2022) 40, https://doi.org/10.3390/toxics11010040.
[36] J.C. Prata, J.P. da Costa, I. Lopes, A.C. Duarte, T. Rocha-Santos, Environmental exposure to microplastics: An overview on possible human health effects, Sci. Total Environ. 702 (2020) 134455, https://doi.org/10.1016/j.scitotenv.2019.134455.
[37] B. Zhao, P. Rehati, Z. Yang, Z. Cai, C. Guo, Y. Li, The potential toxicity of microplastics on human health, Sci. Total Environ. 912 (2024) 168946, https://doi.org/10.1016/j.scitotenv.2023.168946. Epub 2023 Dec 2.
[38] E. Danopoulos, M. Twiddy, R. West, J.M. Rotchell, A rapid review and meta-regression analyses of the toxicological impacts of microplastic exposure in human cells, J. Hazard. Mater. 427 (2022) 127861, https://doi.org/10.1016/j.jhazmat.2021.127861.
[39] Z. Liu, et al., Anionic nanoplastic contaminants promote Parkinson's disease–associated α-synuclein aggregation, Sci. Adv. 9 (2023) eadi8716, https://doi.org/10.1126/sciadv.adi8716.
[40] M. Cetin, F. Demirkaya Miloglu, N. Kilic Baygutalp, O. Ceylan, S. Yıldırım, G. Eser, H.İ. Gül, Higher number of microplastics in tumoral colon tissues from patients with colorectal adenocarcinoma, Environ. Chem. Lett. 21 (639–646) (2023), https://doi.org/10.1007/s10311-022-01560-4.
[41] S. Gündoğdu, A.R. Köşker, Microplastic contamination in canned fish sold in Türkiye, PeerJ 11 (2023) e14627, https://doi.org/10.7717/peerj.14627.
[42] A. Dawson, M. Santana, J. Nelis, C. Motti, Taking control of microplastics data: A comparison of control and blank data correction methods, J. Hazard. Mater. 443 (2023) 130218, https://doi.org/10.1016/j.jhazmat.2022.130218.
[43] Y.Y. Lee, A. Erdogan, S.S. Rao, How to assess regional and whole gut transit time with wireless motility capsule, J. Neurogastroenterol. Motil. 20 (2) (2014) 265–270, https://doi.org/10.5056/jnm.2014.20.2.265.
[44] K.D. Cox, G.A. Covernton, H.L. Davies, J.F. Dower, F. Juanes, S.E. Dudas, Human consumption of microplastics, Environ. Sci. Technol. 2019 53 (12) (2019) 7068–7074, https://doi.org/10.1021/acs.est.9b01517.
[45] CBC (2024) The nature of things, ⟨https://www.cbc.ca/natureofthings/features/is-my-poop-normal-heres-the-scoop⟩. Accessed 27 June 2024.
[46] N. Qian, X. Gao, X. Lang, H. Deng, T. Bratu, Q. Chen, P. Stapleton, B. Yan, W. Min, Rapid single-particle chemical imaging of nanoplastics by SRS microscopy, Proc. Natl. Acad. Sci. USA 121 (2024) e2300582121, https://doi.org/10.1073/pnas.2300582121.
[47] S.R. Shukla, A.M. Harad, D. Mahato, Depolymerization of Nylon 6 waste fibers, J. Appl. Polym. Sci. 100 (2006) 186–190.
[48] M. Kusano, T. Kanai, Y. Arao, M. Kubouchi, Degradation behavior and lifetime estimation of fiber reinforced plastics tanks for hydrochloric acid storage, Eng. Fail. Anal. 79 (2017) 971–979, https://doi.org/10.1016/j.engfailanal.2017.06.004.
[49] N.L. Garrett, A. Lalatsa, I. Uchegbu, A. Schatzlein, J. Moger, Exploring uptake mechanisms of oral nanomedicines using multimodal nonlinear optical microscopy, J. Biophotonics 5 (2012) 458–468.
[50] S.K. Lai, D.E. O'Hanlon, S. Harrold, S.T. Man, Y.Y. Wang, R. Cone, J. Hanes, Rapid transport of large polymeric nanoparticles in fresh undiluted human mucus, Proc. Natl. Acad. Sci. USA 104 (5) (2007) 1482–1487, https://doi.org/10.1073/pnas.0608611104.
[51] D.T. O'Hagan, Intestinal translocation of particulates — Implications for drug and antigen delivery, Adv. Drug Deliv. Rev. 5 (1990) 265–285.
[52] J.W. Yoo, N. Doshi, S. Mitragotri, Adaptive micro and nanoparticles: Temporal control over carrier properties to facilitate drug delivery, Adv. Drug Deliv. Rev. 63 (2011) 1247–1256.
[53] A.M. Hillery, P.U. Jani, A.T. Florence, Comparative, quantitative study of lymphoid and non- lymphoid uptake of 60 nm polystyrene particles, J. Drug Target 2 (1994) 151–156.
[54] N. Hussain, V. Jaitley, A.T. Florence, Recent advances in the understanding of uptake of microparticulates across the gastrointestinal lymphatics, Adv. Drug Deliv. Rev. 50 (2001) 107–142.
[55] G. Volkheimer, The phenomenon of persorption: Persorption, dissemination, and elimination of microparticles. Intestinal translocation, in: P. Heidt, P. Nieuwenhuis, V. Rusch, D. van der Waaij (Eds.), Intestinal translocation (Old Herborn University Seminar Monograph 14), Herborn- Dill, Herborn Litterae, 2001.
[56] G. Volkheimer, Passage of particles through the wall of the gastrointestinal tract, Environ. Health Perspect. 9 (1974) 215–225.
[57] G. Volkheimer, Hematogenous dissemination of ingested polyvinyl chloride particles, Ann. N. Y Acad. Sci. 246 (1975) 164–171.
[58] F. Wang, C.S. Wong, D. Chen, X. Lu, F. Wang, E.Y. Zeng, Interaction of toxic chemicals with microplastics: A critical review, Water Res 139 (2018) 208–219.
[59] S. Li, J.I. Keenan, I.C. Shaw, F.A. Frizelle, Could microplastics be a driver for early onset colorectal cancer? Cancers (Basel) 15 (13) (2023) 3323, https://doi.org/10.3390/cancers15133323.
[60] S. Tutaroğlu, L. Uslu, S. Gündoğdu, Microplastic contamination of packaged spirulina products, Environ. Sci. Pollut. Res 31 (2024) 1114–1126, https://doi.org/10.1007/s11356-023-31130-2.