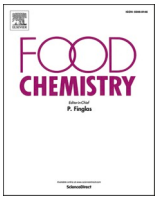
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Evaluating microplastic emission from takeaway containers: A Micro-Raman approach across diverse exposure scenarios

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ABSTRACT

Based on inconsistencies observed in literature regarding microplastic levels released by takeaway plastic containers, this study investigates the release from takeaway containers composed of polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET). To simulate real-world conditions, experiments were conducted using Milli-Q water at room temperature, 100 °C, and at pH 4.5. Containers were subjected to 20-min exposure with agitation, and microplastics were quantified via optical microscopy, with micro-Raman spectroscopy to confirm the particle polymeric nature. The results indicate that PET and PS containers released microplastic in varying quantities: 9 and 1 at room temperature, 7 and 3 in acidified water, and 17 and 30 at 100 °C, respectively. The particle sizes ranged between 13 and 32 μm. Notably, no microplastics were detected from PP containers under any tested conditions. This study underscores the significant release of microplastics from PET and PS containers, particularly at elevated temperatures, suggesting that PP may represent a safer alternative.

1. Introduction

The global food delivery market reported revenues of USD 151.526 million in 2021, with an annual growth rate (CAGR 2021–2024) of 6.4 %. By 2024, projected revenues are expected to reach USD 182.327 million. Over the next seven years, the market is estimated to grow by 52 %, suggesting that the takeaway food segment is occupying a significant share of the overall food market (Kochańska et al., 2021). Takeaway foods are typically stored in petroleum-derived plastic containers due to the numerous advantages offered by these materials, such as cost-effectiveness and their significant contribution to food safety and nutritional preservation, made possible by their chemical-physical properties (e.g., impermeability, thermal resistance, gas barrier properties) (Zhou et al., 2022). However, while the use of plastics in the food sector provides benefits in terms of nutrition, organoleptic properties, and microbiological safety, consumer exposure to microplastics has become a topic of growing scientific concern, mainly due to the lack of evidence regarding the behavior of these particles within the human body. Indeed, recently it has been noted that while the exact concentrations of ingested microplastics within the human body remain difficult to detect, there is still a lack of comprehensive data on their direct implications for human health (Blackburn and Green, 2022). Microplastic exposure primarily occurs through ingestion; considering exposure via the most contaminated food groups (e.g., fish: 1.48 microplastics/g, sugar: 0.44 microplastics/g, honey: 0.10 microplastics/g, salt: 0.11 microplastics/g, alcohol: 32.3 microplastics/L, and bottled water: 94.4 microplastics/L), annual exposure is estimated to be approximately 121,554 microplastics for adult men and 98,305 microplastics for adult women (Cox et al., 2019). For bottled water, it has been hypothesized that plastic packaging significantly influences microplastic release, with capping operations contributing to microplastic contamination, leading to a release ranging from 1 microplastic/L to 317 ± 257 microplastics/L (Samandra et al., 2022; Weisser et al., 2021).

In this context, since 2022, there has been a growing interest in studying the release of microplastics from takeaway food containers. The scientific literature has indicated that these containers can release

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microplastics, with PS being associated with a higher release compared to other plastic materials (e.g., PET, PP) (Du et al., 2020; Zhou et al., 2022). However, for other polymers, the evidence regarding microplastic release remains inconclusive. For instance, PP has been reported to release plastic microparticles (~10 μm) after treatment with hot water (Hu et al., 2023), while other studies suggest that PP does not release microplastics when exposed to water at room temperature. Furthermore, the mere identification of plastic microparticles may not be sufficient to confirm their release from takeaway containers. Some experimental studies highlight the necessity of confirming the correspondence between the polymer composition of the detected microplastics and that of the container from which they may have been released. Laboratory studies have suggested that only a small percentage (~30 %) of the microplastics found after treatment with food simulants were chemically compatible with takeaway containers, indicating that these containers are not the sole source of release (Du et al., 2020).

In light of the inconsistencies observed in the scientific literature, this study seeks to assess the release of microplastics from three common types of takeaway food containers: PS, PP, and PET. These polymers were selected based on existing evidence indicating their potential to release microplastics. To evaluate the impact of the chemical-physical conditions of the food matrix, the containers were exposed to three different environments: hot water (100 °C), acidified water (pH 4.5), and room temperature water (pH 7). To the best our knowledge, this is the first study to compare three different exposure conditions.

2. Materials and methods

2.1. Collection of microparticles released from take-away containers

The polymers considered were PS, PP, and PET. For the experiments, fifty-four ($n = 54$) containers were purchased from an Italian grocery store, with 18 containers of each type: PS, PP, and PET. These containers were labelled as suitable for food contact. The number of containers per type was as follows: 9 containers per polymer (PS, PP, and PET) were treated with aqueous solutions according to the procedure described below. The aqueous solutions were finally filtered through a GF/F filter (Whatman glass fibers, pore size 1.6 μm, diamter 47 mm, Sigma-Aldrich, St. Louis, Missouri, United States) and subjected to visual analysis through the optical microscope. The take-away containers were packed into aluminum foils before entering the laboratory. They were thus stored in aluminum foils until the experiments. A different approach became necessary due to the significant interferences produced by GF/F filters in the Raman spectroscopy analysis. For this reason, stainless steel frits were used to screen particles with the Raman microscope.

2.2. Treatments applied to take-away containers

Take-away containers underwent three different treatments ($n = 3$) with MilliQ water (Millipore Milli-Q system, filter 0.22 μm, Merck, Darmstadt, Germany) to simulate food transportation under three different conditions as well as consumption by customers of foods in three conditions, namely non-hot food (treatment #1), hot food (treatment #2), and slightly acidic food (treatment #3). All containers were treated as follows:

- Treatment 1 (treatment #1): 100 mL of MilliQ water was placed into the containers and agitated with a Mixer Electric Agitator (VEVOR Mixer Electric Agitator, Steel Mixing Blade, Sigma-Aldrich, St. Louis, Missouri, United States) at 10 rpm for 20 min (estimated average time for delivery/transport of take-away food). This step was applied to three take-away containers each for PS, PET, and PP.
- Treatment 2 (treatment #2): 100 mL of MilliQ water was heated to approximately 100 °C and then placed into the containers. MilliQ water was agitated with the Mixer Electric Agitator at 10 rpm for 20 min. This step was applied to three take-away containers each for PS, PET, and PP.
- Treatment 3 (treatment #3): 100 mL of MilliQ water was acidified reaching approximately pH 4.5 and then placed into the containers. MilliQ water was agitated with the Mixer Electric Agitator at 10 rpm for 20 min. This step was applied to three take-away containers each for PS, PET, and PP.

Subsequently to each treatment, for visible analysis, the sample was filtered using GF/F fiber filter and stored in clean Petri dishes. Samples were covered with aluminum foil, until microscopical analysis.

For the Raman microscopy analysis, the aqueous samples were filtered using stainless-steel frits (pore size, 0.2 μm), hold in conventional 1/4“ to 1/16” HPLC column end fitting connected to a 100 × 4.6 mm stainless-steel tube on top and to a vacuum water pump on the bottom. The sample was introduced into the stainless-steel tube using a 50 mL glass syringe. After sample passage the frit was dried by applying vacuum for further one minute the frit was then gently removed from the holder and stored in glass Petri dish prior Raman microscopic analysis.

2.3. Quality assurance/Quality control (QA/QC)

To prevent airborne contamination, QA/QC was conducted as follows: all procedures were carried out under a fume hood. During the experiments, for each type of container (i.e., polymer type) and for each test, a procedural blank (PB) was performed by placing a filter into a Petri dish adjacent to the operational area (Fig. S1). Before their use, the stainless-steel frits underwent to a cleaning procedure consisting in ultrasonication in a 1:1 solution of water and nitric acid for five minutes, followed by rinsing with HPLC-grade water. The frits were finally flushed in both directions with HPLC-grade isopropanol before drying.

To control contamination due to the experimental conditions, all glassware used, vacuum filtration system, tweezers, Petri dishes, beakers, were carefully washed with soap and natural sponge and tap water and the rinsed about 10 times with MilliQ water. Afterwards, all glassware was stored into aluminum foil. All operators wore cotton lab coat and blue nitrile gloves.

2.4. Observation and identification of microparticles in the visible

All filters were visually analyzed using an optical microscope (OPTECH Microscope, Optical Technology, Parabiago, Milan, Italy) to observe and identify microparticles. To assess the number of microparticles for each test, they were counted of the filter three times. Microparticles’ shape and size were analyzed using the Capture 2.4 software (OPTECH, Optical Technology, Parabiago, Milan, Italy), which enables both the shapes and sizes analysis. The same procedure was applied for the analysis of procedural blanks. Furthermore, to minimize the external contamination during the microparticle counting, a microscope was placed under the fume hood.

2.5. Micro-Raman spectroscopy for microplastic’s identification

The chemical composition of particles was assessed using a Raman microscope. The investigation employed a Renishaw InVia Micro-Raman Spectroscopy System integrated with a Leica DM2500 M Microscope and a Near-Infrared (NIR) enhanced Deep Depletion Charge-Coupled Device (CCD) array (1024 × 256 pixels). A comprehensive Raman shift range of 200–3500 cm^{-1} was acquired to encompass the entire spectrum of interest. Initial experiments were performed to optimize the instrument settings. A 785 nm laser, adjusted to 50 % of its power (with an output of 306 mW measured at the source), and a 10 s acquisition time were selected for acquiring each spectrum. Imaging was achieved using a 20× objective lens with a numerical aperture (NA) of 0.4. The mean spectral resolution achieved was 1.3027 cm^{-1}. Data

cubes, each containing 256 spectra, from 4.00 × 4.00 mm mapping, with a step size of 300 μm targeting the frit's central region. Data was stored in Renishaw WDF format. Instrument calibration was conducted daily using a silicon reference internal to the system. To ascertain the presence of microplastics, the spectra obtained from the stainless-steel frits were compared to a spectrum collected from an untreated section of the container material. This comparison aimed to identify any spectral signatures characteristic of the microplastics released during the experiment, thus providing a direct linkage between the container material and the detected microplastics.

3. Results

3.1. QA/QC

Microparticles isolated from procedural blanks using GF/F filters were visually quantified and classified based on their morphology under an optical microscope (Fig. 1). Microparticles detected in the procedural blanks were subtracted from those found on the GF/F filters of the tested samples (Table S1 Supplementary Materials). The morphological distribution of microparticles from the procedural blanks is shown in Fig. 1.

Analysis of the microparticles collected on the GF/F filters from the procedural controls revealed that, on average, more than 80 % of these microparticles were classified as fibers, whereas an average of 20 % of the microparticles found was classified as fragments.

3.2. Visual observation of microparticles

Microparticles isolated using the GF/F filters of the experimental tests were visually quantified by counting them using the optical microscope. The total number of microparticles isolated on GF/F filters is provided in Table S2 Supplementary Material. To specifically determine the number of microparticles potentially released from the tested takeaway containers, all fibrous microparticles isolated from the procedural controls for each test were deducted from the corresponding water/container contact test results. Subsequently, the same methodology was applied to the microfragments. Table 1 shows the number of microparticles obtained after subtracting those detected in the procedural blanks.

Fragment-shaped microparticles were measured using a measuring instrument linked to Capture 2.4 software. The instrument was appropriately calibrated prior to measurements, utilizing spherical polystyrene microparticles of known size (diameter 10 μm) for calibration (Fig. S2 Supplementary Material). The average lengths of the microfragments and their corresponding standard deviations for each type of polymer and test are presented in Table 2.

Table 1
Total number of microparticles per test performed for the investigated polymers obtained by subtraction of procedural blanks. Relative Standard Deviation (RSD %) indicates the variability of the number of microparticles found.

Treatment	Polymer	Counts Exp. 1	Counts Exp. 2	Counts Exp. 3	Mean counts	RSD %
Normal water	PET	6	24	32	21	62 %
	PS	2	10	12	8	66 %
	PP	4	23	3	10	110 %
Water pH 4	PET	9	0	13	7	96 %
	PS	0	0	10	3	193 %
	PP	12	7	14	11	33 %
Water 100 °C	PET	20	12	20	17	27 %
	PS	34	22	33	30	22 %
	PP	35	24	19	26	31 %

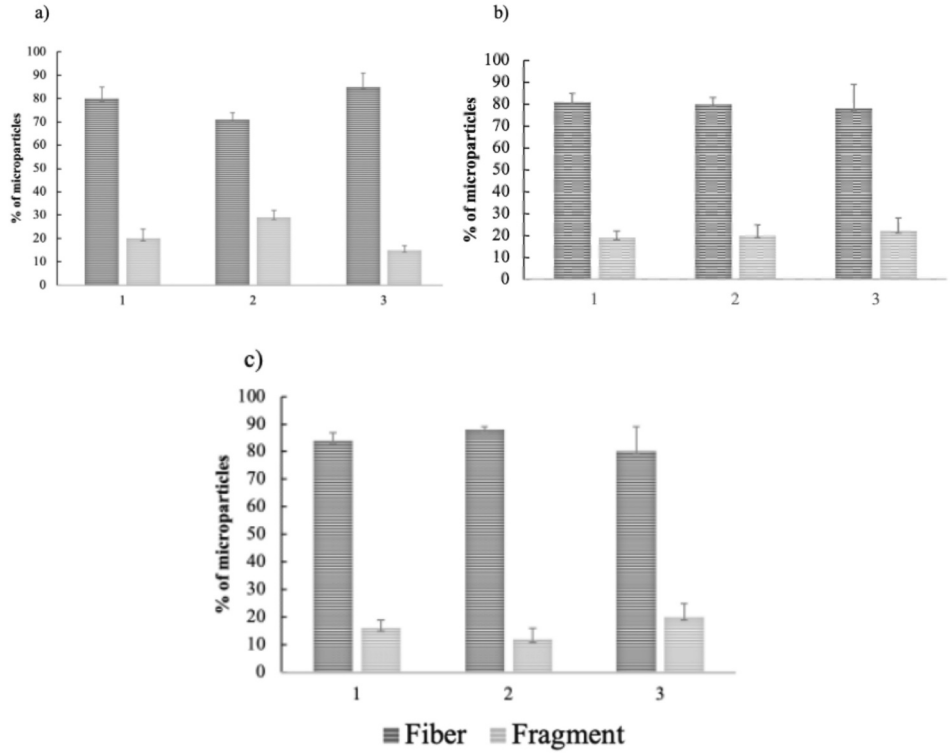


Fig. 1. Morphological distribution of microparticles found on GF/F filters from procedural blanks, expressed as a percentage and based on the average of three blanks for each polymer type. a) Procedural blanks from experimental tests on PET; b) Procedural blanks from experimental tests on PS; c) Procedural blanks from experimental tests on PP.

Table 2
Sizes of microfragments measured using the Capture 2.4 measurement tool after being properly calibrated. Standard Deviation (SD) indicates the variability of the size of microfragments measured.

Treatment	Polymer	Size±SD
Normal water	PET	18 ± 26 μm
	PS	23 ± 13 μm
	PP	33 ± 32 μm
Water pH 4	PET	28 ± 11 μm
	PS	32 ± 12 μm
	PP	20 ± 18 μm
Water 100 °C	PET	13 ± 8 μm
	PS	18 ± 9 μm
	PP	24 ± 34 μm

3.3. Micro-Raman spectral Imaging System results

To confirm the unique origin of the microparticles isolated from contact with the tested takeaway containers, Raman spectra of the containers used in the experimental tests were acquired (Fig. 2a-c).

The polymeric composition of the containers used was confirmed through Raman spectroscopic analysis. It is important to note that the use of stainless-steel frit filters proved essential, as GF/F filters produced significant background noise, hindering the accurate identification of the characteristic polymer bands. In the Raman spectrum of the PS container (Fig. 2a), a prominent band at 1000 cm^{-1} is evident, characteristic of the aromatic C—H bond (Oßmann et al., 2017; Zhou et al., 2021). The Raman spectrum of PET (Fig. 2b) displays a primary peak around 1600 cm^{-1}, attributed to the high Raman scattering intensity of the benzene ring. Additionally, secondary peaks were observed at 629

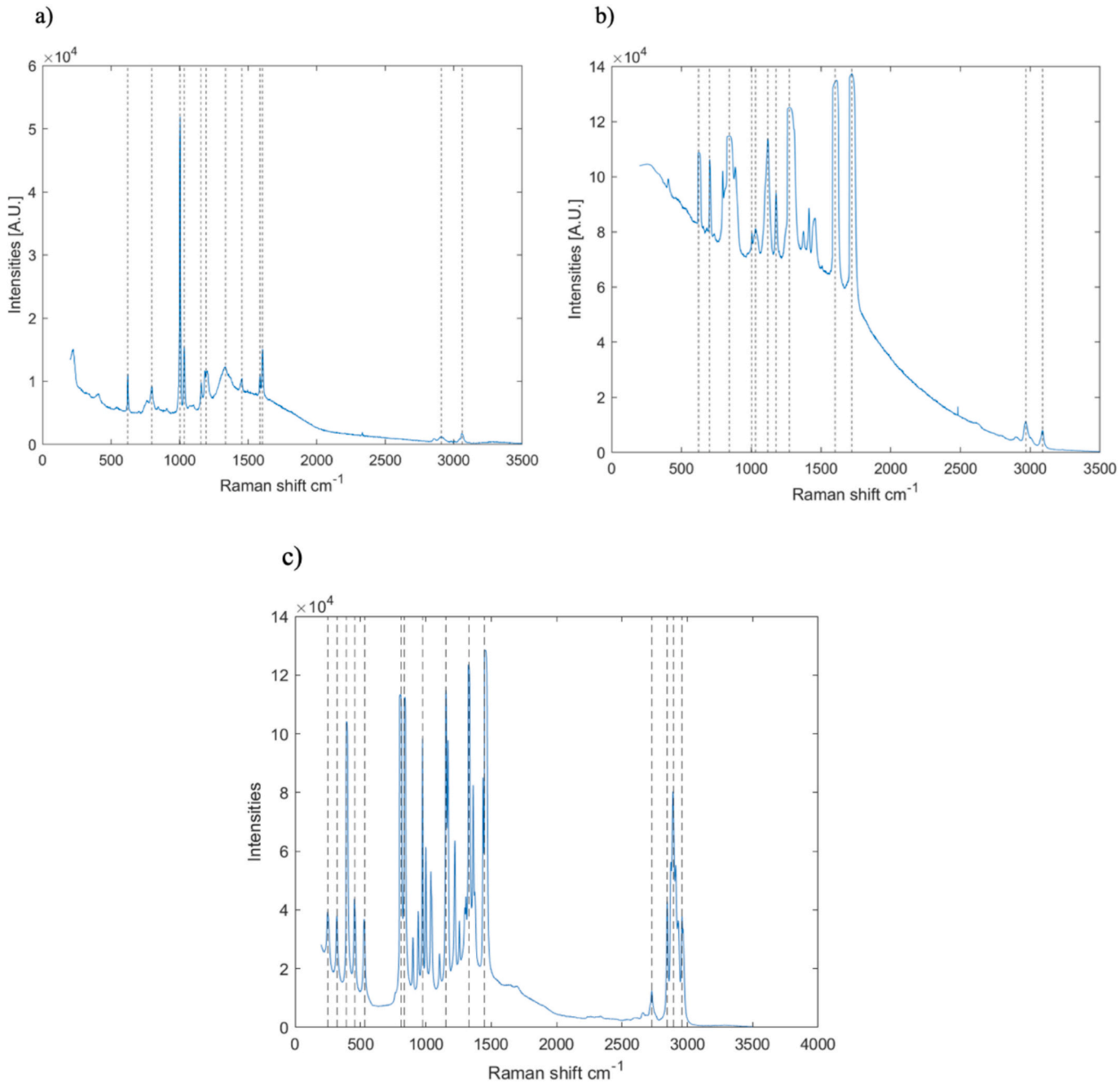


Fig. 2. Raman spectra acquired from the takeaway containers used in the release tests for a) PS, b) PET, and c) PP.

cm^{-1}, 859 cm^{-1}, 1099 cm^{-1}, 1279 cm^{-1}, 1608 cm^{-1}, 1717 cm^{-1}, 2968 cm^{-1}, and 3078 cm^{-1}. The peak at 1717 cm^{-1} is associated with the ester group in the polymer, while the peak at 1099 cm^{-1} corresponds to the asymmetric stretching vibration of the C-O-C group. The low-intensity peak at 3077 cm^{-1} is attributed to the vibration of the benzene ring (Zhu et al., 2015). The Raman spectrum of PP (Fig. 3c) shows nine distinct peaks. According to the literature, the characteristic peaks of PP are observed at 808, 830, 842, 973, 998, 1152, 1167, 1463, and 2963 cm^{-1}. The peaks at 808 and 830 cm^{-1} correspond to the stretching vibrations of the CH_2, CH_3, and C—C bonds, while the peaks at 842, 973, and 998 cm^{-1} are associated with the deformation vibrations of the CH_3 group. The bands at 1152 and 1167 cm^{-1} are related to C—C stretching, while those at 1463 and 2963 cm^{-1} correspond to CH_3 asymmetric deformation and CH asymmetric stretching, respectively (Phan et al., 2022). The microfragments recovered from the stainless-steel frit filters were analyzed to assess the consistency and compatibility of their Raman spectra with those of the takeaway food containers.

Experimental tests conducted with ultrapure water at room temperature and pH 7 revealed that 50 % of the microfragments isolated (9 microfragments out of 18 in average) from the PET container and 17 % (1 microfragment out of 6 in average) of those from the PS container exhibited Raman spectra consistent with their respective original containers. When using ultrapure water acidified to pH 4.5, 86 % of the microfragments (6 microfragments out of 7 in average) from PET and 100 % (5 microfragments out of 5 in average) from PS showed compatible spectra. In tests with water at 100 °C, 88 % of the microfragments (15 microfragments out of 17 in average) from PET and 90 % (27 microfragments out of 30 in average) from PS had spectra consistent with the original containers. In contrast, none of the microfragments isolated from the PP container exhibited compatibility with its original spectrum. For both PET and PS, the spectral peaks successfully characterized the microfragments released from the containers. Specifically, for PS, the peak around 1000 cm^{-1}, indicative of the aromatic C—H bending, was prominent. For PET, significant peaks were identified,

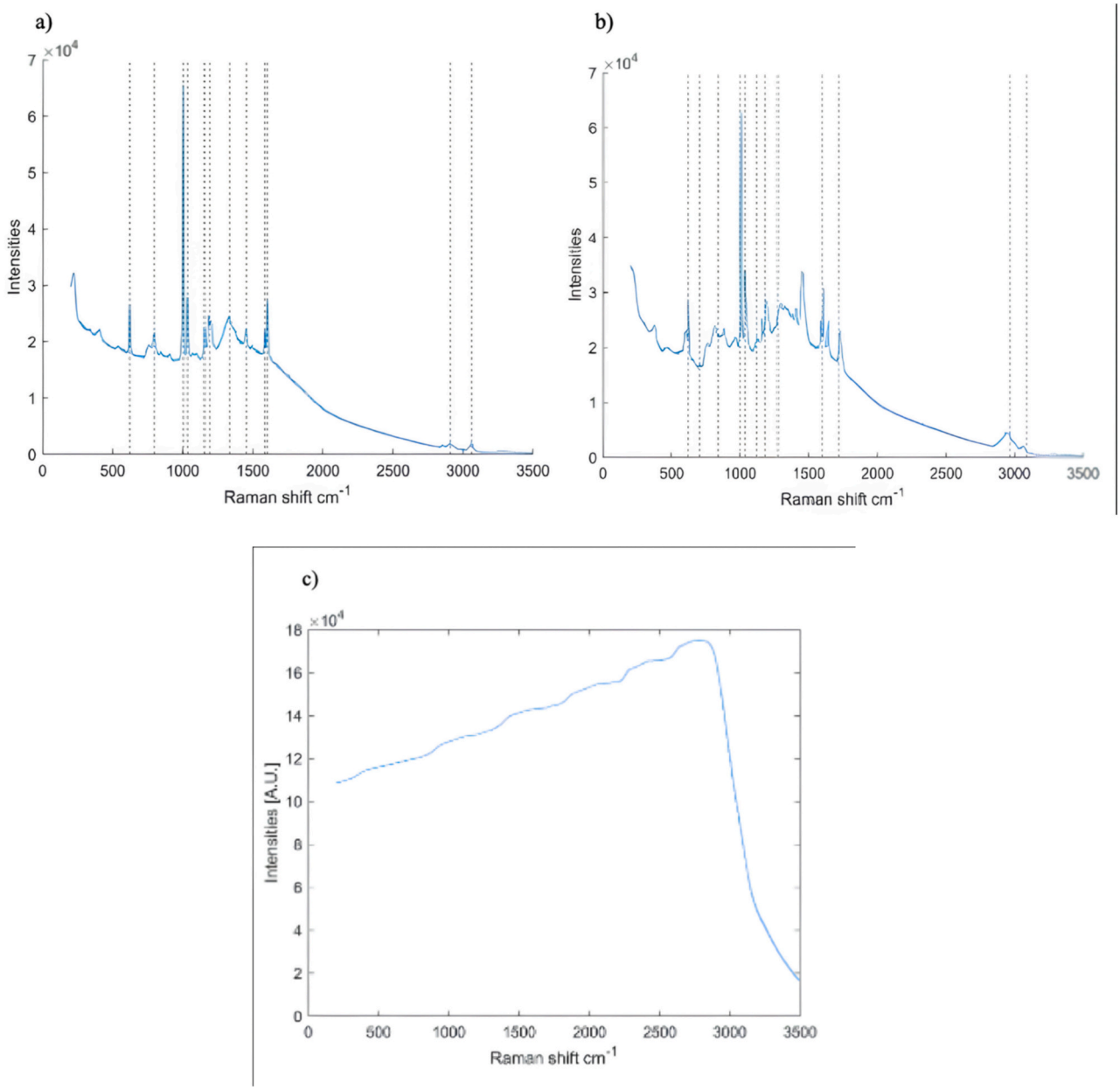


Fig. 3. Raman spectra of microfragments isolated from the experimental tests from a) PS takeaway container; b) PET takeaway container and c) Stainless Steel frit. All the relevant peaks have been underlined by vertical line.

including one at 1600 cm^{-1} associated with the benzene ring, as well as others at 628.5 cm^{-1}, 859.3 cm^{-1}, 1099 cm^{-1}, 1278.8 cm^{-1}, 1608.3 cm^{-1}, 1717 cm^{-1}, 2968.3 cm^{-1}, and 3077.9 cm^{-1}, corresponding to PET molecular vibrations.

4. Discussion

Human exposure to microplastics via ingestion is an increasingly important issue in scientific research. While the contribution of plastic materials in food packaging has been extensively studied for certain products, such as bottled mineral water in polyethylene terephthalate containers—showing average microplastic concentrations of 1.61 μg/L (Gálvez-Blanca et al., 2024) and particle counts ranging from 0 to 91 per liter (Karki et al., 2024; Zhu et al., 2024), with 28–85 particles per 500 mL (Vitali et al., 2024)—new concerns are arising over microplastic release from plastic containers used in the takeaway food industry. The growing use of takeaway packaging raises important questions about the potential for human exposure to microplastics through food contained in these materials. Recent studies have indicated the release of microplastics from takeaway containers. Zhou et al. (2022) tested six types of containers, including polyethylene (PE) ($n = 1$), PP ($n = 3$), PS (n = 1), and PET (n = 1), and reported a total release of 1792 microparticles, with an average of 291 confirmed as plastic. However, only some of these microplastics (number unspecified) had spectra matching those of the original containers, with the highest similarity observed for PS containers, while no microplastic release was detected from PP containers. The greater tendency for microplastic release was further supported by Du et al. (2020). Specifically, PS containers released between 20 and 40 particles per container, while average levels ranged from 5 to 15 for PP, 4 to 6 for PE, and 3 to 5 for PET. μ-FTIR spectroscopy detected an average of 9, 29, 5, and 3 microplastics per container for PP, PS, PE, and PET, respectively. However, only 30 % of these particles, on average, had spectra matching the original container material. The findings of the present study are consistent with those reported by Du et al. (2020). Specifically, the exposure of PS containers to boiling water resulted in a comparable release of microplastics between the two studies (29 vs. 27). However, differences were observed in the case of PP containers. In our study, no microplastic release was detected from PP containers, in contrast to the findings of Du et al. (2020). Similarly, consistency was observed in the tendency for PET containers to release microplastics after exposure to boiling water. However, discrepancies were noted in the number of microplastics released. Comparing different experimental conditions, the tests conducted in the present study indicate a significantly higher tendency for microplastic release when exposed to boiling water, both for PET and PS (9 vs. 15; 1 vs. 27, respectively, for room-temperature and boiling water) (Hu et al., 2023; Du et al., 2020). The thermal stability and morphology of polymers play a crucial role in their tendency to release microplastics. Specifically, unmodified PS deforms at temperatures around 300 °C, while PS modified with functional groups tends to deform at slightly higher temperatures, between 350 and 450 °C (Ahmetli and Cerit, 2007). Similarly, recent studies have indicated limited thermal resistance for PET. In this context, it is important to highlight that PET's poor crystallization capacity prevents the orderly alignment of molecular chains during synthesis (i.e., melting), resulting in a material with low thermal resistance. In fact, the melting point of pure PET is around 238.1 °C. However, PET's thermal resistance can be increased by approximately 10 °C through the addition of other substances, such as elastomers or multi-walled carbon nanotubes (Huang et al., 2023). Nonetheless, in the food packaging industry, PET is generally used in its pure form. Consequently, the greater release of microplastics observed in our study when PET containers were exposed to 100 °C water, compared to room-temperature water, may be attributed to its low thermal resistance. Regarding PP, the experimental results of this study revealed discrepancies compared to existing data in the scientific literature. Previous research indicates a tendency for PP containers to release microplastics. Specifically, exposure to boiling water for 30 min, with agitation at 20 rpm, has been associated with the release of microplastics ranging from 9 particles (Du et al., 2020) to 1.57 ± 0.59 million microparticles/mL of ultrapure water at 100 °C per container (Hu et al., 2023; Liu et al., 2022). However, the experiments conducted in this study did not detect any microplastic release from PP containers under any of the three tested conditions. These findings are consistent with the chemical properties of the polymer: PP, characterized by a high degree of crystallinity (40–60 % composed of crystalline regions), demonstrates significant heat resistance and notable chemical stability (Chen et al., 2007; Maddah, 2016). Additionally, the experiments showed microplastic release from PS and PET containers even after exposure to room-temperature water, with averages of 1 and 9 microplastics, respectively, based on experimental tests. This is consistent with the findings of Xu et al. (2022), which indicate a release of 9.3 ± 1.3 microplastics per 100 mL from PS after exposure to room temperature. The release of microplastics from both PS and PET containers was also observed following contact with slightly acidified water; specifically, the number of microplastics exhibiting spectra compatible with those of the original containers was 6 and 5 for PET and PS, respectively. However, the mechanism underlying microplastic release after contact with water or food remains unclear. It is evident that factors such as material type and structure, pH, temperature, oxygen, and light significantly influence the release of plastic microparticles. Hydrolysis has been proposed as a key chemical reaction responsible for this release (Hussain et al., 2023). Hydrolysis involves the cleavage of the polymer into smaller units through the addition of a water molecule (Morgenroth et al., 2002). This process necessitates hydrolytic scission (Shah et al., 2008), which can be facilitated by biological or chemical catalysis (Ali et al., 2021). Additionally, the presence of a hydrophilic region in the polymer is essential for this reaction. In a catalyzed acid-base reaction, water induces a nucleophilic attack on the carbonyl group (C=O) in ester or amine bonds (Ali et al., 2021). For hydrolysis to occur, the polymer must contain hydrolytically unstable bonds to allow for water ingress (Singh and Sharma, 2008). Hydrophilic polymers can adsorb water on their surfaces, but their capacity for internal diffusion remains unclear. For hydrophobic polymers with crystalline regions or cross-linked structures, hydrolysis is severely suppressed due to limited water entry. This may explain the absence of microplastic release from PP, as the type used in the food industry has a cross-linked structure (Chen et al., 2007). In contrast, both PS and PET used in packaging exhibit semi-crystalline structures, and the presence of amorphous regions may facilitate hydrolysis and subsequent release (Wang et al., 2021). In this context, the size of microplastics plays a crucial role in terms of human exposure. The size range of MPs in the present study did not align with those suggested by Xu et al. (2022), who reported a range of 500 to 1000 μm for microparticles from PS container (Xu et al., 2022). Our study found a range of 18 ± 10 μm and 32 ± 12 μm, for PS containers, significantly smaller than Xu et al. (2022)' s findings.

5. Conclusions

This study would like to investigate the release of microplastics from food containers under various conditions, such as normal water, acidic water (pH 4.5), and hot water (100 °C). our findings reveal a significant release of microplastics from polystyrene (PS) and polyethylene terephthalate (PET) containers across all tested exposure conditions, whereas polypropylene (PP) containers exhibited no detectable release. Specifically, contact with MilliQ water at 100 °C led to an average release of 15 microplastics per container for PS and 27 microplastics per container for PET. Moreover, experimental evidence demonstrated microplastic release even after a brief 20-min contact with MilliQ water at room temperature, corroborating previously established hypotheses in the scientific literature that hydrolysis serves as the primary mechanism driving this phenomenon, with the type of polymer (amorphous or crystalline) influencing the extent of release. However, the

understanding of the impact of slightly acidified MilliQ water remains limited. Our investigations indicated an average release of 6 microplastics per container for PET and 5 for PS under these conditions. This highlights the necessity for further studies aimed at refining the quantification of microplastic release under diverse experimental conditions. Additionally, our study utilized a simplified approach by focusing solely on water. Therefore, it is crucial to investigate trends associated with plastic takeaway containers to establish a solid foundation for future research incorporating food matrices. The interactions among the components of food matrices (carbohydrates, proteins, and fats) may significantly affect microplastic release, necessitating a standardization of experimental methodologies and a comprehensive analysis of polymer behavior under common food-related conditions (such as elevated temperatures and/or slightly acidic environments). Such investigations could yield valuable insights for future research in this area.

CRediT authorship contribution statement

Vicky Caponigro: Writing – review & editing, Formal analysis. **Cristina Di Fiore:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Fabiana Carriera:** Software, Methodology, Formal analysis. **Alessia Iannone:** Investigation, Formal analysis, Data curation. **Antonio Malinconico:** Software, Formal analysis, Data curation. **Pietro Campiglia:** Validation, Supervision. **Carlo Crescenzi:** Writing – review & editing, Validation, Data curation. **Pasquale Avino:** Validation, Supervision, Conceptualization.

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

All data are available in the manuscript

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2024.141716.

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