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# Microplastic and PTFE contamination of food from cookware

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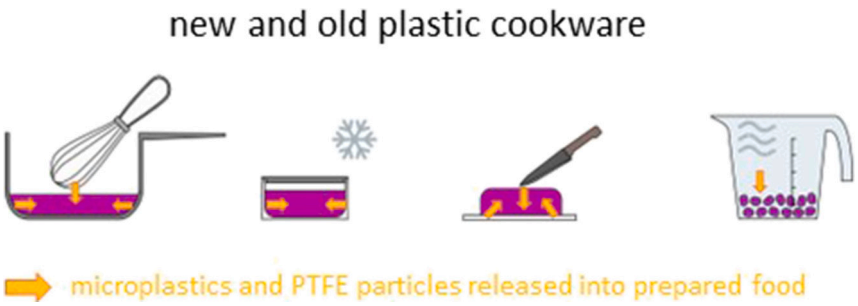
## HIGHLIGHTS

- Plastic and PTFE-coated cookware can release micro- and nanoplastics.
- Non-plastic cookware did not introduce microplastics into prepared food.
- Using new and old plastic cookware significantly increased microplastic load in prepared food.
- Plastic cookware is likely adding thousands of microplastics into the human diet each year.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Microplastics are a prolific environmental contaminant that have been evidenced in human tissues. Human uptake of microplastic occurs via inhalation of airborne fibres and ingestion of microplastic-contaminated foods and beverages. Plastic and PTFE-coated cookware and food contact materials may release micro- and nanoplastics into food during food preparation. In this study, the extent to which non-plastic, new plastic and old plastic cookware releases microplastics into prepared food is investigated. Jelly is used as a food simulant, undergoing a series of processing steps including heating, cooling, mixing, slicing and storage to replicate food preparation steps undertaken in home kitchens. Using non-plastic cookware did not introduce microplastics to the food simulant. Conversely, using new and old plastic cookware resulted in significant increases in microplastic contamination. Microplastics comprised PTFE, polyethylene and polypropylene particulates and fibrous particles, ranging 13–318 μm. Assuming a meal was prepared daily per the prescribed methodology, new and old plastic cookware may be contributing 2409–4964 microplastics per annum into homecooked food. The health implications of ingesting microplastics remains unclear.

## 1. Introduction

Plastics are chemically stable compounds, comprised of a diverse suite of polymers, chemicals and additives used in a variety of industrial, commercial and domestic products (Rochman et al., 2019). Global plastic production (excluding those used in textiles) currently exceeds 390 million tonnes per annum (PlasticsEurope, 2022), with production rates and associated waste generation predicted to increase over the next

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forty years (Lebreton and Andrady, 2019). Physio-chemical degradation of plastic products can result in the release of monomers, oligomers and additives, and plastic particles termed micro- and nanoplastics (Zhang et al., 2021; Singh and Sharma, 2008). Microplastics are solid, insoluble polymeric particles and fibres, 1 μm – 5 mm by longest dimension (Hartmann et al., 2019; Frias and Nash, 2019). Over the past twenty years, microplastics have been identified as a prolific environmental contaminant (Thompson et al., 2004), evidenced in surface water, groundwater, soils, sediment and air sampled from across the globe (Chia et al., 2021; McCormick et al., 2016; Zhang et al., 2020; O'Brien et al., 2023).

Of growing societal concern is the risk microplastics pose to human health (Barboza et al., 2018). To date, microplastics have been found in the gastro-intestinal tract (Ibrahim et al., 2021), lung tissues (Jenner et al., 2022; Amato-Lourenço et al., 2021), blood (Leslie et al., 2022) and the placenta (Ragusa et al., 2021) of humans. Current estimates suggest intake rates for adults range between 258 and 883 microplastics day$^{-1}$ (Mohamed Nor et al., 2021; Cox et al., 2019). Intake can occur via inhalation of airborne microplastics, or ingestion of contaminated food and liquids (Prata et al., 2020; WHO, 2022; Gasperi et al., 2018). Microplastics have been widely evidenced in fresh and bottled drinking water, with concentrations ranging 0–10,000 microplastics L$^{-1}$ (WHO, 2019), and a range of foodstuffs, including seafood, animal-products, plant-products, beverages and salt (Kadac-Czapska et al., 2022). Prior to harvest, microplastics can be ingested, adhered or otherwise taken-up by animals and plants used in food (Smith et al., 2018). Contamination of food can also stem from airborne deposition and the release of microplastic particles and fibres from clothing, production lines and packaging (Gasperi et al., 2018; Walkinshaw et al., 2022; Jadhav et al., 2021; De Falco et al., 2020; Catarino et al., 2018). There is also growing evidence that preparing food with plastic food contact materials and cookware may also be contributing micro- and nanoplastics into prepared food (Luo et al., 2023; Zhou et al., 2022; Luo et al., 2022; Jander et al., 2022; Habib et al., 2022a; Habib et al., 2022b).

Cookware and food contact materials are manufactured from an array of materials, comprising metals, ceramics, glass and plastics, including non-stick silicone and polytetrafluoroethylene (PTFE). PTFE is a hydrophobic and chemically resistant fluoropolymer commonly used as a non-stick coating for cookware (Sajid and Ilyas, 2017). Developed in the 1930s, PTFE was originally manufactured using a perfluorooctanoic acid (PFOA) emulsifier; however, concerns over the toxicity of PFOA resulted in its replacement with alternate organofluorines (Sajid and Ilyas, 2017; Schlummer et al., 2015). Contact with utensils, cleaning with abrasives and high temperatures can result in mechanical stress, physical abrasion, surface modification, coating detachment, embrittlement, cracks and micro-tears on the surface coatings of cookware (Schlummer et al., 2015; Castle et al., 1990; Rondinella et al., 2021). Such physical damage and loss of structural integrity can result in the release of micro- and nanoplastics (Luo et al., 2022; Jander et al., 2022; Marazuela et al., 2022).

This study aims to determine the extent to which preparing food with plastic and PTFE-coated cookware can introduce microplastics into food. Prior studies have focussed on microplastic contamination from singular products and food preparation processes (e.g. slicing food on a chopping board). Here, a food simulant underwent a series of commonly applied food processing steps including heating, cooling, mixing, slicing and storage using a range of cookware. Different types and age of cookware and food contact materials were used to test the hypotheses that plastic cookware, particularly older plastic cookware with existing surface damage, can result in contamination of prepared food with microplastics.

## 2. Materials & methods

### 2.1. Food simulant

Commercially available jelly powder (comprising gelatin, sugar, acidity regulator and food dye) was used as a proxy for food, hereafter termed 'food simulant'. Jelly was considered a suitable food simulant for this study given it can be processed in both its liquid and solid states, and microplastics can be retrieved from the simulant by melting the jelly and filtering the liquid, thereby avoiding complex chemical digestion and density-separation protocols. To determine levels of microplastic contamination in the unprocessed food simulant, 30 g aliquots of jelly powder ($n = 5$) were dissolved in 125 mL of ultrapure water (100 °C) in glass jars. Jars were sealed and shaken at 300 rpm for 1 min on a shaking-incubator (Stuart), refrigerated at 4 °C overnight, and then stored at −20 °C prior to analysis.

### 2.2. Cookware

The food simulant was prepared using either non-plastic, new plastic or old plastic cookware and utensils (Table 1; SI Fig. S1; $n = 5$). Non-plastic cookware was made from stainless-steel and glass, while plastic materials were made from polypropylene (PP), polyethylene (PE), polyamide (PA), or coated in "non-stick" silicone or PTFE. Non-plastic and new plastic cookware were purchased from domestic suppliers, while old plastic cookware was sourced from home kitchens, using equipment of similar polymer and morphology wherever feasible. Old plastic cookware showed signs of prolonged use (e.g. rough textures, staining, heat damage, scratches, yellowing), documented using a stereomicroscope coupled with a high-resolution camera (SI Fig. S2). The interior of the jelly packet, and all plastic cookware and utensils were analysed using Attenuated Total Reflectance Fourier-transform infrared spectroscopy (ATR FT-IR; Perkin Elmer Spotlight 400) to confirm polymer type (SI Figs. S3–S5).

### 2.3. Food preparation

The food simulant was prepared with food processing methods commonly used in home kitchens, including heating, cooling, cutting, whisking and storage (Fig. 1). Every effort was made to keep the methodology consistent, with all processing conducted by a singular researcher in the same laboratory. To avoid cross-contamination, all cookware was cleaned using a household detergent and a non-plastic loofah (Fig. 1A) and twice rinsed with ultrapure water (Thermo Scientific™ Barnstead™ RO System; Fig. 1B) prior to use and between samples. A *pan* was used to heat 100 mL of ultrapure water to ~100 °C on a hotplate (Cusimax CHMP-S106). While the water was heating, 30 ± 0.01 g of food simulant was weighed out in a glass beaker (Fig. 1C) before adding to the *pan*. A *whisk* was used to stir the food simulant (*aq*) for a total of 100 rotations over a 64.8 ± 0.5 s (mean ± SE) time period, with the whisk in constant contact with the pan (Fig. 1D). The food simulant (*aq*) was then carefully poured into *food containers* (Fig. 1E)

**Table 1**
Constituent material of cookware and utensils used in each experimental set-up (treatment). Polymers: PA: polyamide; PE: polyethylene; PP: polypropylene; PTFE: polytetrafluoroethylene.

| Item | Treatment | | |
|---|---|---|---|
| | Non-plastic | New plastic | Old plastic |
| Pan | Stainless steel | PTFE-coated | PTFE-coated |
| Whisk | Stainless steel | Silicone-coated | Silicone-coated |
| Food container | Glass | PP | PP |
| Chopping board | Glass | PE | PE |
| Sharp knife | Stainless steel | Alkyd | Alkyd |
| Measuring jug | Glass | PE | PP |
| Spoon | Stainless steel | PA | PA |

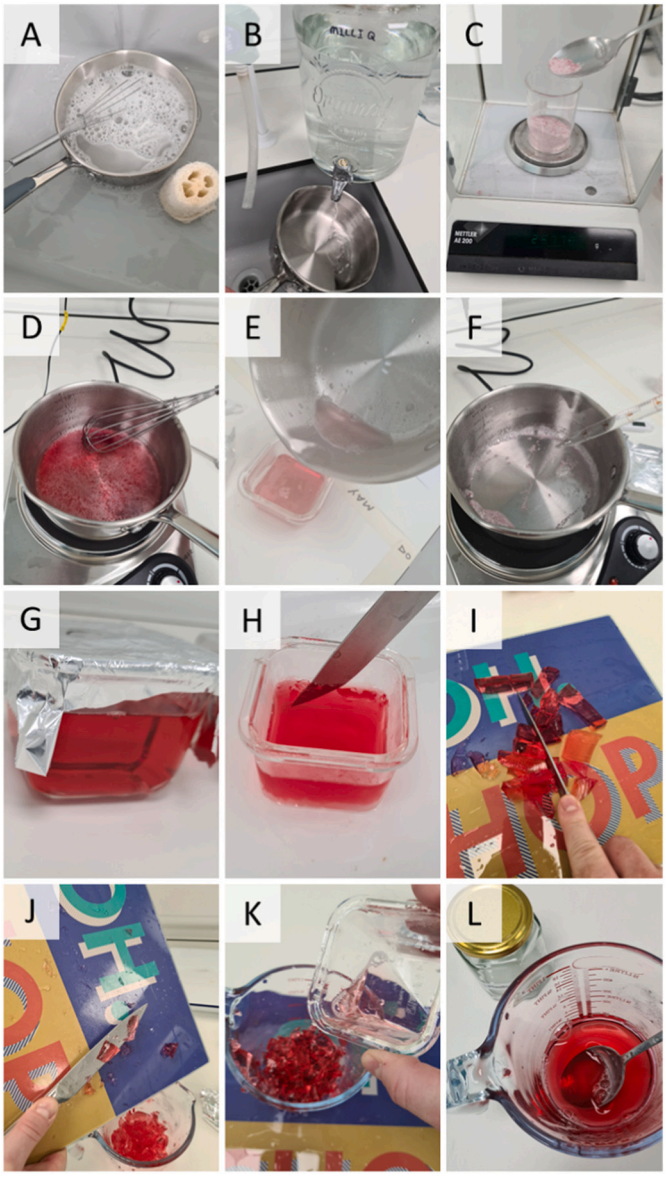


**Fig. 1.** Photographs showing the steps used in preparing the food simulant using non-plastic cookware.

using 20 mL of ~100 °C ultrapure water, dispensed via glass serological pipette, to rinse out the *pan* (Fig. 1F). Aluminium foil was used to cover the food containers to avoid airborne contamination. *Food containers* were cooled for ~15 min at room temperature and then chilled overnight (3–4 °C) to allow the food simulant to solidify (Fig. 1G). To remove the food simulant (*s*) from the food container, a *sharp knife* was used to slice around the edge of the food simulant (Fig. 1H), and the base of the food container immersed in warm water for ~15 s. The food simulant was then turned out onto a *chopping board*. The food simulant was sliced using *a sharp knife* (25 cuts board$^{-1}$), with the knife permitted to make contact with the *chopping board* but not intentionally slicing into the board itself (Fig. 1I). The *sharp knife* was then used to gently scrape (15 scrapes board$^{-1}$) the diced food simulant into a *measuring jug* (Fig. 1J). Next, 15 mL of ~100 °C ultrapure water, dispensed via glass serological pipette, was used to rinse out any remaining food simulant from the *food container* into the *measuring jug* (Fig. 1K). The *measuring jug* was heated at full power in a microwave (900 W) for 30 s and then stirred using a *spoon* (10 rotations$^{-1}$ jug). The liquified food simulant was immediately poured into pre-labelled storage bottles, using 15 mL of ~100 °C ultrapure water, dispensed via glass serological pipette, to rinse out the *jug* (Fig. 1L). Prior to analysis, samples were refrigerated at 4 °C overnight, and then transferred into a − 20 °C freezer.

### 2.4. Microplastics

In this study, particles were characterised using Micro Fourier Transform Infrared Spectroscopy (μ-FTIR) imaging which provided the number, size and shape of microplastics present in the food simulant; such data is valuable in determining the associated risk from plastic particle ingestion. Particles were extracted from the food simulant by placing the storage jars in a water-bath (Thermo Scientific™ TSCIR19) at 80 °C for 20 min, and then pouring the food simulant (*aq*) through a 10 μm stainless steel mesh filter (47 mm ø), using ~5 mL of ~80 °C ultrapure water (1.2 μm GF/A) to rinse out the storage jar and filtration set-up. Particles trapped on the 10 μm stainless steel mesh filters were resuspended onto 13 mm Ø zinc oxide (Whatman Anodisc™) filters. Filters were dried at room temperature overnight covering the filter with a glass beaker to prevent airborne contamination. Identification of polymer types and measurement of particle sizes were performed using μ-FTIR (Thermo Fisher Nicolet iN10 MX Infrared Imaging Microscope). The instrument is equipped with a $N_2$-cooled 64 × 64 line array mapping detector and a quantum mercury cadmium telluride detector and a permanently aligned 15× half angle range 20° to 43.5° objective-condenser with built-in purge collar ring with 6.25 μm pixel size resolution, allowing the detection of microplastics >15 μm. The linear array detector collected 4 scans per acquisition point per time, and the IR spectra of each microplastic particle were recorded in the mid-IR range of 4000–850 cm$^{-1}$, with a spectral resolution of 4 cm$^{-1}$ in transmission mode. Polymer identification was performed by comparing the spectral match of the particles with a reference library (SiMPle, v1.3.1β (Primpke et al., 2018)), with a spectral match ≥70 % considered a positive match. Additionally, the smallest and longest dimension of each particle was recorded.

### 2.5. Carbonyl index

The carbonyl index is frequently used to examine photochemical oxidation process in polymers. Multiple methods for determining carbonyl index are reported in literature. In this study the CI have being calculated by the Specified Area Under Band (SUAB) approach following Simon-Sánchez et al. (Simon-Sánchez et al., 2022) as expressed in the following equation:

$$Carbonyl\ index = \frac{area\ under\ band\ 1850 - 1650\ cm^{-1}}{area\ under\ band\ 1500 - 1420\ cm^{-1}}$$

All the spectra belonging to PE and PP particles were exported and loaded into Spectra Gryph software (rev. 1.2.15). The integrated areas under the selected bands were calculated using the peak analysis tool and used to calculate the index. Averaged carbonyl index were calculated and presented for comparison across the treatments.

### 2.6. Contamination control

To prevent airborne contamination of samples, food processing was conducted in a restricted access, positive-pressure ultraclean laboratory with HEPA filtered air supply, with all researchers wearing cotton lab coats. Glass storage jars were washed, soaked in 10 % HCl (2 h) rinsed with ultrapure water and then incubated at 500 °C (2 h) to remove contaminants prior to sample processing and sample storage. To account for airborne contamination during sample analysis, an open beaker filled with filtered Milli-Q water was placed in the working area in the laboratory each working day; analysis of these wet-trap samples indicated no microplastic contamination. Use of a non-plastic treatment acted as a procedural blank.

### 2.7. Statistical analyses

Datasets were analysed to determine microplastic abundance, particle size and shape. The ratio between minimal and maximal dimension of each particle was determined, with particles with a > 1:3 ratio classed as "fibrous". Statistics were conducted using R statistical analysis software (version 4.3.1). A Shapiro–Wilk test demonstrated the data did not conform with a priori requisites for parametric testing. Therefore, a Kruskal–Wallis test was used to compare levels of microplastic contamination across treatments, with post-hoc pairwise Wilcoxon tests used to compare between treatments. Statistical significance is assigned where $p < 0.05$ (95 % confidence interval). Data is presented as mean ± standard error. Microplastics results refers to particles retained on the 10 μm filter but with minimal dimension >15 μm due to instrumental limitations.

## 3. Results

The unprocessed food simulant contained 2.4 ± 0.2 microplastics. These microplastics comprised of polyethylene (1.2 ± 0.5 particles), polyester (1.0 ± 0.6 particles) and polyamide (0.2 ± 0.2 particles). This was the only sample across all treatments to contain a polyamide particle.

Microplastic contamination was significantly affected by the material and age of cookware used to prepare the food simulant (Kruskal-Wallis chi-squared = 16.65, df = 3, $p < 0.001$; Fig. 2; SI, Table S1). Prepared with non-plastic cookware, the food simulant contained 2.8 ± 0.4 microplastics, which was not significantly different from the unprocessed food simulant (Wilcoxon pairwise test, $p = 0.49$). Food simulant prepared with new plastic cookware contained 9.2 ± 1.2 microplastics, which was significantly greater than observed in unprocessed food stimulant and food stimulant prepared with non-plastic cookware (Wilcoxon pairwise test, $p \leq 0.01$). Further, food simulant prepared with old plastic cookware contained the highest microplastic load (16.4 ± 0.5 microplastics), significantly greater than observed in all other treatments (Wilcoxon pairwise test, $p < 0.01$).

Preparing the food simulant with plastic cookware resulted in significant increases in polyethylene, polypropylene and polytetrafluoroethylene particles contaminating the food simulant (Kruskal-Wallis, p < 0.01; Fig. 3). Food simulant prepared with new and old plastic cookware contained 3.4 ± 0.4 and 5.2 ± 0.7 polyethylene particles respectively, which was significantly greater than the 1.2 ± 0.5 and 1.2 ± 0.4 polyethylene particles observed in unprocessed and non-plastic prepared food simulant (Wilcoxon, $p < 0.05$; Fig. 3A). Across treatments, food simulant contained an average of 0.6–2.2 polyester particles with no significant difference between treatments (Kruskal-Wallis, $p = 0.20$; Fig. 3B). For polypropylene, food simulant prepared with new and old plastic cookware contained 2.4 ± 0.4 and 4.0 ± 0.9 particles respectively, which was significantly greater than the 0.2 ± 0.2 and 1.0 ± 0.3 particles observed in unprocessed and non-plastic treated food simulant (Wilcoxon, $p < 0.05$; Fig. 3C). No PTFE particles were observed in unprocessed or non-plastic treated food simulant. Conversely, food simulant prepared with new and old plastic cookware contained 2.2 ± 0.4 and 4.6 ± 1.5 PTFE particles respectively (Wilcoxon, p < 0.05; Fig. 3D; SI, Fig. S6l). In the old plastic cookware treatment, one sample

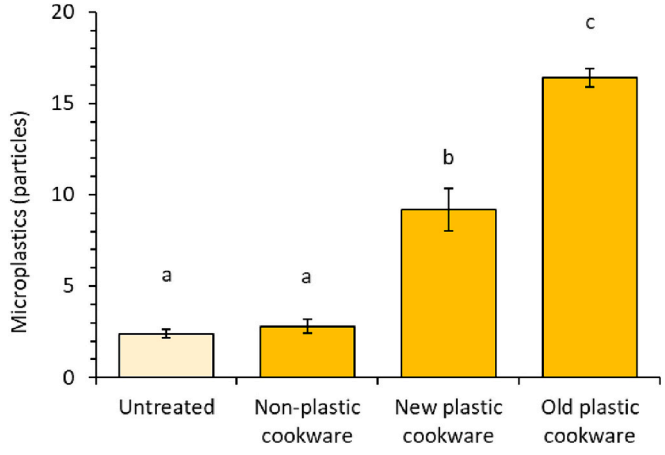


**Fig. 2.** Microplastic contamination of food simulant before (light yellow) and after (dark yellow) cooking using different cookware ($n = 5$ per treatment). Data presented as mean with standard error bars. Different letters denote significant differences between treatments (Kruskal-Wallis with pairwise Wilcoxon test, $P < 0.05$).

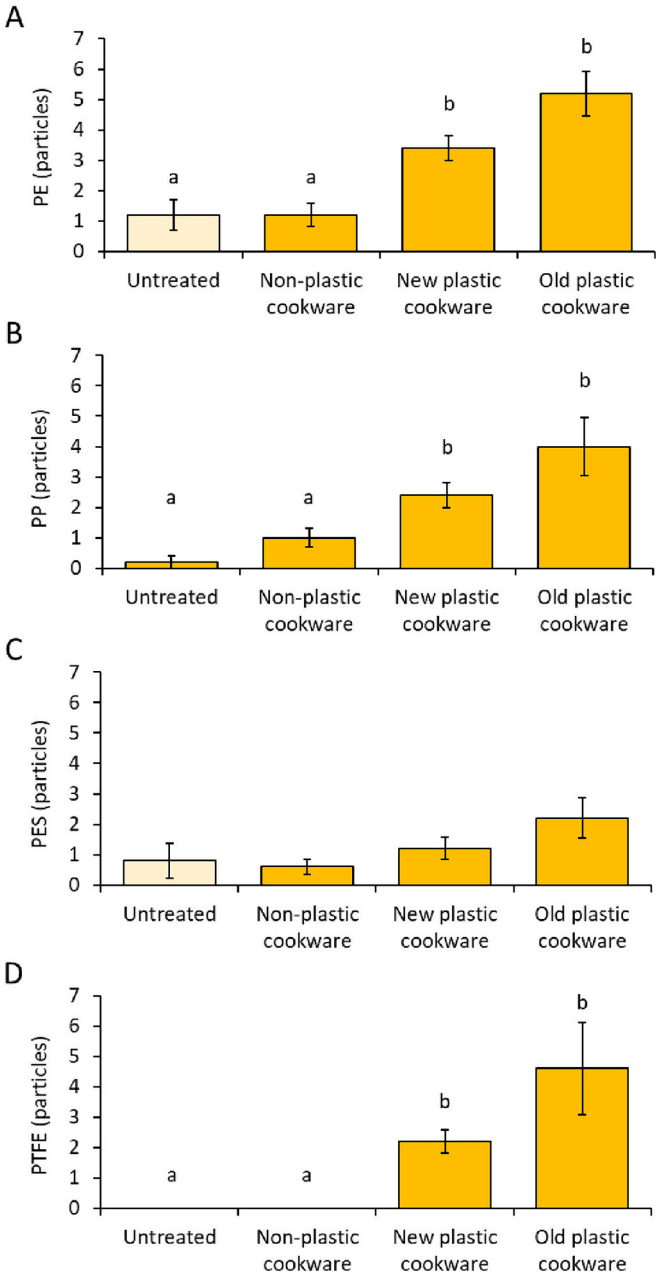


**Fig. 3.** Microplastic contamination of food simulant before (light yellow) and after (dark yellow) cooking using different cookware ($n = 5$ per treatment), for four different polymeric groups: (A) Polyethylene (PE); (B) Polyester (PES); (C) Polypropylene (PP); (D) Polytetrafluoroethylene (PTFE). Data presented as mean with standard error bars. Different letters denote significant differences between treatments (Kruskal-Wallis with pairwise Wilcoxon test, $P < 0.05$).

contained two particles classed as "alkyds"; the spectra of these particles matched the pink coating found on the sharp knives.

Microplastics ranged 13.4–120 μm by smallest dimension and 16.4–318 μm by longest dimension across all treatments. While there was no significant difference in the size of microplastics across treatments (Kruskal-Wallis, $P = 0.07$), a wider variation in the size of particles released by new and old plastic cookware was evident (Fig. 4A). The majority of microplastics were considered particulates (<1:3 ratio between minimal and maximal dimension), with 7.1 %, 3.9 % and 8.6 % of microplastics classified as fibrous (>1:3 ratio between minimal and maximal dimension) in the non-plastic, new plastic and old plastic treatments respectively (Fig. 4B). The carbonyl index calculated for polypropylene and polyethylene ranged 1.00 ± 0.10 to 1.40 ± 0.40 and 0.90 ± 0.08 to 1.26 ± 0.24 respectively, with no statistical difference between treatments. For both polymers, particles extracted from the old plastic cookware treatment had markedly higher carbonyl indices compared with other treatments indicative of mild photochemical oxidation (Fig. 4C).

## 4. Discussion

In this study, plastic cookware and food contact materials are identified as a source of microplastic and PTFE particle contamination in prepared food. Accounting for the mean number of microplastics identified in the untreated food simulant, new and old plastic cookware released an average of 6.6 and 13.6 microplastics through the prescribed food processing steps. Assuming a meal was prepared daily per the prescribed methodology, new and old plastic cookware may be contributing 2409–4964 microplastics per annum into homecooked food. In reality, the figure may be far higher given this data does not include micro- and nanoplastics <10 μm in size. While not a focus of this study, it can be surmised that cleaning plastic cookware with abrasive products will also result in the release of microplastics during washing, with plastic and PTFE-particles potentially entering the natural environment via wastewater (Mason et al., 2016).

### 4.1. Source of microplastic contamination

Plastic cookware introduced significantly greater amounts of polyethylene, polypropylene and PTFE into the food simulant compared with non-plastic cookware. Polymer type can be used to relate the identified microplastics with a source material. For example, the FTIR spectra for alkyd particles observed in the old plastic treatment were directly matched with the coating of the sharp knife. Similarly, polyethylene microplastics most likely derived from preparing the food simulant on polyethylene chopping boards. Two prior studies demonstrated polyethylene chopping boards can release plastic microplastic fragments (8 μm – 13 mm), resulting in microplastic contamination of meat (0.07–68.9 microplastics $g^{-1}$), poultry (0–1.2 microplastics $g^{-1}$) and fish (0–2.6 MP $g^{-1}$) (Habib et al., 2022a; Habib et al., 2022b). A recent study provides evidence that the cutting force of the user and the type of material being cut can significantly affect the release of microplastics from chopping boards (Yadav et al., 2023). In this study, microplastic release derives from processing jelly which is both soft and pliable; preparing other foodstuffs (e.g. meat, vegetables) is likely to require far greater application of force during food processing, which turn will release more microplastics from food-contact materials (Yadav et al., 2023). The polypropylene microplastics observed in the food simulant likely stemmed from storing, freezing and excising the food simulant from the polypropylene food containers. Polypropylene, polyethylene, polystyrene and polyethylene terephthalate food containers (including take-out containers) have all been demonstrated to release microplastics and nanoplastics during cleaning, storage and heating, with losses ranging 0–130 microplastics container$^{-1}$ (Zhou et al., 2022; Du et al., 2020; Hee et al., 2022; Fadare et al., 2020; He et al., 2021). Cleaning, sterilising and mixing water within polypropylene infant feeding bottles

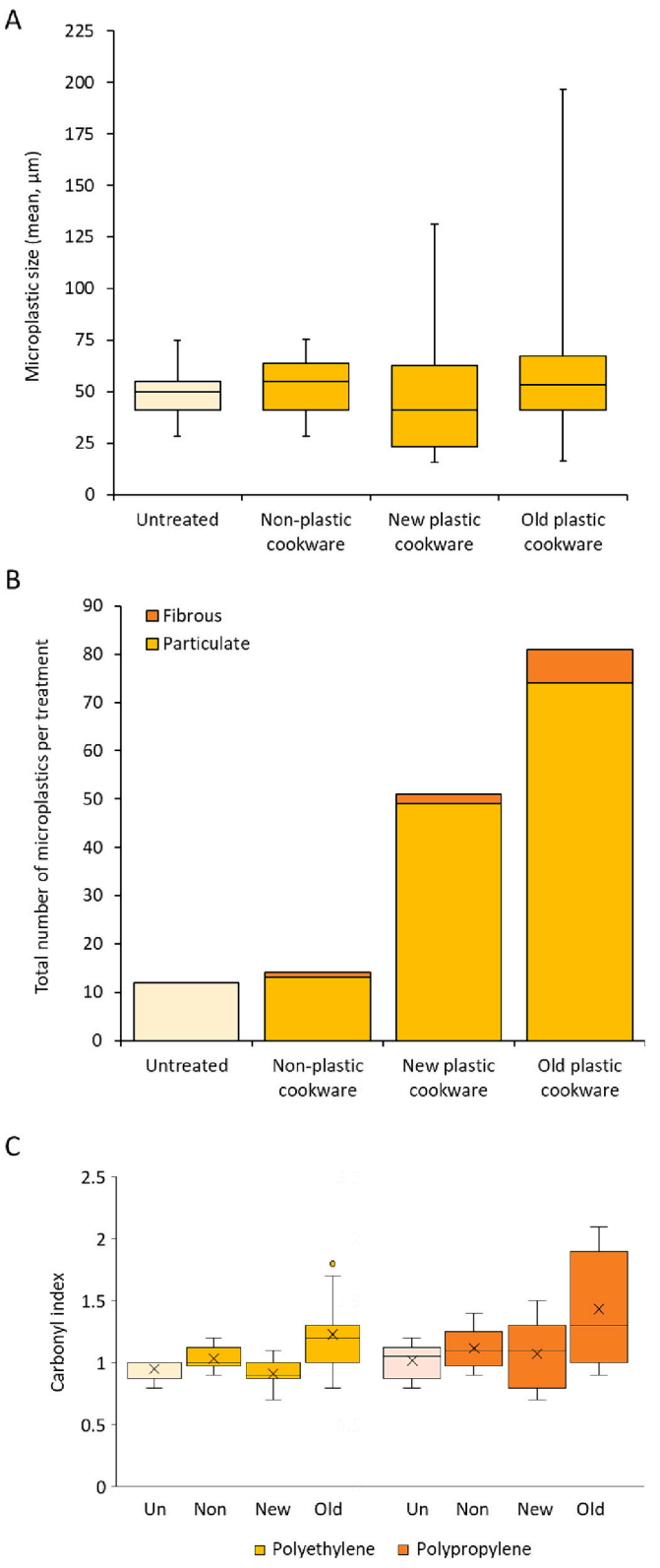


**Fig. 4.** Characteristics of all microplastics identified in food simulant before and after cooking using different cookware across five replicates. (A) Box-and-whisker plot displaying median, interquartile and full range of particle sizes (average of minimum and maximum dimension). (B) Total number of microplastics classed as particulates (<1:3 ratio; yellow) and fibrous (>1:3 ratio; orange) in each treatment. (C) Carbonyl index of polyethylene (yellow) and polypropylene (orange) microplastics identified in each treatment.

has been demonstrated to release millions of <20 μm microplastics (Li et al., 2020). Similarly, milling ice and water in an acrylonitrile butadiene styrene blender has been estimated to release 0.36–0.78 × $10^9$ micro- and nanoplastics (Luo et al., 2023). Furthermore, Jander et al. (Jander et al., 2022) identified that between 331 and 898 microplastics can be released through abrasive mechanical force when using an electronic mixer for 2 min at 200 RPM in plastic mixing bowls, using water as a food simulant. Lastly, PTFE particles (5–227 μm) were likely derived from the non-stick pans used to heat and whisk the food simulant. A recent study demonstrated dry-mixing with a stainless steel spoon for 30 s could scratch and damage the surface of PTFE-coated pans, with scanning electron microscopy used to visualise the release of micro- and nanoplastic PTFE particles (Luo et al., 2022). In this study, the food simulant was stirred with a silicone-coated whisk in the PTFE-coated pan; given the flexibility and non-abrasive coating of this whisk, the release of 2.2 ± 0.4 (new plastic) and 4.6 ± 1.5 (old plastic) PTFE particles was somewhat surprising. The older plastic cookware released significantly greater amounts of microplastic compared with the new plastic cookware. Similarly, heavy metals have been shown to leach more prevalently from older cookware as compared with new cookware (Shamloo et al., 2023). Prolonged use of cookware can result in abrasion and surface damage, with microscopy revealing higher prevalence of cracks and surface degradation in the older cookware; furthermore, the carbonyl indices indicated higher levels of photochemical degradation in polyethylene and polypropylene particles stemming from the old plastic cookware.

### 4.2. Microplastics in the food simulant and non-plastic treatment

The unprocessed food simulant (jelly) contained an average of 0.08 microplastics $g^{-1}$, or 10 microplastics per 125 g packet. A wide variety of processed food and beverages, including milk (1.7–10.0 microplastics $mL^{-1}$), bottled beer (20–80 microplastics $mL^{-1}$) and sugar (0.34 microplastics $g^{-1}$), have been shown to contain microplastics (Afrin et al., 2022; Li et al., 2022; Da Costa Filho et al., 2021). Presence of microplastics in processed food, absent of raw animal and plant tissues, likely derive from contamination during manufacture and packaging (i.e. airborne deposition, or release of microplastics from clothing, equipment or packaging) (Lin et al., 2022). PE was the most prevalent type of microplastic (1.2 ± 0.5 particles in 30 g). Given the interior surfaces of the jelly packaging were coated with low-density polyethylene (LDPE, SI Fig. S3), it is possible the packaging may have contributed to microplastic contamination of the food simulant. Using non-plastic cookware did not result in any significant increase in microplastic load within the prepared food simulant. The non-plastic cookware treatment acted as a control, with the results demonstrating there was no laboratory-derived contamination during food processing or particle analysis (further validated by an absence of microplastics in wet trap samples). While it can be surmised that using non-plastic cookware in kitchens will not introduce any microplastic into prepared food, food may become contaminated from other sources. For example, microfibre concentrations in indoor air can range 1–60 microfibres $m^{-3}$, with deposition rates ranging 1586–11,130 fibres $m^{-2}$ $day^{-1}$ (Gasperi et al., 2018); in examining microfibre deposition in a home settings, Catarino et al. (Catarino et al., 2018) estimated 114 microfibres might deposit on a 25 cm diameter dinner plate across a 20 min period.

### 4.3. Human health risks

The risks microplastics might pose to human health are currently poorly understood (Prata et al., 2020; Jones et al., 2023; Thornton Hampton et al., 2022). In vitro studies have demonstrated adverse health effects stemming from microplastic exposure, for example: 10–45 μm polyethylene microplastics significantly increased genomic instability in human blood lymphocytes (Çobanoğlu et al., 2021); nylon microfibres negatively impacted growth and development of airway organoids (Song et al., 2023); and 1–10 μm polyethylene microplastics caused shifts in gut microbiota composition (Fournier et al., 2023). Adverse health effects may stem from physical interactions between tissues and particle, and the leaching of chemicals from the plastic (Vethaak and Legler, 2021). Indeed, an in vitro human digestion model has demonstrated microplastics, including polypropylene particles derived from a food container, can leach plasticizers, flame retardants and polycyclic aromatic hydrocarbons under physiological conditions; many such compounds are considered to be endocrine disruptors (Peters et al., 2022). In microwaves and conventional ovens, plastic cookware has been shown to reach temperatures of 61–121 °C, with hotspots of >200 °C (Castle et al., 1990); these temperatures can result in leaching of monomers, oligomers, aromatics and plasticisers into prepared food (Castle et al., 1990; Bishop and Dye, 1982). For example, the antimicrobial triclosan was demonstrated to leach into water and ethanol when heated or stored within polypropylene food containers (Marazuela et al., 2022). Heated on a stove for 30 min (without food) PTFE-coated pans can reach temperatures of 250–370 °C (Schlummer et al., 2015). At these high temperatures, PTFE-coated pans can emit gaseous perfluoroalkyl and polyfluoroalkyl substances (PFAS) and the coating can degrade (Sajid and Ilyas, 2017; Schlummer et al., 2015; Ellis et al., 2001), while heating PTFE to 486 °C can result in the formation of airborne PTFE nanoparticles (Johnston et al., 2000). PFAS are soluble fluoropolymers that are considered extremely persistent, often termed "forever chemicals", with the PFAS chemicals perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) causatively and associatively linked with toxicity, cancer and disease in animals and humans (Lohmann et al., 2020; Sunderland et al., 2019; Pelch et al., 2022). Abrasion of cookware through wear-and-tear has been shown to result in significant increases of heavy metal concentrations (aluminium, arsenic, cadmium and lead) when boiling water for 1–4 h in a plastic kettle and PTFE-coated pan (Shamloo et al., 2023). However, there is currently no clear evidence that perfluorochemicals can migrate from PTFE cookware into a food simulant (Bradley et al., 2007). Research relating to the uptake and toxicity of PTFE particles in humans is also limited (Sajid and Ilyas, 2017). In the 1990s, periurethral injection of PTFE paste to treat incontinence led to some reports of migration of PTFE particles that could incite inflammation and granuloma formation (Aragona et al., 1997; Claes et al., 1989). A recent in vitro study demonstrated PTFE particles (6–32 μm; 1–1000 μg $mL^{-1}$) induced oxidative stress in all cell lines tested, and increased inflammatory cytokine secretion in lung epithelial and macrophage cell lines (P.B. et al., 2023). However, whole organism studies have provided no evidence of clinical effects (e.g. weight loss, morbidity, mortality) in rats exposed to PTFE particles (5–50 μm; 0–2000 mg $kg^{-1}$) via dietary intake (Lee et al., 2022).

## 5. Conclusions

This study provides an estimation of the release of >10 μm microplastics from plastic cookware used to prepare food in a real-world scenario. Both new and old plastic cookware were shown to release significantly greater amounts of microplastics and PTFE particles than non-plastic cookware. The results provide a warning that plastic and PTFE-coated cookware may introduce microplastics and PTFE-particles into food. Based on the wider literature, we surmise the release of microplastics stem from thermal and mechanical degradation; as such, microplastic release is likely to be exacerbated if using hard or sharp utensils with plastic and PTFE-coated cookware or heating these materials at higher temperatures. There is currently a paucity of high-quality data assessing the risks posed by microplastics and PTFE particles to human health.

## CRediT authorship contribution statement

**Matthew Cole:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Alessio Gomiero:** Writing – review & editing, Writing – original draft, Validation, Resources, Investigation, Conceptualization. **Adrián Jaén-Gil:** Validation, Investigation. **Marte Haave:** Conceptualization, Funding acquisition, Writing – review & editing. **Amy Lusher:** Conceptualization, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing.

## 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

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172577.

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