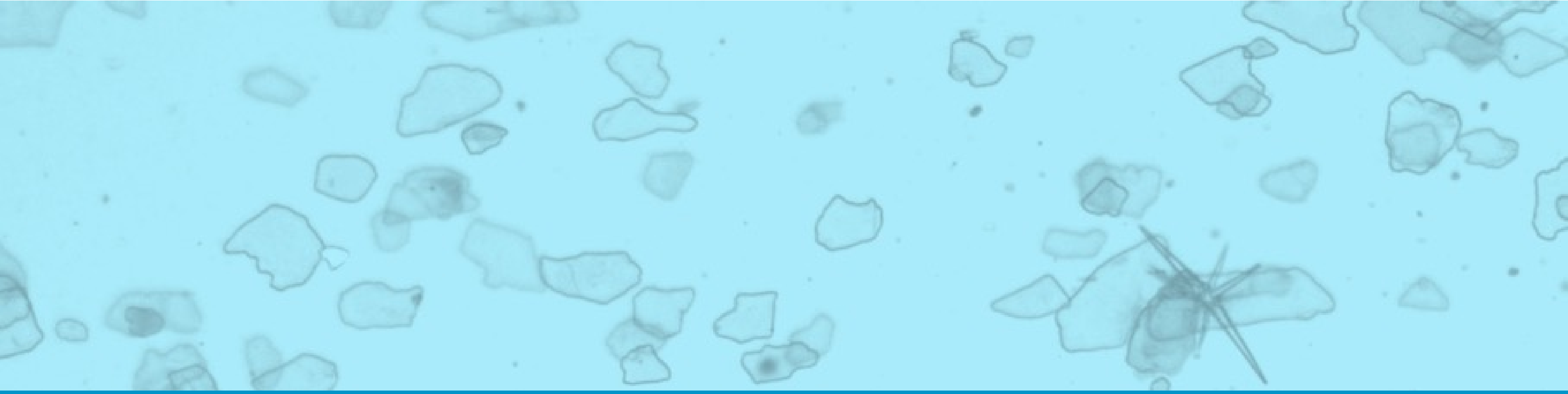
FULL REPORT



Heather A. Leslie, PhD

Exploring Everyday Microplastic Exposures

Recent evidence of products delivering microplastic to humans

2026

Exploring Everyday Microplastic Exposures

Recent evidence of products delivering microplastic to humans

A scoping report reviewing scientific evidence for everyday human exposure to microplastics

Commissioned by the Plastic Soup Foundation with financial support from the Flotilla Charitable Foundation.

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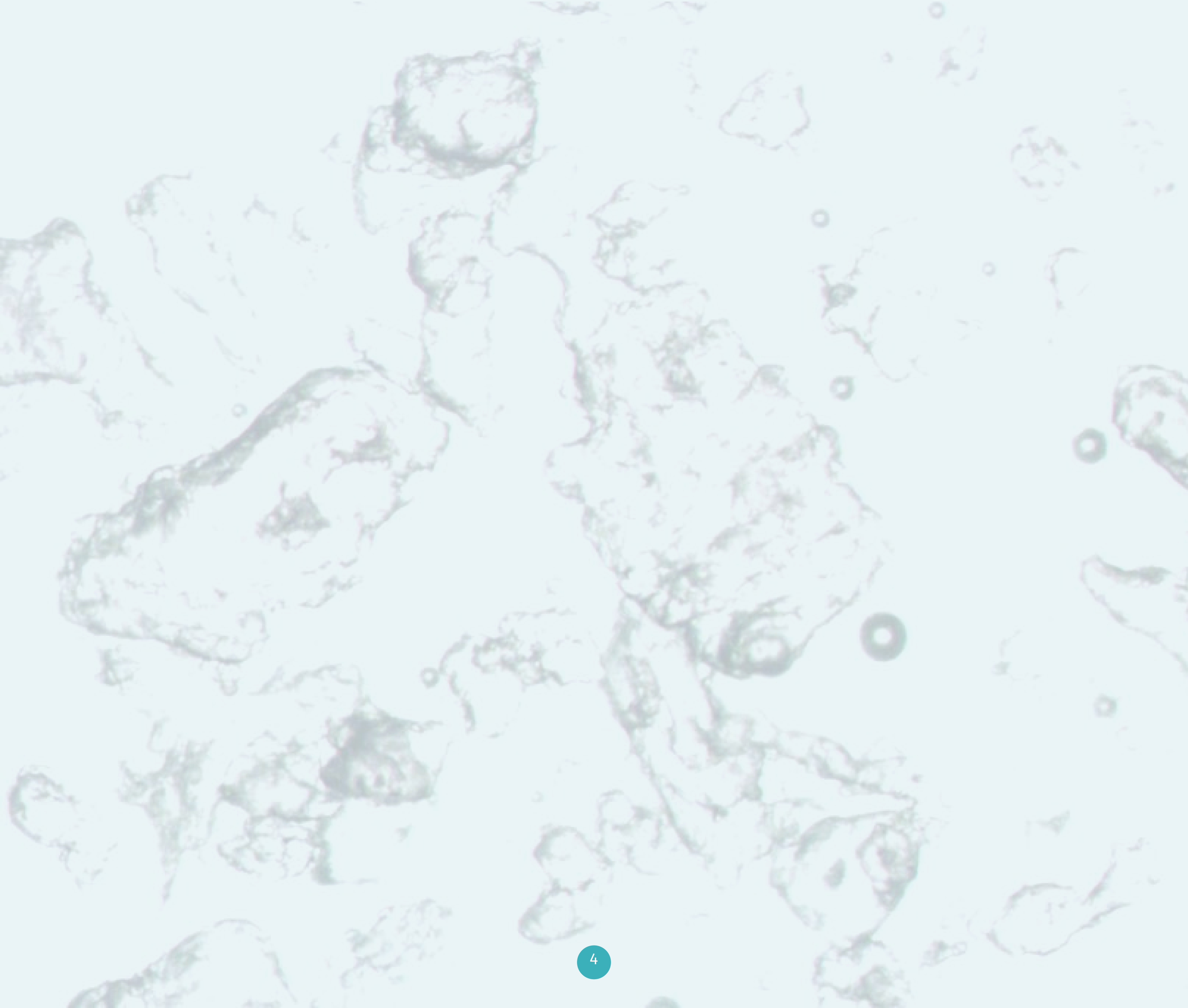


Foreword

Dear Reader,

This is a confronting report. Perhaps one of the most confronting studies ever.
It provides insight into the amount of microplastics we inhale, eat, apply to our bodies, and much more. Day after day after day. Our lives have become plasticized.

I have condensed the research into six societal stories.

1. **What are we eating today? Microplastics again?**
   In your food and as a food ingredient.
   Packaging and kitchen utensils, and appliances.
   Food preparation, such as microwaving food in plastic containers.

2. **Plastic, who didn't grow up with it?**
   Children's products come in all shapes and sizes. From fleece blankets to cribs, diapers, baby food, stuffed animals, and even the paint of toy building blocks.

3. **Plastic Care**
   Tattoos, contact lenses, nasal rinses, orthopaedic implants, the dentist, but also heart surgery.

4. **How intimate are you getting with your microplastics?**
   Condoms, lubricants, tampons, sanitary napkins, wet wipes, and other aids.

5. **The walls could use a new coat of plastic paint, my love**
   Indoor exposure through paint, clothing, sneakers, PVC floors and laminate, carpet tiles and synthetic curtains.

6. **Weather forecast: It's raining microplastics again**
   Wear and tear from car tires, plastic waste incorporated into asphalt, synthetic clothing, atmospheric precipitation, and – most shockingly – solar geoengineering.

If you would like practical tips to reduce microplastic intake for you and your family, check out our PlasticFreeFuture app. The app helps you implement easy, cost-free measures in your daily life that prevent exposure to microplastics via beauty products and soon to be added, fashion. No need to wait for the slow wheels of government regulation. We are closing the plastic tap while making your voices heard. The answer to more microplastics is simply: No.
A 'no' that resonates world-wide among people who are not settling for the status quo and are not waiting for their governments to act, when there's lots we can do.

Join the #plasticdetox movement today.

Maria Westerbos
Founder and Change Maker
Plastic Soup Foundation

Abbreviations and Glossary

µFTIR	micro-Fourier transform infrared spectroscopy – a hybrid-technique combining microscopy to visualise particles and infrared spectroscopy to detect, identify and count microplastics as small as 10–50 µm, measures polymer type and number of particles (no polymer mass data)
ABS	acrylonitrile butadiene styrene – a thermoplastic copolymer of three monomers commonly used in consumer products
AF4-MALS	field-flow fractionation with multi-angle light scattering – a hybrid-technique that separates submicron particles based on size and detects size, molar mass, and structural information
ATR-FTIR	attenuated total reflectance-Fourier transform infrared spectroscopy – a type of FTIR which detects polymer type via direct contact between the ATR crystal and the microplastic particle
BMC	poly(butylmethacrylate-co-(2-dimethylaminoethyl)methacrylate-co-methylmethacrylate), a pH-dependent copolymer used as tablet coating
Cryo-SEM	cryo-scanning electron microscopy – a high-resolution imaging technique used to visualize and count nanoparticles
dw	dry weight
EDI	estimated daily intake – the average individual consumption of a substance daily
FPA-µFTIR	focal plane array-Fourier transform-infrared-micro-spectroscopy – an FTIR-based technique coupled with a FPA detector that operates faster than traditional µFTIR
FTIR	(see definition µFTIR and ATR-FTIR)
g	gram
HDPE	high-density polyethylene – a high production volume thermoplastic polymer used in millions of everyday products
LDIR	laser directed infrared imaging analysis – a technique to detect, identify and count microplastics particles as small as 10-20 µm
LOD	limit of detection – the smallest quantity or concentration that can be detected with an analytical procedure
MP	microplastic – conventionally defined as a particle of plastic under 5 mm, sometimes including submicron plastic particles (see definition NP)
MNP	microplastics and nanoplastics
NIAS	non-intentionally added substances – impurities in plastics that occur alongside additives
nm	nanometer – one billionth of a meter (10^{-9} m)
NP	nanoplastic – a particle of plastic under 1 µm in dimensions
NPoF	nanoparticle-on film – a technique used in conjunction with Raman spectroscopy for detection of trace amounts of microplastics and nanoplastics
NTA	nanoparticle tracking analysis – a technique used to calculate particle size based on rate of individual particle diffusion rate
O-PTIR	optical photothermal infrared spectroscopy – a technique similar to FTIR that targets sub-micron plastic particles
PET	polyethylene terephthalate – a thermoplastic resin in the polyester family
PFAS	per- and polyfluoroalkyl substances – persistent ‘forever chemicals’
PM_{10}	particulate matter <10 µm – inhalable coarse particles up to 10 µm in size
$PM_{2.5}$	particulate matter <2.5 µm – inhalable fine particles up to 2.5 µm in size
PMMA	poly(methyl methylacrylate) – a transparent thermoplastic polymer that is commonly used in consumer products as well as dental work and prosthetics
PTFE	polytetrafluoroethylene (Teflon) – a fluoropolymer used in cookware coatings and food lube
PVC	polyvinyl chloride – a high production volume thermoplastic polymer used in diverse products from water pipes to hospital intravenous tubing

Pyr-GC/MS	pyrolysis-gas chromatography/mass spectrometry – a semi-quantitative technique that thermally degrades plastic particles, separates degradation products on a column, quantifies these in a mass spectrometer, and delivers polymer mass concentrations (not particle counts)
Pyr-GC/MS/MS	similar to Pyr-GC/MS but with a tandem mass spectrometer to measures mass of polymers after multiple ion fragmentation steps
QA/QC	quality assurance and quality control – refers to the overall management and documentation system that ensures quality of data (QA) as well as analytical checks and balances (QC) e.g. controlling for background contamination, analyte recovery, reproducibility, accuracy, and precision of results
Raman or µRaman	(micro)Raman spectroscopy – a non-destructive, laser-based analytical technique named after physicist C.V. Raman, used together with microscopy. Based on unique spectra that are produced, polymer type can be identified. Provides particle counts, particle shape and colour information.
SEM-EDX or SEM-EDS	scanning electron microscopy energy dispersive X-ray spectroscopy – a high-resolution imaging technique used to study morphology and size of nanoplastics (less than 100 nm)
SERS	surface enhanced Raman spectroscopy – a Raman-based technique for ultra-sensitive detection of micro-plastic down to the nanoscale
SRS	stimulated Raman scattering microscopy – a Raman-based technique used for specific polymer detection and particle quantification of very small microplastics (less than 10 µm)
TED-GC/MS	thermal extraction desorption–gas chromatography–mass spectrometry – a technique that thermally desorbs analytes from solid samples for GC/MS analysis
TEM	transmission electron microscopy – a high-resolution imaging technique that high-energy electron beams to visualise nanoplastics (particle characteristics but no particle chemistry information)
UFP	ultrafine particles – airborne particles with a diameter less than 0.1 µm
UPF	ultra-processed food – multi-ingredient, industrially formulated food
WOE	weight of evidence approach
ww	wet weight
XPS	X-ray photoelectron spectroscopy – a technique used to analyze and quantify the elemental composition of particles (not precise polymer identification)
µg	microgram – one millionth of a gram (10^{-6} g)
µm	micron or micrometer – one millionth of a meter (10^{-6} m)

Executive Summary

This report sketches the contours of real-world mixtures of a very large number of microplastic contaminants in everyday human exposure scenarios. Referencing 350 peer-reviewed scientific studies, evidence is presented showing that common consumer plastic products can collectively shed billions of microplastics at close range. Microplastic releases of 60 different polymer types were reported across five major categories: food, indoors, outdoors, children's products and personal care/healthcare. While microplastics in some samples came in under the limits of detection of the methods, there were several cases of extraordinary microplastics release from the normal use of products, and clear signals of very large numbers of submicron particles as well. Whether micro or nanosized, each of these polymeric packages are known to carry a chemical load that adds to their potential to cause mixture toxicity.

Well-known and lesser-known hot spots for microplastics release were identified. Plastic containers that are heated or microwaved, (e.g. take-out trays, kettles, tea bags) and kitchen utensils like plastic cutting boards and mixing bowls emerged as prolific microplastic generators. Children's toys, baby bottles, mother's milk, milk storage bags, baby mats, and house dust are responsible for microplastic exposure in early life. Paint, tires, artificial turfs, textiles, 3D printers, aerosol injection, and other potentially massive sources add to the total microplastic fallout, indoors and out. Personal care product formulations have garnered attention for the past decade with their intentionally added microbeads. Now, toothbrush bristles, dental work, contact lenses, tattoos, and even components in medicines, implants, and common medical procedures are similarly responsible for directly dosing the modern human with microplastics.

The peer-reviewed studies cited in this report have applied basic quality control measures to avoid false positives. While the analytical laboratories have developed a broad array of checks and balances for their analytical work, uncertainties remain for many reasons, e.g. lack of standardization and reference materials, semi-quantitative approaches, and the method maturity level in this challenging analytical field. It should be noted that uncertainty in real-world data sets is common and does not mean the data are useless or wrong. The bulk of data reviewed here carry a degree of uncertainty however are fit for the purpose of scoping a broad spectrum of current knowledge of microplastics exposure. The data are sufficient to firmly reject any hypothesis that humans are unexposed to microplastics via their products. Microplastics exposure via plastic products is commonplace.

The health risk of microplastics is still uncertain, but so is the safety of microplastics. Quantifying health risk starts with measuring microplastic exposure concentrations. This report shows microplastics exposures are commonplace: all plastic products release microplastics. Toxicological data (outside the scope of this review) are beginning to tell us which microplastics doses elicit toxic effects. The large data needs for both exposure and toxicological assessments means that human risk assessment of microplastics will likely still take decades to complete. What we already know is that the risks of plastic particles are scientifically plausible, potentially serious, and '*inequitable to present and future generations*'. When safety signals appear, the precautionary principle prescribes to avoid paralysis by analysis and take action to reduce exposure, while continuing to fill knowledge gaps and monitor to inform decision making on multiple levels. Knowledge of microplastics release patterns holds keys to mitigating these everyday exposures.

This report presents data with a cause, because knowledge is needed to act. We cannot solve a problem we cannot see clearly. This report illustrates how plastic products are clearly causing significant microplastics releases to our living spaces and food systems. It can compel people to rethink the materials we want to live with, and question whether these products are generating comfort, convenience, and the quality of life that we truly want.

Calling for resourceful advocacy to reduce microplastics exposures. In an era of growing awareness of a critical mass of people, the status quo is now being challenged more than ever. Individuals have already started regulating for themselves what they bring into their homes and workplaces, especially if government regulators remain unable to adequately address microplastic exposure on the short term, and manufacturers continue with business as usual. Hand in hand with individual action goes the (long-term) collective action needed to ensure systemic microplastic pollution is adequately controlled.

1. Introduction

Analytical chemistry has powered a great disclosure of contamination leaching from plastic and spreading not only to the environment, food systems, and indoor spaces, but also to inner world of the human body. Methodological advances have opened the possibilities for millions of measurements of plastic-associated chemicals in humans – and now also plastic particles – in places where they are in position to do harm [PlastChem 2025; Landrigan et al. 2025; Lamoree et al. 2025; Wu et al. 2022; Ramsperger et al. 2023; Feng et al. 2023; Nelis et al. 2023; Danopoulis et al. 2022; Mohamed Nor et al. 2021; Paul et al. 2020].

Microplastics are already being detected inside the human body.

Microplastic detection in human samples means we cannot pretend our bodies are eliminating plastic just as fast as they are absorbing it. Reports of microplastics being measured in human bloodstreams, organs, bodily fluids, and joints are being released, many of them pilot studies pending larger scale human biomonitoring programmes [Amato-Lourenço et al. 2021; Jenner et al. 2022; Leslie et al. 2022; Horvatits et al. 2022; Zhao et al. 2023; Guan et al. 2023; Pironti et al. 2023; Brits et al. 2024; Li et al. 2024; Amato-Lourenço et al. 2024; Cui et al. 2025].

Human babies come into the world already exposed to microplastics via umbilical cord blood, amniotic fluid, placenta, and breast milk [Braun et al. 2021; Ragusa et al. 2021; Ragusa et al. 2022; Sripada et al. 2022; L. Liu et al. 2023; Halfar et al. 2023; Zurub et al. 2024; Sun et al. 2024; S. Liu et al. 2023; Adjama et al. 2024; Nadarasan et al. 2025].

Environmental microplastic exposure studies have been ongoing for decades, and more recent methodological advances in the field have broadened the research scope to the detection and quantification of the smallest size fractions: submicron plastic particles, termed 'nanoplastic' [Ivleva 2021].

Plastic particles at the nanometer and micrometer scales are reaching the human body but which products are responsible for this exposure?

Microplastics detection in humans compels us to better understand the sources of the contamination in human living environments. This report is reviews the emerging evidence on the range of plastic applications contributing to real-world human microplastic exposure scenarios. A range of exposure-limiting measures are imbedded in information on the pathways and sources of microplastic exposure in humans.

> *The term microplastics refers to plastic particles smaller than 5 mm in dimension. Nanoplastics are plastic particles smaller than 1 micron. 'Microplastics' and 'MNP' are umbrella terms used to refer to both micro- and nanoplastics.*

Microplastics: tiny polymeric packages of chemicals

For decades, reports have been describing how toxic chemical additives are off-gassing and leaching out of all kinds of plastic products and finding their way into the air, water, and soil worldwide [UNEP 2023; Monclús et al. 2025; PlastChem 2025]. The chemicals associated with plastic fall into different categories: chemical additives such as dyes, biocides, flame retardants, the phthalates ('everywhere chemicals'), PFAS ('forever chemicals'), residual monomers and catalysts (often metals) leftover from the polymerization phase, fillers, non-intentionally added substances (NIAS) as mentioned above, or chemicals that have sorbed to the plastic somewhere along the lifecycle. It has become apparent that these chemicals infiltrate the world's biological systems, food systems, and the human body [Landrigan et al. 2025].

In the wake of the chemical exposure data coming out of nascent microplastic human biomonitoring studies, reports are emerging about the human exposure to microplastics via products commonly used world wide. Microplastics are tiny plastic particles that are released from normal use, and wear and tear of millions, possibly billions of different types and brands of products that made of or that contain plastic components. Like the chemicals associated with microplastics, the contamination is not contained in the environment only.

> *Microplastics are tiny packages of chemical additives, residual monomers, catalysts fillers and non-intentionally added substances.*

Every plastic particle that is detected in a sample from a human body carries its own unique chemical load. This is because plastic contains more than just polymers. Polymers are big molecules. As macro-molecules they form the structural framework of plastic materials. But there are always other chemicals present within that framework. Many of these are the small molecules which have been intentionally added by the producers to enhance the properties and functionality of the polymer material.

PlastChem [2025] reports there are more than 16,000 chemicals currently being added to plastics across diverse product applications, up to 400 in a single plastic product. Of these 16,000 chemicals, 4,200 have hazardous properties for health and the environment. Plastic is more than a polymer alone; plastic's polymeric chains are as 'noodles' surrounded by a chemical 'sauce'.

> *PlastChem reports 4,200 known hazardous chemicals to be among the 16,000 chemicals added to plastic. Up to 400 chemicals can be present in a single plastic product.*

A great number of other unplanned chemicals also end up in plastic: NIAS. The raw materials used for making plastics are typically not highly purified, 'analytical grade' chemicals. The actual profile of chemicals in a seemingly simple plastic product can be a lot more complex than one might expect. For instance, transparent polyethylene sheets used to cover crops of strawberries can contain hundreds of chemicals [Menger et al. 2024]. This is a prime example of a typical plastic product that during normal use weathers and fragments into smaller and smaller pieces. Erosion and shedding processes of the bulk material creates micro-sized and nano-sized plastic pollution at sites of food production.

Plastic products and the microplastics that they shed are constantly sorbing chemicals they encounter in the ambient environments they find themselves in after leaving the factory. This adds to the chemical complexity we observe when we zoom in on what plastic carries with it throughout its entire product cycle.

Human exposure measured inside and outside the body

Measured concentrations of microplastics in human samples comprises evidence of what scientists call *internal exposure* – the presence of pollutants inside the body [Escher et al. 2004]. Internal exposure concentrations are important indicators of the amounts of chemicals that are already in position to interfere with normal healthy bodily functioning. Internal exposure measurements leave no doubt as to which fraction of the contaminants present outside the body will end up inside the body. Information on the sources of the exposure cannot be deduced from human biomonitoring data however. For that, microplastics need to be measured outside the body.

External exposure concentrations are those measured in the air being breathed, the water people drink, or the products that come in contact with their skin. Measurements of concentrations outside the human body are important, especially for studying where the hot spots are, and for designing and monitoring mitigation strategies that prevent external exposure and circumvent internal exposure altogether. Scientists also use external concentration data to estimate how much of the microplastics in those samples will end up being absorbed in the body.

> *Microplastic detection in human samples means we cannot assume the body is eliminating microplastic just as fast as it is absorbing it. This compels us to understand the range of sources of microplastics causing the pollution of people's bodies.*

A growing effort has been put into quantifying actual human exposure to microplastics and/or chemicals through normal product use for several product categories. This research zeroes in on the human-product interface to study for a given product, used in context, and asks whether microplastic release and exposure can be detected, and if so, what exposure concentrations are being measured or estimated.

Exposure assessment is a key element of human risk assessment of microplastics. The other key element is toxicity assessment to determine how microplastics interfere with biological functioning. The toxic effects of microplastics are outside the scope of this report. Effects such as cytotoxicity, oxidative stress and immune endpoints have been reported and have been extensively reviewed elsewhere [Paul et al. 2020; Danopoulis et al. 2022; Wu et al. 2022; Feng et al. 2023; Nelis et al. 2023; Landrigan et al. 2025; Lamoree et al. 2025].

A note on the methods for measuring microplastics

Microplastics are measured by analytical chemists using a variety of approaches. The steps include sampling, storage, sample preparation, sample purification, and instrumental analysis, with quality control of each step. Protocols for sampling and storage focus on acquiring sufficient sample volume and avoiding introduction of external microplastic contamination. Next the sample must be prepared for instrumental analysis to determine quantities and identify polymer types. Microplastics cannot be measured directly in most types of samples. They are usually first extracted from the sample and the extract is then further purified to remove as much of the original sample material as possible while retaining the microplastics to be analysed. Many methods include a filtration step for this purpose. The efficiency of these steps is controlled during the procedure. Next microplastics in the sample extract are measured using analytical instruments.

Which polymers are plastic?

Multiple definitions of the term microplastic have attempted to define which polymers should be included as ‘plastic’. The European REACH Regulation (EU) 2023/2055 uses its own definition of microplastics, exempting several polymer types that the scientific community is interested in from environmental and human exposure perspectives. This report is primarily concerned with synthetic polymer particulates originating from common product applications that humans may be exposed to. They are referred to as microplastics (MP) or nanoplastics (NP) throughout the report.

The selection of the instruments depends on the goal of the study, and many times two or more instruments are used in tandem to achieve results (Fig. 1). Some instruments characterize particle size, shape, colour, number of particles and polymer type present. Other approaches based on mass spectrometry generate mass concentrations per polymer, and do not count particles or generate particle images. Sometimes researchers choose to first separate particles based on their size (fractionation).

Mass of particles	**Number of particles**
Pyr-GC/MS Pyr-GC/MS/MS TED-GC/MS	µFTIR, ATR-FTIR, FPA-µFTIR LDIR, O-PTIR µRaman, SERS, SRS
Fractionation of particles	**Imaging and characterization**
AF4-MALS	Cryo-SEM, TEM, SEM-EDX NPoF, NTA

Fig. 1. Instruments for microplastic and nanoplastic analysis. An overview of instruments from the cited studies can be found in Abbreviations and Glossary of Terms.

There is usually a size limit on particles that a given technique can measure – some are suited for submicron particles while others perform better for microplastics above 10 or 20 µm. Electron microscopy-based instruments are used to characterize nanoparticles, though do not determine the polymer type.

Depending on the instruments, concentrations are reported in either mass units or numbers of particles. These are complementary data. Environmental contamination and norms for pollution are almost always reported as mass-based concentrations, even for air particulates (PM_{10} means the mass concentration of particles under 10 µm in size). Mass concentrations are beneficial for studying mass balances, and when the particles are too small to be imaged by instruments that can determine the polymer type, and abundant enough for their mass to be sufficiently high for the sensitivity of the mass spectrometer to handle.

2. Approach

This report aims to review the published evidence of microplastics shedding from common plastic products that contribute to microplastic exposures in humans. The peer reviewed and gray literature was reviewed non-systematically using search terms microplastic, nanoplastic, polymer, in combination with release, consumer product, and human exposure. Because these human exposure measurements indicate a positioning of microplastics near the human body, emerging evidence of toxicological hazards are highly relevant, although outside the scope of this report.

The definition of ‘microplastics’ (MP) used for this report is plastic particles under 5 mm in size, including submicron particles called nanoplastics. The term ‘nanoplastics’ (NP) is used in this report where it is relevant to specify that the plastic particles are submicron sized.

Sources of human microplastics exposures are presented in the five following categories:

- food, food processing, packaging, and preparation;
- indoor sources;
- outdoor sources and recreation;
- children’s products;
- personal care and healthcare.

3. Food, Packaging and Preparation

Key takeaways – Food-related sources

Microplastics gain access to the human body via food ingestion – a key exposure route.

Microplastics in food samples including such staples as rice, sugar, fish, fruit, and meat ranged from undetectable to concentrations of hundreds of particles per gram.

Processed food tended to have higher microplastics concentrations than fresh, unprocessed counterparts.

Tap water, soft drinks, and alcoholic beverages presented a range of concentrations from under detection limits up to several dozen microplastics per liter.

One gram of chewing gum was reported to release over 600 intentionally added microplastic particles into the saliva.

‘Food lube’ is microplastic officially approved for food contact lubrication in industrial food processing.

Plastic chopping boards can release approximately hundreds of microplastics per cut.

Plastic mixing bowls released between 300 and 900 microplastics per bowl during normal use.

Microplastic exposure via ingestion could be increased greatly by microwaving food in plastic containers, heating water in plastic kettles or disinfecting bottles with hot water.

Up to 1 million microplastics were released from take-out trays after being microwaved.

Plastic kettles released between 5 to 35 million microplastics to the boiled water (microplastic release decreases gradually in the first weeks of new kettle use).

Synthetic tea bags were reported to release 2.3 million microplastics per cup of tea, (and over a billion nanoplastics).

Given that over a lifetime one might consume 80 tonnes of food and beverages, and the microplastics in these products are transferred to the human body, food is one of the sources of exposure that individuals can address by gradual changes in food basket content and in the kitchen.

The food category represents a very important human exposure route in terms of microplastic contaminant loads and opportunities for exposure reduction. In a European country like the Netherlands, the average adult consumes 2.9 kg of food and drink daily [RIVM 2016], roughly a third of that being food. Preschool children consume less, 1.5 kg/d, adult men up to 3.5 kg/d. Over the course of a long lifetime, that can translate to upwards of 80 tonnes of consumed food and drink per person. Microplastics and associated chemical contaminants imbedded in this food and drink enter the body, and depending on bioavailability, a fraction of the consumed microplastic-chemical 'packages' may be absorbed and later eliminated (via e.g. urine, milk, semen etc.), and the remainder may be eliminated directly via the bowels, as *in vivo* studies on animal models have demonstrated e.g. [Staufer et al. 2025] and measurements in human feces indicate [Schwabl et al. 2019; Zhang et al. 2021; Hasanah et al. 2024].

> *An adult may eat 80,000 tonnes of food and drink over an average lifespan, roughly one-third food and two-thirds drinks. On a daily basis, food materials have the potential to introduce microplastic contaminants they carry into to the body.*

Even the non-absorbed fraction of microplastics that passes through the gastrointestinal tract is relevant, considering common microplastic types may be tampering with the gut microbiome [Bora et al. 2024; Jiménez-Arroyo et al. 2023; Pacher-Deutsch et al. 2025], oral microbiota [Zha et al. 2023], esophageal cells [Guanglin & Shuqin 2024], and compromising barrier integrity, elevating intracellular reactive oxygen species and stimulating intestinal cytokine secretion, as observed in microplastic hazard testing using intestinal epithelial cell models [Brouwer et al. 2025]. Microplastics are known to be highly resistant to metabolization [Chow et al. 2023; Jiménez-Arroyo et al. 2023], which can lead bioaccumulation scenarios unless the materials are eliminated.

As concentrations in food and beverages become more available, a picture of ingestion as a major exposure route for humans can emerge. Even inhaled particles that are too large for absorption in the lung may end up being coughed up and swallowed: healthy adults spontaneously swallow around once a minute [Bulmer et al. 2021].

Multiple categories of food products are subject to microplastic contamination, and are direct routes for ingestion of microplastic contamination into the human body. Not only mussels and oysters but also other fish, shrimp, lobsters, table and sea salts, sugar, tea, bottled beverages, tap water, honey, milk, fruit, vegetables, meats, processed foods, chewing gum, soft drinks, beer and dietary supplements have been reported to carry microplastic loads.

The sum microplastic exposure via food is a parameter that varies among individuals as it depends on personal choices of food products consumed. Microplastic residues in food may have been introduced in situ, prior to harvesting, but how food is packaged and prepared significantly impacts the microplastic content of food products. As this chapter illustrates, these 'food basket' choices - along with different packaging and preparation features - can vary considerably in terms of the microplastics content they bear.

3.1 Food

Seafood and animal products

It has been known for some time that filter feeding marine mussels and oysters used for human consumption are high microplastic accumulators. Van Cauwenberghe & Janssen [2014] alerted the public that Belgian mussels and oysters analysed at their laboratory contained on average 0.36 ± 0.07 MP/g mussel (wet weight, ww) and 0.47 ± 0.16 MP/g oyster tissue (ww). They estimated that a European seafood consumer might be consuming 11,000 microplastics annually.

Not only benthic filter feeders, but also wild fish muscle tissue from the Atlantic Ocean, relevant for human consumption, tested positive for microplastic contamination in 32% of the samples [Barboza et al. 2020]. The mean measured concentration in that study was 0.054 ± 0.099 MP/g fish. The average human intake of microplastics via consumption of the three fish species in that study was then estimated to be 842 MP/year. They also estimated a mean annual intake from 518 to 3078 MP/year from the consumption of fish muscle in the EU and the Americas based on literature data of microplastic in fish muscle.

Edible tissues of Nile tilapia (fillets) raised in aquaculture were assessed for microplastic content [Sefiloglu et al. 2024]. The researchers detected trace amounts of microplastics (average of 0.14 ± 0.32 μg/g fillet) in 42% of the 24 samples analysed with pyrolysis-gas chromatography/mass spectrometry (Pyr-GC/MS). Polystyrene, polyethylene, polypropylene and poly(methyl methylacrylate) (PMMA) were the polymers detected in this study.

Other important seafood species such as wild squid, blue crabs, and sardines and farmed prawns and oysters were analysed with Pyr-GC/MS in Australia [Ribeiro et al. 2020]. Sardines were the most contaminated, with a total concentration of 2.9 mg MP/g tissue. Microplastic content in crabs was 0.34 mg MP/g, in oysters 0.1 mg MP/g, in prawns 0.07 mg MP/g, and in squid 0.04 mg MP/g. These concentrations were considerably higher compared to the tilapia fillets acquired from aquaculture [Sefiloglu et al. 2024]. The polymers detected in this study included polyvinyl chloride (detected in all samples), polyethylene, polystyrene, polypropylene, and PMMA [Ribeiro et al. 2020].

Lobster meat analysis in Nova Scotia, Canada revealed on average 6.65 ± 5.36 MP/g ww with polyethylene vinyl acetate, polyester, and polysulfone being the dominant polymer types identified via a combination of Nile red staining and μRaman confirmation of 10% of the samples [LeBlanc et al. 2025]. None of the samples analysed were under detection limits, (<LOD).

Microplastics monitoring and research started in the marine environment and perhaps because of this, seafood has been one of the first food categories recognized as a source of human microplastic exposure [EFSA 2016; M. Smith et al. 2018; Van Raamsdonk et al. 2020] and since then, a limited number of additional food categories have since appeared [Garrido Gamarro & Costanzo 2022; Sewwandi et al. 2023].

Livestock can be exposed to microplastic via their own feed, water and ambient air. Beef and pork samples from the Netherlands were reported to contain between 53 and 7700 μg MP/g in one of the few studies so far that determined mass concentrations of microplastics in meat products and livestock [Van der Veen et al. 2022].

Microplastics have been detected in samples of unprocessed seafood samples as well as minimally-processed meat samples, though at relatively low concentrations 0.01 ± 0.01 MP/g in chicken breasts and pork loin chops [Milne et al. 2024].

Plant based whole food

Some preliminary evidence that plants absorb microplastics via root systems has been published. Though plant cell walls have pores too small to facilitate uptake, it has been suggested in a study of wheat and lettuce plants that microplastics enter root systems where lateral root emergence takes place, via the ‘crack-entry mode’, and are subsequently transferred to shoots [L. Li et al. 2020a,b].

Radishes hydroponically grown on perlite spiked with microplastics also showed evidence of microplastic uptake when root sections were examined with Raman [Tympa et al. 2021]. The amounts of microplastics in root sections were not quantified.

> *Microplastic uptake by plant roots or stomata openings on leaves is a new area of research revealing the exposure via dietary plant-root based foods or leaves.*

A unique study of particles in fruit and vegetables detected particles in the food products with scanning electron microscopy (SEM) and elemental analysis by energy-dispersive X-ray spectroscopy (SEM-EDX) [Oliveri Conti et al. 2020], although these instruments cannot specifically identify plastic or polymer types. In that report, adult consumption of particles was estimated to be 462,000 and 29,600 particles per year from apples and carrots respectively. These data must be confirmed with techniques that can distinguish between plastic and other carbon-based non-plastic materials. The study is noted here because it represents a pioneering attempt at particle detection and quantification in fruit and vegetable samples.

The following year, the potential for carrots to absorb microplastics was demonstrated by dosing plants with known microplastic particles. Small amounts of polystyrene microplastics (1 μm in size) were observed to be taken up into the inter-cellular layer of carrot roots, without being able to enter the cells

[Dong et al. 2021]. Smaller particles (0.2 µm) were reported to be able to migrate to the leaves of the carrot plant. In the presence of arsenic (III), polystyrene (< 200 nm) appeared to be able to enter cells, in part because of disturbances to the cell walls [Dong et al. 2021].

Besides roots, plant leaves have been reported to be able to internalize microplastic via stomata, which are small openings on the leaf surface (25 µm × 3-10 µm) [Gan et al. 2023]. Lettuce leaves were observed to take up polystyrene particles via their stoma when exposed to a suspension of nanopolystyrene (ca. 100 nm particle size) [Lian et al. 2021].

While laboratory exposures to study uptake and accumulation are important, it remains difficult to measure such small unknown nanoparticles in field samples and determine if the nanoparticle detected is in fact a plastic. Polymer type determination in the low nanometer particle size range is the next frontier in microplastics research. Sample preparation and particle extraction is also particularly challenging when working with fruit and vegetables [Lăzăr et al. 2024].

Plastic may also be deposited on the surface of fruits for human consumption. Microplastics (21 different polymers) were detected by laser directed infrared imaging analysis (LDIR) and cryo-scanning electron microscopy (Cryo-SEM) on the surface of strawberries at concentrations between 52.50 and 134.16 MP/g [Bai et al. 2024]. The researchers investigated different strawberry washing methods and reported that water immersion was superior for microplastic removal compared to rinsing (wash water contained between 32.79 and 115.81 MP/cm^2 of strawberry surface). When grown in contact with polyethylene mulching film, strawberries were more highly contaminated by polyethylene compared to berries subject to air deposition only. However, the average abundance of microplastics associated with strawberries grown in contact with mulching film was 64.33 ± 9.76 MP/g, which was significantly lower than that of strawberries grown in the open air 115.27 ± 10.18, MP/g (data given for the same water washing method) [Bai et al. 2025].

Salt

Abiotic food products such as drinking water and sea salt are known to contain microplastics that in part originate from the source, e.g. the ocean or drinking water reservoirs. Peixoto et al. [2019] reviewed the data on microplastic in sea salt and concluded that 90% of commercially available salts, covering samples from 128 brands in 38 different countries on five continents, exhibited various levels of microplastic contamination, from low single digit MP/kg levels to high contamination levels reaching 19,800 MP/kg.

The estimates made were that a typical salt consumer could potentially ingest over 36,000 plastic particles annually only from eating salt, particularly if eating the more contaminated varieties.

Data for commercial salts continue to be produced. Italian sea salts were analysed with Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy resulting in measurements of 1653 ± 29 MP/kg salt, where polypropylene, polyamide and polyethylene and other plastic types were present [Di Fiore et al. 2023]. In samples from Atlantic and Mediterranean locations, Fleur de Sel's total microplastic content determined by Pyr-GC/MS ranged from 138 to 1993 µg/kg [Fischer et al. 2019]. These were higher concentrations than measured in regular sea salts in the same study, which ranged from 14 to 60 µg/kg. The differences are likely attributable to different harvesting conditions of the two types of salt.

Drinking water and beverages

One of the earliest studies to examine tap water and beverages focused on all anthropogenic particulates including synthetic fibers. These were detected in many globally sourced tap waters (mean 5.45 MP/L) and in beer (mean 4.05 MP/L) [Kosuth et al. 2018]. This followed a report published four years earlier of microplastics being detected at concentrations between 2 and 79 fibres/L, between 12 and 109 fragments/L and between 2 and 66 granules/L in all 24 brands of German beer tested [Liebezeit and Liebezeit, 2014]. A more recent study reported concentrations between 12 and 56 MP/L in eight different craft beers, and between 18 and 98 MP/L in six different industrially processed beers, making use of FTIR for particle identification [Diaz-Basantes et al. 2020].

Other early reports of microplastics in drinking water indicated that microplastics were variable but could be very abundant, particularly if the methodology was able to detect small micron-sized particles. Bottled water showed highly variable concentrations of small particles ranging from 2649 ± 2857 MP/L in single-use polyethylene terephthalate (PET) bottles up to 6292 ± 10521 MP/L in glass [Oßmann et al. 2018].

Schymanski et al. [2018] also found low micron particles (5-20 µm) in bottled drinking water. Returnable bottles had higher microplastics concentrations (118 ± 88 MP/L) than single use bottles (14 ± 14 MP/L). The latter was similar to the blank value, i.e. the level of background contamination introduced during analysis - not from the product itself. Even water in glass bottles contained microplastics ranging from undetectable to 253 MP/L, mean 50 ± 52 MP/L.

> *Beer, soft drinks and the tap waters they are made from are sources of microplastics whether they are packaged in glass or plastic bottles.*

A French study reported abundant microplastics in glass-bottled beverages, particles that were identified as paint chips identical to the paint used on the bottle caps [Chaïb et al. 2025]. This illustrates how important not only the choice of main construction material is for microplastic exposure reduction, but also the paints applied (see also Chapter 4). It was observed that the most contaminated containers were glass bottles. Mean microplastic concentrations measured in that study were reported for a variety of beverage products: 2.9 ± 0.7 MP/L water, 31.4 ± 16 MP/L cola, 28.5 ± 13.1 MP/L tea, 45.2 ± 21.4 MP/L lemonade, 82.9 ± 13.9 MP/L beer and 8.2 ± 3.3 MP/L wine.

Water can be contaminated not only at the source or packaging choices, but also during processing and transport. Tap water transported via polyvinyl chloride (PVC) pipes has been observed to release up to 11 MP L^{-1} water [Temam et al. 2023]. The degradation of both polyethylene and PVC materials of water pipes increases with many factors and operating conditions, such as water velocity, temperature, chlorine-based disinfectants, biofilms, diameter and age of the water pipe [Świetlik & Magnucka 2025].

Bäuerlein et al. [2022] reported 2 MP/L (particles >20 µm) in Dutch drinking water from the tap, water that is produced using a combination of groundwater and microplastic-rich surface waters as raw materials in the treatment process. The most frequently detected polymers in the final drinking water product were polyamide (33%), polyethylene terephthalate (15%), rubbers (10%), polyethylene (10%) and chlorinated polyethylene (7%).

A recent study of Dutch drinking water showed that treated drinking water is effective at removing 97-98% of microplastics, predominantly PET, PVC or polyethylene [Sefiloglu et al. 2025]. Using Pyr-GC/MS microplastics were measured at concentrations of 50.6 ± 34.7 µg/L (n = 14) and 47.5 ± 33.7 µg/L (n = 14) in raw water samples used for the drinking water supply, 0.80 ± 0.44 µg/L (n = 12) and 1.65 ± 2.1 µg/L (n = 14) in treated drinking water samples and 0.21 ± 0.12 µg /L (n = 20) in household tap water samples.

Early signals of microplastics in beer and tap water led to further investigations into microplastics in other beverages made with tap water, such as soft drinks, iced or warm teas and energy drinks. Beverage samples packaged in either glass (n=24) or plastic (n=33) bottles sourced in Mexico were studied using µRaman spectroscopy [Shruti et al. 2020]. Microplastics were present in 48 of the 57 samples tested. Mean concentrations reported were 11 ± 5.26 MP/L iced tea, 40 ± 24.53 MP/L soft drinks, 14 ± 5.79 MP/L energy drinks and 152 ± 50.97 MP/L beer. The researchers identified particles of polyamide, poly(ester-amide), acrylonitrile-butadiene-styrene (ABS) and PET [Shruti et al. 2020].

Another study using Raman to study microplastics in international brands of beer purchased in China found much higher levels, 20-80 MP/ml beer, and detected polystyrene and polypropylene [Li et al. 2022]. Mineral water in the Chinese study was also reported to contain relatively high concentrations: 10 MP/ml. In that water, polypropylene was identified.

Brewed tea, one of the most popular beverages in the world, has also been the focus of study for micro-plastics contamination. Li et al. [2022] studied four types of Chinese tea leaves (black, green, white and dark tea) and detected between 200 and 500 MP/g tea leaves. Only polyethylene and PET were identified to be present across all tea types in that report.

In a study that looked at different steps in tea leaf production in India, tea in the drying stage contained the fewest microplastics [Mondal et al. 2025]. Various plastic tea processing equipment contributed to contamination levels found in tea products. Concentrations of 0.4-1.1 MP/g tea were reported, and particles of polyethylene, polyacrylates, PVC and nylon were identified [Mondal et al. 2025]. Annual microplastic ingestion was estimated by the researchers to be between 6 and 74 µg per tea drinker.

Sixty samples of packaged herbal teas from five different brands in Turkey were used to make tea and analyse microplastics in the tea prepared for drinking [Gökkaya & Izmirli 2025]. Between 9 and 27 MP/100 ml prepared tea were detected in different tea types (linden, chamomile, green and sage). One brand contained no detectable microplastic. In samples from the remaining brands, particles of ethylene vinyl acetate, PET, and polyacrylonitrile were identified with attenuated total reflectance (ATR) sampling and FTIR. Longer infusion times (5 min.) were correlated with higher microplastic release [Gökkaya & Izmirli 2025].

Milk

Milk is another beverage type tested for microplastics contamination. In Mexico, between 3 ± 2 to 11 ± 3.54 MP/L were detected in 13 different local and foreign milk brands [Kutralam-Muniasamy et al. 2020]. For the complete set of samples, an average of 6.5 ± 2.3 MP/L were reported.

Using microscopy and FTIR detection, between 34 and 254 MP/L were reported in milk samples tested in Ecuador [Diaz-Basantes et al. 2020]. In a different pilot study of 26 cow's milk samples collected either by hand milking, from the tank (robot milking), or supermarket (packaged), microplastic measurements above the limits of quantification were very rare when screening for six polymer types using a pyrolysis gas chromatography/mass spectrometry (Pyr-GC/MS) method [Van der Veen et al. 2022].

Sugar and honey

Another staple food product is sugar. German researchers published an early study on microplastics in sugar and honey from European sources. In commercial refined sugar products, fibers were more abundant, (mean 217 ± 123/kg sugar) and fragments were also present in significant numbers (32 ± 7/kg sugar) [Liebezeit and Liebezeit, 2013]. Their unrefined cane sugar samples were the most contaminated in this series of samples, with concentrations of 560 fibres and 540 fragments/kg product.

Turkish researchers sampled granulated sugar, powdered sugar and sugar cubes for microplastics analysis, finding on average 291 MP/g sugar across all types [Yurtsever et al. 2025]. In granulated sugar samples packaged in plastic, the microplastic concentrations measured ranged from 117 ± 63 MP/g to 534 ± 96/g. The cube samples, which happened to be packaged in cardboard boxes, had even higher average concentrations than the plastic packaged samples. Based on measured concentrations and local consumption patterns, MP particles ingestion was estimated to be 196 MP/adult/day and 857 MP/child/day [Yurtsever et al. 2025].

In an early study of microplastics in honey samples, predominantly fibres were detected at concentrations ranging from 40 MP/kg to 660 MP/kg of honey, (mean 166 ± 147 MP/kg) [Liebezeit and Liebezeit, 2013].

Honey from Ecuador was reported to contain concentrations between 82 and 178 MP/L in eight different craft honeys and between 20 and 166 MP/L in eight industrially processed honeys [Diaz-Basantes et al. 2020].

Microplastics (ethylene-vinyl acetate, polyethylene, polypropylene, and nylon–6) were detected with FTIR at an average concentration of 314 ± 353 (range 0–1280) MP/kg in 32 honeys sampled in Turkey [Basaran et al. 2024]. The researchers estimated the average microplastic intake via honey consumption to be 382 microplastics/person/year. Monofloral honeys contained significantly more microplastics than multifloral ones.

In all honey samples of a native Brazilian bee species, microplastics were detected with FTIR at concentrations ranging from 0.1 to 2.6 MP/mL of honey [Rani-Borges et al. 2024].

In a study that circumvented microplastic contamination sources that arise during processing and packaging, natural honey was sampled directly from 10 beehives in Italy [Schiano et al. 2024]. Polyethylene was found to be prevalent in natural honey, as well as trace amounts of many different polymers: acrylonitrile butadiene styrene, polycaprolactone, polycaprolactone, polytetrafluoroethylene, polyvinyl stearate, polyamide, ethylene vinyl acetate and polyester. Resident honeybees sampled from each hive also carried microplastics, alongside pollen, in their hairs. The sources of microplastics in honey are likely to be partly the outdoor contamination and partly the indoor packaging and processing.

Rice

Rice is a staple food and part of half the world's daily diet. With hundreds of millions of tonnes of rice being consumed annually, it is a highly relevant food matrix to test for microplastics.

Rice samples (n=52) purchased in Australia were analysed using Pyr-GC/MS [Dessì et al. 2021]. Polyethylene was present in all rice samples (45 to 317 µg/g dry weight, dw), polypropylene was found in 40% of the samples at concentrations up to 105 µg/g dw. A preliminary estimate of the intake of plastic through rice consumption was established at 3.7 mg plastic per 100 g-serving if the rice had not been washed prior to cooking, and 2.8 mg per 100 g-serving if rice had been washed. For Australians, the consumption of microplastics via rice was estimated to be around 1 g/year per person.

> *Global food staples such as rice and sugar contribute to the daily intake of microplastics.*

Indian rice analysed by µFTIR and µRaman spectroscopy found microplastics in every sample tested with the main polymer types being polyethylene, PET, followed by polypropylene and polyamide [Bhavsar et al. 2024]. Maximum estimated daily intakes (EDI) for Indian men, women and children were calculated to be 1.292, 1.527, and 1.313 MP/kg/day via the rice consumption route.

In a study using Raman spectroscopy to determine microplastics in rice in the Philippines, 5 MP/kg washed and cooked rice were reported [Espiritu et al. 2024]. The study found that washing the rice prior to cooking removed some but not all microplastic traces. A typical Filipino meal of 140 g of cooked rice would be expected to contain around 1 MP, based on the study data. PET was the main polymer detected in the rice, which the researchers suggested could have been introduced by the polyester rice bag packaging and/or during processing and transport prior to packaging.

Dietary supplements

Dietary supplements in Australia have recently been reported to release microplastics, resulting in estimated daily intake of 5.89 ± 2.89 MP/day on average [Panneerselvan et al. 2025], opening up a previously unknown product category for microplastic exposure. Most of the microplastics detected in the nine dietary fibre powders and gummies tested were in the form of fibers (83.4%) with fragments making up the remainder. A variety of polymer types were determined using µ-FTIR: polyamide, polydiallyl phthalate, polyethylene, polypropylene diene, polyurethane, polyethylene terephthalate, poly-ethylene and ethylene acrylic acid copolymer.

> *Using dietary supplements can add small numbers of microplastics to one's daily microplastic intake.*

Encapsulation of vitamins with pH-sensitive polymers has been proposed to facilitate absorption of vitamin and mineral in supplements or applications as microparticle food additives. The rationale is that the nutrient is only released when the polymer comes into contact with gastric acid and degrades. For this, engineers are using poly(butylmethacrylate-co-(2-dimethylaminoethyl)methacrylate-co-methyl-methacrylate) (1:2:1), abbreviated as BMC, to coat micronutrients [Anselmo et al. 2019]. These products are being marketed to disadvantaged communities as a solution to nutritional problems, though they concomitantly introduce another (hidden) source of microplastic contamination to our food systems.

Geophagy

An unusual and relatively minor source of microplastics comes from the practise of 'geophagy', the intentional ingestion of soil or clay for culinary (e.g. red ochre deposits used as food additives and flavourings) or for health purposes (e.g. detoxification clays sold at health food stores) [Amiri et al. 2022]. Amiri and colleagues explored this possibility by extracting microplastics from red soil used for culinary purposes in Iran and using detected µRaman to measure between 2 and 10 MP/100 g soil.

Plastic as 'food' ingredient

Some foods are formulated with plastic as a key ingredient, as is the case with the 'synthetic gum base' ingredient in chewing gum. On contemporary chewing gum packaging ingredient lists, this term has replaced the chemical names of the individual synthetic polymers that were commonly listed on chewing gum packaging in the past.

The result is that hundreds of thousands of microplastics are released into the oral cavity through chewing gum. During one hour of chewing and sampling the saliva at three time points, around 250,000 microplastics were detected in saliva samples of a human volunteer [Pant et al. 2025]. For testing, a package of chewing gum was purchased from a UK supermarket, brand unidentified. A blend of polyethylene and polyvinyl acetate plastics were identified using Surface Enhanced Raman Spectroscopy (SERS). Coupling this technique to a copper foil-based nanoparticle on film (NPoF) platform, researchers developed a method for the detection nanoplastics down to concentrations of 1 µg/ml. Though not quantified in this study, nanoplastic particles were observed in the saliva fraction filtrate containing particles <1 µm.

In a pilot study performed by researchers at the University of California, Los Angeles, from 4 up to 636 MP/g chewing gum were reported to be released into the saliva [Lowe et al. 2025]. The particles were typically under 50 µm in size and the polymers detected with FTIR included polyethylene, polypropylene, PET, polystyrene and polyacrylamide. The microplastics were released for the most part during the first 8 minutes of chewing.

Ultra-processed food

Ultra-processed food (UPF) goes hand in hand with plastic packaging and migration of microplastics and associated chemicals. Highly processed, mass produced and profitable-to-sell food exists in symbiosis with cheap, lightweight, microplastic-releasing, chemical leaching plastic packaging – a recipe for a toxicity [Yates et al. 2024]. Extensive processing involves not only the use of additives for colouring, flavouring or emulsification, but also many food modification steps such as puréeing, fractioning, hydrolysis, hydrogenation, prefrying, extrusion, moulding.

> *'Food lube' is a term applied to food-contact microplastic functioning as lubricant ball bearings in food processing technologies.*

Each processing step brings processed food into contact with many pre-consumer plastic food contact materials which can release microplastics to the final product. An example is the plastic food contact bearings used in lubricants for industrial food processing machinery, so-called 'food lube'. Virgin polytetrafluoroethylene (PTFE) ball bearings (microplastic particles) are one such application, approved by the US Food and Drug Administration (CFR 21-177.2600) as well as EU Regulation 10/2011 for food and beverages (as well as cosmetics and pharmaceuticals). Other polymers are also on the market which may eventually replace PTFE in such applications.

Honey is an example of a bulk raw material and a natural product that is only sometimes highly processed. Even without ultraprocessing it, honey still needs to be collected, transported and stored prior to packaging. Storage of bulk honey is commonly done in large plastic vats, which are sawed open prior to transferring to consumer packaging. Such common practises may introduce additional microplastic to the final product, even if that product is a natural food product like honey or meat.

In the above-mentioned study of protein-rich food products, the amount of microplastics was significantly higher in ultra-processed food products, e.g. 1.3 ± 1.9 MP/g or 370 ± 580 MP/serving of breaded shrimp, compared to levels unprocessed or minimally processed products e.g. ca. 0.01 ± 0.01 MP/g shrimp or pollock [Milne et al. 2024].

The same pattern was observed for highly processed meat categories such as chicken nuggets (0.31 MP/g or 62 ± 78 MP/serving) compared less processed chicken breasts (0.01 MP/g or 2 ± 2 MP/serving). Processed plant-based nuggets contained similar microplastic amounts as chicken nuggets: 0.33 MP/g or 73 ± 90 MP/serving.

Including protein-rich products from all processing levels, the mean annual human exposure via protein-rich (mostly animal-based) food products was estimated to be 11,000 ± 29,000 MP, with a maximum of 3.8 million MP/adult/year, based on the average American diet [Milne et al. 2024].

> *Highly processed products harboured more microplastics than minimally processed counterparts. For instance, 30 times more microplastics were detected a serving of chicken nuggets than a serving of unprocessed chicken breast.*

3.2 Food packaging sources

Food packaging is considered a major source of microplastics to be reckoned with because of its contact with food and beverages and therefore the high risk of transfer to the human body. Mechanical stress on the plastic packaging materials is one of the several causes of release of microplastics [European Food Safety Authority 2025]. Release of microplastics from plastic applications in contact with food tends to increase with aging processes, wear, heating, microwaving, freezing and thawing cycles, abrasion, mechanical stress, UV radiation, release of coatings, various forms of damage such as cracks, the original quality of the manufactured plastic material, as well as dry deposition of microplastics from air [Muhib et al. 2023; Snekkevik et al. 2024].

A systematic review of microplastic release from plastic food contact materials examined 103 studies and concluded that regular, everyday use of food packaging such as bottles, cups, bags, containers and feeding accessories may result in microplastic migration to the food it contains [Zimmerman et al. 2025]. These researchers compiled the reviewed data in a searchable database along with assessments of study quality levels (see also Chapter 8).

Migration testing has repeatedly revealed microplastic release from the majority of items tested in laboratory settings, e.g. [Jadhav et al. 2021; Shruti & Kutralam-Muniasmy 2024; Muhib et al. 2023]. In the literature, these materials are reported to release a variety of different microplastic shapes fibers, filaments, flakes, fragments, cubic shapes and spheres [Shruti & Kutralam-Muniasamy 2024]. Expanded polystyrene microplastics were detected in packaged meat packaged in polystyrene, with concentrations ranging from 4.0 to 18.7 MP/kg [Kedzierski et al. 2020]. The scientists concluded that the packaging was a likely route by which the food product had been contaminated. While microplastics release from everyday plastic food contact materials is common, reports range from a few particles up to millions or more being released, depending on the testing conditions [Shruti & Kutralam-Muniasamy 2024].

Canning

Canning is a potential source of microplastics that is used to package approximately 10% (19 MT) of seafood annually [Silva et al. 2024, FAO 2025]. Cans are typically lined with a polymer layer between food and the metal can material. These plastic layers have been previously studied for the leaching of chemicals, and evidence is emerging that these layers also release microplastics. Canned tuna and mackerel were analysed with a combination of µRaman microscopy and SEM-EDX to determine that 80% of 50 samples collected contained microplastic, (predominantly PET) [Akhbarizadeh et al. 2020].

The sources of the microplastics were not pinpointed, but were potentially a combination of the fish itself, various food additives, other food ingredients (e.g. vegetables, oils), the cleaning and canning processes, and packaging food contact materials. The average human intake for adults was estimated to be 572 to 3432 MP/year [Akhbarizadeh et al. 2020].

In a Portuguese study of six canned seafood products, average concentrations of 0.043 ± 0.070 MP/g tissue, 0.006 ± 0.015 MP/mL liquid, and 3.5 ± 5.2 MP/can were reported, with octopus in tomato sauce (5.2 ± 7.5 MP/can) and tuna in olive oil (5.2 ± 5.1 MP/can) being the most contaminated [Silva et al. 2024].

Bottles

The effects of bottle opening and closing (1, 10 and 100 times) and squeezing plastic bottles (for 0, 1 and 10 min.) on microplastic release from plastic water bottles with PET bottlenecks and high-density polyethylene (HDPE) caps was studied, showing large differences between brands [Winkler et al. 2019]. The inner surfaces of HDPE bottle caps of different brands released 120, 373 and 2150 MP/mm^2. SEM was used to image the materials and the particles released from them, while EDX was used to acquire elemental composition signatures of the particles (note that these are not equivalent of polymer identification via e.g. MS, FTIR or Raman techniques). There were no significant differences in microplastic release among the bottles undergoing squeezing treatments, where a mean concentration of 148 ± 253 MP/L released microplastics was reported [Winkler et al. 2019].

Cups

Paper drinking cups are typically lined with an inner layer (20-40 µm) of low-density polyethylene [Zangmeister et al. 2022]. Cup samples were exposed to boiling ultrapure water for 20 minutes following which particles released from the cups were collected and measured. The particles were irregularly shaped, and around 40 nm in size. Plastic particle release was observed to be significantly lower when the water exposure was performed at 22 °C. Using 100 °C liquid in plastic lined cups doubled the number of plastic particles released and tripled the mass of the plastic particles released [Zangmeister et al. 2022].

In a different single use drinking cup study, cups made of polypropylene, polystyrene, polyethylene-coated paper, and expanded polystyrene cups released microplastics to both hot and cold drinks at levels ranging from 126 MP/L to 1420 MP/L, with an average transfer of 556.80 ± 31.39 MP/L [Akbulut et al. 2024]. ATR-FTIR was used to confirm polymer types of the cups, and SEM was used for particle imaging. The impact of heat on the microplastics release was evident. Polypropylene-lined cups heated for 20 min. at 50°C released the highest numbers of microplastics (1420 ± 380 MP/L), while polyethylene-lined cups at 4°C for (<1 min. exposure) released the lowest numbers (126.6 ± 75.71 MP/L). The researchers estimated an average microplastic exposure in Turkey of 18,720–73,840 MP per person per year via hot and cold beverages consumed from disposable cups [Akbulut et al. 2024].

Food grade nylon bags

Food grade nylon bags are approved in the U.S. for food preparation at temperatures up to 204 °C. Microplastic release from food grade nylon bags exposed to ultrapure water were observed to release ultrafine nanoplastic particles under 100 nm in size, when placed in a slow cooker for 1 hour [Zangmeister et al. 2022]. When performing the experiment at 22 °C, 24 ± 2 particles were detected while at 90 °C, more particles were generated: 35 ± 4. The concentration in was also higher at the higher temperature (20 ± 5 mg/L) than at 22 °C (8 ± 1 mg/L).

Opening and closing packaging

Also, multiple cycles of opening and closing polycarbonate water bottles and baby feeding bottles made from polyphenylene sulfone resins released 53 to 393 particles/mL (after 100 opening/closing cycles) [Song et al. 2021]. The particles were detected with µ-FTIR and LDIR, and measured between 20 and 500 µm. The study found that higher quality plastic and glass bottles released lower amounts of microplastics [Song et al. 2021].

Using µRaman spectroscopy, a similar study was carried out on reusable PET bottles with polypropylene and polyethylene screw caps, opening and closing once and 11 times and measuring microplastics release per liter of bottle of filtered water [Giese et al. 2021]. Opening once released 131 ± 25 MP/L, while opening 11 times released 242 ± 64 MP/L. The polypropylene material was particularly sensitive to fragmentation upon repeated opening and closing [Giese et al. 2021].

Everyday motions of cutting open packaging with scissors or a knife, or tearing, twisting to open packaging such as bags, containers, tapes and caps can release microplastics. The act of opening regular plastic packaging has been reported to release between 0.46 and 250 MP/cm, in a study using Raman and FTIR to analyse the released particles [Sobhani et al. 2020].

Expanded polystyrene microplastics were detected in packaged meat packaged in polystyrene, with concentrations ranging from 4.0 to 18.7 MP/kg [Kedzierski et al. 2020]. The scientists concluded that the packaging was a likely route by which the food product had been contaminated.

Tea bags

One of the most striking examples of microplastic release from food grade packaging came from a Canadian group which showed that a single empty teabag brewed with water for 5 minutes at 95°C could result in the release of approximately 2.3 million microplastics (1-150 µm) and 14.7 billion nanoplastics into a single cup of tea [Hernandez et al. 2019]. The polymers were identified with FTIR and elemental analysis was performed with X-ray photoelectron spectroscopy (XPS). The polymer types of particles matched the original teabag material (nylon and PET). The particles were imaged and sizes determined using SEM and nanoparticle tracking analysis (NTA). SEM was used to count the particles in subsamples of the dried tea leachates for calculating the particle counts per sample.

Tea bag materials from three tea bag brands tested in Europe were identified to contain nylon-6 and polypropylene (the third brand was made of cellulose, which is not a microplastic) [Banaei et al. 2024]. In experiments simulating tea preparation, a very high abundance of microfibers and nano-sized particles were present in the leachates. The particles were characterized using multiple analytical techniques: ATR-FTIR, SEM, transmission electron microscopy (TEM), NTA etc. Calculations from the NTA data resulted in approximate numbers of released submicron plastic particles of 1.20 billion MP/mL (from a polypropylene tea bag) and 8.18 million MP/mL (from a nylon-6 tea bag) [Banaei et al. 2024].

These studies illustrate the impact of high temperature conditions on plastic material integrity in a food contact material approved for use with boiling water.

> *Everyday plastic tea bag use may release extraordinarily high numbers of microplastics to a cup of brewed tea: over 2 million microplastics and billions of nanoplastics.*

3.3 Food preparation sources

Kitchen utensils and appliances

Sponges, microfiber cloths, kitchen brushes, chopping boards, and bowls - when made of plastic - are potential microplastic sources in an area where food is prepared and dishes are being washed. As far as utensils go, polypropylene is the global polymer of choice for the manufacture of diverse food preparation and storage applications such as lunch boxes, baby bottles and other everyday goods [Alsabri et al. 2022; Yates et al. 2021].

Using plastic chopping boards to prepare food has been shown to increase microplastics exposure [Luo et al. 2022a]. Both microplastics and nanoplastic particles appeared to be released from each cut on the chopping board. The particles remained on the board or the blade of the stainless-steel knife (in the absence of food). SEM images provide insight into fragmentation of the plastic material down to the submicron scale. The researchers estimated a few hundred particles might be released from each cut made on the board, depending on the technique, pressure and angle of the cutting motion. In any case, this study provided evidence that plastic particles could easily be released from plastic chopping boards, likely introducing microplastic contamination to the food being prepared [Luo et al. 2022a].

In another study of microplastics in chicken meat and fish, the highest microplastic contamination was observed when using polyethylene chopping boards as opposed to other materials for food preparation; washing the meat and fish reduced the contamination to some degree but microplastics were still detected on washed specimens [Habib et al. 2022]. Microplastic counts in the chicken samples of that study ranged from 0.03 ± 0.04 up to 1.19 ± 0.72 MP/g, and in fish, from 0.014 ± 0.024 to 2.6 ± 2.8 MP/g.

In another study of polyethylene and polypropylene chopping boards, researchers found the most particles released were below 100 nm in size [Yadav et al. 2023]. Based on their measured data and assumptions about chopping board use, they calculated estimates of annual exposure per individual of the mass of plastic ingested from chopping board origin. For someone using a polyethylene board they estimated 7.4–50.7 g of microplastics ingested per year, and 49.5 g for polypropylene board users.

Plastic kitchen mixing bowls made of ABS, polypropylene, melamine, polyethylene, polystyrene and styrene–acrylonitrile were tested for microplastic release during exposure to a mixer for 2 min at 200 rpm [Jander et al. 2022]. Different tests were run, with 100 ml water, and the ABS bowl was also tested with water plus rock salt (a type of salt without microplastics). A glass bowl was used as a negative control. Microplastics were filtered out of the test water from the bowls and analysed with FTIR, targeting particles >25 µm in size. The bowls released between 331 and 898 MP/bowl. The glass bowl tested released no microplastic from the bowl material itself (glass being a better choice for microplastic-free mixing), though 1 MP was detected in the water used in the test. The ABS bowl containing salted water released 1890 MP, triple the amount released from the ABS bowl with water only (591 MP) [Jander et al. 2022].

New plastic electric kettles tested with deionized water released a reported 30 million particles to the water as it boiled [Sturm et al. 2019]. The particles were analysed with a dynamic image analysis system to count particles, though not identify the polymer types. Other researchers later tested whether aging of the kettle would have an impact on microplastics release [Shi et al. 2022]. A sharp decrease in microplastics released to the water in the kettle was observed over the first 15 days of use (25.0–35.0 million/L to around 5.0–10.0 million/L), using a combination of Raman, SEM-EDX, AFM, XPS to identify and characterize the particles [Shi et al. 2022].

A follow-up study used different instruments to quantify the mass of released microplastics from polypropylene kettles in tests of between 1 and 150 boil cycles [Shi et al. 2025]. The study employed asymmetrical flow field-flow fractionation with multi-angle light scattering (AF4-MALS) followed by Pyr-GC-MS/MS to determine mass of plastic in the various particle size fractions. The first time water was boiled in the new polypropylene kettles, 0.011 ± 0.005 µg NP/cm^2 and 0.032 ± 0.016 µg MP/cm^2 of kettle surface were released. After 50 boils, microplastic release was 8 times lower, and 32 times lower after 150 boils. Nanoplastic release similarly decreased by factor 6 after 50 boils, and 27 times after 150 boils [Shi et al. 2025].

New plastic tea kettles released between 5 and 35 million particles per liter to boiling water boiled during the early days of use. Vast numbers of nanoplastics are released too. Particle release appears to decrease with kettle use, at least for several weeks.

Luo et al. also explored testing Teflon (polytetrafluoroethylene) coated non-stick cookware [2022b], kitchen sponges [2022c] and plastic (ABS) kitchen blenders blending ice cubes [2023]. They used Raman imaging and SEM-EDX to study microplastic release and found evidence for fragmentation and release of microplastic and nanoplastic particles from all plastic products studied. Kitchen sponges commonly used for doing dishes or cleaning were found to be made of nylon-6 (soft side) and PET (abrasive side) [Luo et al. 2022c]. If dishes are not thoroughly rinsed, such applications introduce another exposure route.

The estimates for abundance of particles released are uncertain but microscopic damage to these common kitchen materials could be releasing between thousands and billions of particles, both microsized and nanosized, according to this research team [Luo et al. 2022c].

The importance of thoroughly rinsing washed dishes is also apparent when plastic articles in a dishwasher can release about 920,000 microplastics per cycle [Okoffo et al. 2025]. Also, considering that many liquid detergent pods on today's market contain a polyvinyl alcohol component [Rolsky & Kelkar 2021], the possibility of trace residues on plates, glasses and cutlery potentially adds to exposure routes in the kitchen.

Microwaving food in plastic containers

The use of plastic containers to heat or reheat food in the microwave is now being shown to significantly increase release of microplastics from the containers, albeit with high variation in microplastic abundance observed among the different studies. Often the plastic containers for microwave use are made of polypropylene, and sometimes other polymers such as styrene-acrylonitrile copolyester and Tritan polyester. Each product may have a characteristic microplastic release pattern, depending on the formulation.

All three types were tested by [He et al. 2021]. Using Raman spectroscopy to identify particles and SEM to image them, thousands, and up to one million MP/L have been reported to be able to migrate from microwavable plastic food containers to food [He et al. 2021].

If take-out food heated in plastic containers were to be consumed daily, the researchers estimated an annual microplastic intake of 150 million MP per person.

Microwaving food in plastic containers may be introducing millions of microplastics to food. Daily use of such products has been estimated to add from around 3000 to over 150 million microplastics to the diet of an individual per year, depending on the type of container

Another study, using a combination of SEM and µFTIR estimated that 2977 MP/person/year are being ingested via the use of take-out food containers subjected to microwave heating studied by Du et al. [2020]. Four types of take-out containers were tested: polypropylene sauce cups (mean release to test fluid was 9 MP/L), an expanded polystyrene tray with cover (29 MP/L), a polyethylene lined cup (5 MP/L) and a PET 'oyster shell' type food container (3 MP/L).

These data were lower than reported elsewhere but are likely due to both methodological differences and differences in the quality and composition of the materials themselves [Du et al. 2020].

Release of microplastics from plastic containers and plastic food pouches was reported as high as 4.22 million microplastic and 2.11 billion submicron plastic particles per square centimeter, after 3 minutes of heating in the microwave [Hussain et al. 2023].

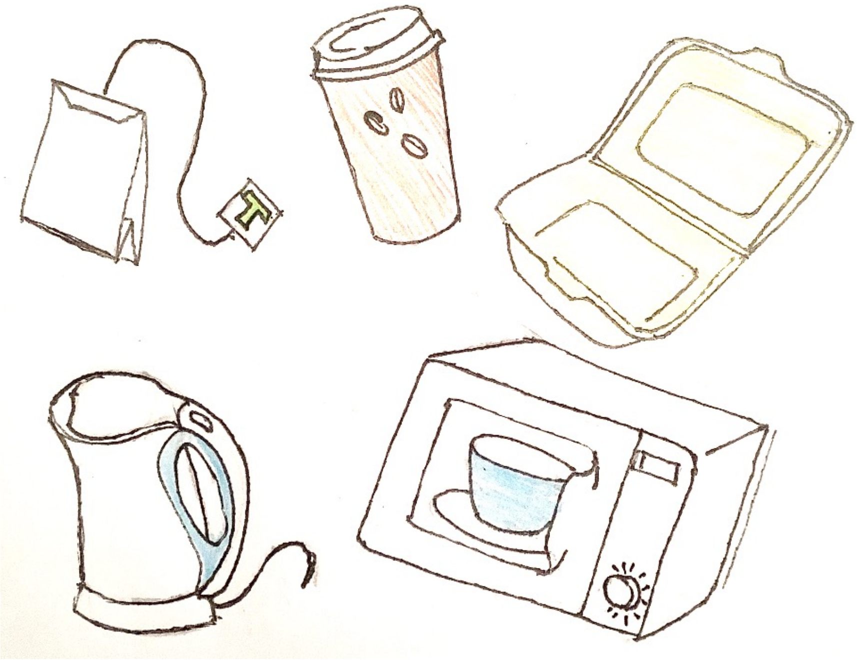
Even room temperature storage resulted in shedding of millions of microplastics from these products. The estimates made from the data in this study were that via this source, up to 20 ng plastic/kg/day could be ingested by infants via drinking microwaved water, and toddlers could be ingesting up to 22 ng plastic/kg/day through consuming microwaved dairy products packaged in polypropylene [Hussain et al. 2023].

Heating plastic packaging

Preparation of food in plastic bottles involving adding boiling water to disinfect them, or filling and heating them in the microwave, was observed to alter the structure of the inside walls of the containers. These underwent significant observable deformation and degradative processes which researchers claimed are likely to enhance microplastic releases over time [Xu et al. 2023].

A more recent study of takeaway containers showed microplastic release from PET and polystyrene (13 and 32 µm particle sizes) [Caponigro et al. 2025]. The test conditions were set up to simulate realistic use by exposing an aqueous test solution to containers for 20 min. with agitation. Water was tested at room temperature, at 100°C, and acidified (pH 4). µRaman was used to quantify and identify the particles extracted from the test solution. The mean microplastic release of PET was 9 particles (room temperature), 7 (acidic water), and 17 (100°C). The mean release of polystyrene was 1 particle (room temperature), 3 (acidic water) and 30 particles (100°C). In agreement with other studies, heating increased the microplastic release from PET and polystyrene in this study [Caponigro et al. 2025].

In the pursuit of convenience, some consumers have fallen for the new phenomenon of ‘self-heating food packaging’. The convenience comes at a cost of microplastics (98% of which are <20 µm) being released to the food, resulting in concentrations of 1.7×10^6 to 3.4×10^6 particles/L, with an average of 2.4×10^6 particles/L, as determined by µRaman spectroscopy [Xu et al. 2024].



4. Indoor Sources

Key takeaways – Indoor sources

Inhalation is a key microplastic exposure route. Humans inhale 6 L of air per minute, giving ambient airborne microplastics access to the nose, mouth, wind pipe, and in the case of ultrafine particles, the lungs.

Polyester garments released 108 to 347 MP/g garment in tests simulating normal wear. When woven polyester garments were tested, the microplastic release dropped significantly to around 1 MP/g.

Airborne polyester fiber concentrations of 70,000 MP/m^3 were reported in the air of a garment factory, and 26,000 MP/m^3 in office air.

Plastic particles are a main component of contemporary synthetic paints. A coat of paint covering 100 m^2 was estimated to contain 17–68 quadrillion (10^{15}) polymeric paint particles.

These start to be released when paint wears down and when old layers are scraped off. Emissions of 260 tonnes were attributed to the wearing of paint layers and 210 tonnes to the removal of old paint layers in the Netherlands.

Spray paint: 50 to 60% of the total paint volume sprayed typically does not reach the surface, becomes airborne microplastic and eventually falls out.

110,00 to 290,000 MP/kg soil have been reported near Berlin’s famous graffiti walls.

3D printing uses a range of different polymers. Between 1000 and 1 million ultrafine particles of these polymers are released per cm^3 of air during the printing.

Emissions of 2 to 4 billion nano-ABS particles per second to the air of 3D printing rooms have been reported. ABS is a popular type of plastic used toys, electronics and many other consumer products.

In addition to the ingestion uptake route, humans inhale 6 L of air per minute, giving ambient airborne microplastics access to the nose, mouth, wind pipe, and in the case of ultrafine particles, the lungs. All plastic present in the indoor environment carries a potential to emit microplastics as it undergoes any number of mechanical stresses or aging. The modern indoor environment is encased in and filled with plastic: building materials and insulation, pipes, switches, meters, shower stalls, toilet seats, paints, flooring carpets, upholstery, curtains, clothing, carpets, mats, bedding, towels, clothes, devices, appliances, packaging, toys, sponges, brushes, buckets, detergents, lamps, decorations, fast moving consumer goods, kitchen items, sporting equipment etc. are commonly made of plastic. Inhalation is a key microplastic exposure route in humans [Cox et al. 2019].

As many people nowadays spend up to 90% of their time indoors amidst these items, indoor exposure is highly relevant for human exposure [Ageel et al. 2022], as well as for exposure of pets. Dust contains a collection of microplastic fragments that often mirror the plastic types present in the products in place in the indoor environment. Dust is present indoors both suspended in indoor air and on indoor surfaces. The most widely known plastic components in indoor dust that come from an identifiable source include textile fibers, plastic paint particles, and 3D printing particles [Quik et al. 2021]. Indoor air as such is regarded as a source of outdoor air microplastics where, and according to one Swiss model, it makes up over a third of the total microplastic component of outdoor urban samples [Kawecki and Nowack, 2020].

Settled dust

The dust that falls out from indoor air onto surfaces reflects the microplastic released from interiors of homes and workplaces, where fibers and fragments dominate the samples [Ageel et al. 2025]. While these particles can be inhaled, dust ingestion is known to occur in the home, particularly in toddlers, a phenomenon that increases exposure to contaminants in indoor dust. Measured microplastic concentrations of 155 ± 222 MP/mg dust in 30 homes, and 125 ± 209 MP/mg in 30 workplaces were reported. Using a dust ingestion rate model, the researchers estimated exposure via dust ingestion for toddlers to be 103 MP/day and for adults 56 MP per day [Ageel et al. 2025]. What is not inhaled as an airborne particle may be ingested.

> *Young children experience higher microplastic exposures via indoor dust than adults.*

Researchers using a human exposure model manikin attempted to simulate, sample and quantify the human exposure to indoor airborne microplastics in three typical Danish apartments, using Focal Plane Array-μFTIR to that detected particles down to 11 μm [Vianello et al. 2019]. The manikin inhaled 16.8 m^3 of indoor air in each apartment over a 24-h period, and with the air, up to a maximum of 272 MP. Polyester was the predominant microplastic type in all samples, followed by polyethylene, nylon and polypropylene, though many other polymer types were present including polystyrene, acrylic/acrylates polymers, polyurethane/polyether-urethane, ethylene-propylene-diene-monomer, polyvinyl acetate, ethylene vinyl acetate, epoxy resin, phenoxy resin, cellulose acetate and triacetate, polylactic acid, polycarbonate, acrylic paint, polyurethane paint, and alkyd. Only 13% of all microplastics characterized were fibers, most were fragments of other shapes [Vianello et al. 2019].

> *Airborne microplastics are more abundant in indoor air than outdoor air.*

These data suggest the microplastics in the air came from a wide variety of sources, not only textile fibers, micro-debris from packaging or other plastic household items, but also particles of polyurethanes and paints that are known to carry high toxic chemical loads such as hazardous flame retardants, heavy metals and pigments [Vianello et al. 2019].

Indoor exposure in Australia was measured using μFTIR [Soltani et al. 2021]. From 22 to 6169 microfibers/m^2 were reported, 99% of which were microfibers (200-400 μm long), and 39% were synthetic, petro-chemical based fibers. In carpeted homes in particular, polyethylene, polyester, polyamide, polyacrylic, and polystyrene particles were present in high abundance. Exposure was estimated for different age groups, indicating that young children were the most highly exposed group: the highest inhalation rate was reported for the <6 month old group: 0.31 mg MP/kg-body weight/year. The mean inhalation rate in the study was 0.2 ± 0.07 mg MP/kg-body weight/year and 12891 ± 4472 fibres/year. Exposure by ingestion was also calculated to be 6.1 mg MP/kg-body weight/year for ages 1-6, while >20-year-old age group ingestion rates were 0.5 mg/kg-body weight/year [Soltani et al. 2021]. Young children breathe in more air per kilogram bodyweight compared to adults, which may explain their higher microplastic intake via the inhalation route.

Air conditioning (AC) units were shown to both filter microplastics out of the air and supply microplastics back to the rooms they serve [Chen et al. 2022]. Using μFTIR to detect and quantify particles on AC filters, where typical concentrations ranged from 1.47 to 21.4×10^2 microfiber/cm^2 of filters in the first set of 20 filters analysed. The plastic types identified in the microfibers from AC filters included PET, polypropylene, polystyrene-polyacrylonitrile, polyphthalamide (a type of nylon), polypropylene-polyethylene, and polyurethane. Pigmented microfibers were placed on AC filters and when the AC unit was running, labeled fibers were emitted between 1 and 23 m from the unit at concentrations of between 1.19 ± 0.03 and 1.35 ± 0.03×10^4 items/m^2/day, approximately double the concentrations measured when the AC unit was switched off. Human exposure for a 70-day air conditioning period was estimated to be 11.2 ± 2.2 to 44.0 ± 8.9 fibers/kg-body weight/day [Chen et al. 2022].

In a review of microplastics in indoor air, mean concentrations measured in different studies ranged from below detection limits (<1 MP/m^3) to 1583 ± 1181 MP/m^3 (PET, polyethylene and polypropylene) [O'Brien et al. 2023].

Textiles

Microfibers from textiles have been identified not only in settled dust indoors, but are recognized as a major source of microplastic for the environment and human exposure alike [Dris et al. 2015, 2016 & 2017; Hazlehurst et al. 2023; Wright et al. 2019, 2020 & 2024; De Falco et al. 2020; Sillanpää & Sainio 2017; Zwart & de Valk 2019; O'Brien et al. 2023; WHO 2022; Quik & Waaijers-van der Loop 2021]. Textiles made from synthetic components shed synthetic microfibres and microfilaments over the life span of the textile, whether it be clothing, bedding, interior design elements such as curtains, upholstery, rugs and mats, or technical textiles. Rooms where washing machines and dryers are located may be considered airborne microplastic hotspots in homes [Snekkevik et al. 2024].

> *Synthetic textiles in clothing and indoor spaces become sources of airborne microplastics during regular use and wear.*

In an early study performed in Paris, indoor air samples contained between 1 and 60 fibers per m^3 while outdoor air contained between 0.3 and 1.5 fibers per m^3, representing a mix of synthetic and natural textile fibers [Dris et al. 2017]. Between 1586 and 11,130 fibers/day/m^2 were found to be deposited indoors, resulting in concentrations in settled dust of 190-670 fibers/mg dust. Roughly a third of the settled dust samples analysed in that study were synthetic fibers predominantly of a polymer type common in carpeting and furnishings: polypropylene. Airborne fibres from textiles are thought to make up a dominant fraction of the indoor air particulates.

Domestic laundry dryers were shown to generate airborne emissions of microplastics from synthetic textiles [O'Brien et al. 2020]. After a minimum of 20 minutes of drying time, a 660 g polyester blanket released between 1.6 and 1.8 MP/m^3 to indoor air. The machine's filter captured 77 ± 22.4 mg of polyester - the equivalent of about 1.1 million fibers - and about 0.012% of the blanket mass that was released per drying session [O'Brien et al. 2020].

Many studies have examined the emission of textile fibers to wastewater via the washing machine under various conditions of water temperature, detergent etc., as well as methods to mitigate fiber release [Sillanpää & Sainio 2017; Zwart & De Valk 2018; Periyasamy et al. 2022; Hazlehurst et al. 2023; De Falco et al. 2020; Vassilenko et al. 2021; Ramasamy & Subramanian 2023]. Textile fibers released to wastewater are as such not part of the human exposure scenario directly. Though it more difficult to quantify, it is well known that fibers are shed during wear, handling and use of textiles, not only during laundering.

Microplastic release to air was tested in a realistic test case where volunteers wore polyester or polyester blend garments in a controlled indoor environment, simulating everyday wear [De Falco et al. 2020]. FTIR was used to identify polymer types of released fibers after 20 minutes of wear that included standardized movements by volunteers wearing garments. Microplastics (microfibers) were collected after deposition from the air onto damp filters.

A knitted 100% polyester garment ('staple' type) released 347 ± 102 MP/g fabric. A knitted 100% polyester garment ('filament' type) released 108 ± 44 MP/g fabric. Woven polyester garments released significantly less: 1 ± 1 MP/g fabric, pointing to the mitigating effect on microplastic release of woven fabric construction. The woven polyester microfibers on average were 494 ± 15 µm long with a diameter of 15 ± 4 µm. These were shorter than the other 100% polyester microfibers released from the knitted 'filament' fibers which were on average, 1036 ± 393 µm long (diameter 18 ± 4 µm) and the knitted 'staple' fibers 1023 ± 467 µm long (diameter of 18 ± 3 µm) [De Falco et al. 2020].

While airborne, these particles were potentially inhalable (entering nose and mouth), but were likely too large to be part of the 'respirable fraction' of particles penetrating to the unciliated airways in human exposure scenarios [Brown et al. 2013; Wright et al. 2024].

> *Synthetic textiles release microfibers during production, handling, wear, and laundering.*
> *Certain polyester garments released hundreds of microplastics per gram fabric in 20 minutes of active wear.*

In another study providing insights into microplastic release from polyester textiles to the air, a factory producing 100% polyester t-shirts was selected as the study location [Visileanu et al. 2025]. There, textiles are handled, cut, sewn, etc., creating an environment with airborne, inhalable microplastic fibers. Using a laser light scattering technique to carry out aerosol measurements in real time, polyester particles between 0.25 and 32 µm were detected in the air of the factory floor, offices and the surrounding outdoor air.

Additional filtered air samples were measured by thermal extraction desorption TED-GC/MS to confirm polyester and other polymer markers in the samples. 96-97% of all particles detected were in the smallest size range (<500 nm) [Visileanu et al. 2025]. These particles were predominantly made up of a what has been termed the 'respirable fraction' for human exposure [Brown et al. 2013; Wright et al. 2024]. The average of all particle sizes summed together for the three measurement timepoints indicate concentrations in factory floor air were 70,000 MP/m^3, 26,000 MP/m^3 in office air, and 48,000 MP/m^3 in the open air outside the factory [Visileanu et al. 2025].

There are significant efforts to standardize microplastic release from textile testing that resulted in ISO standard protocol 4484-1 for the determination of material loss from fabrics during washing [ISO 2023], which is being used in both research and by the textile industry to assess their own textile products. An additional ISO norm for microfiber release from textiles to the air would be beneficial.

Paints

The paint and coatings industry estimated the global demand for their product is 48.9 billion liters, a market that was worth $202 billion in 2024 [ChemQuest Group 2025]. The bulk of the paint market is for buildings, both inside and out. Most contemporary paints are plastic based (polyester, acrylic, vinyl etc.). The plastic component in paints acts as a binder for pigments and forms an adhesive film, which breaks down with age, damage (e.g. scratches), and cleaning. Paint chips have been observed in early microplastics research on marine environmental samples, and paint is now becoming recognized as a major source of microplastic exposure worldwide [Diana et al. 2024].

Fang et al. [2024] used ATR-FTIR, µRaman and SEM to characterize the particles in paint, and found gigantic numbers of micro- and nanosized composites of polymer binders and titanium dioxide pigment nanoparticles. In one 5 µm × 6 µm image (1 µm thickness) between 50 and 100 particles were typically detected. Extrapolating to a home with an indoor wall area of 100 m^2 with a coat of paint of normal thickness, they estimated that 17–68 quadrillion (10^{15}) particles could be potentially present. They additionally measured off-gassing of volatile chemicals benzene, toluene, ethylbenzene and xylene (BTEX) during the 40-day study.

> *Spray painting creates microplastic aerosols. Typically, half of the spray paint reaches the object, and the other half presents an airborne inhalation hazard.*

Besides architectural uses, plastic paint is used for artworks, coating furnishing, and large-scale industrial spraying applications such as cars, home appliances, ships, road markings etc. Spray painting is a technique that creates aerosols and airborne paint particulates. Spray efficiency is rather low, with up to 50 to 60% of the total paint volume sprayed not

Textiles, settled dust, paint and even 3D printing are major known indoor microplastic sources reaching the surface to be painted [Wang et al. 2022; Poozesh et al. 2017]. This considerable airborne fraction of microplastics and associated chemicals is a well-known inhalation hazard for people using spray paint in both home or occupational settings. Eventually, the fallout of microplastics from the sprays gets deposited on the ground below the spraying area.

Some of the world's highest concentrations of microplastics in soil have been measured in the direct vicinity of popular graffiti walls in Berlin, where 110,00 to 290,000 MP per kg dry soil have been reported [Xu et al. 2022]. Spherical particles in the soil samples were thought to have originated from the aerosol source, while paint chips, sometimes with multiple different coloured layers, were suspected to have fallen off the walls due to aging of the paints. In the samples, polymer types typically applied as paint binders were detected, including alkyd and styrene-acrylic resins and some polyvinyl acetate.

In the Netherlands, an estimated 490 tonnes of microplastics emissions from paints come from professional building work and 'do-it-yourself' painting jobs, and 200 tonnes from shipping activities. Of the 490 tonnes, 260 tonnes were attributed to the wearing of paint layers and 210 tonnes to the removal of old paint layers [Verschoor et al. 2016]. These large figures attest to the significant contribution of paint to the overall known sources of microplastics emissions.

> *Weathering processes and stripping old paint layers are estimated to produce 490 tonnes of microplastics emissions in the Netherlands.*

3D printing

Ultrafine particles, or UFPs (<100 nm) are often reported as part of the problematic emissions from 3D printing. Nowadays, 3D printing facilities are commonly found in schools, universities, and libraries for educational purposes [Q. Zhang et al. 2025]. The printing uses polymers such as polyvinyl alcohol, polylactic acid, polycarbonate, ABS, acrylonitrile styrene, polyurethane, acrylate, copolyester and nylon, and the various particle release concentrations appear to be polymer dependent and tend to peak at the beginning of a print job [Chýlek et al. 2019]. For the different polymeric materials being emitted from a closed cover 3D printer, between 1000 and 1 million particles/cm^3 were measured using thermogravimetric analysis [Chýlek et al. 2019].

Several studies to date have reported high levels of UFPs, smaller than 100 nm in size, as low as 20 nm, that can penetrate deep into lungs [Mandler et al. 2025], along with volatile chemicals, being emitted from printing with such equipment [Zhang et al. 2017, 2018, 2019; Youn et al. 2019; Mendes et al. 2017; Stabile et al. 2017; Gu et al. 2019; Chýlek et al. 2019; Bossa et al. 2021].

> *During 3D printing, billions of inhalable nanoplastic particles may be released to the ambient air per second.*

3D printing is a source of diverse plastic filaments and the emissions potentially run into the billions (10^9) of particles per gram printed material. For instance, the total particle number emitted per mass of object printed was reported in one study to be $1.42×10^{11}$ NP/g and $1.52×10^{10}$ NP/g for ABS printing, $1.35×10^9$ NP/g for PLA printing, and $1.58×10^9$ NP/g for nylon printing [Zhang et al. 2019]. The rates of ABS aerosol emissions were also high in room measurements where 3D printers were operating at normal, recommended temperatures: $2.0×10^9$ to $4.0×10^9$ ABS-NP emitted per second [Mendes et al. 2017].

Researchers are using microplastic and in particular ultrafine plastic particle emission data in combination with models to estimate internal doses in different regions of the human respiratory tract of adults and children (extrathoracic, tracheobronchial, and pulmonary) [Byrley et al. 2021]. There can be age differences in airway architecture and ventilation that are thought to affect deposition of ultrafine particles in different regions. In the model simulations, the 9- to 18-year-olds were predicted to have the highest mass of polymeric particles in their respiratory tracts [Byrley et al. 2021].

5. Outdoor Sources and Recreation

Key takeaways – Outdoors and recreation

Atmospheric fallout: 575 to 1008 MP/m^2/d were measured in the air of London UK. An earlier study in Paris air detected 2 to 355 particles/m^2/day, of which one third were plastic.

French researchers estimated 3 to 10 tonnes of fibers being deposited in the Paris region (2500 km^2) annually.

The estimated world-wide emission of tire particles calculated using data on mileage and number of vehicles on the planet comes to a staggering 5,917,518 tonnes/year.

Artificial turf football fields covered with granular infill constitute one of Europe's largest intentionally added microplastic issues. On the order of 100 tonnes of tire crumbs are applied to an average field.

Between 2433 to 5067 MP/L have been measured in sport field stormwater runoff.

Swimming pools and aquaparks are home to many varieties of microplastics sources from buoys, ropes and paints to fins, goggles, balls, noodles, bathing suits, cosmetics, and the water itself. Testing of intensive use pools resulted in over 40,000 microplastics per cubic meter pool water.

Multiple patents exist describing the application of microplastics in Stratospheric Aerosol Injection (SAI) - a form of solar geoengineering. The polymeric microparticles between 2 and 20 microns in size are designed to be released at altitudes of 10 or 20 km.

SAI forms a yet unquantified but potentially 'terascale' source of intentionally added airborne microplastics and fallout, since SAI programs typically use units of 'teragrams per year' to express the volume of particles injected into the air (1 Tg is equivalent to 1 billion kilograms).

Atmospheric fallout from outdoor air

In the past 10 years, a considerable number of studies has indicated that it is raining microplastics. In outdoor air in Paris, Dris et al. [2015] measured total atmospheric fallout which was predominantly microfibers of 29–280 particles/m^2/day. In a follow-up study, 2-355 particles/m^2/day were reported, with just under a third being microplastic fibers [Dris et al. 2016]. They estimated that between 3 and 10 tonnes of fibers were being deposited in the Paris region (2500 km^2) annually.

In an urban location in southern China, an average wet and dry deposition rate of 36 ± 7/m^2/d was reported [Cai et al. 2017]. Using μFTIR, polyethylene, polypropylene and polystyrene were observed on collection filters, though the majority of fibers present were cellulose (73%).

In London, microplastic depositions in outdoor air ranging from 575 to 1008 MP/m^2/d were measured and polymer types were determined with μFTIR [Wright et al. 2020].

According to American research, deposition of microplastics in outdoor air averaged 132 MP/m^2 per day in remote, protected land areas where over 1000 tonnes of microplastic per year is being deposited [Brahney et al. 2020]. Microplastic fragments detected in hundreds of samples ranged from 4 to 188 µm in size, and microplastic fibers detected were between 20 µm and ~3 mm in length.

In a field study in the French Pyrennes, 249 fragments, 73 films and 44 fibres per m^2 were observed to be deposited from the air [Allen et al. 2019]. Air mass trajectory analysis indicated that the microplastics measured there could have been transported up to 95 km through the atmosphere.

> *It's raining microplastics. Atmospheric fallout is a diffuse source of microplastic exposure. Wet deposition has been reported to be responsible for more microplastic fallout than dry deposition.*

Recreation in the wilderness nature areas studied by Allen et al. [2019] may result in airborne microplastics exposures similar to breathing outdoor air in Paris, where 29–280 particles/m^2/day and 2-355 particles/m^2/day were reported in 2015 and 2016, consisting of a mix of synthetic and natural textile fibers [Dris et al. 2017]. Due to different reporting traditions and different size fractions targeted in different studies, it is not possible to make direct comparisons of exposures measured across studies.

Tire and road wear

Tire and road wear particles are a special category of microplastic and have consistently been assessed as one of the most significant sources in terms of volume and toxicity and a significant contributor to particulate air pollution. Tire tread rubbers have 40-60% polymer content and the concern that began decades ago for the particles that they release continues today [Schneider et al. 1996; Unice et al. 2012; Panko et al. 2013; Zhu et al. 2024. Christou et al. 2025; Lenssen et al. 2025; Özen & Mutuk 2025]. Wind and air currents created by traffic can resuspend particles from roads to the air and transport them, if they do not first get washed off the road by rainwater [Federico et al. 2023]. Despite the concerns, only a handful of studies have been fully devoted to elucidating human exposure via airborne tire and road wear. (More work has been done on assessing general environmental tire pollution than on the airborne fractions that humans breathe in.)

> *Researchers calculated that around 6 million tonnes of microplastics get released annually from vehicle tires driving on the world's highways and roads. Even bicycles emit microplastics, although lower amounts than heavier vehicles.*

Particulate matter is often grouped in the categories PM$_{10}$, which is the fraction inhalable particles up to 10 µm in dimension, and PM$_{2.5}$. which is the fraction of fine inhalable particles up to 2.5 µm in dimension. Most of the particulate air pollution from vehicles on the road comes from non-exhaust sources that make up 90% of total PM$_{10}$ and 85% of total PM$_{2.5}$ [Timmers et al. 2016]. The per capita emissions of tire particles estimated for 13 countries including Asia (China, Japan and India), Australia Brazil, USA and 7 European countries averaged 0.95 kg/capita/year [Kole et al. 2017]. India has the lowest annual emission rate (0.23 kg/capita/year) and the USA has the highest (4.7 kg/capita/year). The world-wide emission estimate calculated using data on mileage and number of vehicles on the planet comes to a staggering 5,917,518 tonnes/year [Kole et al. 2017].

Tire emissions increase with weight of vehicle, tire size, speed, distance travelled and even driving style, e.g. stopping and going [Mayer et al. 2024]. Electric cars are significantly heavier (by 24%) than conventional cars and due to their weight are larger emitters of tire particles [Timmers et al. 2016].

One of the early field studies of airborne tire and road wear emissions reported concentrations ranging from 0.05 to 0.70 µg/m^3, (average 0.16 µg/m^3) across locations in in France, the USA and Japan [Panko et al. 2013]. (Tire particles are generally adhered to particles of the road surface and are often studied together.) These particles were a major component of the overall PM$_{10}$. The highest concentration measured in that study of 81 air samples was 1.34 µg/m^3, observed in the Troyes, France.

A study that covered different traffic conditions at sites in Utrecht, the Netherlands measured airborne particles and coupled these data to biomarkers of exposure measured in students cycling through these areas [Lenssen et al. 2025]. Pyr-GC/MS analyses of air samples collected on quartz filters produced relatively low concentrations of 2.9 to 42.5 ng synthetic rubber/m^3 and 1.6 to 26.8 ng natural rubber/m^3 in air. The lowest concentration was measured in a park area, (3.1 to 5.1 ng/m^3). Greater concentrations were measured next to a highway (7.8 to 18.1 ng/m^3), and the highest concentrations were measured at a 'stop-and-go' location (10.7 to 23.0 ng/m^3) where cars brake and accelerate [Lenssen et al. 2025].

> *Microplastics are being measured in outdoor air and outdoor dust but also in road dust at a wide range of concentrations, up to hundreds of microplastics per gram.*

Airborne microplastic particles were sampled using portable active samplers in high traffic areas, and a correlation was found between periods of high traffic and high airborne microplastic concentrations [Özen & Mutuk 2025]. In low traffic periods 0.0576 MP/m^3 were measured, while in high traffic periods, up to 0.1541 MP/m^3 were reported. The mean concentration over all the samples was 0.0979 MP/m^3. Polybutadiene particles ranging from 250 µm to 500 µm in size were identified as tire wear, and were a major contributor to overall airborne microplastic loads. Other polymers identified by µFTIR in air were polyethylene, polypropylene, polystyrene and polyamide.

In a review of 124 peer reviewed articles, O'Brien et al. [2023] collected various outdoor concentrations of microplastics in the air ranging from <1 to >1000 MP/m^3, and rates of microplastics deposition of 0.5 to 1357 MP/m^2/day. Microplastics were reported present road dust at concentrations between 2 and 477 MP/g road dust (polyethylene and PVC), and in general outdoor dust between 18 and 225 MP/g dust (PET, polypropylene, polyamide) [O'Brien et al. 2023].

Though motor vehicle tires emit much greater amounts of tire wear particles, mountain bike tires have also been studied as emitters of microplastics. Mountain bike tires, released microplastics at a rate of 3.62 g/100 km on average [Sommer et al. 2025]. The researchers found rear tires to wear down faster than front tires, and the abrasion rates decreased with tire use. German mountain bikers were estimated to be emitting 59 to 88 g of tire particles per year by practicing their sport [Sommer et al. 2025].

Granular infill material

Granular infill material is made of pulverized worn-out tires. Used extensively as a 'synthetic dirt' to improve the performance of artificial turf sports fields, on the order of 100 tonnes of tire crumbs are applied to an average field at a time. Granular infill is considered by the European Commission to be one of the largest sources of intentionally released microplastics in the environment, which is the motivation to ban this practice, applicable from 17 October 2031, according to Commission Regulation (EU) 2023/2055 [https://echa.europa.eu/hot-topics/granules-mulches-on-pitches-playgrounds].

The artificial turfs are a source microplastics which can be collected at concentrations from 2433 ± 493 to 5067 ± 839 MP/L in stormwater runoff [X. Zhang et al. 2025a]. The combination of tire crumbs and plastic grass and athletic uses result in not only granules but also fibers and other fragments of plastic being released, which athletes come in contact with, whether they be airborne particles, or fine particles that end up in water bottles, or stuck to skin under the socks and clothing.

Sports equipment

Athletes are becoming more conscious of their potential exposures not only from artificial turf, but also other synthetic sports equipment and clothing [Jiao et al. 2025]. Foam rollers and mats used by athletes and yoga practitioners degrade during use. Synthetic workout clothing, including fabrics made of polyester, nylon, and the polyurethane-polyurea copolymer known as Spandex, are another exposure concern for athletes [Jiao et al. 2025], as they are worn during strenuous exercise and sweating, laundered often, and in some cases also are designed to be tightfitting, such as bathing suits.

> *Synthetic sports clothing and other plastic sporting gear are potential sources of microplastic exposure to athletes. Swimming pool water samples have been shown to contain 100 to over 40,000 microplastics per cubic meter.*

Swimmers may also be exposed via the water in swimming pools and aquaparks. The sources supplying water could be coming from users' equipment and accessories such as buoys, ropes, paints, fins, goggles, balls, noodles, bathing suits, cosmetics etc. [Moraczewska-Majkut et al. 2025]. Indeed, typical polyamide microplastics from bathing suits were abundant in the pools studied. An aquapark pool for circuit swimming contained up to 41,360 MP/m^3 pool water, while in backyard pools very low concentrations were measured, below 100 MP/m^3. Aquaparks were more microplastic-rich than most pools, which was attributed to more intensive use.

Solar geoengineering

A potential outdoor source of plastic particles in the air we breathe comes from the planetary scale dry deposition (or washout) of stratospheric aerosol injections (SAI). Public explorations began decades ago [The Royal Society 2009; Bonnheim 2010] and today SAI is one of the most popular geoengineering practices worldwide [Hack et al. 2024]. The most cited purpose of geoengineering is weather manipulation, such as cloud seeding or diming the sun's rays at planetary scale through high altitude injection of nanoparticles and microparticles to decrease global temperatures [Biermann et al. 2021].

SAI traditionally focused on sulphates and other mineral (e.g. alumina) aerosols [Hack et al. 2024] though polymers of plastic have emerged in the mixes as well with different functions. While there is a lack of publicly available studies on microplastics loads introduced by SAI applications, multiple patents have been published describing various mixtures of polymeric particles, typically 2-20 µm in size, manufactured for injection into the Earth's stratosphere at altitudes of 10 km or 20 km above sea level. This would indicate a potentially high-volume input of airborne microplastics (Fig. 2).

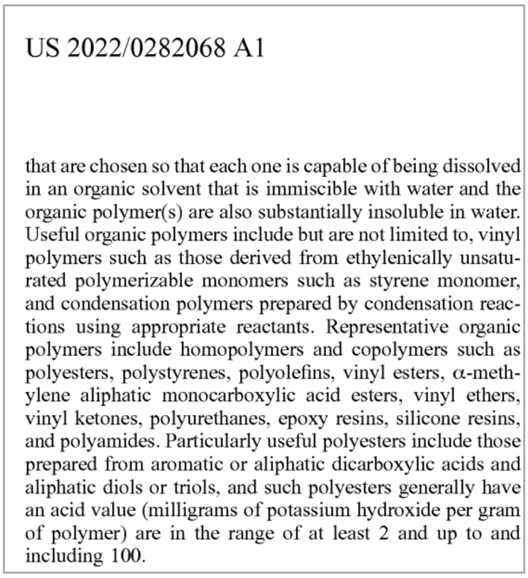
The plastic particles for such applications listed in patents include organic polymers and copolymers, e.g. vinyl polymers, polyesters, polystyrenes, polyolefins, vinyl esters, polyurethanes, epoxy resins, silicone resins and polyamides [Patent WO-2022186970-A1Patent and US 2022/0282068 A1]; Patent US6315213]. For instance, one such patent makes use of solid continuous organic polymer particles with nanosized pores which contain air [Patent WO-2022186970-A1 and US-20220282068-A1], another describes porous polymeric particles designed to absorb water for weather modification by seeing clouds [Patent US6315213]. Patents provide some valuable transparency about geoengineering materials, markets and stakeholders [Ramos & Santos 2025].

In addition to patents, literature research for this report uncovered a health hazard evaluation report published two decades ago by the US government Center for Disease Control. It was a study initiated because two workers had developed thyroid disease while occupationally exposed to chemicals in cloud-seeding materials on a production line in which silver iodide, strontium nitrate, potassium perchlorate, aluminum, and magnesium powders are combined with a polyester resin containing styrene [CDC-NIOASH 2006]. This report gives a concrete example of a polyester resin ingredient in a geoengineering product application that can be classified as a significant source outdoor air microplastic pollution.

> *Multiple patents for intentionally-added microplastic for tera-scale release into the stratosphere are a recipe for airborne microplastic exposure and microplastic fallout pollution on a planetary scale.*

Microplastics researchers have published a protocol for measurement of microplastic in atmospheric aerosols [Hasager et al. 2026], and such methodologies may pave the way to assessments of actual microplastic loads introduced through geoengineering. Massive volumes of particles are involved: SAI scientists use units of 'teragrams per year' to express the volume of particles injected into the air (1 Tg is equivalent to 1 billion kilograms) [Hommel & Graf 2022]. SAI programs require hundreds of thousands to millions of tons of material to be 'lofted' annually [Smith & Wagner 2018].

Some voices, particularly environmental ethicists, have questioned or even condemned such practices as it experiments on a global scale, in a way that is inexorably undemocratic, and have raised the issue of 'permissible pollution' (pollution as a solution) [Hale and Dilling 2010, Gardiner 2010, Royal Society 2009; Schneider 2008], while others wonder if it is the 'lesser of two evils' [Preston 2011], despite the large uncertainties surrounding actual beneficial impacts on 'climate' and the uneven impacts on nations [Robock 2008; Bunzel 2008].



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that are chosen so that each one is capable of being dissolved in an organic solvent that is immiscible with water and the organic polymer(s) are also substantially insoluble in water. Useful organic polymers include but are not limited to, vinyl polymers such as those derived from ethylenically unsaturated polymerizable monomers such as styrene monomer, and condensation polymers prepared by condensation reactions using appropriate reactants. Representative organic polymers include homopolymers and copolymers such as polyesters, polystyrenes, polyolefins, vinyl esters, α-methylene aliphatic monocarboxylic acid esters, vinyl ethers, vinyl ketones, polyurethanes, epoxy resins, silicone resins, and polyamides. Particularly useful polyesters include those prepared from aromatic or aliphatic dicarboxylic acids and aliphatic diols or triols, and such polyesters generally have an acid value (milligrams of potassium hydroxide per gram of polymer) are in the range of at least 2 and up to and including 100.

Fig. 2. Screenshot of polymers in geoengineering application described in Patent US 2022/028068A1.

There is some awareness of SAI risks among scientists, [Hack et al. 2024; Baum et al. 2022 & 2024; Biermann et al. 2021], although not usually from the environmental pollution science or microplastic fields of research, as they are largely unaware of the potential of microplastic spraying of the stratosphere. Hundreds of prominent environmental and climate policy scientists from over 50 countries have spoken out against solar radiation management practices and called for an international non-use agreement on solar geoengineering with support from civil society, concluding that the whole idea is “not governable in a globally inclusive and just manner” [Biermann et al. 2021].

In the context of this present report’s focus on microplastic pollution sources, we can add that the geoengineering practices described here have the potential to pollute the skies with thousands of teragrams of intentionally added microplastics on a global scale, analogous to metal oxide and other particles in widespread use in such applications.

6. Children’s Products

Key takeaways – Children’s products

Infants and children represent a vulnerable microplastic-exposed population.

Human mother’s milk and formula contain low levels of microplastics, with additional sources being bottles and milk bags.

Intake of polyethylene, PET and nylon-6 through the drinking of stored mother’s milk was reported to be 0.61–0.89 mg MP/day.

Baby formula intake exposes babies to microplastics at levels from <1 to 17 MP per gram formula. Packaging type may play a role in releasing the observed microplastics.

Baby bottles released up to 16 million MP/L formula. Sterilizing baby bottles with hot water degrades the inside walls of the bottles and stimulates microplastic release.

Steam washing pacifiers, teethers and silicone rubber teats accelerates degradation of the materials and microplastic release.

PET, polyethylene and PVC baby play mats released up to 27 MP per square meter daily.

Pens and erasers emit billions of submicron PVC and synthetic rubber particles during normal use.

Children are exposed to microplastics via the indoor air in schools. In a Portuguese study, school children were reported to have a median daily exposure of 1.57 ng/kg body weight per day from indoor air inhalation.

3D printers in schools emit microplastics. In a Chinese school, up to 5000 ultrafine plastic particles/cm^3 were released to the air during use of a 3D printer.

Playground sand in Australia contained 72 MP/kg.

Plastic building blocks release thousands of microplastics/mm^2 during play.

Young children ingest more dust than adults due to direct mouth contact with toys, textiles and playing on the floor, and breathing in more air per kilogram body weight than adults.

Microplastics of PET and polyethylene were measured in feeding solutions administered via infused neonatal parenteral nutrition circuits. Neonates in hospital being fed intravenously could be receiving between 1 and 115 MP over the course of 72 h.

The fetal environment and early life stages are crucial for health and well being, yet babies and children are not protected from microplastics exposure. It is well known that babies are being born from wombs littered with microplastics in amniotic fluid, placentas, umbilical cord blood from their mothers [e.g. Sun et al. 2024; Lamoree et al. 2025; Anifowashe et al. 2025; Nadarasan et al. 2025; Sripada et al. 2022]. After birth, infants drink mother's milk containing microplastics made from the mother's blood in her mammary glands [Adjama et al. 2024].

Human breast milk

Researchers in Rome detected microplastics with μRaman spectroscopy in 26 of the 34 human breast milk samples, mainly polyethylene, polyvinyl chloride and polypropylene sized 2-12 μm [Ragusa et al. 2022]. Eight samples were under detection limits of the method, and the remaining samples ranged between 0.20 and 2.74. MP/g human breast milk, with a mean of 1 ± 0.67 MP/L.

Polyurethane, polyamide, PMMA, polyethylene and PET microplastics were detected at in milk, ranging in size between 20 and 50 μm, with a median sum concentration of 20.2 MP/g human breast milk [S. Liu et al. 2023]. Breast milk storage bags may have been a source of microplastics in this study.

Baby food

Various polymers have been detected in baby formulas: polyamide, polyurethane, polyethylene, PET, polyvinyl chloride, polytetrafluoroethylene, polyoxymethylene, polypropylene, ethylene vinyl acetate copolymer, chlorinated polyethylene, polystyrene, PMMA, polylactic acid [S. Liu et al. 2023]. In that study the median number of microplastics of all polymer types detected in the formula was 17.3 MP/g. Polyurethane microplastics were encountered the most often; they were present in nearly half all samples tested.

An assessment of 18 brands of 'follow-on' formulas for babies (6-12 months old), detected microplastics in every formula tested, which were mostly between 0.1 and 20 μm in dimension, and predominantly fibers (68.5% of all particles analysed) [Kadac-Czapska et al. 2025]. Analysis by μRaman showed polyamide (28.9 %), polyethylene (27.9 %), polypropylene (27.2 %), PET (13.8 %), polyacrylamide (1.0 %), polystyrene (0.6 %), and polycarbonate (0.3 %) to be represented in the samples.

> *Exposure to microplastics begins with the first spark of life in the fetal environment and continues through infancy and childhood.*

Based on the measured concentrations and formula volume intake, the researchers estimated an average daily intake of 6.9 MP/kg body weight/day which amounts to about 58 MP/day per baby. Depending on the product babies are drinking, exposure per baby could range from 23 to 104 MP/day, and does not include additional microplastics that may be introduced from feeding bottles or water used to prepare the formula.

An earlier study of 13 baby formulas in China using a different methodology quantified microplastic release from polyethylene lined milk boxes, feeding bottles, and from the process of preparing the formula in a way that simulated a baby's daily formula routine [Zhang et al. 2023]. Microplastics were detected in the formulas at levels between 1 ± 1 and 11 ± 1 MP/100 g (average, 5 ± 3 MP/100 g; median, 4 ± 3 MP/100 g).

The boxed milk was the most contaminated. The estimates for microplastics ingestion in the first year of life based on the measured concentrations and typical formula intake volume were 580 ± 348 MP/year for babies drinking boxed milk powder formulas and 305 ± 208 MP/year for those drinking canned milk powders [Zhang et al. 2023].

Baby bottles and breast milk storage bags

The above mentioned microplastic exposure via baby food can be further significantly augmented via microplastic release from baby bottles. Baby bottles being used under normal conditions have been reported to release up to 16.2 million microplastics per liter formula [D. Li et al. 2020]. Higher amounts of microplastics were observed when hot water is used to sterilize the bottles, as it acts to degrade the inside walls of the bottles. In that study, polypropylene baby bottles were studied over a period of 21 days in which microplastic release fluctuated. The researchers estimated that between 14,600 and 4,550,000 MP/infant/day were being released from the bottles in China [D. Li et al. 2020].

In another Chinese study, opening and closing the baby's feeding or water bottles 100 times released from 53 to 393 particles/mL [Song et al. 2021].

Breastmilk storage bags that underwent testing released microplastics resulting in an estimated infant exposure of 0.61–0.89 mg MP/day through the drinking of stored milk [L. Liu et al. 2023]. The particles babies could be drinking via this route included polyethylene, PET and nylon-6.

Baby bottles and breast milk storage bags were also tested for microplastic release both at room temperature and 80°C [Zhao et al. 2025]. The bottles released microplastics of polyethylene, PET and acrylate, at a median concentration of 1465–5893 particles/L milk over product types tested (3 brands of bottles and 3 brands of milk bags).

The particles were predominantly in the 20–50 µm size range (70%). When heated, the release of polyethylene and PET microplastics doubled. The researchers estimated that together with baby bottles, their daily intake could be between 2080–5910 MP/day [Zhao et al. 2025].

Another way babies can be exposed is via silicone-rubber baby teats. Synthetic teats were steam washed under normal conditions and the microplastic release observed included particles between 0.6 and 332 µm in the wash water [Su et al. 2021].

Extrapolating to microparticles that infants sucking on these teats potentially could swallow, the study concluded with an estimate that by the time a baby turns one, his or her cumulative exposure could possibly amount to >660,000 elastomer-derived microplastics. Steam disinfection caused rubber decomposition into micro(nano)plastics (0.54–15.7 µm) and NP release from the interior of bulk rubber and micro-sized plastics [Su et al. 2021].

In addition to silicone-rubber baby teats, also pacifiers and teethers pose a microplastic exposure route in infants [Su et al. 2022]. Steaming the materials accelerated degradation processes, cracking, and fragmentation, as imaged by optical photothermal infrared spectroscopy (O-PTIR) and SEM-EDS.

Toys

Microplastic release has been measured in toy building bricks made from ABS, polycarbonate, and polyamide that were subjected to simulated play involving 10 cycles of assembly and disassembly of the blocks [Luo et al. 2024]. Microplastic particles released from the blocks were examined by both Raman and SEM giving detailed sense of how scratches are made, and how micro and nanoparticles are shed and linger on the surface of the toy blocks. Between thousands and hundreds of thousands of particles per mm^2 were observed, the majority of which were < 20 µm in dimension.

Young children are exposed via their mother's milk, formula, bottles, milk bags, toys, textiles, clothing, wet wipes, and dust.

Baby play mats made of PET, polypropylene, polyethylene and polyvinyl chloride (PVC) were tested again using Raman polymer identification and SEM for visualisation of the particles [Ou et al. 2025]. The PET mat released the most particles of the four types, 1.45 ± 0.35 mg/m^2.d, or 27 ± 1 MP/m^2.d. The researchers tested the effect of UV degradation on the mats, and observed that more than double the number of microplastics were released under these conditions.

> *Building bricks, baby play mats and other products for children release PET, polypropylene, polyethylene and PVC into a child's living environment. Children naturally ingest more settled dust during play, increasing their microplastics exposure.*

Even pens and erasers have been shown to release billions of submicron plastic particles of PVC and synthetic rubber (0.6–1.2×10^9 from erasers and (0.2–1.6×10^8 from pen grips) upon skin contact [Wu et al. 2023]. In these products both plastic and plasticizer additives are present in significant percentages.

Children's higher exposure than adults

Young children often experience high exposure to environmental contaminants because of both inhalation and direct mouth contact with mixed local microplastics in indoor dust at home [Ageel et al. 2025] in childcare facilities [Perera et al. 2023], at playgrounds [Koutnik et al. 2023] and at schools [Ferraz et al. 2025].

In an indoor air study in Australia, the greatest indoor microplastic concentrations were detected at a childcare facility (2.25 ± 0.38 MP/m^3), followed by an office (1.20 ± 0.14 MP/m^3) and a school (1.03 ± 0.40 MP/m^3) [Perera et al. 2023]. More microplastic contamination was reported in children's playgrounds relative to other urban park areas in California, possibly due to the plastic structures for play [Koutnik et al. 2023]. For example, playground sand contained 72 MP/g, which is higher than the perimeter of the playground (42 MP/g). Outside the playground, concentrations of 13 MP/g were detected in sand [Koutnik et al. 2023].

School children in NW Portugal were reported to have median daily exposure to MP of 1.57 ± 0.93 ng/kg body weight/day from school indoor inhalation exposure. Inside the school the concentrations were 21.8 ± 16.3 ng/m^3 (n = 35) while outside the school they were 13.4 ± 13.6 ng/m^3 (n = 36) [Torres-Agullo et al. 2025].

In Brazil, the atmospheric deposition of microplastics ranged from <LOD to 168.03 items/m^2/day, with school supplies and synthetic clothing cited as key sources of microplastics. Polyester and ethylene-vinyl acetate were the most abundant polymers in the samples from the school [Ferraz et al. 2025].

3D printing in schools has led to exposure to ultrafine particles of ABS or polylactic acid (UFPs, smaller than 100 nm in size) for school children K-12 [Q. Zhang et al. 2025]. Up to 5000 UFP/cm^3 were observed to be emitted from 3D printers in a learning environment.

Textile fibers released from children's clothing are also known to leach PFAS [Xia et al. 2022], along with flame retardants and plasticizers and hundreds of other chemicals from synthetic blend fabrics of infant garments [Pérez-Serrano et al. 2025] and bisphenol A and parabens from socks with size ranges of 6 to 48-month-olds [Freire et al. 2019].

> *Intravenous feeding of neonates introduces up to hundreds of microplastics into the body per week.*

Microplastics exposures also affect children in hospital, where high plastic and single-use plastic use has led to significant exposures to plastic additives such as phthalates also [Urrutia-Pereiraa et al. 2025]. A recent study investigated the release of microplastics from an infused neonatal parenteral nutrition circuit that is used for neonates who are still unable to drink and must be fed intravenously [Vercauteren et al. 2024]. In the two types of solutions administered, PET and polyethylene were dominant microplastics. Based on the measured concentrations, and a typical feeding rate of a 1-kg neonate, between 1 and 54 MP could be administered over the course of 72 h just from one of the solutions typically given. Adding the second solution (lipids) adds 8-115 MP over the same time frame [Vercauteren et al. 2024].

7. Personal Care and Healthcare

Key takeaways – Personal care and healthcare

Microplastics can gain direct access to the human body via certain medical procedures, personal care products, tattoo ink, and permanent makeup.

Wet wipes and feminine protection products are often rich in synthetic polymers and generate microplastics. Healthy skin is considered a good microplastic barrier exposure via personal care products, though inflamed skin is not.

Toothpaste with microbeads, plastic toothbrush bristles and even dental work are potentially huge sources of microplastics: for example, 2.3 million bristle particles per year may be released.

A plastic contact lens wearer may be exposed to 90,000 MP annually via their eyes.

Synthetic polymer orthopedic and breast implants release up to millions of microplastics per gram tissue and have been imaged with stimulated Raman spectroscopy (SRS).

Medical injectables via syringes, infusion sets, needles, intravenous fluid, and cardiopulmonary bypass surgery machines appear to be inadvertently dosing patients with microplastics.

Polymeric nanocarriers and excipients are sources of medical microplastics that enter the body with active ingredients in medicines in tablet, injections or aerosol form increasing exposure in a medication-volume dependent manner.

Hospital rooms are places we hope to heal in, however they are subject to airborne microplastics eventually depositing on floors and surfaces too. Concentrations in operation rooms ranged from undetectable up to 9258 MP/m^2, for different 12-h sampling periods.

Besides food and beverages, many other common products are applied directly to or inside the body. Personal care products have long been known to contain microplastic and were targeted early in the EU's Marine Strategy Framework Directive's mitigation measures lists. They were subject to early public awareness campaigns such as Beat the Microbead [https://www.beatthemicrobead.org/]. Cosmetics became recognized as a source of microplastic pollution [Leslie 2015], and have been subject to regulation under REACH. Despite these developments in societal and policy realms, personal care products are still carriers of polymeric particles, causing microplastics exposures in humans [Giustra et al. 2024; Kukkola et al. 2024; Gamage et al. 2024].

Personal care products

Growing concerns for human health are the large volumes of microplastics contained in rinse-off (e.g. toothpaste, soaps, shampoo) and leave-on products (e.g. nail polish, moisturizing creams, sunscreens) [Leslie et al. 2015; Kukkola et al. 2024], which together result in chronic skin exposure of low and sub-micron microplastics of dozens of polymer types [EU Cosing Database https://ec.europa.eu/growth/tools-databases/cosing/; Beatthemicrobead.org]. Microplastics applied to the skin may get lodged in hair follicles, sweat glands, keratinocytes or of course any damaged skin areas such as wounds or abrasions [Kukkola et al. 2024; Han et al. 2025].

Microplastics were observed to be retained in scalp hair, facial skin and hand skin 24 hours post-application [Abassi & Turner 2024]. Evidence is emerging that polyethylene particles such as those extracted from facial scrubs and creams, are able to significantly decrease the growth and viability of normal human dermal fibroblasts (skin cells), and increased oxidative stress when brought in contact with these skin cells *in vitro* [Saha & Chandrasekaran 2025]. Oxidative stress and other biochemical disruptions in skin cells have been reported for polystyrene particles as well [Schmidt et al. 2023].

For decades the research community has reported that microplastics do not cross a healthy skin barrier and thus would normally be unable to cause systemic effects [Niebel et al. 2026; Schneider et al. 2009; Zou et al. 2017; Try et al. 2016; Becker et al. 2011]. However, the observations of oxidative stress and other cellular effects in microplastic-skin cell contact studies raise questions as to whether microplastic exposure could illicit toxicity in the absence of particles penetrating the epidermal skin layer. Toxicity testing of fine and ultrafine polymeric particles using dermal models (e.g. pig) has shown, that unlike healthy skin, inflamed skin is readily penetrable [Try et al. 2016; Schneider et al. 2009].

Wet wipes and women's sanitary products

Another category of microplastics exposure via personal care products arises from the use of disposable wet-wipes. These have been identified as a major source of plastic environmental pollution [Nacci et al. 2025], however, analogous to rinse-off products, also wet-wipes are in direct contact with the skin and release of microplastics is plausible, but still a data gap for human exposure scenarios.

Women's sanitary products (or parts thereof) are frequently made of plastic materials. Tampon samples investigated were found to contain plastic parts e.g. strings, absorbent materials and covers, including such polymers as polyester, polyethylene, polypropylene, polyether as well as a synthetic wax (ethylene bis(stearamide)) [Munoz et al. 2022].

As part of that study, an *in vitro* experiment was designed that simulated conditions of vaginal pH, temperature and friction to measure fiber release from 12 tampon types that contained plastic parts that come in contact with the body. Seven of these products released microplastics, which were all submicron sized particles (36 to 848 nm). When the same tests were run at pH 7, significantly fewer particles were released. The researchers found that 0.28 mg of tampon fibers were released during a 4-h *in vitro* test, and estimated a woman could be exposed to up to 9.4 billion particles released during a monthly period, though the released fibers were a mix of cellulose and microplastic fibers.

Contact lenses

Contemporary contact lenses are constructed from polymers or copolymers. Common materials found in lenses worn by millions of people worldwide include methylacrylate, polyvinyl alcohol, polydimethylsiloxane, hydroxy ethyl methylacrylate hydrogel, silicone hydrogel and others [Musgrave et al. 2019].

> *Humans can inadvertently pollute their bodies through personal care, vision correction, and oral care.*

Laboratory testing of a variety of contact lenses for 1-day, 1-month and 6-months wear was performed to measure microplastic release [Y. Liu et al. 2023]. Each pristine lens tested was rinsed with ultrapure water and irradiated with UV light simulating normal wear conditions, and kept at a temperature of 25 °C. After 10 h, the lenses were rinsed with ultrapure water and returned to the test system for several rounds, simulating normal wear conditions equivalent of either 30 d or 90 d [Y. Liu et al. 2023].

SEM and FTIR were used to visualise the particles released and determine the polymer type of the contact lenses. The lenses subject to 30-d wear treatment released on average 4258 MP/lens, while lenses subject to 90-d treatment released on average 9590 MP/lens, as well as larger debris. The wear-period (1 day 1 month or 6 months) did not have a significant effect on the microplastics released – only one 6-month wear lens type showed significantly higher release than all other lenses tested. Based on the data across all lens types, and across both UV light irradiation treatments, the researchers calculated that a contact lens wearer (of two lenses) for 10 h per day could be exposed to over 90,000 microplastics over the course of one year [Y. Liu et al. 2023].

Tattoo inks

There is a potential for microplastic exposure via tattoos and permanent makeup (PMU). Polymeric binding agents are added to the tattoo (or PMU) inks as pigment carrier particles and also to improve the ease of ink application to the skin. Commonly used binders include polyether (polymers consisting of monomers linked by ether, C-O-C), polyvinyl-pyrrolidone (an amphiphilic polymer), block copolymers and Shellac (a natural polymer secreted by lac bugs) [Piccinini et al. 2016].

> *'Think before you ink.' Tattoos introduce microplastics and chemicals into the skin and lymph nodes.*

The inflammatory effects of tattoo ink constituent mixtures have been under study in the medical sciences for some time [Kluger et al. 2012; Laux et al. 2016; Giulbudagian et al. 2024]. While some particles stay put in the skin, significant amounts of tattoo particles are known to accumulate in the lymph nodes, though focus has centered more on pigments and less on binding agents [Soran et al. 2017; Schreiver et al. 2017; Friedman et al. 2003].

Pluronic polymer coatings of carbon black pigment particles have been proposed as alternative particles for improved biocompatibility and lower inflammatory response. Pluronic block copolymers consisting of hydrophilic poly(ethylene oxide) side chains connected through a hydrophobic central poly(propylene oxide) block applied as tattoo ink pigment carriers [Oh et al. 2025]. Despite the claims of biocompatibility of these or other copolymers for dermal injection, the advice the U.S. FDA and some European counterparts have communicated to the public may still be prudent: 'think before you ink'.

Oral care

Microplastic exposure comes from various sources in primary oral care [Saha et al. 2025]. Toothpaste is a known source of microplastic exposure due to polymeric components listed as ingredients in diverse brands worldwide [www.beatthemicrobead.org; Leslie et al. 2015; Chengappa et al. 2023; Madhumitha et al. 2022]. Despite awareness raising campaigns and pressure on the producers, microplastics are still added to toothpastes, leading to large releases e.g. in a country like India, where a reported 1400 tonnes of microplastic are estimated to be emitted annually from toothpaste use alone [Madhumitha et al. 2022]. Toothpastes in that study consisted of 0.2% to 0.9% microplastic by weight. Polypropylene, polyvinyl chloride and polyamide were the dominant types of microplastics detected (using FTIR) [Madhumitha et al. 2022].

In addition to toothpaste products microplastic release has been measured from plastic toothbrushes, orthodontic implants, and denture materials [Saha et al. 2025]. Six brands of toothbrushes made from e.g. polybutylene terephthalate and nylon were tested for microplastic release using a 3D-modeled zirconium dental arch to simulate brushing twice daily for a week [Aytulun et al. 2025]. ATR-FTIR was used to determine the polymer types of the bristles, showing a great diversity of polymers: nylon-6, polybutylene terephthalate and a mixed bristle brush containing polybutylene terephthalate, nylon-6 and a substance identified as liquid paraffin. Particles released were analysed by µRaman. Every toothbrush they tested released microplastics, up to a maximum of 39 MP/d. Particle sizes ranged from 8 to 1995 µm [Aytulun et al. 2025].

In a Chinese study, researchers used µRaman to measure microplastics release from toothpaste and toothbrushes alike, and came to an average exposure estimate of 11.83×10^5 MP/year/person from their toothpaste and an average of at least 23.3×10^5 particles/year/person from the toothbrush bristles [Wang et al. 2025]. SEM was used to image the break down of bristle materials of toothbrush, which progressed considerably during use, esp. in the case of PET bristles. The toothpastes studied contained polyethylene and polyethylene-vinyl acetate, and predominantly polypropylene was released from the toothbrush bristles. New brushes released more microplastics than brushes initially and gradually released fewer particles with continued use [Wang et al. 2025].

Gentle use and rinsing toothbrush bristles with water often have been recommended to reduce microplastics release [Fang et al. 2023a]. However, if bristles are made of plastic they will release microplastics, whereas material substitution would address the problem more fundamentally.

New methods are being developed to understand microplastic exposure from orthodontic clear aligners (clear plastic trays used to straighten teeth, typically made of polyurethane), following concerns of particle release and cracks and material fatigue following friction caused by chewing, swallowing and general wear and aging of the materials [Barile et al. 2025]. Clear evidence of microscopic particle release has been shown for various brands of clear aligners.

Surgical masks

The healthcare sector has become highly dependent on single use plastic applications [Rizan et al. 2020]. Important microplastic exposure scenarios also play out in hospitals, e.g. in neonatal units as discussed above [Vercauteren et al. 2024], but also the single use plastic contained in swabs, tubing, bottles, syringes, and surgical masks are potential microplastics sources.

Microplastic release has already been measured via the use of surgical masks [Zhao et al. 2024]. Disposable plastic mask wearing has become more widespread and recent studies have measured microplastic fiber exposure via the inhalation route, though the masks appear to let many different microplastics through, not only those corresponding to the polymers that the masks are composed of.

Common masks materials comprise polymers such as polystyrene, polyamide, poly(ethylene-propylene) diene monomer, polyester, polyethylene, polyvinylidene fluoride, polypropylene, and polyvinyl chloride [Zhao et al. 2024]. Via nasal lavage, microplastics were collected from mask wearers and analysed. The average concentrations of 28.3 ± 15.6 MP/5 mL nasal solution were indications of the transfer of airborne microplastics through face masks to the nasal passages of test subjects [Zhao et al. 2024].

> *Health care comes at a cost of microplastic exposure. Injectables, surgeries, single use plastic applications and drug delivery introduce microplastics to the human body.*

However, mask wearers also test positive for many other microplastic types, indicating that nasal lavage is a method that can be used to gauge inhalation of airborne microplastics, and in that case, the fraction that does not make it to the lung [Torres-Agullo et al. 2023].

Nasal irrigation bottles and swabs

Nasal irrigation bottles release microplastics, in particular if they are used for longer periods of time [Kim et al. 2024]. In nasal irrigation fluid 33.00 ± 20.42 MP/300 mL were detected from use of control bottles, whereas bottles in use for 1, 3, or 6 months shed on average 68.66 ± 30.07, 261.66 ± 20.59, and 204.33 ± 52.16 MP/300 mL, respectively.

PCR-test swabs with ‘brush’ formed tips release polyamide (nylon) fibers including in the submicron range (0.2–2 µm) in simulated use tests using adhesive surfaces, followed by analysis with SEM–EDS and Raman [Fang et al. 2023b]. The swabs tested also contained an additive, nano-TiO_2 that was observed to be covering the fibers released, which has been implicated in nasal and pulmonary toxicity in rats [Kwon et al. 2012].

Fang et al. [2023b] estimated between 12 and 44 polyamide particles could be potentially transferred from the swab to the nasal cavity during a single swab sampling event, and noted that to minimize polyamide release, a gentle handling of the swab before and during sampling was required. However, with adjustments to the nasal sampling method, polyamide particle exposure could be completely avoided.

Medical injectables

Besides the oral, inhalation and, in some cases, dermal uptake routes for microplastics, humans are also exposed via injected and implanted plastic materials, as well as via the plastic instruments used to carry out medical procedures that can shed microplastics directly into the body. Via common medical injections, microplastics are being introduced into the body [Li et al. 2025].

Based on measured data, the average microplastic release per patient per year was estimated to be 3.75 MP for syringes, 6.22 MP for infusion sets, and 0.35 MP for vein detained needles [Li et al. 2025].

Single use plastic injectors commonly used for insulin delivery (for diabetics) and antibiotics (for farm animals) were tested for microplastic release, resulting in mean release of 1.74 MP every time the injector was used [Song et al. 2021]. The polymer type injected this way was identified as polypropylene, and the particle sizes detected with both FTIR and TEM were from the micrometer down to the submicron range.

Intravenous infusion fluids are stored and administered via plastic bottles, typically polypropylene. The fluids are prefiltered to avoid particulates but nevertheless, microplastics can be abundant in samples of fluids. On the order of 7500 polypropylene microplastics with sizes ranging between 1 and 62 µm were detected using Raman and SEM in fluids for intravenous injection into the patient bloodstream [Huang et al. 2025].

Intravenous infusion is also becoming recognized as a source of direct internal microplastic exposure in humans. Different infusion bags tested released between 522 and 5455 particles/L fluid content [X. Zhang et al. 2025b]. The composition of the infusion fluid was a major factor driving microplastic release from the bag, though the authors also cited storage period, mechanical shaking, and storage temperature as contributing factors to the observed release.

Other researchers fitted intravenous infusion sets with various filters and measured the microplastics released using FTIR [Cui et al. 2025]. They found a mean abundance of 1.24 ± 1.44 MP/unit (2.91 ± 3.91 MP/L), mainly consisting of polyethene and polypropylene particles in the range of 15–100 µm.

Surgical environments

Surgeries have been identified as a microplastic exposure source [Yang et al. 2023], albeit not an everyday occurrence for individual people as many of the previously cited exposure sources. Nine different polymer types of microplastics measuring up to 469 µm in diameter were identified in pre- and post-operative blood samples from cardiac surgeries [Yang et al. 2023]. Up to seven different polymer types were detected in a single sample, and these reflected to some degree the polymers present in the medical applications in use, e.g. tubing, blood bag filter, surgical face masks, intravenous bag, sutures, anesthetic mask, syringe barrel, etc. It cannot be determined to what extent the measured particles were of hospital origin however.

Cardiovascular disease leads to consistently high numbers of hospitalizations [OECD 2025]. In cardiopulmonary bypass surgery, the functioning of the heart and lungs is taken over by a machine through which the patient's blood flows. Such a machine can be a conventional cardiopulmonary bypass (CPB) type or minimally invasive extracorporeal circulation circuits (MiECC).

The blood contact tubing in such machines has been previously reported to release PVC particles, resulting in calls for measures to reduce exposure via this route over 40 years ago [Knopp et al. 1982]. Using a 0.22 µm-Millipore filter to collect particles circulating in the intravenous fluid flowing through the tubing, and SEM to count the particles, researchers detected 51.2 MP/mm^2 filter after one recirculation period; the number of particles in the volume of intravenous fluid used was calculated to be 70,943 [Knopp et al. 1982]. Such particle release appears to occur in a nonlinear manner, in spurts [Bernardski-Spiwak et al. 2008].

A recent study found conventional CPB circuits to be generating micro-sized particles at a rate of 60.4 ± 7.6 MP/L/h (77.0% of total particles), while MiECC circuits generate 48.4 ± 31.3 MP/L/h (45.3% of total particles) [Green et al. 2025].

Hospital rooms contain many plastic products that can contribute to airborne microplastics. To study this specific indoor space, deposition of microplastics from the air onto passive sampler surfaces over a 12-h shift in hospital operation and adjacent anaesthetic rooms was quantified [Field et al. 2022]. High variation in microplastic deposition was observed between sampling periods. In the operation room, the mean concentration measured using µFTIR was 1,924 ± 3,105 MP m^2 (range <LOD to 9258 MP/m^2).

The anaesthetic room mean concentration was 541 ± 969 MP (range <LOD to 3368 MP/m^2). The microplastic fragments were primarily polyethylene terephthalate (37 %), polypropylene (25 %), polyethylene (7 %) and nylon (13 %).

Cardiac catheters

Cardiac catheters that are common to cardiac surgeries, 21 in total, were studied for microplastics release when simulating flow conditions similar to normal use [Dewika et al. 2024]. They have polytetrafluoroethylene (Teflon) inner surfaces, while outer surfaces are made of polyurethane-nylon or polyethylene-nylon blends. Raman spectroscopy was used to identify and quantify plastic particles. All catheters tested leached microplastics in the test setup. 739 MP leached from a diagnostic catheter sample. The average MP count from guider catheter samples was 575, (range 525–619), and 530 MP (range 418–739) for the diagnostic catheter, and 524 MP (range 429–648) for the guider catheter tested.

Cardiac surgeries are frequently performed world wide, so while this is not an everyday source, it is one that affects millions of patients.

Silicone gel breast implants

Silicone gel breast implants are known to sometimes rupture, releasing significant volumes of gel, though they also can slowly leach particles of their polymeric contents into surrounding breast tissue (‘sweating’). Such processes have been evaluated with stimulated Raman scattering (SRS) microscopy, where silicone fragments as small as 2 µm were detected in both human breast and lymph node tissue samples [van Haasterecht et al. 2020]. Polyurethane shedding from a foam-covered implant was also observed in the tissue histology samples in the same study.

> *Implants introduce plastic materials to the human body which over time release microplastics to surrounding tissues.*

Silicones are synthetic polymers with plastic-like properties though there are differences in the chemical structure compared to traditional plastics, e.g. the polydimethylsiloxane in the breast implant study is made of a siloxane backbone of alternating silicon and oxygen atoms, to which methyl side chains are attached. As such, particles of siloxanes are often included in microplastics research.

Orthopedic implants

Orthopedic implants are highly susceptible to polymeric debris release for instance in joints, which are typically subject to high amounts of wear and tear. Shedding of microplastics from these implants has been well studied because the release is often associated with inflammation pain in patients caused by plastic particles shedding. The histological study of orthopedic implant microplastic release does show similarities with the release of small breast implant particles, except orthopedic particles typically present in the submicron size range [Hallab et al. 2019]. In addressing the plastic wear debris problem, new cross-linked and ultra high molecular weight polyethylene (UHMWPE) materials have been applied and tested for inflammatory responses [Tomazic-Jezic et al. 2001; Illgen et al. 2009; Sukur et al. 2016; Nine et al. 2014; Musib 2011]. Studies have shown that the volume of wear debris from these newer plastics materials is lower than for conventional polystyrene, though e.g. cross-linked PE wear debris is characterized by smaller particle sizes and higher surface reactivity [Sukur et al. 2016].

Patients with wrist, elbow and finger implants can experience inflammation due to microplastic release. Between 0.99 and 24.8×10^9 MP/g (dry weight) of tissue were measured, almost exclusively silicone particles have been reported [Hirakawa et al. 1996]. Common medical procedures leading to direct internal exposures to microplastics compel us to revisit risk-benefit balances and material design choices as the adverse effect data for microplastic grows.

Drug delivery

Drug delivery innovations have heralded in the age of polymeric pharmaceutical excipients[1] for tablet, capsule, and many other types of drug delivery formulations [Debotton and Dahan, 2017]. The consumption of pharmaceuticals has been growing for decades [OECD 2025], which also increases the exposure to the polymeric components that are a common ingredient in medicines.

Plastic particles have been reported to traverse the blood brain barrier in humans [Amato-Lourenço et al. 2024; Bu et al. 2026], mice [Shan et al. 2022; Paing et al. 2024; Kaur et al. 2024; Chen et al. 2025], fish [Mattsson et al. 2017; Ding et al. 2018; Guerrera et al. 2021] and the blood-retinal barrier [Yang et al. 2022]. This is something that many drugs would fail to do on their own unless they are being ‘carried’ by a particle, hence the field of nanomedicine addresses this.

Polymeric excipients cover a vast range of polymers and copolymers, including polyvinyl pyrrolidone, copovidone, crospovidone, polyvinyl alcohol, polymethylacrylates, carbomer, poly(methylacrylate acid-co-methyl methylacrylate, among many others [Baning et al. 2024; Debotton and Dahan, 2017].

Polymeric nanocarriers are pharmaceutical excipients consisting of many common types of plastic in nano-format including familiar polymers such as PMMA, polystyrene, polyethylene, etc. Being aware of such particles being associated with inflammation, pharmaceutical developers have resorted to coating

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[1] Substances in drugs which are not active pharmaceutical ingredients, e.g. fillers, dilutants, binders, nanocarriers.

the polymeric nanocarriers with certain specific substances such as glycine which appear to - at least initially - not elicit their oxidative stress or inflammatory effect [Hardy et al. 2017].

However, the use of such plastic nanocarriers introduces small plastic particles directly into the body and even the coatings may not provide long-term protection. Other studies indicate plastic nanoparticle delivery systems are risk factors in clinical drug delivery trials [De Jong and Borm 2008; Forte et al. 2016]. New drugs are also being dosed on plastic nanocarriers to be inhaled [Blank et al. 2017].

Carriers in the nanomedicine field and microfragments of other polymeric pharmaceutical excipients continue to introduce plastic particles into patients world wide. Excipients have been the subject of some controversy regarding whether their benefits outweigh their unintended consequences. Recognizing this, we may be entering a paradigm shift towards biomimetic design strategies in biomedical nanotechnology [Fang et al. 2017; Lamparelli et al. 2023].

> *Plastic nanocarriers introduce ultrafine plastic particles directly into the body via medicines.*
> *For optimal healing, medicines need to be biocompatible, not bioaccumulative, not toxic and not persistent.*

The studies described in this chapter raise valid questions about the clinical implications of microplastic exposure in hospital settings.

The polymers and copolymers of microplastic exposure

polyester	polyacrylates	acrylonitrile butadiene styrene
polyamide/nylon	polysulfone	polyethylene terephthalate
polystyrene	polyethylene	poly(methyl methylacrylate)
polyurethane	polypropylene	polytetrafluoroethylene
polybutadiene	polycarbonate	cellulose acetate and triacetate
polypropylene	polyoxymethylene	ethylene vinyl acetate copolymer
polyvinyl chloride	polylactic acid	chlorinated polyethylene
polypropylene diene	Tritan polyester	styrene-acrylonitrile copolyester
styrene–acrylonitrile	polyvinyl alcohol	ethylene acrylic acid copolymer
epoxy resin	alkyd	acrylic/acrylates polymers
melamine	phenoxy resin	ethylene-propylene-diene-monomer
polyphthalamide	polyurethane-polyurea	polyurethane/polyether-urethane
copolyester	methylacrylate	polystyrene-polyacrylonitrile
polyvinylpyrrolidone	polyvinylidene fluoride	polybutylene terephthalate
polyurethane-nylon	ultra high molecular weight polyethylene	poly(ethylene-propylene) diene monomer
polyethylene-nylon	silicone hydrogel	polydimethylsiloxane
polyether	polypropylene-polyethylene	hydroxy ethyl methylacrylate hydrogel
polydiallyl phthalate	polyethylene vinyl acetate	poly(butylmethacrylate-co-(2-dimethylaminoethyl)methacrylate-co-methylmethacrylate)

Fig. 3. Overview of polymers and copolymers of microplastic exposure reported in the studies cited.

8. Discussion

8.1 Data interpretation

The data presented above illustrate how scientists have aimed to quantify and characterize the microplastic sources in the spaces humans live, and in some cases, also estimate the human exposure based on consumption and behavioural patterns.

Whether it is food packaging or textiles, the data is showing that there is microplastic release across all product categories. For a product to release microplastics it must contain the plastic in the first place. Every plastic product life cycle includes microplastic release stages.

> *Modern lifestyles feature an all-encompassing exposure to microplastics due to a wide variety of plastic applications releasing microplastics.*

In the studies reviewed here, the microplastics detected from various sources comprised around 60 different polymers (Fig. 3).

While it is extremely plausible that plastic products are a source of microplastic contamination in the modern living environment and food systems, such measurements reveal real-world information that is stronger than assumed plausibility.

Importance of quality control in data interpretation

As for all target analytes in analytical environmental chemistry, attention is always needed for the quality assurance and quality control (QA/QC) of the analyses. Across the sector of analytical quality control, proficiency testing providers and accreditation bodies, there is a common philosophy: it is about continuous improvement. The analytical chemistry being applied to measure microplastics is constantly advancing and maturing.

Several published works have examined reporting of analytical quality control of microplastics data, giving important insight into the analytical performance in the field of microplastics and where improvements still need to be made.

Dawson et al. [2023] analysed analytical quality control reporting, reproducibility, representative sampling, extrapolation in a large number of microplastics publications. They found that methodological details and quality control metadata regularly are missing from reports. Replicate samples are often omitted from analytical series [Shruti and Kutralam-Muniasamy 2024]. Lin et al. [2023] found that very few studies of microplastics in seafood met a high standard of quality criteria. The same was observed for microplastic release from food contact materials [Zimmerman et al. 2025]. In recent reviews of publications focused on microplastics in human sample matrices, many QA/QC issues were identified that are valid for all microplastics studies, e.g. controlling for background contamination, insufficiently detailed reporting of methodologies, quality control of sampling, method validation data such as repeatability, robustness, recovery, [Malafaia & Barceló 2023; Lamoree et al. 2025].

Analyte recoveries need to be not only determined but also optimized for each new category of sample material being tested with in-house methods [Kwon et al. 2020]. These positive controls for establishing analyte recovery in the test protocol, or negative controls to account for background contamination during sampling and analysis are not always reported [Lamoree et al. 2025].

Studies aiming to measure direct microplastic exposure via product use require custom sampling and analysis protocols for each product. For example, measuring microplastic release from dental work required creating a new model, and development of fit for purpose sampling and analytical procedures [Barile et al. 2025]. Unlike chemical additives that passively diffuse in ways that are somewhat predictable [Leslie et al. 2025], microplastic release measurements come with extra challenges including the patchiness of particles in samples, and the vast diversity of physical-chemical properties of the analytes themselves. It should also be noted that in any analysis there is a margin of error, and 100% accuracy and precision[2] are extremely rare for any type of chemical analysis.

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[2] Accuracy refers to how near the measured microplastics concentration value is to the true value; precision refers to the consistency and repeatability of microplastics measurements.

Quality control tools. Laboratories working on analyte classes for which methodologies are in the research and development phase, such as microplastics, always search for an objective way to verify the accuracy of their results. For this there is an entire sector of companies and public bodies that provide quality control tools, materials, testing and training for established analyte classes. The overall quality of the data is being improved with better access to quality control tools such as reference materials [Martínez-Francés et al. 2023; Altmann et al. 2025; Hauffe et al. 2025; Hagelskjær et al. 2025], sample collection and preparation procedures, as well as continuing methodological advancements, training, and experience with these analytes in different matrices.

Suitable proficiency testing schemes for sample matrices, and certified or standard reference materials are normal quality control tools in analytical laboratories. Inroads are being made on this front for microplastics analyses, with interlaboratory comparisons providing insights into laboratory proficiency in microplastic analysis and creating a network of analysts working towards common goals [van Mourik et al. 2021; Ciornii et al. 2025].

Small sample sizes. Many of the pioneering studies published to date report data from pilot projects which are limited to relatively small numbers of samples, which are valuable for range finding and to give direction to larger studies as well as help get those studies funded. Even established national environmental and water monitoring programmes currently still may resort to small pilot study sample sizes, referred to by Dutch water managers as 'guerrilla studies' [Freriks et al. 2023].

Dynamics of release. The dynamics of microplastic release from a given plastic material depends on multiple factors, starting with the chemical composition of the plastic material itself. Weathering, or 'aging' is an important function that accelerates plastic material breakdown and generate microplastics: UV light, biofilms, temperature changes, moisture, wear, mechanical stress, additives leaching, as well as chemical contact (e.g. chlorinated substances in a water pipe). Such processes can start to occur early in the product life time, for instance, during pre-consumer product transport and storage.

Differences in plastic batches within a brand can arise as manufacturers source feedstock materials with varying compositions and impurities that potentially affect microplastic release from the finished product. Testing products on the market occurs without having the full back story on chemical composition, production, transport, storage conditions prior to acquisition.

Heat is particularly important for microplastics release, as the food contact materials studies in Chapter 3 illustrate. The range of different conditions leads to a reality that microplastics released from one product brand is not necessarily predictive of what will be released from a different product brand, or even the same product brand from a different batch or lot.

Product characteristics are not constant and the microplastic shedding behaviour is not necessarily comparable among the same brand of product from different batches due to manufacturing and/or weathering-related factors. The range of concentrations in any product or any human for that matter is a dynamic metric.

A microplastic measurement is a snapshot for a product, or a batch of products, under a set of conditions (e.g. heat or cold), and the concentrations are not necessarily the same for measurements of a different batch, brand, or product application using the same polymer type.

What do these microplastic exposure data mean?

Analytical scientists working on microplastics aim to reduce uncertainty as much as possible by reducing systematic and random error in sampling, sample preparation, analysis, and acquiring funding for large studies with large sample sizes. Uncertainty is never zero, and this is why it is important to understand it.

Uncertainty in real-world data sets is common and does not mean the data are useless or wrong. In microplastics research, uncertainties imbedded in sampling and analysis procedures makes us aware of the limitations that the methodologies have so we can work with them, neither overestimate nor underestimate their significance, and understand the range of outcomes of the scientific studies in the public domain.

The peer reviewed studies cited in this report have applied basic quality control measures to avoid false positives. The aim of this scoping review was to gain a perspective on available data signaling microplastics release and for this reason, less strict exclusion criteria were applied for quality control. Data reporting units are not harmonized because both particle counting and mass concentration methods were included in the review.

Compared to environmental monitoring or bio-monitoring data, the microplastic concentrations measured close to the source tend to be higher. Analysis of trace amounts of microplastic in the same range as background contamination is more strongly subject to false positives. For high microplastic concentrations, even if a researcher were not to measure the background contamination using blanks, or if blanks were not corrected for, the impact on the data is lower. However, when there are millions or billions of nanoplastic particles released, (e.g. heated plastics or 3D printing emissions) it becomes difficult to accurately quantify such large numbers, and in those cases, researchers provided estimates.

Improvements in quality control and in analytical methodologies may change or nuance the outcomes of studies cited above, but such improvements are not likely to fundamentally change the conclusion that our plastic products are shedding significant quantities of microplastics. This is because the main problem is not answering the question if plastic particles are released with plastic product use, 'yes' or 'no'. The challenging questions to answer accurately and precisely are how much, how many, what are the particle characteristics, the differences between brands, and how efficient is the transfer of microplastics from the product to the human body?

> *Improvements in analytical quality control will not fundamentally change the conclusion that plastic products are shedding microplastics and creating significant sum exposure scenarios for humans.*

Judging data quality is context-dependent since we must decide if the data carries enough quality for the purpose they are being used for.

The thousands of data points presented in the roughly 350 articles reviewed here represent real-world data that firmly reject any hypothesis that humans are unexposed to microplastics via their products. This report does not pin down all-source exposure levels for specific human populations or individuals because of the enormity of such an exercise and extremely high data volume required for that. Instead, this report scopes out the everyday exposure hot spots, and uniquely collates a wide variety of sources which may not yet be on the radar of key stakeholders.

The question arises, what would we do with the data if each series of products coming off the production line were to be delivered with technical specifications including an accurate microplastic release prediction over its lifetime? How would maximum accuracy in microplastic release data change how we view (and act on) the microplastic exposure problem?

Product microplastic release can inspire mitigation strategies

Our growing knowledge of microplastic release from products is key to devising mitigation strategies as it highlights the point sources which can be targeted for non-regrettable material substitution and/or functional substitution [Tickner et al. 2015; Maertens et al. 2021].

An example of a substitution that reduces microplastic exposure could be a polypropylene chopping board (see 3.3) that is substituted by a simple wooden one, treated with walnut or linseed oil. (A regrettable substitution would be replacing a polypropylene board with a polyethylene one that only reduces microplastic exposure somewhat.)

A 'functional substitution' is a substitution in which the function is retained via a different type of product or approach. For instance, when we substitute plastic teabags with a tea infuser for loose tea leaves – the 'function' of tea drinking is achieved, only the plastic bag is replaced not by a different tea bag material, but by a different tea making process: loose tea and a tea infuser. A different product approach that achieves the same goal: tea drinking.

> *Choosing a wooden cutting board instead of a polypropylene one is an example of an easy, non-regrettable material substitution. Using a tea infuser instead of plastic tea bags for tea drinking is a 'functional' substitution.*

8.2 Microplastic release and human exposure

Serious exercises in estimating human microplastic exposure via external measured concentration data have been carried out in the studies above, as well as in studies that calculate sum-exposure from different sources taken together, e.g. an estimate of. 74000 to 121000 MP/year was made in 2019 for inhalation and ingestion combined [Cox et al. 2019]. Other estimates in the literature cite median microplastic a median intake of 553 MP/capita/day (184 ng/capita/day) for adults and 883 MP/capita/day (583 ng/capita/day) for children [Mohamed Nor et al. 2021].

Using food consumption data, the daily intake per person of a given food type for a certain population can theoretically be estimated via the food basked approach. The UN Food and Agriculture Organization (FAO) estimated maximum per capita consumption of MP per person per year, for a small number of food categories for which published data was available, e.g. mussels (1.2 million MP/capita/year), though the exercise is a starting point and further study is needed to improve the accuracy of the human intake figures [Garrido Gamarro & Costanzo 2022]. Data is restricted to a relatively small number of food categories [Kwon et al. 2020], and a small fraction of the millions of plastic products and exposure scenarios that contemporary human populations are facing.

While great strides have been made to measure microplastics in food products from across the globe, it is still premature to make accurate estimates of total microplastic exposures via food and drink consumption in human populations [Sewwandi et al. 2023; Nelis et al. 2023; EFSA 2025] and other sources.

As more data continue to emerge, especially the inclusion of powerful microplastic emitters cited, e.g. teabags, baby bottles, tea kettles, textiles, tires, 3D printers, solar geoengineering, tattoos, toothbrushes, contact lenses, medicines and medical procedures, the magnitude of potential average exposures begins to come into focus.

Exposure and Risk. The exposure to plastic particles and the chemical load that is associated with them, coupled to the toxicological hazard that they carry creates a scientific and risk assessment imperative to characterize the toxicological and epidemiological risks to the human population. This is done by coupling data on chemical exposures to the adverse effects measured using toxicological testing and in more extensive studies on human population level. Depending on the testing approach, science can study interference of chemicals with biological systems on the molecular level, but also on the level of the cell, organ, individual, population, community [Ankley et al. 2010].

Coverage of all levels of biological organisation provides a deep understanding of the toxicological mechanisms – the how and why chemicals cause the adverse effect - as well as what kind of overall adverse outcome can be expected to be caused by a given chemical exposure. Most toxicity testing today is focused on the molecular or cellular levels, which is an excellent place to start. On the other end of the spectrum, epidemiological studies have been carried out for a tiny percentage of all chemicals in use, as these are large scale projects with large scale price tags. Microplastics epidemiological studies are now starting to emerge. There is a lot of interest in producing a reliable human risk assessment for microplastics but this is a long and arduous process that will likely span decades.

> *Everyday microplastics exposure data paint a semi-quantitative picture of extensive daily microplastic exposure in the world population.*

Known toxicological effect signals coupled to the exposure signals reviewed here and internal exposure measured inside the human body together warrant a full investigation into risks for humans as well as the environment.

8.3 Recommendations for Further Research

The more we learn about microplastic exposure in the living environment, the more we want learn. Some knowledge gaps and areas for future research for microplastics and health are listed for inspiration.

- Studies of how healthy, relatively low-exposed human populations avoid microplastics and how this impacts their health status.

- Feasibility and effectiveness studies of mitigation measures for short, medium and long term for groups of stakeholders.

- In addition to small sample size ‘guerrilla studies’ that are useful for scoping, a move to larger sample sizes will reduce margins of error and produce even harder evidence.

- Continued advances in sampling and analytical methods, quality control tools, reference materials, proficiency testing, and the peer review process.

- Human exposure assessments for selected product categories, living environments and vulnerable populations (such as babies, children, occupationally exposed workers, patients receiving healthcare), and populations with different lifestyles, diets, policies, and geographies.

- Human toxicological effect assessment for microplastics: advancing methods, tools and data collection.

- Epidemiological assessment for microplastics: seek to demonstrate causality of health outcomes resulting from exposures

- Continue to work towards a full human health risk assessment for microplastics.

10. Conclusions

This report sketches the contours of real-world mixtures of a very large number of microplastic contaminants in everyday human exposure scenarios.

The question whether humans are exposed to microplastics in their daily lives can be answered with a resounding, evidence-based yes. Microplastics are pervasive, abundant, invisible, chemical-mixture-carrying pollutants that are lurking in every corner of our lives, starting before birth.

Analytical chemistry has come a long way since the first microplastics were observed through microscope lenses or with the naked eye in the case of nurdles. As the methodologies, tools, and community of analysts advance and mature, the uncertainties in the current datasets will shrink. The picture of exposure this report paints for us leaves little doubt that our human existence is riddled with microplastic exposures indoors, outdoors, in infants and in old age, at home, work and play, and in the very medical institutions where people of all ages go to heal.

> *The question whether humans are exposed to a multitude of microplastics in their daily lives can be answered with a resounding, evidence-based yes.*

Microplastics exposure in humans can vary according to lifestyle, behaviour, age, geography, health status, and many other factors. The currently available data sets reviewed here suggest highly microplasticized living environments and food systems are a world-wide phenomenon.

Coupled with environmental microplastics measured concentrations from diffuse sources, exposure scenarios have been established and are likely to remain an issue. This and other reports [Sripada et al. 2022; Vercauteren et al. 2024; Nadarasan et al. 2025; Lamoree et al. 2025] highlight the need to further investigate the special case of high microplastics exposure scenarios in babies and children.

> *This report presents 'data with a cause', because knowledge is needed to act both individually and collectively. We cannot solve a problem we cannot see clearly.*

Plastic became a prevailing answer to most product design questions, setting up the products to become microplastics generators. The world population responded to massive, pervasive advertising campaigns by purchasing plastic in high volumes for the last hundred years, and thereby have co-financed the pollution of their living environment with microplastics, including the vast numbers of chemicals associated with them.

Plastic applications with huge potential to generate microplastic exposure may go unnoticed by almost everyone, apart from a relatively tiny group of experts operating in their niches. For instance, 3D printing is widely believed to be 'green', but is it?

The first scientific articles signalling microplastics pollution started appearing in the 1960s [Ryan 2015], making microplastics a contaminant class that can hardly be labeled as 'emerging' after 60 years of data collection. The studies cited here attest to how far we have come in our understanding of exposure, because of the methodological advances, continuous quality control improvements, and research efforts that have spanned decades. With thousands of microplastics articles, symposia, and stakeholder meetings behind us, we can conclude that the regulatory environment has a history of largely ignoring this contaminant class.

Policy and regulatory institutions addressing the public health risks of microplastics often rely on a weight of evidence approach (WOE) and 'environmental burden of disease' [EEA 2025], in which all data taken together either about the true health damage to the human population, effectiveness of any proposed mitigation measures, and rational policy options. The disadvantage of the WOE approach is the long waiting time until general microplastics study rigour and overall quality increase – something that every analyte class from pharmaceuticals to pesticides also continue to address.

On top of that, colossal data sets are required if we are ever to prove causality of diverse microplastic fractions and mixtures and adverse health outcomes at population level. This gives new meaning to the old English expression, ‘woe is waiting’. For air pollution particulates ($PM_{2.5}$), the WOE is strong due to the volume of exposure, toxicological and epidemiological data collected over multiple decades. Air pollution provides a template for what is needed when building a similarly strong WOE for microplastic risks.

The microplastic release data coupled with internal exposure data adds support to the ‘not safe’ hypothesis. The plausibility of such particulate exposure resulting in risk is real and consistent with the body of knowledge from particle and fibre toxicology and nanotoxicology.

The precautionary principle is warranted [World Commission on the Ethics of Scientific Knowledge and Technology (COMEST), 2005, p.14]. ‘Mitigating human exposure now is supported by the rationale that risk is scientifically plausible but uncertain, it is potentially serious, and could be considered ‘inequitable to present and future generations,’ [Leslie & Depledge 2020].

> *‘Mitigating human exposure now is motivated by the rationale that risk is scientifically plausible but uncertain, it is potentially serious, and could be considered ‘inequitable to present and future generations.’*

At the same time this requires filling scientific knowledge gaps related to microplastic risk to underpin the mitigation strategies that go beyond ‘low hanging fruit’ and budget neutral or quick techno fixes. The sense of urgency to team up and take action comes from both new microplastic release data coupled with the large existing body of evidence that chemical substances in microplastic materials and are associated with microplastics exposures [Trasande et al. 2025; Landrigan et al. 2025]. If government regulators remain unable to adequately address microplastic exposure and manufacturers continue with ‘business as usual’, individuals may already start regulating for themselves what they bring into their homes and workplaces.

This report presents data with a cause, because knowledge is needed to act. Hand in hand with individual action goes the (long-term) collective action to ensure systemic microplastic pollution is eradicated and doing no more harm.

Epilogue

Humans have a deep, complicated relationship with plastic. Fueled by both public and private investments, plastic products get made, advertised, bought, worn, lived in, walked on, worked on, communicated through, injected, played with, eaten with, chewed, sprayed, and of course, packaged in plastic. Plastic even takes us where we need to go in the form of cars and trucks, busses and bikes, trains, and planes. It all appears to be very normal: the accepted status quo.

We don't expect any of these goods to be bad for us. We buy them – and thereby 'vote' for them, complying with and feeding (financing) the product manufacturing machines. We want these products because we believe them to make our lives better. We do not want plastic applications to wreck havoc on our living environments or health.

The design and manufacturing decisions behind today's microplastic pollution have been made by people have never heard of, based on criteria that we have never seen. We were not consulted beforehand, but our laboratories can now measure the result of those actions.

This report shines a light on both known and lesser-known microplastic exposures of everyday plastic usage in our human reality and the disregard for microplastics shedding in product design, manufacturing, and regulatory circles. With such evidence we become more aware of the consequences of ubiquitous plastic use.

Such evidence compels us to rethink the world we want to live in, and question whether these products are generating comfort, convenience, and the quality of life that we truly want, and that we ultimately need. Is it worth living among all these plastic products if we know that plastic bites back?

Heather A. Leslie, Amsterdam, 2026

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Patent US6315213. Patent describes a method for weather modification by seeding clouds with polymers designed to absorb water. Once the polymers have absorbed water, they would be dehydrated to a powder.

Patent WO 2022/186970 and PCT/US 2022/016256. Method of Geoengineering to Reduce Solar Radiation. https://patentimages.storage.googleapis.com/63/47/4e/fc1b42eb4e5884/WO2022186970A1.pdf

Patent WO-2022186970-A1 and US-2022/0282068-A1. Proposes introducing porous, polymeric particles into the stratosphere to reflect solar radiation and cool the Earth. Each particle is described as having a continuous polymeric phase with dispersed pores, which are filled with air and optionally a hydrocolloid. https://portal.unifiedpatents.com/patents/patent/US-20220282068-

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