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FROM PACK TO PLATE

A Global Assessment of Micro- and Nanoplastics Migrating from Food Packaging into Food

2026

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earth action

Earth Action (EA) is a mission-driven research consultancy dedicated to advancing evidence-based action on plastic pollution and climate change. EA designs solutions and develops decision-ready knowledge that enables policymakers, businesses, and civil society to prioritise and accelerate effective environmental action.

EA consists of a team of scientists, data analysts, and change-makers, and is a member of the Environmental Footprint Centre (EF Centre).

Discover

Our objective

EA's objective is to create robust knowledge around plastic pollution and to develop data, methodologies, and tools that enable practical decision-making. We work at the interface between science, policy, and implementation, translating complex evidence into actionable insights.

EA's research agenda focuses on identifying blind spots in existing frameworks and pushing emerging topics "onto the agenda"–from plastic leakage and footprinting to exposure pathways and prevention levers across value chains.

Publications & reports

EA has developed a leading body of public research on plastic pollution, including landmark global assessments and thematic deep dives. Our work has contributed to shaping international discourse, regulatory debates, and corporate strategies.

Key publications include the first global assessment of primary microplastics in the oceans, as well as numerous reports addressing plastic leakage, footprinting, exposure pathways, and systemic prevention. A complete list of publications is available at www.e-a.earth.

Methodologies

EA is the developer of several widely used methodologies that underpin plastic footprinting and leakage assessments globally, including:

- Plastic Leak Project (PLP) – a methodology to quantify and reduce plastic leakage along value chains.
- Plastic Footprint Network (PFN) – a collaborative platform enabling organisations to measure, disclose, and reduce their plastic footprint.
- Plastic Overshoot Day (POD) – a science-based indicator illustrating when plastic waste generation exceeds global waste management capacity.

EA's methodologies are used by companies, governments, NGOs, and international organisations, and are regularly applied in policy support initiatives such as Swiss Plastic Action and Swiss Climate Action.

Data platforms

EA develops and maintains data platforms that support transparency and decision-making on plastic pollution:

- Plasteax – a global plastic leakage database providing country-level estimates of plastic waste generation, management, and leakage.
- Packaging Data Hub – a dedicated platform compiling packaging-specific data to support footprinting, exposure assessment, and prevention strategies.

These platforms enable users to move from high-level indicators to granular, decision-relevant insights.

Research & governance

Scientific research activities are conducted under EA For Impact, a Swiss non-profit association that ensures scientific independence, transparency, and open-access dissemination. EA For Impact is funded by Earth Action SA and philanthropic contributions, and leads collaborative research and multi-stakeholder initiatives.

Together, Earth Action SA and EA For Impact operate as a single ecosystem–combining applied consultancy expertise with independent research to address critical sustainability knowledge gaps and drive systemic environmental change.

“To what extent does food packaging contribute to micro- and nanoplastic exposure at the point of ingestion?”

Julien Boucher, PhD
Founder, Head of Research and co-CEO of Earth Action

In 2017, we published the first global assessment of primary microplastics entering the oceans. At the time, the central challenge was one of quantification: understanding where microplastics were coming from, in what quantities, and through which pathways they were leaking into the environment. That work helped shift the global conversation, moving microplastics from a marginal concern to a recognized component of the plastic pollution crisis.

Since then, the field has evolved rapidly. Research has expanded beyond environmental compartments, revealing the presence of plastic particles throughout ecosystems–and increasingly, within the human body itself. Micro- and nanoplastics have now been detected in air, water, food, blood, lungs, and placental tissue. The question is no longer whether plastics reach us, but how, through which pathways, and under what conditions exposure occurs. At Earth Action, our role has always been to explore the frontiers of emerging evidence, particularly where scientific knowledge, policy frameworks, and real-world decisions have not yet caught up with one another. As attention has progressively shifted from environmental leakage to human exposure, one pathway has remained surprisingly under-examined: food and beverage packaging (hereafter referred to as “food packaging”). Packaging is designed to be in direct, repeated contact with what we ingest, yet discussions around its safety have largely focused on chemical migration, leaving particulate exposure at the margins of both science and regulation.

The question that motivated this report is therefore simple, but fundamental: to what extent does food packaging contribute to micro- and nanoplastic exposure at the point of ingestion? This report focuses specifically on food and beverage packaging. Other food-contact materials – including food processing equipment, kitchen utensils, and tableware – are also recognised sources of plastic exposure but fall outside the scope of this assessment. Their omission reflects a deliberate boundary, not an assumption of lesser relevance. Addressing this question requires moving beyond isolated studies and fragmented evidence, toward a structured, comparative, and global perspective, one that can distinguish what dominates from what is marginal, and what is preventable from what is inherent.

This report represents a first step in that direction. By synthesising available data across packaging formats, use conditions, and generation mechanisms, it aims to clarify orders of magnitude, identify dominant drivers, and highlight where targeted action could meaningfully reduce exposure. It does not assess health risks, nor does it seek to draw conclusions beyond what the evidence can support. Its ambition is more foundational: to bring coherence to a rapidly expanding body of knowledge and to open a new, necessary chapter in the conversation on plastics, packaging, and human exposure.

As with earlier work, we see this assessment not as an endpoint, but as a starting point–for scientific dialogue, regulatory reflection, and innovation in packaging design. Exploring questions that are not yet fully framed, but already consequential, remains central to Earth Action’s mission. We hope this report contributes constructively to that ongoing effort.

– **Julien Boucher**

Why Packaging, Why Now

Svanika Balasubramanian, Board Chair, Innovation Alliance for a Global Plastics Treaty

The science on microplastics has advanced faster than most industries have been willing to acknowledge. For years, the dominant narrative focused on environmental pollution – plastic in oceans, rivers, ecosystems. What has been slower to enter mainstream conversation is the more personal dimension: the plastics that enter our bodies, through the food and beverages we consume every day.

For those of us working at the intersection of plastic pollution and corporate accountability, the question of food packaging has long felt like an uncomfortable blind spot. Brands have made significant commitments on recyclability, recycled content, and waste reduction. Far fewer have asked what their packaging is doing at the moment of consumption – when it is in direct contact with food, heated, handled, and ingested.

This report brings rigorous, independent evidence to that question for the first time at global scale. Its findings are both clarifying and actionable – and we believe they should change how brands and manufacturers think about packaging design.

Key Findings on Exposure and Risk

What emerges from this research is both sobering and clarifying. First, the scale of exposure is far from negligible. The report quantifies a consistent, everyday intake of microplastics from packaging into food systems - an exposure pathway that has largely gone unaccounted for in both public discourse and product design decisions. Even more concerning is the nature of these particles. A significant share falls below critical size thresholds, small enough to interact with biological systems in ways we are only beginning to understand. At this small scale, microplastics are not just inert fragments, they are capable of crossing biological barriers and interacting with tissues and cells.

Alongside microplastics, we are exposed to intentionally added substances (IAS) and non-intentionally added substances (NIAS) such as stabilizers, colorants, processing aids, and degradation byproducts. These substances do not exist in isolation. They migrate together, interact, and create exposure profiles that are far more complex than any single variable can capture.

Designing for Reduced Exposure

One of the most important contributions of this report is that it does not stop at diagnosis. It moves decisively into design and intervention.

Microplastic emissions are, to a meaningful extent, engineered design outcomes – a function of material choice, structural design, and real-world use conditions. From the way closures interact with containers, to how packaging responds to heat, friction, and repeated handling, to whether it is designed for single use or durability, these variables materially shape exposure.

By identifying the specific levers that drive emissions, this work provides a practical starting point for manufacturers and brands to rethink packaging – not just through the lens of sustainability or compliance, but through the lens of human exposure.

Building Solutions Across the Value Chain

At the Innovation Alliance for a Global Plastics Treaty, our focus has always been on building the systems and evidence base needed to move from awareness to action on plastic pollution, across the full value chain, from waste infrastructure to brand accountability.

We are proud to have commissioned this research as a foundational step*. We hope this report gives brands, manufacturers, policymakers, and researchers something they have not had before: a clear, comparable picture of where packaging-related plastic exposure originates, which formats and conditions drive it most, and where intervention is both feasible and proportionate.

The absence of comprehensive regulation today should not be read as permission to wait. The exposure is happening now, it is measurable, and much of it is preventable through design choices that are already within reach. We look forward to working with partners across the value chain to turn these findings into action.

**This research was independently conducted by Earth Action. The Innovation Alliance for a Global Plastics Treaty had no involvement in the analytical framework, data selection, or conclusions.*

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HEADLINE FINDINGS

Food packaging is one of the most direct and recurrent pathways of plastic exposure in everyday life. Unlike most environmental sources of micro- and nanoplastics (MNP), packaging is designed to be in continuous contact with products that are ingested, often under conditions of light exposure, mechanical handling, and thermal stress. This proximity means that even comparatively small emissions can translate into systematic human exposure, positioning packaging as a critical interface between plastics and the human body.

This section distils the report's main conclusions for rapid understanding, highlighting what matters most and at what order of magnitude. The evidence base and analytical steps supporting these findings are developed in Sections 3 and 4.

This report provides the first global synthesis of packaging-related MNP emissions across a fragmented literature

This assessment presents the first cross-format, global synthesis of micro- and nanoplastic (MNP) generation from food packaging. By harmonising evidence across packaging formats, mechanisms, and use conditions, it separates robust, decision-relevant signals from noise in a rapidly expanding and heterogeneous literature. Results are expressed at the level of orders of magnitude, rather than isolated experimental outcomes.

A limited set of packaging formats captures a large share of global food packaging use

The analysis covers seven representative food packaging formats, accounting for approximately 66% of global food packaging volumes placed on the market. These formats capture the dominant materials, designs, and use conditions driving packaging-related MNP emissions, providing a robust basis for global scaling and prioritisation.

Food packaging contributes MNP at the scale of ~10^3 tons per year globally and may range from billions to trillions of particles per year

Packaging-related transfer of MNP into food is estimated at approximately ~1,050 tons per year globally, with an uncertainty range of ~650–3,150 tons per year. While this contribution is orders of magnitude lower than global microplastic emissions from major diffuse sources (e.g. tyre wear or mismanaged plastic waste, which occur at the scale of millions of tons per year), it represents a non-negligible, direct emission flux into food. Crucially, particle count – not mass alone – is a critical exposure metric: smaller particles carry less mass but are more likely to cross biological barriers and interact with tissues. Mass-based estimates should therefore always be read alongside particle number and size distribution.

Packaging is not the dominant environmental source by mass, but it is a major ingestion pathway

Although MNP emissions from packaging into food is not a leading contributor to MNP emissions by mass – when compared to major sources such as tyre wear and environmental releases – it represents a major human ingestion pathway, because MNPs are directly transferred to food and beverages at the point of consumption, with minimal environmental dilution or dispersion.

(i) Per-capita intake is on the order of ~130 mg/person/year on average, increases to several hundred milligrams under high-use scenarios, and may exceed ~1 g/person/year for very high-use consumers, corresponding to hundreds of millions to billions of particles annually. Crucially, particle count – not mass alone – is a critical exposure metric: smaller particles carry less mass but are more likely to cross biological barriers and interact with tissues. Mass-based estimates should therefore always be read alongside particle number and size distribution.

(ii) A small number of packaging formats dominate exposure, driven by both emission intensity and consumption volume, with PET bottles alone contributing approximately one-third, followed by rigid PET and flexible PE packaging. This finding should be interpreted in light of uneven study coverage, whereby well-studied formats (PET bottles, rigid PET, flexible PE) may appear dominant due to greater data availability.

(iii) Both use conditions and material properties play a critical role in driving MNP emissions. Use-conditions such as irradiation, mechanical handling, and thermal exposure influence emission levels, while intrinsic properties determine the material's propensity to form microplastics[1]. Their interaction is critical, as the same use-conditions can yield orders-of-magnitude differences across materials.

(iv) Packaging-related MNP exposure is systemic, with particle ingestion implying co-exposure to tens of milligrams of associated intentionally added substances (IAS) – such as plasticizers, stabilizers, or colorants deliberately incorporated during manufacturing – and non-intentionally added substances (NIAS) – degradation products, impurities, or reaction by-products that arise unintentionally. Both categories include compounds of recognized toxicological concern, some of which are already subject to regulatory scrutiny, though significant gaps remain, particularly for NIAS mixtures. This co-exposure occurs at levels of comparable order of magnitude to the MNPs themselves.

(v) Large variability across scenarios of exposure reveals clear prevention potential, as emissions are concentrated, predictable, and in part avoidable through targeted design and supply-chain interventions.

(vi) Packaging-related MNP exposure is dominated by particles small enough to interact with biological systems – the majority fall below 150 µm, the threshold associated with intestinal crossing. Nanoplastics (<1 µm), though harder to detect, are of greatest concern: they can enter circulation, interact with cells, and may dominate particle counts even when their contribution to total mass appears modest.

FROM PACK TO PLATE: THE INVISIBLE MIGRATION OF PLASTICS INTO OUR DIET

While often viewed as inert, food packaging dynamically degrades under normal conditions, releasing micro- and nanoplastics directly into food.

DOMINANT DRIVERS OF RELEASE

Irradiation is the primary driver
Sunlight and UV exposure increase particle release by up to two orders of magnitude

Mechanical stress and abrasion
Repeated opening and closing (caps especially) and stacking friction generate significant micro-fragments.

Thermal stress amplification
Microwaving and hot-filling weaken the polymer matrix, accelerating the detachment of particles.

THE SCALE OF INGESTION

Total global MNP migration into food from all packaging formats

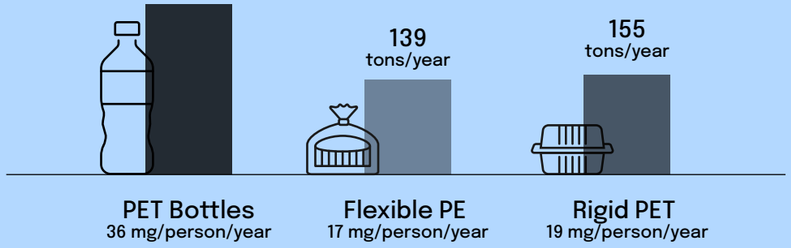
~1,050 tons
consumed/year

Average individual intake equivalent to hundreds of millions of particles annually

~130mg
per person/year

Unlike environmental leaks, packaging MNPs enter food directly with zero dilution.

A direct ingestion pathway



Annual per-capita ingestion from food packaging reaches the order of ~10² mg/person/year
When scaled to realistic consumption patterns, packaging-related MNP exposure corresponds to an estimated ~130 mg per person per year when extrapolated to full market coverage (range: ~80–400 mg/person/year). This intake corresponds to hundreds of millions to several billion particles per person per year, depending on particle size assumptions, highlighting that particle number—not mass alone—is also a critical exposure metric. Smaller particles carry less mass but pose greater biological risk: they are more likely to cross tissue barriers, enter circulation, and interact with cells. A mass-only lens systematically underestimates the health relevance of nanoplastic-dominated exposures.

Packaging-related MNP exposure is of comparable order of magnitude to chemical exposure from packaging
Although direct risk comparison is constrained by limited toxicological data—particularly for nanoplastics—the orders of magnitude involved are comparable to those of intentionally added substances (IAS) and non-intentionally added substances (NIAS) migrating from packaging. Order-of-magnitude evidence suggests that particle ingestion may imply concomitant exposure to tens of milligrams of associated IAS/NIAS, indicating that MNP represent a systemic and insufficiently characterised component of overall packaging-related exposure.

A small number of packaging formats dominate estimated exposure
Estimated exposure is highly concentrated. PET (polyethylene terephthalate) bottles alone account for roughly one-third of total packaging-related MNP exposure, followed by rigid PET food packaging and flexible PE (polyethylene) packaging, reflecting the combined effects of high market volumes and sensitivity to dominant generation mechanisms. Multilayer packaging consistently contributes only marginally. It should be noted that this finding may partly reflect the uneven distribution of existing studies, with well-studied formats (PET bottles, rigid PET, flexible PE) appearing dominant due to greater data availability.

A limited number of use conditions dominate emissions across formats
Across all formats, emissions are driven by a small set of high-leverage use conditions. Irradiation and light exposure emerge as the dominant amplifier, increasing emissions by up to one to two orders of magnitude where applicable. Repeated mechanical interaction (e.g. opening–closing, friction) and thermal stress further contribute to cumulative emissions.

Large variability across scenarios indicates substantial room for exposure reduction
The large spread between low-, medium-, and high-emission scenarios reflects not only uncertainty, but also significant potential for exposure reduction. Because emissions are concentrated in specific formats, mechanisms, and foreseeable use conditions, targeted interventions in packaging design, supply-chain management, and high-stress use scenarios can reduce exposure without requiring blanket material substitution.

Packaging-related MNP exposure is dominated by particles small enough to interact with biological systems.
Particle size is a key determinant of biological relevance: particles larger than ~150 µm are mostly excreted, while smaller particles can interact with tissues or cells. In this assessment, the majority of MNP from food packaging fall below this threshold, meaning that exposure occurs in a biologically relevant size range. Although direct health impacts remain uncertain, reducing the release of small particles represents a clear and actionable leverage point to lower potential exposure.

(1)

SCOPE & RESEARCH QUESTIONS

Over recent decades, plastic has become the dominant packaging material across many sectors. This expansion has been driven less by intrinsic suitability than by economic and systemic factors, including low production costs, versatility, light weight, and compatibility with large-scale, globalised supply chains. As a result, plastic packaging is now ubiquitous in everyday life.

Through this widespread use, packaging has come to play a central role in modern societies not only by shaping how products are transported, stored, and distributed, but by forming the final material boundary between products and the human body. For food and beverages (hereafter referred to as “food” throughout this report), packaging constitutes the surface through which substances destined for ingestion must pass or reside. It is therefore one of the most intimate and continuous material interfaces in everyday life, repeatedly touched, opened, heated, squeezed, and brought into close contact with mouths, hands, and skin. This scale and proximity fundamentally shape routine human exposure to packaging materials.

Packaging safety frameworks have historically focused on a limited set of chemical hazards, relying largely on substance-by-substance risk assessment and migration testing. While these approaches have enabled the regulation of some known substances, they remain fundamentally incomplete. Many components of packaging materials – including non-intentionally added substances (NIAS), degradation products, and complex mixtures – are poorly characterised or entirely unassessed. In this context, the absence of regulatory restriction cannot be interpreted as evidence of safety.

At the particulate level, the assumption that packaging functions as an inert barrier is even less defensible. Plastics are dynamic materials that age, abrade, and degrade under normal conditions of use. Mechanical stress, heat, irradiation, and repeated handling can generate micro- and nanoplastics throughout the packaging life cycle, including during consumer use. These processes make the transfer of packaging-derived particles into food not an exceptional event, but a plausible and foreseeable outcome of everyday interactions with packaged products.

At the same time, micro- and nanoplastics are now detected across environmental compartments and within the human body. Their presence confirms that exposure pathways exist and that assumptions of inertness are flawed. While the health implications of this exposure are not yet fully quantified, plastics are known to contain complex chemical mixtures, including substances with endocrine-disrupting, carcinogenic, or otherwise hazardous properties. Micro- and nanoplastics may therefore act not only as particles, but also as vectors of chemical exposure, reinforcing concerns already raised by gaps in chemical regulation.

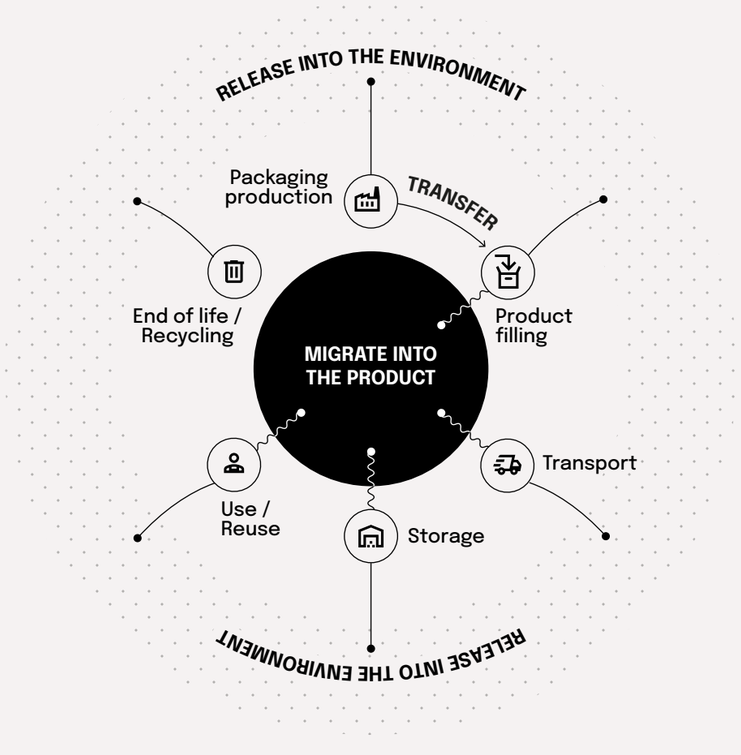


Figure 1
Packaging-related micro- and nanoplastic (MNP) emission pathways across the life cycle, distinguishing environmental leakage from direct migration into food products. This figure illustrates the main stages of the packaging life cycle at which micro- and nanoplastics may be generated and released, either into the environment or directly into the packaged product. While environmental leakage pathways have been increasingly quantified (e.g. Earth Action plastics leakage assessments),[2] direct migration into products intended for ingestion or direct human contact remains poorly characterised and is the focus of this report.

It is well established that plastic packaging contributes to microplastic pollution in the environment through multiple leakage pathways across its life cycle. These include losses during primary plastic production, such as pellet and powder release; the loss or mismanagement of packaging during use, for example through littering, leading to fragmentation into secondary microplastics; and emissions at end-of-life during waste handling and treatment processes, including recycling, disposal, or other inadequately managed pathways. Quantitative estimates of these environmentally oriented leakage sources have been developed in several studies, including recent assessments such as the Earth Action (EA) Plastics Leakage Barometer, which report substantial releases from these pathways.

By contrast, the fraction of micro- and nanoplastics released **directly into products intended for ingestion or direct contact with the human body**, such as food, has to date not been systematically quantified. This distinction between environmental leakage and direct migration into products is illustrated in Figure 1. This represents a critical gap in current assessments, as such emissions are likely to be particularly important from an exposure perspective. In this report, a distinction is therefore made between *leakage into the environment* and *migration into the product*, with a specific focus on food-contact packaging. Throughout the report, the term *micro-* and *nanoplastics (MNP)* is used to reflect the fact that packaging-related releases often occur at very small particle sizes, including sub-micron and near-molecular scales, as will be discussed in later sections.

Despite a rapidly growing scientific literature and increasing visibility of microplastics in public debate and media coverage, there is still no compelling, integrated assessment that clarifies what matters most in practice. Existing studies document the presence of micro- and nanoplastics in food and their potential release from packaging materials, but they rarely provide a coherent picture of relative importance, orders of magnitude, or priorities across packaging types, use conditions, and exposure pathways. As a result, it remains difficult to determine which sources are most relevant, how they compare to other known contributors to microplastic exposure, and where preventive efforts should be focused.

This lack of synthesis also limits the development of benchmarks and reference points needed to guide policy action, regulatory priorities, and further research.

Moreover, considerations related to micro- and nanoplastic emissions are still rarely accounted for in packaging design and use practices, reflecting both data gaps and limited awareness of these exposure pathways. This report is intended as a step toward addressing these gaps by improving the understanding and consideration of micro- and nanoplastic emissions associated with food packaging under realistic conditions of use. More specifically, it aims to address the following research questions:

Question 1: What mechanisms drive the migration of micro- and nanoplastics from food packaging into food?
This question examines the mechanical, physico-chemical, and use-related processes that generate and transfer micro- and nanoplastics under normal conditions of use, including mechanical abrasion, thermal degradation, and material ageing. It also considers how different mechanisms produce particles across distinct size ranges and how these processes may coincide with, or contribute to, the release of intentionally added substances (IAS) and non-intentionally added substances (NIAS).

Question 2: Which packaging formats, materials, and use conditions contribute most to micro- and nanoplastic release?
With a focus on food, this question examines how packaging type, material properties, and typical consumer uses (e.g. heating, mechanical stress, storage duration) influence the release of MNP.

Question 3: How much micro- and nanoplastic is released from food packaging, globally and per person, and how does this compare to other exposure sources?
This question assesses whether emissions from food packaging are substantial relative to other microplastic sources, including non-food-related packaging emissions.

Question 4: Are micro- and nanoplastics as concerning for health as packaging chemicals (IAS and NIAS)?
This question explores the relative significance of particulate versus chemical exposures from packaging, considering current evidence on toxicity, exposure pathways, and uncertainties.

(2)

MAIN FINDINGS & IMPLICATIONS

2.1 Question 1: What mechanisms drive the migration of micro- and nanoplastics from food packaging into food? 12

2.2 Question 2: Which packaging formats, materials, and use conditions contribute most to micro- and nanoplastic release? 14

2.3 Question 3: How much micro- and nanoplastic is released from food packaging, globally and per person, and how does this compare to other exposure sources? 15

2.4 Question 4: Are micro- and nanoplastics as concerning for health as packaging chemicals (IAS and NIAS)? 16

2.5 Recommendations by stakeholder and limitations 17

(2) MAIN FINDINGS & IMPLICATIONS

(2.1) Question 1: What mechanisms drive the migration of micro- and nanoplastics from food packaging into food?

Understanding how food packaging contributes to micro- and nano-plastic (MNP) exposure requires clarifying both where particles may ultimately reach the consumer and, more importantly, how they are generated in the first place. While several exposure pathways can be identified–such as migration into the product or direct ingestion from packaging components–the central concern of this report is the total transfer of packaging-derived material to the consumer, regardless of the specific route.

In practice, the key determinant of MNP exposure is the set of mechanisms by which particles are generated. These mechanisms govern when, how, and in what form particles are released from packaging materials. This section therefore focuses on the underlying generation processes, situating them within the relevant stages of the packaging life cycle.

Life-cycle stages relevant for particle generation and transfer

Micro- and nano-plastic generation associated with food packaging may occur at different stages of the packaging life cycle, but not all stages are equally relevant for direct human exposure. In this report, attention is restricted to stages that can lead to **direct transfer into the packaged product or to the consumer during normal use**, as illustrated in Figure 1.

(i) Packaging production and handling prior to product filling (inherited micro- and nanoplastics). Particle generation may occur during polymer synthesis, packaging manufacturing, and industrial handling before the product is introduced into the packaging. Micro- and nanoplastics formed at these early stages may remain embedded within the packaging material and subsequently be released after filling. Throughout this report, such particles are referred to as inherited micro- and nanoplastics, as they are generated before any contact between the packaging and the food product and are therefore entirely outside consumer control. These inherited particles may already be present at the time of filling and can later migrate into the product during subsequent stages of the life cycle.

(ii) Post-filling transport, distribution, storage, and consumer use of the packaging-product system. Once the product has been introduced into the packaging, particle generation and transfer may occur during transport, distribution, and storage, prior to any consumer interaction. During this pre-consumer phase, the coupled packaging-product system is exposed to mechanical stresses, temperature variations, and light, which can promote the migration of previously generated particles as well as additional particle release. Following this stage, further particle generation and transfer may occur during consumer use, including opening and closing, routine handling, and continued exposure to environmental conditions. Across both phases, these processes are typically cumulative, leading to progressive increases in micro- and nanoplastic transfer rather than isolated emission events.

Packaging **end-of-life stages**, such as waste handling, recycling, or disposal, are recognised sources of environmental microplastic pollution. However, as they do not contribute directly to ingestion-related exposure from packaged food, they are considered outside the scope of this section and are addressed in section 3.11 for contextual comparison.

Mechanisms – How are micro- and nanoplastics generated?

To understand how particles are generated, it is first necessary to clarify what is meant by plastic as a material. Food packaging plastics are predominantly **thermoplastics**, such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), or polystyrene (PS). In these materials, polymer chains are covalently bonded along the backbone but are held together as a material primarily through physical entanglement and weak intermolecular interactions. By contrast, **thermoset polymers** form covalently cross-linked networks in which polymer chains are chemically bound to each other, resulting in much greater structural stability.

This distinction is important, as the non-cross-linked nature of thermoplastic packaging materials constitutes a **structural vulnerability** with respect to particle release. Because cohesion relies on reversible and relatively weak interactions, the polymer matrix can be destabilised by modest environmental or use-related stresses, such as temperature changes, exposure to light, contact with specific food chemistries, or mechanical abrasion. These perturbations may facilitate the release of additives, **low-molecular-weight polymer fractions, loosely associated polymer fragments,** and other **poorly bound polymer chains,** spanning a wide range of particle sizes.

In addition, packaging plastics typically contain a variety of **additives** – including plasticisers, stabilisers, antioxidants, colorants, and processing aids – that are not covalently bound to the polymer backbone. These substances, along with low molecular weight polymer fractions, are therefore sensitive to changes in temperature, acidity, hydrophobicity, irradiation, and mechanical stress, which can disrupt local equilibria within the material and promote release.

Against this background, the generation of micro- and nanoplastics from packaging materials is governed by **mechanical, physico-chemical,** and **combined mechanisms,** which may act independently or in combination over time, as illustrated in Figure 2.

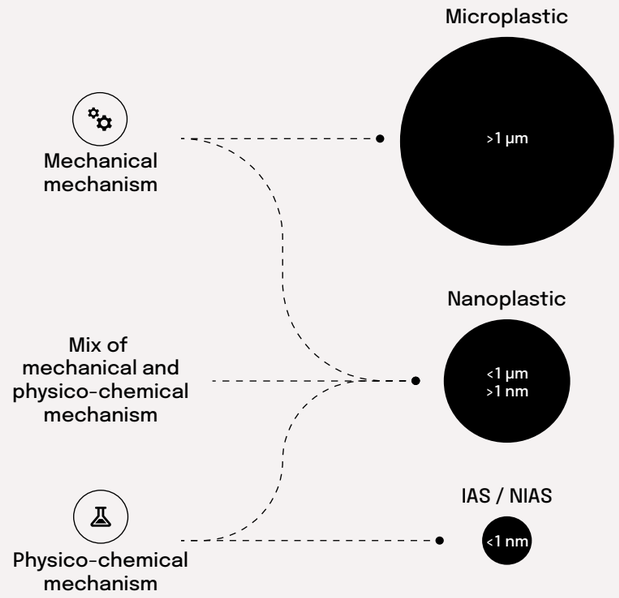


Figure 2
Mechanisms of particle generation from plastic packaging and associated size continuum. This figure illustrates the main mechanisms by which plastic packaging can release material into products, ranging from mechanical detachment to physico-chemical processes within the polymer matrix. Mechanical stresses primarily generate larger microplastic fragments (typically > 1 µm), while physico-chemical processes involve the diffusion or release of small molecules and poorly bound polymer fragments, including intentionally added substances (IAS), non-intentionally added substances (NIAS), and nanoplastics (< 1 µm). In practice, mixed mechanisms are common, reflecting the combined action of mechanical stress and chemical ageing, and resulting in a continuum of particle sizes rather than discrete categories.[3]

i. Mechanical mechanisms

Mechanical mechanisms involve the physical detachment of fragments from the packaging surface under stresses such as opening and closing, friction between components, cutting, deformation, squeezing, or vibration during transport and handling. These processes typically generate particles in the microplastic size range.

ii. Physico-chemical mechanisms

Physico-chemical mechanisms involve degradation of the polymer matrix through processes such as hydrolysis, oxidation, and photo-oxidation. These processes weaken polymer chains and material structure, particularly under the influence of heat, moisture, UV or visible light, and contact with specific products. Physico-chemical degradation is closely linked to the release of intentionally added substances (IAS) and non-intentionally added substances (NIAS), but may also lead to the formation and release of very small plastic fragments, including nanoplastics.

In practice, **mechanical and physico-chemical mechanisms often act together.** Progressive chemical ageing can make packaging surfaces more brittle over time, even in the absence of visible damage. Under such conditions, relatively minor triggers–such as shaking, internal pressure from hot liquids, or routine contact with the product–may lead to the release of particles that are much smaller than those generated by purely mechanical abrasion. Because many of these processes occur at or near the **material surface,** surface properties and surface ageing play a disproportionate role in particle generation compared to bulk material properties.

From a regulatory perspective, microplastics are often defined within a specific particle size range. However, packaging-related releases span a **continuum from visible fragments to sub-micron and molecular-scale material,** or material **approaching molecular dimensions.** For this reason, this report uses the term *micro-* and *nanoplastics (MNP)* to explicitly cover this broader size spectrum, reflecting both the diversity of generation mechanisms and the range of materials potentially transferred to the consumer. This continuum also contributes to **analytical challenges**, as detection and quantification methods differ substantially across size ranges.

Together, these considerations explain why MNP generation from packaging is not random, but systematically linked to **material properties, formulation, design features, product compatibility, and conditions of use,** with different mechanisms dominating under different scenarios.

KEY TAKEAWAY

Micro- and nanoplastic generation from food packaging is driven by a small number of identifiable mechanical and physico-chemical mechanisms that act cumulatively during normal use. This means exposure is predictable and structured, rather than accidental, making prevention through design and use conditions technically feasible.

(2) MAIN FINDINGS & IMPLICATIONS

(2.2) Question 2: Which packaging formats, materials, and use conditions contribute most to micro- and nanoplastic release?

This assessment shows that micro- and nanoplastic (MNP) emissions from food-contact packaging are highly unevenly distributed across packaging formats, materials, and use conditions. Rather than being diffuse, emissions are concentrated in a limited number of packaging-use combinations, driven by the interaction between packaging design, material properties, and exposure to specific stressors during use.

	MNP emissions per volume of product (µg/L)	MNP emissions per weight of packaging (µg/g)	Global emissions (t/year)	MNP emissions per person (mg/person/year)
PET bottles (PET)	305 (275 – 520)	15 (14 – 26)	292 (263 – 498)	36 (33 – 62)
Flexible packaging (PE)	78 (5 – 456)	16 (1 – 91)	139 (9 – 812)	17 (1 – 101)
Rigid food packaging (PET)	760 (738 – 844)	25 (25 – 28)	155 (151 – 173)	19 (19 – 22)
Rigid food packaging (PP)	719 (67 – 4022)	18 (2 – 101)	101 (9 – 567)	13 (1 – 71)
Rigid food packaging (PS)	68 (1 – 442)	5 (0.07 – 29)	3 (0.05 – 20)	0.4 (0.006 – 3)
Multi-layer containers (PE lining)	3 (0.9 – 10)	0.6 (0.2 – 2)	1.0 (0.3 – 4)	0.1 (0.04 – 0.4)
Multi-layer bottles (PE)	2 (0.03 – 13)	0.05 (9.14e-04 – 0.4)	0.04 (7.00e-04 – 0.3)	0.004 (8.75e-05 – 0.04)

Figure 3
Heatmap showing MNP emissions for the packaging studied under a global-use scenario, representing a mix of low, medium, and high use conditions. Four key emission indicators are presented: MNP emissions per volume of product (µg/L), per weight of packaging (µg/g), total global emissions (t/year), and per capita emissions (mg/person/year). Values are shown as averages with uncertainty ranges in parentheses (min–max), reflecting variability in the underlying data rather than differences between scenarios. Colour intensity is scaled independently for each indicator, so that only comparisons across packaging types within the same indicator are meaningful.

Packaging formats: dominant contributors

Across the analysed case studies, rigid food packaging made of PET and PP shows high emission levels, both per unit of packaged content and per weight of packaging material. PET bottles also exhibit elevated emission levels under the considered use conditions.

At the aggregate level, PET bottles, flexible PE packaging, and rigid PP food containers account for a large share of packaging-related MNP emissions into food, reflecting their widespread use across applications.

By contrast, **multilayer packaging formats with thin plastic liners** consistently show low emission levels across documented use conditions, reflecting limited material exposure at the food–material interface and fewer high-stress interactions.

Material properties and use conditions as interacting drivers of emissions

While polymer identity influences material behaviour, it is not a reliable predictor of MNP emissions on its own. Differences within the same polymer category are often comparable to, or greater than, differences between polymers, reflecting the importance of packaging geometry, wall thickness, interfaces (e.g. caps and closures), material formulation, and compatibility with the packaged product. Crucially, emissions are driven by the interaction between these intrinsic material properties and use-related conditions. Across packaging formats, factors such as irradiation and light exposure (during transport, storage, retail display, or use), repeated mechanical interactions (e.g. opening/closing, friction at interfaces, handling), thermal stress (including hot contents or microwave heating), and product-packaging interactions (notably with acidic or fatty foods) act on the material and govern both the generation and transfer of particles.

These stressors act cumulatively over time, meaning that emissions are shaped by repeated and prolonged use, rather than by first-use conditions alone.

Role of inherited MNP

In addition to use-related generation, a fraction of MNP is already present prior to food contact, reflecting upstream and production-related sources (“inherited MNP”). This inherited contribution establishes a baseline level of particles across packaging formats. However, for the applications identified as main contributors, use-related mechanisms dominate total emissions, and inherited MNP represent a secondary component relative to stresses occurring during the use phase.

KEY TAKEAWAY

Differences in MNP release between packaging formats are substantial but highly context-dependent, with design features and use conditions often outweighing polymer type alone. This implies that ranking “good” and “bad” materials in isolation is insufficient; exposure reduction depends on format-specific design and handling choices.

Across packaging formats, exposure to irradiation and repeated mechanical stress dominate micro- and nanoplastic generation, often by one to two orders of magnitude compared to other mechanisms. This matters because a small number of stressors explain most exposure, allowing mitigation efforts to focus on use conditions rather than material substitution alone.

(2) MAIN FINDINGS & IMPLICATIONS

(2.3) Question 3: How much micro- and nanoplastic is released from food packaging, globally and per person, and how does this compare to other exposure sources?

Global emission perspective

When scaled from format-level emission intensities to market volumes, packaging-related micro- and nanoplastic (MNP) emissions can be expressed as **annual global emission fluxes.** Based on the packaging formats covered in this assessment (approximately **66% of global food packaging volumes**), total environmental emissions into food are estimated at a **central value of ~692 t/year,** with an **uncertainty range of 433–2,074 t/year.** Linear extrapolation to full market coverage yields an estimated **~1,050 t/year**, with an associated range of **657–3,146 t/year.**

At the global scale, these emissions are **orders of magnitude lower** than those attributed to major diffuse sources of microplastics, such as tyre wear, synthetic textiles, paints, and mismanaged plastic waste, which dominate environmental releases by mass.

Per-capita exposure perspective

Translating global emission fluxes into **per-capita intake estimates** provides a complementary perspective that is more directly relevant to individual exposure. When scaled to realistic consumption patterns, packaging-related MNP emissions correspond to an estimated ~**130 mg/person/year** when extrapolated to full market coverage.

This intake corresponds to hundreds of millions to several billion particles per person per year, depending on assumed particle size. This highlights that, at the individual level, particle number – beyond mass alone – is a critical metric for interpreting potential exposure relevance, particularly given the predominance of small particle sizes in packaging-related emissions.

Comparison with other sources

Comparing packaging-related emissions to other major sources of microplastics requires going beyond mass-based metrics. Large environmental sources are characterised by a **limited number of emission processes,** each associated with very high material throughput and broad environmental dispersion. Their contribution to human exposure **typically occurs indirectly,** following dilution and transport through the environment.

By contrast, food packaging represents a **very large number of individual emission sources,** corresponding to **tens of billions of packaging units placed on the market each year.** Although emissions per unit are relatively low, the combination of **high source multiplicity, repeated emission events, and direct contact with food** results in a cumulative exposure profile that is not captured by global mass fluxes alone.

Taken together, these perspectives explain why packaging-related MNP emissions – despite representing a minor share of total environmental microplastic release – are **relevant in the context of human exposure,** particularly due to direct ingestion. The comparison underscores that **low per-source emissions multiplied by a very large number of sources and repeated use events** can translate into meaningful exposure at population and individual levels.

KEY TAKEAWAY

Even though packaging-related MNP emissions are small compared with other major environmental sources, the sheer number of packaging units and their direct contact with food make them an important contributor to human exposure. Reducing exposure requires strategies that target the cumulative impact of many small sources, such as improving packaging design, and optimizing handling practices.

(2) MAIN FINDINGS & IMPLICATIONS

(2.4) Question 4: Are micro- and nanoplastics as concerning for health as packaging chemicals (IAS and NIAS)?

Assessing the potential health relevance of micro- and nanoplastics (MNP) remains scientifically challenging. Robust dose–response relationships are not available, particularly for nanoplastics, and existing studies span a wide range of particle characteristics and experimental conditions. These limitations preclude quantitative health risk assessment or attribution of disease outcomes. Accordingly, this report does not estimate health risks, but instead evaluates whether the exposure patterns identified are potentially meaningful within the broader context of packaging-related health concerns.

Food-contact plastics contain complex chemical mixtures. Intentionally added substances (IAS), including plasticisers, colorants, and stabilisers, are added by design. Non-intentionally added substances (NIAS) arise as byproducts of manufacturing or degradation. Many of these compounds have known endocrine-disrupting or carcinogenic properties and are already a recognised concern in food safety regulation, though significant gaps remain, particularly for NIAS mixtures. It is against this backdrop that packaging-related MNP exposure must be understood.

A central observation is that MNP exposure cannot be meaningfully separated from chemical exposure. Food-contact plastics contain complex mixtures of intentionally added substances (IAS) and non-intentionally added substances (NIAS), and MNP are generated directly from these same materials under real-world use conditions. Particle and chemical exposures are therefore intrinsically coupled rather than independent. Moreover, MNP are not inert entities: they may carry or co-occur with additives and degradation products, and may locally influence exposure at biological interfaces such as the gastrointestinal tract. In this sense, MNP represent a particle-mediated extension of an already recognised chemical exposure landscape, rather than a wholly distinct hazard category.

From an exposure perspective, packaging-related MNP challenge conventional mass-based assessment paradigms. While total mass emissions from packaging are modest, estimated dietary intake is on the order of ~130 mg/person/year on average and increases to several hundred milligrams–and potentially up to ~1 g/person/year–under high-use conditions. This mass corresponds to hundreds of millions to several billion particles annually, depending on particle size assumptions, underscoring the importance of particle number, size distribution, and surface properties as critical exposure descriptors.

Experimental evidence, although not directly translatable to human health risk, indicates that plastic particles are biologically active rather than inert. Repeated oral exposure in animal models has been associated with effects on gut microbiota, immune responses, and metabolic regulation at concentrations within orders of magnitude of estimated dietary exposure. Notably, these endpoints overlap with those reported for certain IAS and NIAS, suggesting convergence rather than independence of potential impact pathways.

From a governance perspective, the relevance of packaging-related MNP exposure does not hinge on definitive hazard proof, but on the convergence of direct and repeated dietary exposure, plausible particle-specific interaction mechanisms, and the known chemical complexity of plastic materials already recognised as a regulatory concern. In this context, uncertainty should not be interpreted as evidence of safety. Rather, the principal implication is recognition of a non-negligible, widespread, and difficult-to-control exposure pathway

KEY TAKEAWAY

While this assessment does not quantify health risks, packaging-related micro- and nanoplastic exposure occurs at the final interface before ingestion and overlaps with known chemical exposure pathways. This positions packaging as a relevant leverage point for precautionary action, even in the absence of particle-specific toxicological thresholds.

(2) MAIN FINDINGS & IMPLICATIONS

(2.5) Recommendations for stakeholder and limitations

Implications and recommendations for consumers

While meaningful exposure reduction depends primarily on upstream action, some precautionary choices can reduce avoidable exposure where alternatives are available.

THESE RECOMMENDATIONS FOCUS ON REDUCING EXPOSURE TO MNPS AND DO NOT EVALUATE OTHER SUSTAINABILITY INDICATORS SUCH AS CLIMATE CHANGE, WHICH WOULD REQUIRE A MORE HOLISTIC ASSESSMENT.

Light
Avoid prolonged exposure of plastic packaging –particularly PET bottles – to **sunlight and high temperatures,** including storage in vehicles or direct sunlight.

Wear & tear
Limit unnecessary **repeated opening-closing cycles** and avoid reusing single-use packaging beyond its intended purpose. Abrasion increases with age and scrubbing.

Heat
Where possible, **avoid heating food or beverages in plastic packaging;** transfer contents to e.g. glass or ceramic before heating.

Choice
Prefer **inert packaging materials** (e.g. glass, uncoated metal) where feasible, while recognising that some paper – and metal – based packaging contains plastic coatings.

These actions may reduce exposure at the margin but **cannot eliminate it,** as packaging may already have been exposed to stress during production, transport, or retail storage. Responsibility for meaningful exposure reduction therefore lies primarily with **packaging design, supply-chain management, and regulation,** rather than with individual consumers.

Implications and recommendations for designers, manufacturers, and supply-chain actors

The most effective intervention points lie upstream of consumer use, where exposure can be reduced systematically:

Protect from UV
Minimise exposure to sunlight and UV radiation during transport, storage, and retail display; this represents the single highest-impact preventive measure identified.

Optimise packaging design
particularly at high-stress interfaces such as caps, closures, and seals. Prioritise designs that deliver larger volumes of product per unit mass of packaging, thereby reducing emissions when expressed per unit of consumed product.

Realistic testing
Explicitly account for foreseeable use scenarios (e.g. repeated handling, heating, long storage durations) during packaging design, testing, and specification.

Targeting these factors offers high leverage for exposure reduction without relying on changes in consumer behaviour.

Implications and recommendations for assessment frameworks and policymakers

The findings support the integration of MNP emissions alongside chemical migration in food packaging assessment frameworks:

1

Scenario-based evaluation of realistic and foreseeable use conditions, rather than reliance on a single “normal-use” assumption, is essential to capture exposure ranges.

Require that packaging approval processes test realistic use conditions – including repeated handling, extended storage, and UV exposure – not just first-use or laboratory conditions.

2

Assessment approaches should reflect that **material type alone is not a sufficient predictor of emissions**; packaging design, interfaces, and use conditions are equally critical.

Revise food-contact material regulations to assess packaging systems as a whole, including geometry, closures, and use conditions, not polymer identity alone.

3

Although MNP emissions from packaging into food is not a leading contributor to MNP emissions by mass – when compared to major sources such as tyre wear and environmental releases - it represents a direct, widespread, and largely controllable exposure pathway, **making it a pragmatic focus for proportionate policy action.**

Establish MNP emission limits or disclosure requirements for high-volume food packaging formats – starting with PET bottles, rigid PET, and flexible PE, which together account for the majority of estimated exposure.

Reducing avoidable exposure through design standards, use guidance, and improved transparency does not require waiting for definitive health outcomes and is consistent with precautionary principles.

Limitations and research needs

Several limitations should be considered when interpreting these results. The underlying literature exhibits substantial variability in experimental methods, analytical techniques, detection limits, and reported particle size ranges, particularly for nanoplastics. Absolute concentration values therefore remain subject to **data-related uncertainty.**

Available data cover only a subset of packaging designs and are largely based on controlled laboratory conditions. **Pre-retail stages** – including transport, storage, and retail display – remain under-characterised despite their apparent importance for irradiation-driven ageing. Product-related effects, such as the influence of acidity, fat content, or carbonation, remain incompletely quantified.

The scenario-based approach adopted here is intended to capture **plausible ranges rather than precise exposure distributions.** While this limits precision, the **relative ranking of dominant mechanisms and intervention priorities appears robust** across studies.

Further research would benefit from harmonised analytical methods, improved characterisation of nanoplastics, and systematic investigation of pre-retail exposure conditions and product-packaging interactions.

(3)

APPROACH AND DETAILED RESULTS BY CATEGORY

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What this assessment adds

Existing studies have documented MNP release from food packaging – but in isolation, using inconsistent methods, with no way to compare formats or understand what matters most.

This report does three things no prior work has done together: it harmonises the available experimental evidence into a single comparable framework; translates findings into realistic use scenarios reflecting what consumers actually do; and scales results to global and per-capita levels across the formats that make up the majority of food packaging worldwide.

The result is the first cross-format, globally scaled picture of packaging-related MNP exposure – designed not just to describe the problem, but to show where action is most warranted.

Before this assessment

Isolated studies measuring MNP release from single packaging types, under controlled lab conditions, using inconsistent metrics (particle counts, mass, surface area) with no common basis for comparison.

No systematic distinction between what happens in the lab and what consumers actually experience.

No global picture of how much MNP food packaging contributes to human ingestion, or how this compares to other sources.

What we did

Reviewed and harmonised 20+ experimental studies into a single analytical framework – converting particle counts to mass, normalising to a common unit (µg per litre of product), and building low, normal, and high emission scenarios for each packaging format.

Grounded scenarios in realistic use conditions: storage duration, opening frequency, heat exposure, and UV irradiation – the stressors that matter in everyday life.

Scaled findings to global emission fluxes (~1,050 t/year) and average per-capita intake (~131 mg/person/year), covering ~66% of global food packaging volumes.

Why it matters

For the first time, it is possible to compare formats directly, identify which packaging types and use conditions drive the most exposure, and estimate what this means at global and per-capita scale – turning fragmented evidence into decision-relevant priorities.

Results are actionable: they point to specific formats, mechanisms, and supply-chain interventions where exposure reduction is both feasible and proportionate.

Packaging-related MNP exposure can now be contextualised alongside other known microplastic sources – and its unique relevance as a direct ingestion pathway made visible.

(3) APPROACH AND DETAILED RESULTS BY CATEGORY

(3.1) Approach and method to narrow down complexity

This report applies a pragmatic, stepwise analytical framework to translate heterogeneous experimental evidence into comparable and decision-relevant insights. The framework is explicitly grounded in the life-cycle stages and generation mechanisms described in section 2 and is designed to support comparison across packaging formats, use conditions, and orders of magnitude rather than precise exposure quantification.

The objective of the analysis is threefold:
(i) to identify **which life-cycle stages and mechanisms dominate** micro- and nanoplastic (MNP) generation;
(ii) to estimate **plausible ranges of emissions** under low, normal, and high use conditions;
(iii) to translate these findings into **population-level relevance and actionable insights** for consumers and industry stakeholders.

Results should be interpreted as **screening-level and comparative.** Absolute values are subject to uncertainty due to variability in experimental methods, particle size coverage, and harmonisation assumptions. The primary value of the analysis lies in identifying **relative importance, orders of magnitude, and priorities for action,** rather than precise exposure estimates.

(3) APPROACH AND DETAILED RESULTS BY CATEGORY

(3.2) Stepwise analytical approach to assess MNP generation

Based on a comprehensive review of the scientific literature (full list of articles identified and screened provided in Appendix 1) the analysis follows a structured sequence of steps to narrow down complexity, harmonise heterogeneous data, and derive robust conclusions on both the magnitude of impacts and the key drivers of variability.

Step 1: Identify relevant packaging formats and select high-quality evidence

For each packaging format considered, the analysis begins with a systematic inventory of the available scientific literature. Priority is given to:

- → **high-quality review articles,** providing synthesis across multiple studies;
- → **primary experimental studies** with clearly described methodology, controlled conditions, and transparent reporting of particle size ranges, detection limits, and analytical techniques.

Only studies deemed sufficiently robust to support **order-of-magnitude comparison** are retained for the core analysis. The detailed list of studies included for each case study is provided in Appendix 1.

In parallel, each packaging format is contextualised by identifying the **global volume of packaging used for food-contact applications** and its relative importance compared to total packaging use. This ensures that subsequent scenario analysis and scaling are grounded in **realistic material flows and consumption patterns**

Step 2: Identify dominant life-cycle stages, mechanisms, and driving parameters

For each packaging format, the analysis identifies the life-cycle stages and generation mechanisms that contribute most to MNP release. A clear distinction is made between:

- → **production-related (“inherited”) MNP,** originating from polymer processing, packaging manufacturing, finishing operations (e.g. capping), and pre-use handling; present in the product before consumer use;
- → **post-filling and use-related MNP,** generated after filling as a result of stresses occurring during transport, storage, retail display, and consumer use.

The coverage of packaging formats and the corresponding generation mechanisms is detailed in Appendix 1.

Generation mechanisms include mechanical, physico-chemical, and combined processes. For each mechanism and life-cycle stage, key driving parameters are identified, such as:

- → number of opening and closing cycles (mechanical abrasion),
- → temperature levels and duration of exposure (thermal effects),
- → intensity and duration of light or UV exposure (irradiation),
- → duration of product contact and product chemistry (e.g. aqueous, acidic contents).

Where available, parameter ranges reported in the literature are documented. This makes it possible to identify not only which mechanisms dominate, but also how emissions vary across realistic and foreseeable parameter ranges.

Step 3: Construct low, normal, and high emission use scenarios

Based on the dominant mechanisms and parameter ranges identified in Steps 1 and 2, three representative scenarios are constructed for each packaging format:

- → a **low-emission scenario,** reflecting limited cumulative stress during transport, storage, and use;
- → a **normal-use scenario,** serving as a reference point representing typical and foreseeable distribution, storage, and consumer use conditions;
- → a **high-emission scenario,** capturing the upper end of plausible cumulative stress, including prolonged irradiation, extended storage, and repeated mechanical interaction.

These scenarios are not intended to represent behavioural statistics. Rather, they define **plausible bounds on real-world emissions** and provide a structured way to aggregate multiple mechanisms acting together.

Uncertainty is handled transparently. For each packaging and parameter, representative **low, central, and high values** are defined based on expert judgment and the characteristics of each case study. The assumptions defining these scenarios are documented further the report, in each case-study.

Step 4: Quantify and compare scenario-level emissions

For each packaging format, scenario-level emissions are quantified by aggregating the contributions of the relevant mechanisms under the defined scenarios. Results are expressed primarily in **µg of MNP per litre of packaged product (µg/L)** and interpreted at an order-of-magnitude level.

The objective of this step is to identify:
- → which mechanisms dominate under normal use,
- → how emissions increase under cumulative stress, and
- → which life-cycle stages contribute most to overall exposure.

Details on how data were harmonised across studies and expressed in µg/L are provided in Appendix 2. Details on how uncertainty was handled are provided in Appendix 3.

Step 5: Scale results to global and per-capita levels

Scenario-level results are subsequently scaled to derive **indicative global and per-capita orders of magnitude.** Scaling is performed specifically for food-contact applications, using packaging flow data from Plasteax[4] (volumes placed on the market).

This step links packaging-specific findings to **potential population-level relevance** and allows comparison across formats and with other known sources of microplastic exposure. Scaling results are presented as **indicative rather than predictive,** with explicit acknowledgment of assumptions and uncertainty.

Scenario-level results are subsequently combined to represent **global patterns of packaging use across the population.** Rather than assuming a single, uniform use condition, the analysis accounts for variability in consumer practices by assuming that:
- → **2/3** of uses reflect **normal-use conditions**,
- → **1/6** reflect **low-stress use conditions**, and
- → **1/6** reflect **high-stress use conditions**, corresponding to more intensive handling (e.g. repeated opening, heating, prolonged storage, or irradiation).

The resulting estimates are then scaled to derive indicative **global annual emissions** and **average per-capita** emissions. Scaling is based on packaging flow data and representative consumption patterns.

The full scaling methodology, together with the underlying packaging flow data (Plasteax), is documented in Appendix 4.

As in previous steps, results are interpreted at an **order-of-magnitude level**, with explicit acknowledgment of uncertainty. Details on how uncertainty was handled are provided in Appendix 3.

Step 6: Derive insights and leverage points for action

Finally, results are synthesised to identify **key insights and leverage points for exposure reduction,** including:
- → **use-related parameters** that consumers can influence (e.g. handling conditions, exposure to heat or light);
- → **design, material, and supply-chain parameters** that industry stakeholders can control (e.g. packaging design, closure systems, transport and retail practices).

Step 7: Place packaging-related MNP emissions in a broader life-cycle context

To support prioritisation and avoid over-interpreting food-contact emissions in isolation, results are placed in relation to **typical microplastic emissions associated with other life-cycle stages and broader plastic-related pathways** (e.g. transport-related sources such as tyre and road wear particles, and end-of-life pathways including mismanaged waste and littering). This step relies on existing synthesis studies and EA datasets, adapted to the packaging categories and volumes considered in this report.

The objective is not to attribute full life-cycle responsibility to packaging formats, but to provide an **order-of-magnitude comparison** that helps readers understand:
- → how food-contact, ingestion-relevant emissions compare to other major microplastic sources in the environment,
- → which stages are likely to dominate emissions at the system level,
- → and where prevention levers may differ (consumer use and supply chain vs end-of-life management).

Where feasible, results are scaled using the same packaging quantities used in this study to ensure consistency of comparison across pathways.

The full methodology used to estimate MNP in the broader life-cycle context, together with the underlying data, is documented in Appendix 5.

Step 8: Compare indicative health relevance of particle exposure versus chemical exposure from packaging

Finally, the analysis provides a high-level, order-of-magnitude comparison between potential impacts associated with particulate exposure (MNP) and those associated with chemical exposure from packaging, including intentionally added substances (IAS) and non-intentionally added substances (NIAS). This comparison is based on published literature and existing assessments (including synthesis reports on packaging-related chemical migration), and is explicitly framed as a coarse screening exercise, not a quantitative risk assessment.

The objective is to help interpret the relative "health relevance" of different packaging-related exposure pathways by:
- → contrasting particle mass and/or particle-number exposure ranges (where available) with typical ranges of chemical migration reported for relevant packaging categories,
- → identifying where evidence is strong or weak for each pathway (notably for nanoplastics and NIAS mixtures),
- → and highlighting whether exposure reduction measures are likely to be aligned (e.g. design and supply chain controls) or require distinct strategies (chemical formulation vs particulate generation).

Given the heterogeneity of toxicological endpoints, metrics (mass vs particle number), and the current uncertainty on hazard characterisation–especially for nanoplastics and complex NIAS mixtures, this step is presented as qualitative and order-of-magnitude, with transparent assumptions and clear limitations.

This step provides the analytical basis for the recommendations presented in each case study and in the synthesis sections of the report, as well as for identifying remaining gaps in knowledge.

(3.3) Selection of the case studies

To operationalise the analytical framework described in Section 3.2, a limited number of case studies were selected to represent the most relevant food-contact packaging formats and use patterns. The objective of this step is not to be exhaustive, but to capture the dominant mechanisms and realistic use conditions that drive micro- and nanoplastic (MNP) generation across the bulk of food packaging in use.

Rationale and selection criteria

Case studies were defined by combining:
- a typical packaging format (material, geometry, and functional design), and
- a set of representative use patterns reflecting normal and foreseeable conditions of handling, storage, and consumer interaction.

The framing of these case studies builds on the pre-existing Plasteax [4] taxonomy, complemented by a targeted review of the scientific literature. Selection was guided by four main criteria:
- Relevance for food contact, focusing exclusively on packaging formats used for food and beverages.
- Scale of use, prioritising formats with large global volumes and widespread consumption.
- Evidence availability, favouring packaging types for which experimental data on MNP release under realistic conditions exist.
- Diversity of mechanisms, ensuring coverage of the main generation pathways (mechanical stress, thermal stress, irradiation, product-packaging interaction).

Together, these criteria ensure that the selected case studies are both scientifically grounded and meaningful from an exposure and prioritisation perspective.

Coverage & representativeness

Applying these criteria resulted in the selection of seven case studies, which together cover approximately **66 % of the total global volume of food packaging.** The aggregated volume represented by these case studies is estimated at approximately 43,000 kt, out of an estimated 65,000 kt of food packaging placed on the market globally (based on Plasteax estimates).

Overview of selected case studies

The selected case studies apply the analytical framework to common food packaging formats, illustrating how material properties, design features, and cumulative use conditions combine in practice. The categories include:
- PET bottles
- Flexible polyethylene (PE) packaging
- Rigid (PET) packaging
- Rigid polypropylene (PP) food packaging
- Rigid polystyrene (PS) packaging
- Multilayer containers
- Multilayer bottles

Figure 4.
Packaging categories considered and the corresponding volumes included in the analysis (Plasteax)

Packaging	Polymer	Volume, in kt	Food share, in %	Final volume, in kt
PET bottles	PET	21,294	90%	19,165
Flexible packaging	PE	22,251	40%	8,900
Rigid food packaging	PET	6,130	100%	6,130
Rigid food packaging	PP	5,643	100%	5,643
Rigid food packaging	PS	692	100%	692
Multi-layer containers	PE	2,232	80%	1,785
Multi-layer bottles	PE	958	80%	766
Total covered by study		**59,199**		**43,082**
Other food packaging				22,265
Total food packaging				**65,346**

Overview of selected use cases

For each packaging format, a defined set of **life-cycle stages and use conditions** was considered in order to capture the mechanisms most relevant to micro- and nanoplastic (MNP) generation. These use conditions are **not intended to represent the full diversity of consumer behaviours,** but to reflect **normal and foreseeable conditions of use** under which MNP release has been documented in the literature.

For each mechanism, a limited number of discrete parameters (e.g. duration, frequency, or intensity) were selected to represent increasing cumulative stress. This approach allows comparison across packaging formats while remaining consistent with the underlying experimental evidence.

The mechanisms considered, together with the corresponding parameters and their operational definitions, are summarised in Figure 5.

Mechanism	Parameter levels	Description
Inherited (pre-use)	Same for all	Background MNP present prior to consumer use, originating from production and filling
Product contact	• Aqueous/ Fat/Acidic • Temperature of contact • Time of contact	Influence of product chemistry, temperature of product and time of exposure on MNP release
Irradiation	1h, 2h, 3h, 4h	Exposure to light or UV radiation inducing physico-chemical ageing
Microwaving	Power	Influence of microwaving on MNP release
Opening/ closing	1 time, 10 times, 100 times	Repeated mechanical abrasion at interfaces
Squeezing	10 min, 30 min, etc	Low-intensity mechanical stress during handling
Stacking	-	Contact-to-contact abrasion during transport

Figure 5.
Mechanisms considered in the analysis, with associated levels and descriptions

(3) CASE STUDY

(3.4) Results for PET bottles

This case study focuses on still drinking water packaged in PET bottles, one of the most widespread food-contact packaging formats globally and the single largest contributor to the volumes covered in this analysis. The scope reflects the availability of robust experimental evidence, which is currently limited to water; no reliable data were identified for acidic beverages or fat-containing liquids. Three scenarios–low-emission, normal-use, and high-emission–were constructed to reflect realistic consumer handling and storage practices, combining key stressors known to drive micro- and nanoplastic (MNP) emissions, including contact duration, mechanical deformation, repeated opening and closing, and irradiation exposure.

Figure 6.
Key assumptions defining the low-emission, normal-use, and high-emission PET bottles.

Low-emission scenario

17% stored **6 months** (contact)

1x Open/Close

1 min Squeeze

No Irradiation

Normal-Use scenario

50% stored 6 months (contact)

11x Open/Close

10 min Squeeze

1h Irradiation

High-emission scenario

100% stored **6 months** (contact)

100x Open/Close

30 min Squeeze

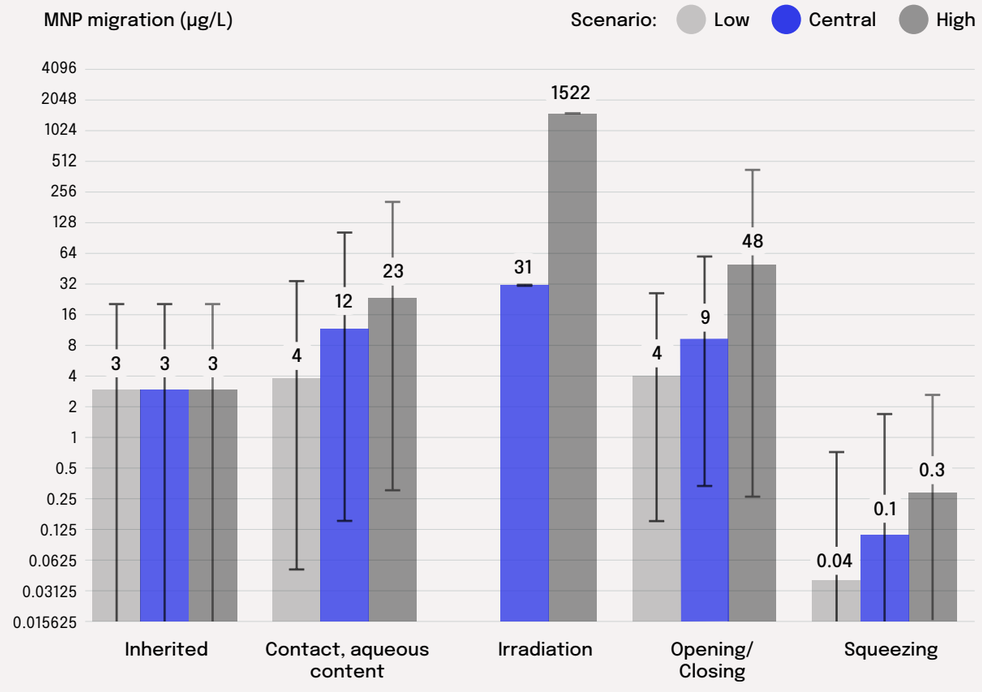
4h Irradiation

Aggregated results and contribution analysis

Figure 7.
Aggregated MNP emission estimates from PET bottles across use scenarios and scales

Indicator	Low-emission scenario	Normal-use scenario	High-emission scenario
Per volume of product 1 L of packed product, in µg/L	11 (0.2 – 81)	55 (31 – 216)	1597 (1522 – 2174)
Per weight of packaging 1 g of packaging, in µg/g	0.5 (0.01 – 4)	3 (2 – 11)	80 (76 – 109)
Global emission annual, world scale, in tons/year	10 (0.2 – 78)	53 (30 – 207)	1530 (1459 – 2083)
Per capita emission annual, average consumption, in mg/person/year	1 (0.02 – 10)	7 (4 – 26)	191 (182 – 260)

Figure 8.
Contribution of mechanisms to MNP emissions from PET bottles across low-, normal-, and high-use scenarios.



Bars show scenario-based estimates of MNP release expressed in µg/L of packaged product (y-axis in $\log_2$ scale). The normal-use scenario is displayed with uncertainty ranges derived from data extraction and harmonisation of the literature. Low- and high-use scenarios illustrate plausible bounds associated with different intensities of use-related parameters. Differences across scenarios reflect sensitivity to use conditions and cumulative stresses rather than statistical uncertainty.

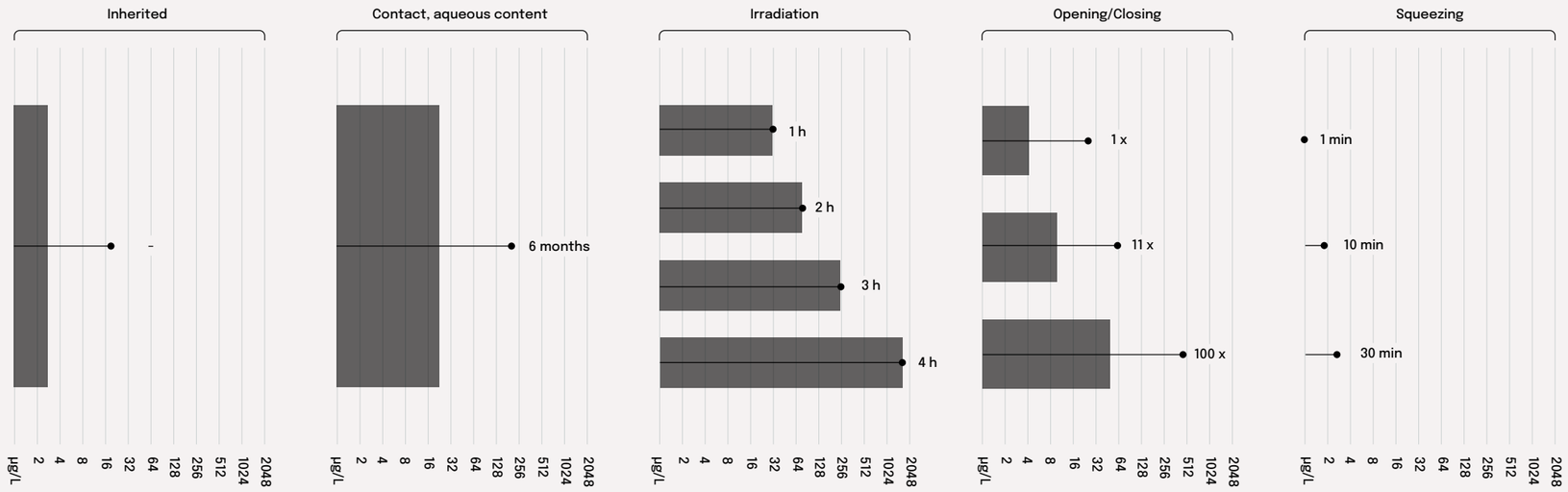


Figure 9.
Detailed contribution of mechanisms to MNP emissions from PET bottles.

Each panel represents a distinct mechanism. Each horizontal bar corresponds to a specific mechanism–parameter combination and shows the associated MNP emissions (µg/L of packaged product). Bars are ordered from top to bottom according to increasing cumulative stress, reflecting progressively more intensive use conditions. Error bars reflect uncertainty in the underlying studies.

Interpretation

Results per 1 L of packed product (functional unit 1) and per 1 g of packaging (functional unit 2)

Under the normal-use scenario, migration from the PET bottle into the beverage is on the order of **55 µg/L,** with a plausible range of **31–216 µg/L.** This corresponds to approximately **3 µg/g of packaging,** with a plausible range of **2–11 µg/g.** The results are summarized in Figure 7.

This migration reflects the combined contributions of irradiation-driven ageing and repeated opening and closing. Under normal-use conditions, irradiation-related pathways account for approximately **three-quarters of total MNP generation.**

Under low-emission conditions, MNP concentrations remain close to inherited background levels, with only limited additional release during use. By contrast, under high-emission conditions, cumulative stresses markedly amplify MNP release, with concentrations reaching the order of ~**1 600 µg/L,** representing **more than an order-of-magnitude increase** relative to the normal-use scenario.

Scaling to global emissions from packaging into food

Extrapolating scenario-level estimates to global PET bottle consumption suggests that PET bottles may contribute approximately **53 tons of MNP per year** to the food chain, with a plausible range of **30–207 tons** (Figure 7).

Per-capita exposure

Translating these global emissions into per-capita exposure indicates that, under normal-use assumptions, average intake is on the order of **7 mg per person per year**, with a plausible range of **4–26 mg/person/year** (Figure 7).

For high consumers, exposure may be substantially higher. For example, an individual consuming approximately 1.5 L per day from PET bottles could ingest on the order of several tens of milligrams per year under normal-use conditions, and up to ~1 g per year under high-use scenarios characterised by prolonged irradiation and cumulative handling stresses.

Identification of dominant mechanisms and amplification potential

The contribution of each mechanism to MNP emissions across scenarios and the effects of cumulative stress for each mechanism are illustrated in Figures 7 and 8, respectively. Variability across scenarios is driven by a limited number of mechanisms with strong amplification potential, while others remain marginal even under intensified conditions.

- → **Irradiation** clearly emerges as the most influential mechanism, with increases in duration and intensity leading to multiplicative effects of up to ~50× relative to low-use conditions.
- → **Product contact** contributes consistently to MNP emissions and acts as a secondary amplification pathway, particularly for longer storage durations.
- → **Repeated opening and closing** produces a moderate multiplier effect, on the order of ~5× between low- and high-use assumptions. This contribution is strongly design-dependent – for instance, a continuous cap ring generates less abrasion than a segmented one.[5]
- → **Squeezing and low-intensity mechanical deformation** show only weak amplification (typically ≤3×) and remain negligible contributors even under intensified conditions.

Inherited MNP, originating from production, capping and transport, establish a systematic background exposure on the order of a few µg/L. While always present, inherited contributions do not drive variability across scenarios and do not control upper-bound exposure outcomes. Their role is best interpreted as a **baseline upon which use-related mechanisms act cumulatively.**

CASE-STUDY TAKEAWAY

For PET bottles, exposure to irradiation, prolonged contact with water and repeated opening/closing dominate MNP emissions, while squeezing play a secondary role under typical use conditions.

Recommendations. Do not store PET bottles in direct sunlight or vehicles. Design caps with lower-friction interfaces to reduce abrasion. Prefer larger bottle formats – MNP emissions per litre decrease as bottle size increases, because the cap-to-volume ratio drops.

(3) CASE STUDY

(3.5) Results for flexible PE packaging

Flexible PE packaging is widely used across food and consumer goods applications, including pouches, wraps, bags, and zip-lock packaging. These formats are produced at very large scale and are valued for their light weight, flexibility, and versatility. Flexible PE packaging is used for a wide range of products, from dry foods to liquids, and is often handled repeatedly during filling, storage, opening, and resealing. Unlike rigid formats, flexible packaging is characterised by thin material layers, large surface-to-volume ratios, and frequent manual handling, which expose it to repeated mechanical deformation and, in some cases, thermal and light exposure.

Figure 10.
Key assumptions defining the low-emission, normal-use, and high-emission of flexible polyethylene packaging.

Low-emission scenario

20% in contact with hot aqueous content

1x Open/Close

0% are exposed to irradiation

Normal-Use scenario

40% in contact with hot aqueous content

10x Open/Close

1% are exposed to irradiation

High-emission scenario

60% in contact with hot aqueous content

10x Open/Close

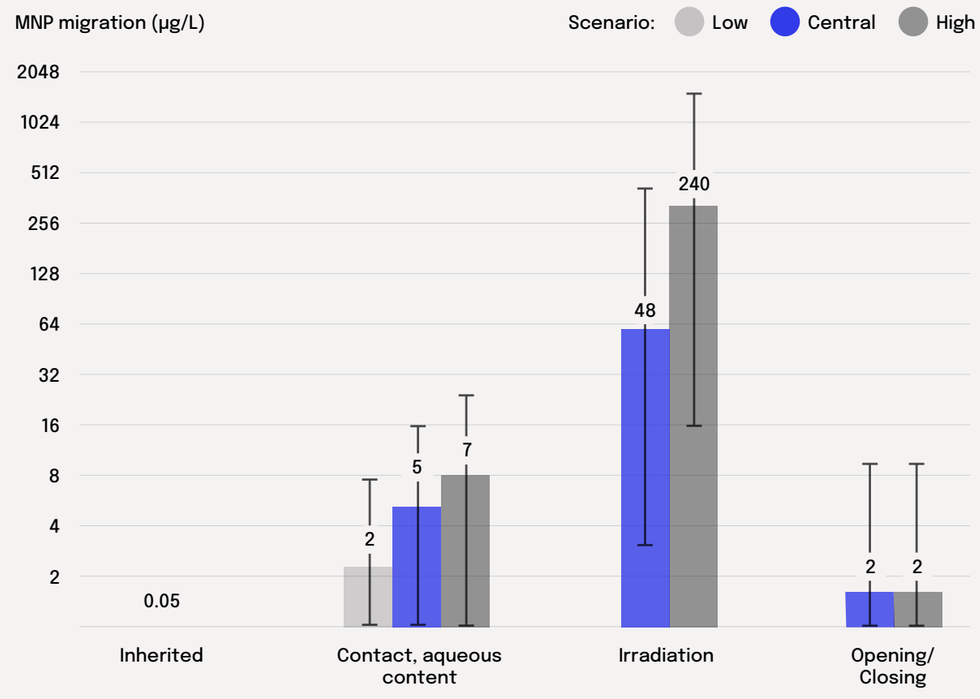
5% are exposed to irradiation

Aggregated results and contribution analysis

Figure 11.
Aggregated MNP emission estimates from PE flexible packaging across use scenarios and scales

Indicator	Low-emission scenario	Normal-use scenario	High-emission scenario
Per volume of product 1 L of packed product, in µg/L	3 (0.3 – 8)	55 (4 – 313)	249 (16 – 1,479)
Per weight of packaging 1 g of packaging, in µg/g	0.5 (0.07 – 2)	11 (0.7 – 63)	50 (3 – 296)
Global emission annual, world scale, in tons/year	5 (0.6 – 14)	97 (7 – 557)	443 (28 – 2,632)
Per capita emission annual, average consumption, in mg/person/year	0.6 (0.08 – 2)	12 (0.8 – 70)	55 (4 – 329)

Figure 12.
Contribution of mechanisms to MNP emissions from PE flexible packaging across low-, normal-, and high-use scenarios.



Bars show scenario-based estimates of MNP release expressed in µg/L of packaged product (y-axis in $\log_2$ scale). The normal-use scenario is displayed with uncertainty ranges derived from data extraction and harmonisation of the literature. Low- and high-use scenarios illustrate plausible bounds associated with different intensities of use-related parameters. Differences across scenarios reflect sensitivity to use conditions and cumulative stresses rather than statistical uncertainty

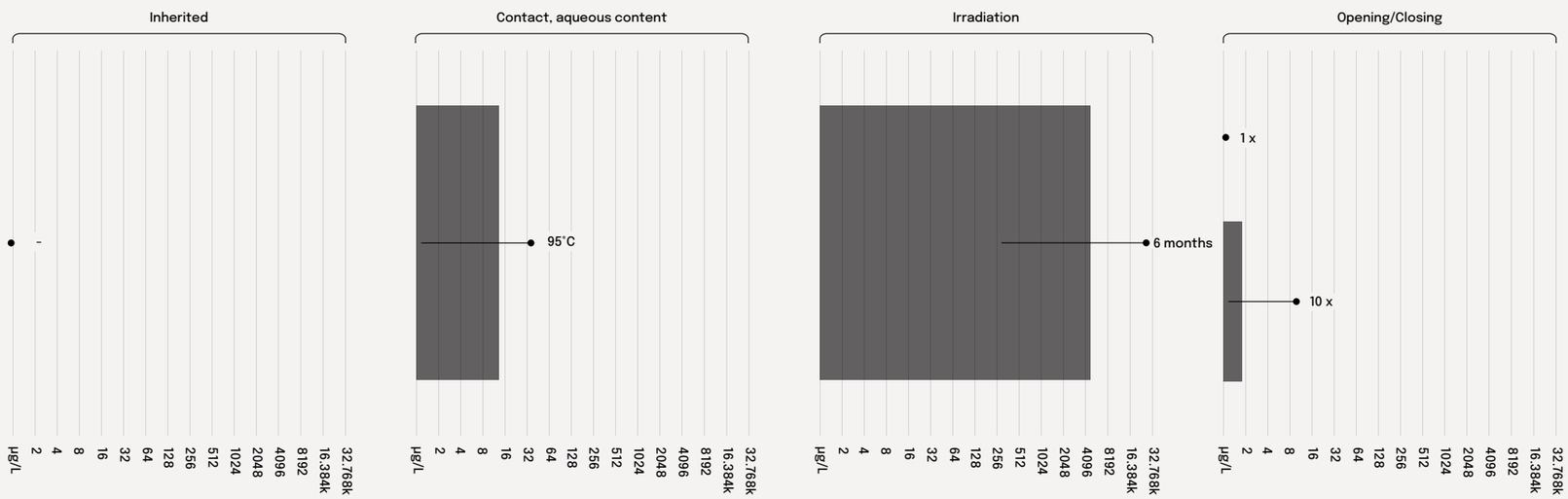


Figure 13.
Detailed contribution of mechanisms to MNP emissions from PE flexible packaging under different conditions.

Each panel represents a distinct mechanism. Each horizontal bar corresponds to a specific mechanism-parameter combination and shows the associated MNP emissions (µg/L of packaged product). Bars are ordered from top to bottom according to increasing cumulative stress, reflecting progressively more intensive use conditions. Error bars reflect uncertainty in the underlying studies.

Interpretation

Results per 1 L of packed product (functional unit 1) and per 1 g of packaging (functional unit 2)

Under the normal-use scenario, MNP migration from flexible PE packaging into food is estimated at approximately **55 µg/L**, with a plausible range of **4–313 µg/L.** When expressed per mass of packaging, this corresponds to **11 µg/g of packaging,** with a plausible range of **0.7–63 µg/g.** The results are summarized in Figure 11.

Under low-emission conditions, MNP concentrations are substantially lower, on the order of **3 µg/L,** corresponding to **0.5 µg/g of packaging.** By contrast, under high-emission conditions, cumulative stresses markedly amplify MNP release, with concentrations reaching approximately **249 µg/L,** or **50 µg/g of packaging.**

Across scenarios, flexible PE packaging exhibits a wide dynamic range, with differences of nearly two orders of magnitude between low- and high-emission assumptions, highlighting its strong sensitivity to use conditions.

Scaling to global emission from packaging into food

Extrapolating scenario-level estimates to global flexible PE packaging consumption suggests that flexible PE packaging contributes approximately **97 tons of MNPs per year** to the food chain under normal-use assumptions, with a plausible range of **7–557 tons per year** (Figure 11).

Under low-emission conditions, global emission is estimated at **5 tons per year**, while under high-emission conditions emissions may reach **443 tons per year.**

Per-capita exposure

When translated into per-capita exposure, emissions from flexible PE packaging correspond to an average intake of approximately **12 mg per person per year** under normal-use assumptions, with a plausible range of **0.8–70 mg/person/year** (Figure 11).

Under low-emission conditions, per-capita exposure is estimated at **0.6 mg/person/year**, while under high-emission conditions intake increases to approximately **55 mg/person/yea**r.

Identification of dominant mechanisms and amplification potential

The contribution of each mechanism to MNP emissions across scenarios and the effects of cumulative stress for each mechanism are illustrated in Figures 11 and 12, respectively. Scenario-to-scenario variability in MNP release from flexible PE packaging is driven by a small number of mechanisms with strong amplification potential, among which **irradiation is the dominant driver,** followed by repeated opening and thermal exposure.

- **Irradiation** (sunlight or UV exposure) is consistently associated with the highest MNP generation. Photo-induced ageing weakens the polymer surface, promotes embrittlement, and facilitates particle detachment, making irradiation the primary determinant of upper-bound emissions.
- **Repeated opening and closing,** particularly for resealable or zip-lock packaging, acts as a strong mechanical amplification pathway. A clear dose-response relationship is observed, with increasing numbers of opening–closing cycles leading to progressively higher MNP release.
- **Contact with hot contents** further increases MNP release by weakening the polymer matrix and enhancing susceptibility to particle detachment. While less influential than irradiation, heat acts as an effective secondary amplifier when combined with photo-ageing or mechanical stress.

CASE-STUDY TAKEAWAY

For flexible PE packaging, MNP emissions are primarily driven by irradiation, with repeated opening and thermal stress acting as secondary amplifiers.

Recommendations. Do not expose flexible PE packaging to sunlight during storage or retail display. Resealable zip-lock formats should specify a maximum number of open-close cycles on-pack. Hot-fill into flexible PE pouches should be avoided – transfer to glass or metal before heating.

(3) CASE STUDY

(3.6) Results for rigid PET packaging

Rigid polyethylene terephthalate (PET) packaging is commonly used for clamshell containers, cups, and other rigid food-contact formats. These products are valued for their transparency, strength, and barrier properties, and are used across a wide range of food applications. Rigid PET packaging is typically in direct contact with food, may experience temperature variations or exposure to irradiation during storage or use, and is often associated with a variety of products, including fresh produce, ready-to-eat meals, or desserts.

Figure 14.
Key assumptions defining the low-emission, normal-use, and high-emission of rigid PET packaging.

Low-emission scenario

80% in contact with aqueous content

20% in contact with acidic content

20% in contact with hot aqueous content (no data for hot acidic content)

No irradiation

Normal-Use scenario

80% in contact with aqueous content

20% in contact with acidic content

50% in contact with hot aqueous content (no data for hot acidic content)

1h irradiation

High-emission scenario

80% in contact with aqueous content

20% in contact with acidic content

80% in contact with hot aqueous content (no data for hot acidic content)

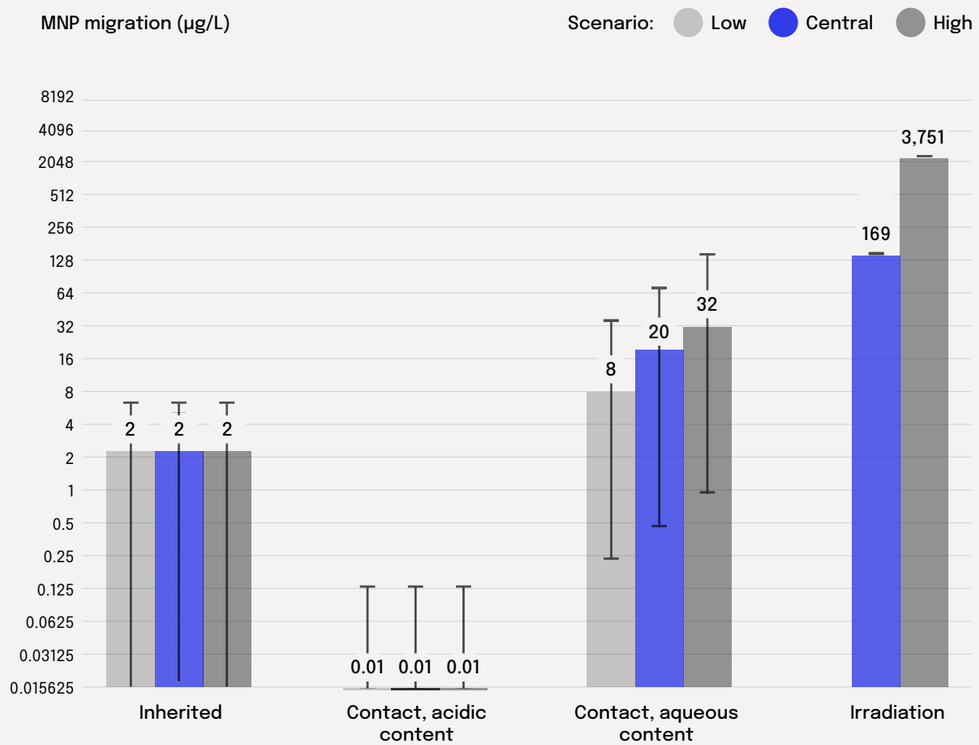
4h irradiation

Aggregated results and contribution analysis

Figure 15.
Aggregated micro- and nanoplastic (MNP) emission estimates from rigid PET packaging across use scenarios and scales

Indicator	Low-emission scenario	Normal-use scenario	High-emission scenario
Per volume of product 1 L of packed product, in µg/L	10 (0.4 – 46)	191 (169 – 276)	3,785 (3,753 – 3,918)
Per weight of packaging 1 g of packaging, in µg/g	0.3 (0.01 – 2)	6 (6 – 9)	126 (125 – 131)
Global emission annual, world scale, in tons/year	2 (0.09 – 9)	39 (35 – 56)	773 (767 – 801)
Per capita emission annual, average consumption, in mg/person/year	0.3 (0.01 – 1)	5 (4 – 7)	97 (96 – 100)

Figure 16.
Contribution of mechanisms to MNP emissions from rigid PET packaging across low-, normal-, and high-use scenarios. Temperature was varied for the contact with aqueous content case.



Bars show scenario-based estimates of MNP release expressed in µg/L of packaged product (y-axis in $\log_2$ scale). The normal-use scenario is displayed with uncertainty ranges derived from data extraction and harmonisation of the literature. Low- and high-use scenarios illustrate plausible bounds associated with different intensities of use-related parameters. Differences across scenarios reflect sensitivity to use conditions and cumulative stresses rather than statistical uncertainty.

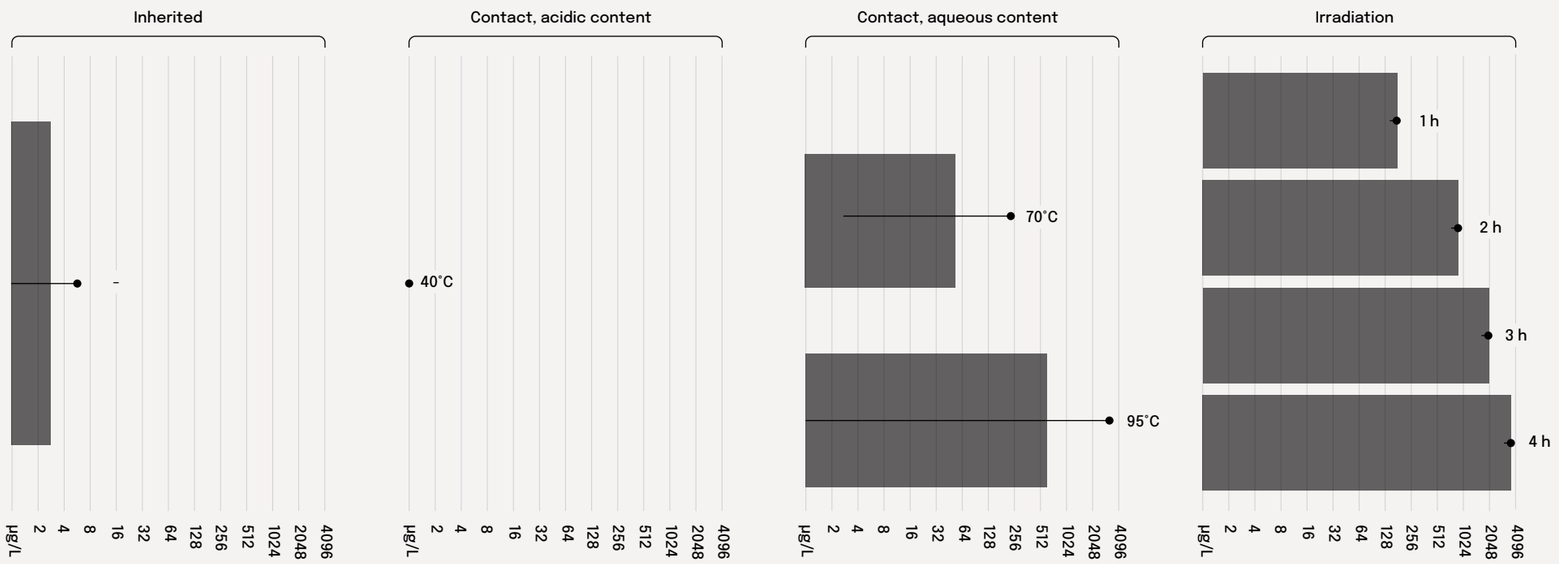


Figure 17.
Detailed contribution of mechanisms to MNP emissions from rigid PET packaging under different conditions.

Each panel represents a distinct mechanism. Each horizontal bar corresponds to a specific mechanism-parameter combination and shows the associated MNP emissions (µg/L of packaged product). Bars are ordered from top to bottom according to increasing cumulative stress, reflecting progressively more intensive use conditions. Error bars reflect uncertainty in the underlying studies.

Interpretation

Results per 1 L of packed product (functional unit 1) and per 1 g of packaging (functional unit 2)

Under the normal-use scenario, micro- and nanoplastic (MNP) migration from rigid PET packaging into food is estimated at approximately **191 µg/L,** with a plausible range of **169–276 µg/L.** When expressed per mass of packaging, this corresponds to **6 µg/g of packaging,** with a plausible range of **6–9 µg/g.** The results are summarized in Figure 15.

Under low-emission conditions, MNP concentrations are substantially lower, on the order of **10 µg/L,** corresponding to **0.3 µg/g** of packaging. By contrast, under high-emission conditions, cumulative stresses lead to a very strong amplification of MNP release, with concentrations reaching approximately **3,785 µg/L,** or **126 µg/g of packaging.**

Across scenarios, rigid PET packaging increases of more than two orders of magnitude between low- and high-emission assumptions.

Scaling to global emissions from packaging into food

Extrapolating scenario-level estimates to global rigid PET packaging consumption suggests emissions of approximately **39 tons of MNPs per year** to the food chain under normal-use assumptions, with a plausible range of **35–56 tons per year** (Figure 15).

Under low-emission conditions, global emissions is estimated at **2 tons per year,** while under high-emission conditions emissions increase sharply to approximately **773 tons per year.**

Per-capita exposure

When translated into per-capita exposure, emissions from rigid PET packaging correspond to an average intake of approximately **5 mg per person per year** under normal-use assumptions, with a plausible range of 4–7 mg/person/year (Figure 15).

Under low-emission conditions, per-capita exposure is estimated at **0.3 mg/person/year,** while under high-emission conditions intake increases to approximately **97 mg/person/year.**

Identification of dominant mechanisms and amplification potential

The contribution of each mechanism to MNP emissions across scenarios and the effects of cumulative stress for each mechanism are illustrated in Figures 15 and 16, respectively. Scenario-to-scenario variability in MNP release from rigid PET packaging is driven by a limited number of mechanisms with very strong amplification potential, among which **irradiation clearly dominates.**

- **Irradiation** (sunlight or UV exposure) is the primary driver of MNP generation from rigid PET packaging. Photo-induced ageing strongly weakens the polymer surface and promotes particle detachment, leading to disproportionate increases in MNP release under high-exposure conditions. This mechanism largely controls upper-bound emissions and explains the extreme amplification observed between normal- and high-emission scenarios.
- **Thermal exposure to hot aqueous contents** acts as a secondary amplification pathway. Increasing temperature enhances polymer mobility and accelerates degradation processes, resulting in higher MNP release compared to ambient conditions.
- **Content acidity** appears to generate lower MNP release compared to aqueous contents, but available data remain sparse and associated uncertainties are high. As a result, the influence of acidic contents should be interpreted cautiously and cannot be robustly ranked among dominant drivers at this stage.

CASE-STUDY TAKEAWAY

In rigid PET packaging other than bottles, MNP emissions are primarily driven by irradiation, with thermal stress acting as a secondary amplifier. Product acidity appears to have a minor influence, but uncertainties remain high.

Recommendations. Avoid using rigid PET containers for hot-fill applications above 40°C. Do not expose transparent rigid PET packaging to direct light during retail display – opaque secondary packaging or shielded shelving meaningfully reduces irradiation-driven degradation.

(3) CASE STUDY

(3.7) Results for rigid polypropylene (PP) packaging

Rigid polypropylene (PP) packaging is widely used across multiple food categories, including ready-meal containers, takeaway boxes or single-use cups. Owing to its low cost, mechanical resistance, and heat tolerance, PP represents a significant share of rigid food packaging placed on the market globally.

These packaging formats are frequently exposed to thermal stress, including direct contact with hot food and microwaving, as well as stacking during storage and transport, which can generate friction at contact surfaces. In addition, PP packaging is frequently used in contact with acidic or fatty food matrices, which may interact with the polymer surface under elevated temperatures.

Experimental evidence indicates that these combined use conditions–thermal exposure, stacking, and food contact–can promote surface degradation and particle detachment, leading to the release of micro- and nanoplastics into food.

Irradiation was not included in this case study due to a lack of data.

Figure 18.
Key assumptions defining the low-emission, normal-use, and high-emission of rigid PP packaging.

Low-emission scenario

70% in contact with aqueous content

15% in contact with acidic content

15% in contact with fat content

5% are stacked during transport

20% contains **hot** content (aqueous, acidic and fat)

5% are put in the microwave

Normal-Use scenario

70% in contact with aqueous content

15% in contact with acidic content

15% in contact with fat content

15% are stacked during transport

50% contains **hot** content (aqueous, acidic and fat)

10% are put in the microwave

High-emission scenario

70% in contact with aqueous content

15% in contact with acidic content

15% in contact with fat content

30% are stacked during transport

80% contains **hot** content (aqueous, acidic and fat)

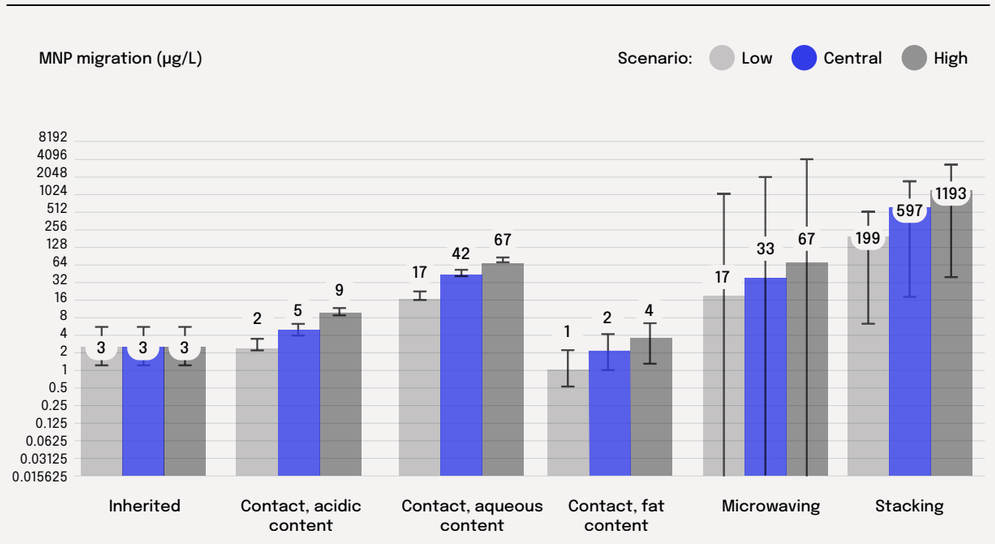
20% are put in the microwave

Aggregated results and contribution analysis

Figure 19.
Aggregated MNP emission estimates from PP rigid packaging across use scenarios and scales

Indicator	Low-emission scenario	Normal-use scenario	High-emission scenario
Per volume of product 1 L of packed product, in µg/L	239 (26 – 1,591)	683 (66 – 3762)	1,342 (112 – 7,495)
Per weight of packaging 1 g of packaging, in µg/g	6 (0.6 – 40)	17 (2 – 94)	34 (3 – 187)
Global emission annual, world scale, in tons/year	34 (4 – 224)	96 (9 – 531)	189 (16 – 1,057)
Per capita emission annual, average consumption, in mg/person/year	4 (0.5 – 28)	12 (1 – 66)	24 (2 – 132)

Figure 20.
Contribution of mechanisms to MNP emissions from PP rigid food packaging across low-, normal-, and high-use scenarios.



Bars show scenario-based estimates of MNP release expressed in µg/L of packaged product (y-axis in $\log_2$ scale). The normal-use scenario is displayed with uncertainty ranges derived from data extraction and harmonisation of the literature. Low- and high-use scenarios illustrate plausible bounds associated with different intensities of use-related parameters. Differences across scenarios reflect sensitivity to use conditions and cumulative stresses rather than statistical uncertainty.

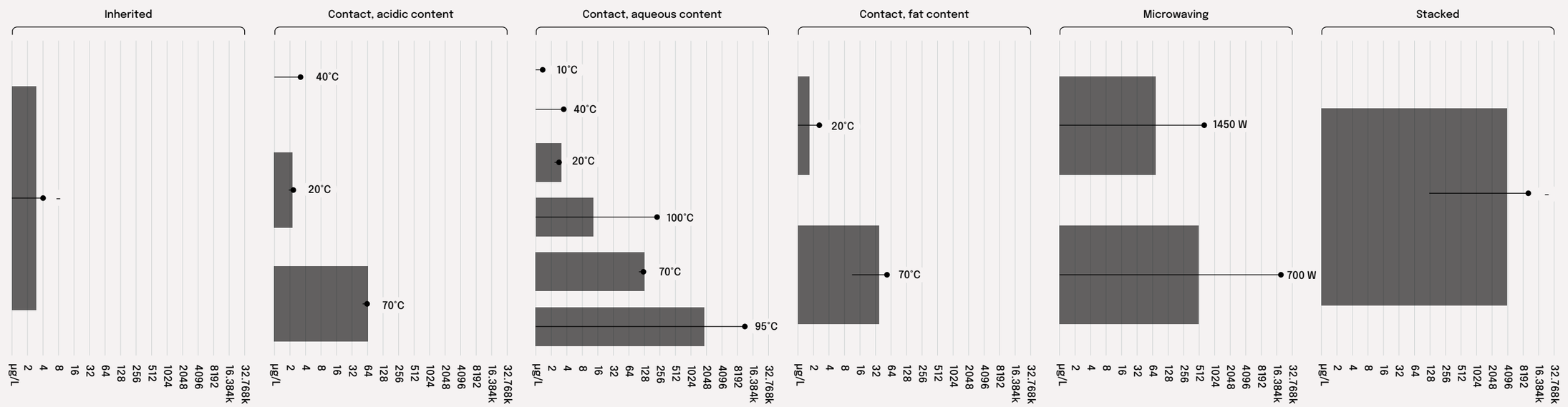


Figure 21.
Detailed contribution of mechanisms to MNP emissions from PP rigid packaging under different conditions

Each panel represents a distinct mechanism. Each horizontal bar corresponds to a specific mechanism-parameter combination and shows the associated MNP emissions (µg/L of packaged product). Bars are ordered from top to bottom according to increasing cumulative stress, reflecting progressively more intensive use conditions. Error bars reflect uncertainty in the underlying studies.

Interpretation

Results per 1 L of packed product (functional unit 1) and per 1 g of packaging (functional unit 2)

Under the normal-use scenario, MNP migration from rigid PP packaging into food is estimated at approximately **683 µg/L,** with a plausible range of **66–3 762 µg/L.** When expressed per mass of packaging, this corresponds to **17 µg/g of packaging,** with a plausible range of **2–94 µg/g.** The results are summarized in Figure 19.

Under low-emission conditions, MNP concentrations are lower, on the order of **239 µg/L** corresponding to **6 µg/g of packaging**. By contrast, under high-emission conditions, cumulative stresses substantially increase MNP release, with concentrations reaching approximately **1,342 µg/L, or 34 µg/g of packaging.**

Across scenarios, rigid PP packaging exhibits differences of nearly one order of magnitude between low- and high-emission assumptions, indicating a pronounced sensitivity to use conditions.

Scaling to global emissions from packaging into food

Extrapolating scenario-level estimates to global rigid PP packaging consumption suggests that rigid PP containers contribute approximately **96 tons of MNPs per year** to the food chain under normal-use assumptions, with a plausible range of **9–531 tons per year** (Figure 19).

Under low-emission conditions, global emissions is estimated at **34 tons per year** (4–224 tons per year), while under high-emission conditions emissions increase to approximately **189 tons per year,** with a plausible range of **16–1,057 tons** per year.

Per-capita exposure

When translated into per-capita exposure, emissions from rigid PP packaging correspond to an average intake of approximately **12 mg per person per year** under normal-use assumptions, with a plausible range of **1–66 mg/person/year** (Figure 19).

Under low-emission conditions, per-capita exposure is estimated at **4 mg/person/year,** while under high-emission conditions intake increases to approximately **24 mg/person/year.**

Identification of dominant mechanisms and amplification potential

The contribution of each mechanism to MNP emissions across scenarios and the effects of cumulative stress for each mechanism are illustrated in Figures 19 and 20, respectively. Scenario-to-scenario variability in MNP release from rigid PP packaging is driven by a limited number of, among which **mechanical stress during stacking and thermal stress emerge as the two dominant drivers.**

- **Stacking and surface-to-surface** contact strongly promote MNP generation through repeated friction and micro-abrasion between containers stored in direct contact. This process predominantly generates nanoscale particles that tend to accumulate on packaging surfaces. In the absence of rinsing, these surface-deposited particles can be directly transferred to food, making stacking a key determinant of upper-bound emissions.
- **Thermal stress** acts as a major amplification pathway by weakening the polymer matrix and accelerating surface degradation. Elevated temperatures associated with hot filling, or microwave use facilitate particle detachment and increase overall release.
- **Product-packaging interactions** have a secondary but systematic influence on MNP release. Acidic contents tend to slightly enhance release compared to aqueous contents, while fatty contents generally show lower release. These effects modulate baseline emissions but do not independently drive extreme outcomes.
- **Packaging design and material formulation** influence baseline release levels by conditioning sensitivity to stress. Thinner containers and materials with lower mechanical resistance tend to release more MNPs under thermal stress.[6]

CASE-STUDY TAKEAWAY

In rigid PP packaging, MNP emissions are primarily driven by cumulative mechanical stress from repeated surface-to-surface contact and thermal stress, while product composition plays a secondary role.

Recommendations. When transporting, avoid stacking PP containers directly on each other without protective separators, and rinse them before first use. Avoid microwaving food in PP containers beyond manufacturer specifications and do not fill them with hot food or beverages. If heat exposure is unavoidable, opt for containers with thicker walls.

(3) CASE STUDY

(3.8) Results for rigid polystyrene (PS) packaging

Rigid polystyrene (PS) packaging is widely used for food trays (e.g. meat trays), takeaway food containers, or cups. These formats are valued for their rigidity, light weight, and insulation properties, and are used across a range of food applications. Rigid PS packaging is typically in direct contact with food, may be exposed to temperature variations during storage or use, and is often associated with fat-containing products, particularly in meat and takeaway applications.

Irradiation was not included in this case study due to a lack of data.

Figure 22.
Key assumptions defining the low-emission, normal-use, and high-emission of rigid PS packaging.

Low-emission scenario

70% in contact with aqueous content

15% in contact with acidic content

15% in contact with fatty content

20% in contact with hot content (no data for hot acidic content)

Normal-Use scenario

70% in contact with aqueous content

15% in contact with acidic content

15% in contact with fatty content

50% in contact with hot content (no data for hot acidic content)

High-emission scenario

70% in contact with aqueous content

15% in contact with acidic content

15% in contact with fatty content

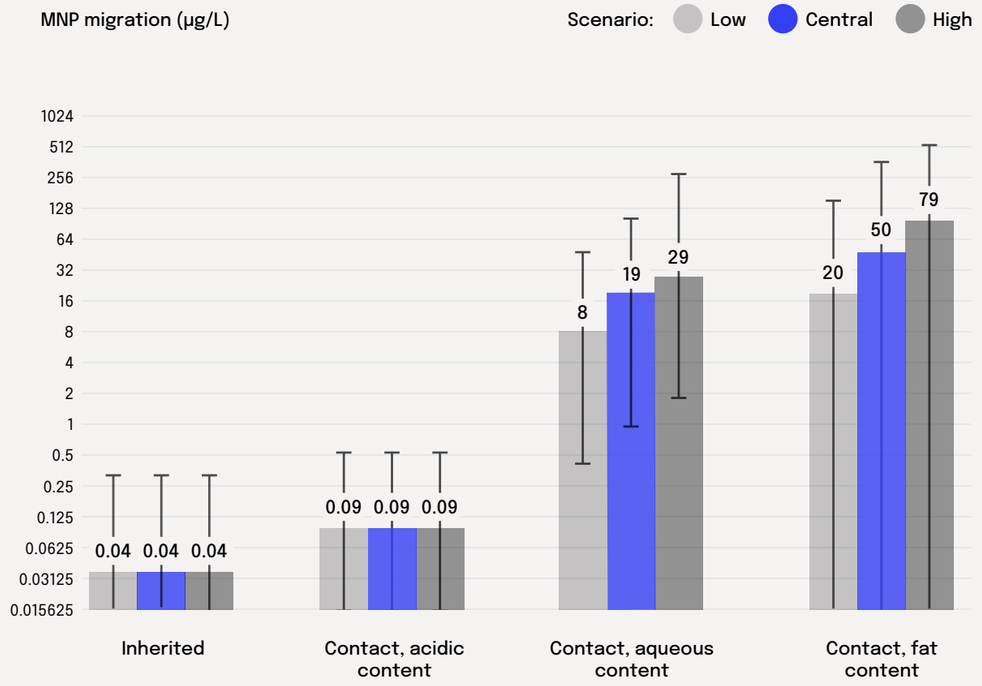
80% in contact with hot content (no data for hot acidic content)

Aggregated results and contribution analysis

Figure 23.
Aggregated MN emission estimates from rigid PS packaging across use scenarios and scales

Indicator	Low-emission scenario	Normal-use scenario	High-emission scenario
Per volume of product 1 L of packed product, in µg/L	28 (0.4 – 180)	68 (1 – 442)	109 (2 – 705)
Per weight of packaging 1 g of packaging, in µg/g	2 (0.03 – 12)	5 (0.07 – 29)	7 (0.1 – 47)
Global emission annual, world scale, in tons/year	1 (0.02 – 8)	3 (0.05 – 20)	5 (0.08 – 33)
Per capita emission annual, average consumption, in mg/person/year	0.2 (0.003 – 1)	0.4 (0.006 – 3)	0.6 (0.009 – 4)

Figure 24.
Contribution of mechanisms to MNP emissions from rigid PS packaging across low-, normal-, and high-use scenarios. Temperature was varied for the contact with aqueous content case.



Bars show scenario-based estimates of MNP release expressed in µg/L of packaged product (y-axis in $\log_2$ scale). The normal-use scenario is displayed with uncertainty ranges derived from data extraction and harmonisation of the literature. Low- and high-use scenarios illustrate plausible bounds associated with different intensities of use-related parameters. Differences across scenarios reflect sensitivity to use conditions and cumulative stresses rather than statistical uncertainty.

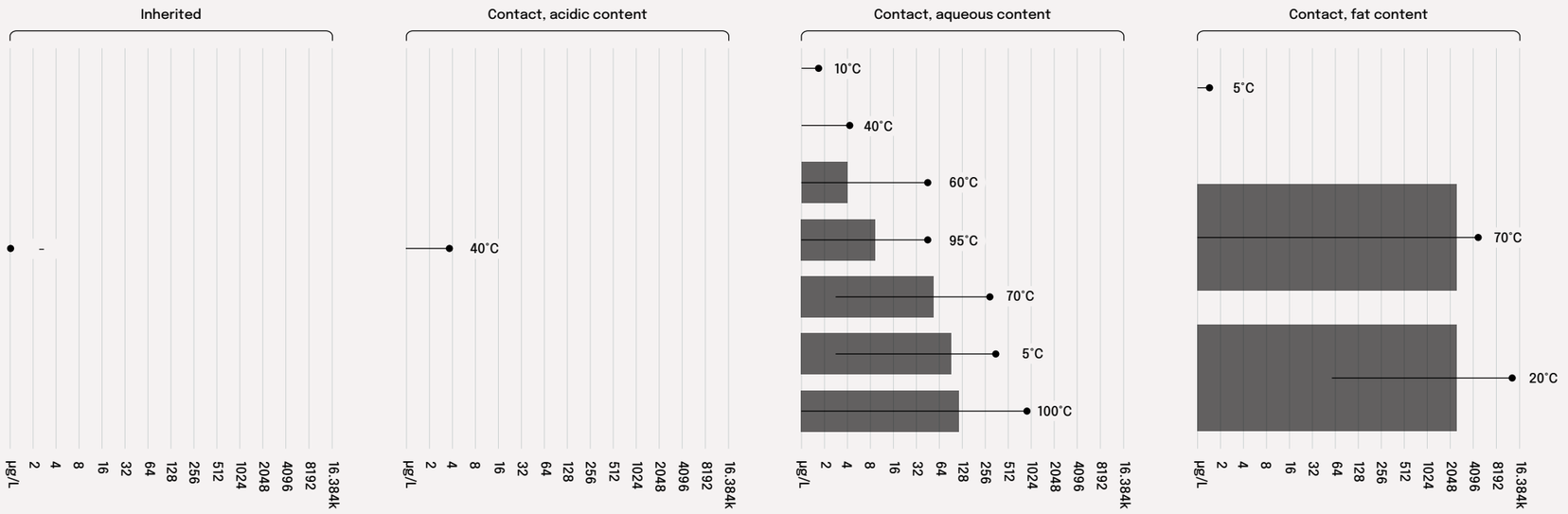


Figure 25.
Detailed contribution of mechanisms to micro- and MNP emissions from rigid PS packaging under different conditions.

Each panel represents a distinct mechanism. Each horizontal bar corresponds to a specific mechanism-parameter combination and shows the associated MNP emissions (µg/L of packaged product). Bars are ordered from top to bottom according to increasing cumulative stress, reflecting progressively more intensive use conditions. Error bars reflect uncertainty in the underlying studies.

Interpretation

Results per 1 L of packed product (functional unit 1) and per 1 g of packaging (functional unit 2)

Under the normal-use scenario, micro- and nanoplastic (MNP) emissions from rigid PS packaging into food is estimated at approximately **68 µg/L,** with a plausible range of **1–442 µg/L.** When expressed per mass of packaging, this corresponds to **5 µg/g of packaging,** with a plausible range of **0.07–29 µg/g.** The results are summarized in Figure 23.

Under low-emission conditions, MNP concentrations are lower, on the order of **28 µg/L,** corresponding to **2 µg/g of packaging**. Under high-emission conditions, cumulative stresses increase MNP release to approximately **109 µg/L,** or **7 µg/g of packaging.**

Scaling to global emissions from packaging into food

Extrapolating scenario-level estimates to global rigid PS packaging consumption suggests global emissions of approximately **3 tons of MNPs per year** under normal-use assumptions, with a plausible range of **0.05–20 tons per year** (Figure 23).

Under low-emission conditions, global emissions is estimated at **1 tonne per year**, while under high-emission conditions emissions increase to approximately **5 tons per year.**

Per-capita exposure

When translated into per-capita exposure, emissions from rigid PS packaging correspond to an average intake of approximately 0.4 mg per person per year under normal-use assumptions, with a plausible range of 0.006–3 mg/person/year (Figure 23).

Under low-emission conditions, per-capita exposure is estimated at 0.2 mg/person/year, while under high-emission conditions intake increases to approximately 0.6 mg/person/year.

Identification of dominant mechanisms and amplification potential

The contribution of each mechanism to MNP emissions across scenarios and the effects of cumulative stress for each mechanism are illustrated in Figures 23 and 24, respectively. Scenario-to-scenario variability in MNP release from rigid PS packaging is primarily driven by content type. Temperature may also play a role, although its effect is not conclusive, with inconsistent trends observed across scenarios. Further data are required to better understand this effect.

- → **Content type** influences MNP release from rigid PS packaging, with fatty contents tending to generate higher emissions than aqueous contents. This trend suggests stronger interactions between fatty matrices and the polymer surface, which may enhance particle detachment.
- → **Temperature influence MNP generation from rigid PS packaging.** MNP release generally increases with increasing temperature, reflecting accelerated polymer degradation and enhanced particle detachment. Notably, very low temperatures can also increase MNP release, as PS becomes more brittle under cold conditions, promoting fragmentation. These results indicate that both high and very low temperatures act as stressors, through distinct mechanisms.

The limited number of mechanisms investigated for rigid PS packaging constrains scenario variability. Additional stressors, such as mechanical abrasion or repeated handling, could potentially increase variability if explored in future studies.

CASE-STUDY TAKEAWAY

In rigid PS packaging, MNP emissions are primarily driven by content type, particularly fatty contents. Temperature also influences MNP emission, with both high and very low temperature increasing emissions through different mechanisms.

Recommendations. Do not use PS trays for hot food above 60°C. Avoid refrigerating fatty foods in PS containers for extended periods – cold temperatures increase PS brittleness and particle release.

(3) CASE STUDY

(3.9) Results for multilayer containers

Carton packaging coated with a plastic liner is widely used for hot beverage cups (e.g. coffee cups) or takeaway food containers. This type of packaging combines a paperboard structure, which provides rigidity and insulation, with a thin internal plastic lining that ensures liquid resistance and prevents migration.

Such packaging is designed for direct food and beverage contact, often under elevated temperature conditions, and is typically used for hot drinks or freshly prepared foods. Carton-based packaging with plastic liners therefore represents a common composite food-contact format in everyday consumer use.

Figure 26.
Key assumptions defining the low-emission, normal-use, and high-emission of multilayer containers.

Low-emission scenario

80% in contact with aqueous content

20% in contact with acidic content

20% in contact with hot content (aqueous, no data for hot acidic)

Normal-Use scenario

80% in contact with aqueous content

20% in contact with acidic content

50% in contact with hot content (aqueous, no data for hot acidic)

High-emission scenario

80% in contact with aqueous content

20% in contact with acidic content

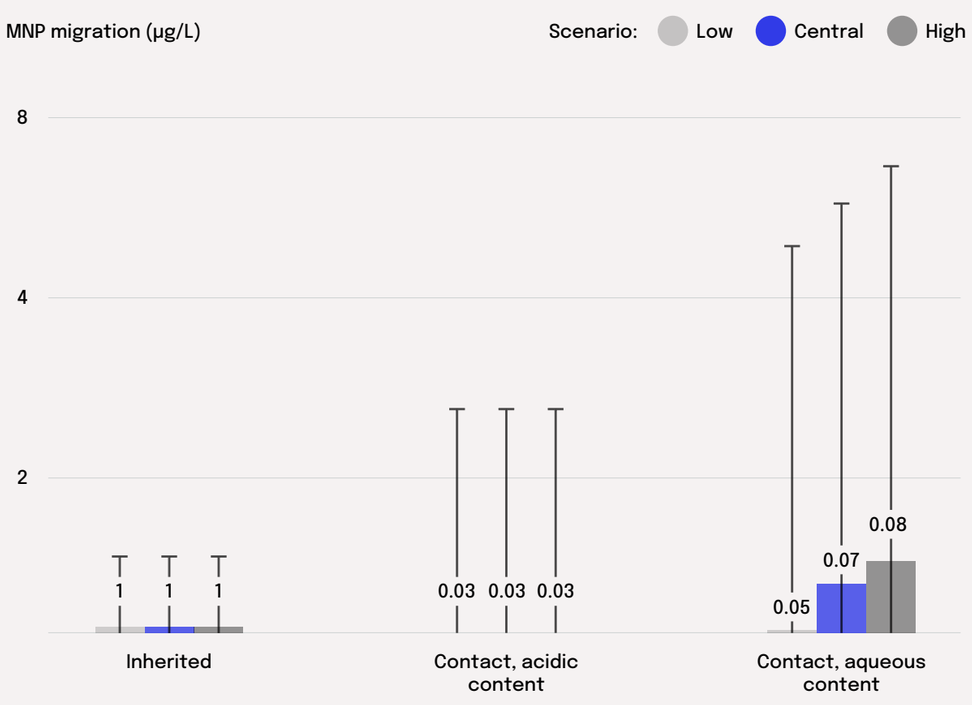
80% in contact with hot content (aqueous, no data for hot acidic)

Aggregated results and contribution analysis

Figure 27.
Aggregated MNP emission estimates from multilayer containers across use scenarios and scales

Indicator	Low-emission scenario	Normal-use scenario	High-emission scenario
Per volume of product 1 L of packed product, in µg/L	3 (0.9 – 9)	3 (0.9 – 10)	3 (0.9 – 11)
Per weight of packaging 1 g of packaging, in µg/g	0.5 (0.2 – 2)	0.6 (0.2 – 2)	0.6 (0.2 – 2)
Global emission annual, world scale, in tons/year	0.9 (0.3 – 3)	1.0 (0.3 – 4)	1 (0.3 – 4)
Per capita emission annual, average consumption, in mg/person/year	0.1 (0.04 – 0.4)	0.1 (0.04 – 0.4)	0.1 (0.04 – 0.5)

Figure 28.
Contribution of mechanisms to MNP emissions from multilayer contained across low-, normal-, and high-use scenarios. Temperature was varied for the contact with aqueous content case.



Bars show scenario-based estimates of MNP release expressed in µg/L of packaged product (y-axis in $\log_2$ scale). The normal-use scenario is displayed with uncertainty ranges derived from data extraction and harmonisation of the literature. Low- and high-use scenarios illustrate plausible bounds associated with different intensities of use-related parameters. Differences across scenarios reflect sensitivity to use conditions and cumulative stresses rather than statistical uncertainty.

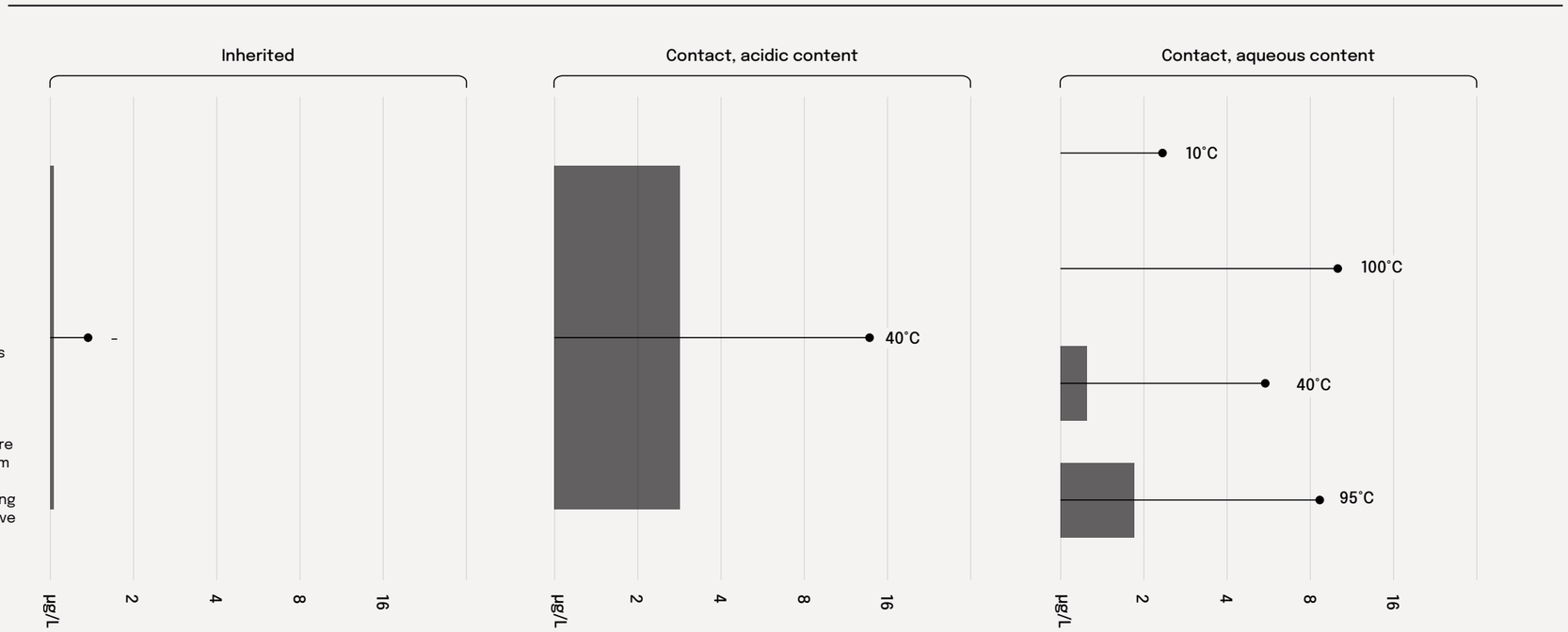


Figure 29.
Detailed contribution of mechanisms to micro- and MNP emissions from multilayer containers under different conditions.

Each panel represents a distinct mechanism. Each horizontal bar corresponds to a specific mechanism-parameter combination and shows the associated MNP emissions (µg/L of packaged product). Bars are ordered from top to bottom according to increasing cumulative stress, reflecting progressively more intensive use conditions. Error bars reflect uncertainty in the underlying studies.

Interpretation

Results per 1 L of packed product (functional unit 1) and per 1 g of packaging (functional unit 2)

Under the normal-use scenario, micro- and nanoplastic (MNP) emissions from coated carton containers into food is estimated at approximately **3 µg/L,** with a plausible range of **0.9–10 µg/L.** When expressed per mass of packaging, this corresponds to **0.6 µg/g** of packaging, with a plausible range of **0.2–2 µg/g.** The results are summarized in Figure 27.

Scaling to global emissions from packaging into food

Extrapolating scenario-level estimates to global coated carton packaging consumption suggests global emissions of approximately **1 tonne of MNPs per year** under normal-use assumptions, with a plausible range of **0.3–4 tons per year** (Figure 27).

Per-capita exposure

When translated into per-capita exposure, emissions from coated carton containers correspond to average intakes of approximately **0.1 mg per person per year** under normal-use assumptions, with a plausible range of **0.04–0.4 mg/person/year** (Figure 27).

Identification of dominant mechanisms and amplification potential

The contribution of each mechanism to MNP emissions across scenarios and the effects of cumulative stress for each mechanism are illustrated in Figures 27 and 28, respectively. Scenario-to-scenario variability in MNP release from coated carton containers appears limited, primarily because only a restricted set of use-related mechanisms has been investigated in the available literature.

→ **Temperature emerges** as the dominant driver among the mechanisms studied. Exposure to hot liquids or hot food increases MNP release by accelerating degradation and weakening of the plastic liner, facilitating particle detachment into the content. Despite this effect, temperature-driven amplification remains moderate compared to that observed for fully plastic packaging formats.

→ **Content chemistry** acts as a secondary modulating factor. Acidic contents tend to generate slightly higher MNP release than aqueous contents when in contact with plastic-lined carton packaging. While systematic, this effect remains limited in magnitude and does not substantially alter scenario-level outcomes.

The apparent stability of MNP release across scenarios reflects the limited diversity and intensity of stressors explored to date, suggesting that additional mechanisms (e.g. mechanical abrasion, repeated handling, or ageing) could potentially increase variability if investigated.

CASE-STUDY TAKEAWAY

In coated carton containers, MNP emissions show limited variability across reported scenarios, with temperature being the primary driver and content chemistry a secondary modulator.

Recommendations. Avoid filling coated carton containers with hot beverages. Note that acidic contents (e.g. fruit juices or coffee) may slightly increase MNP release compared to neutral liquids.

(3) CROSS ANALYSIS

(3.10) Cross-analysis: comparison across packaging formats and mechanisms

This section aggregates results across all selected case studies to enable systematic comparison between packaging formats and dominant generation mechanisms. The objective is to identify relative patterns, consistent hierarchies, and key drivers of variability across formats, rather than to provide format-specific detail already covered in the individual case studies.

Comparison across formats at the product level (Functional unit: per litre of packaged content)

Results are first compared using a **functional unit normalised to the amount of packaged product** (µg MNP per litre). This perspective is most relevant for **consumer exposure**, as it directly reflects the concentration of micro- and nanoplastics in the ingested product.

A heat map representation, shown in Figure 30, is used to visualise differences across packaging formats and use scenarios, highlighting:

- → relative emission levels under normal-use conditions,
- → the magnitude of amplification under high-emission scenarios,
- → contrasts with low-emission conditions.

The parameters underpinning the different scenarios are documented in the corresponding case studies, along with their associated uncertainty ranges. This representation facilitates rapid comparison across packaging formats and highlights those consistently associated with higher or lower emissions per unit of consumed product.

Figure 30. Heat map of scenario-based MNP emissions per litre of packaged product across packaging formats.

Results are shown for a combined case integrating low- (1/6), normal- (2/3), and high-emission (1/6) use scenarios, reflecting different intensities of use-related stress (e.g. irradiation, storage duration, and handling conditions). Values in brackets indicate the uncertainty range. Blank cells indicate that the scenario is not relevant for the given format or that no value has been reported in the literature. For contact mechanisms (aqueous, acidic, fatty), both temperature effects and product-related effects are assessed.

MNP emissions span a wide range across packaging formats and mechanisms.
Across the full dataset, central estimates of MNP emissions per litre of packaged product range from approximately 0.01 µg/L to several $\times 10^3$ µg/L, with uncertainty ranges spanning multiple orders of magnitude depending on packaging format and use-related stressors.

Rigid food packaging exhibits the highest central emission levels.
Rigid food packaging formats show the highest format-level central values when emissions are aggregated across mechanisms. Rigid PET displays central estimates on the order of ~760 µg/L, followed by rigid PP at approximately ~720 µg/L, while rigid PS remains lower, with a central value around ~70 µg/L. For these formats, ranges are wide, reflecting strong sensitivity to use-related conditions.

PET bottles and flexible PE packaging show intermediate central emission levels.
For PET bottles and flexible PE packaging, central values are in the order of several tens to several hundreds of µg/L per litre of packaged product. Their associated ranges extend from near-background levels to several hundred µg/L, indicating substantial variability across use conditions while remaining lower than rigid formats on average.

Multilayer packaging consistently exhibits the lowest emissions.
Multilayer packaging formats show low central values, typically in the range of ~1–3 µg/L, with comparatively narrow ranges, indicating limited MNP release per unit volume of packaged product across the considered conditions.

Multiple mechanisms contribute to total emissions, with distinct uncertainty profiles.
Total MNP emissions reflect the combined contributions of inherited sources (upstream and production-related) and use-phase mechanisms. Among use-related mechanisms, irradiation-driven ageing emerges as the dominant contributor to elevated central values and upper-value outcomes when applicable. Stacking represents an additional contributor in relevant packaging-food combinations, while other mechanisms generally contribute at lower central levels.

Central values reflect a weighted mix of use conditions.
Reported central estimates correspond to a combined representation of use scenarios, as described in the figure caption, while the ranges capture uncertainty arising from variability in use-related stress intensity, material properties, and data availability.

Comparison across formats at the packaging level (Functional unit: per g of packaging material)

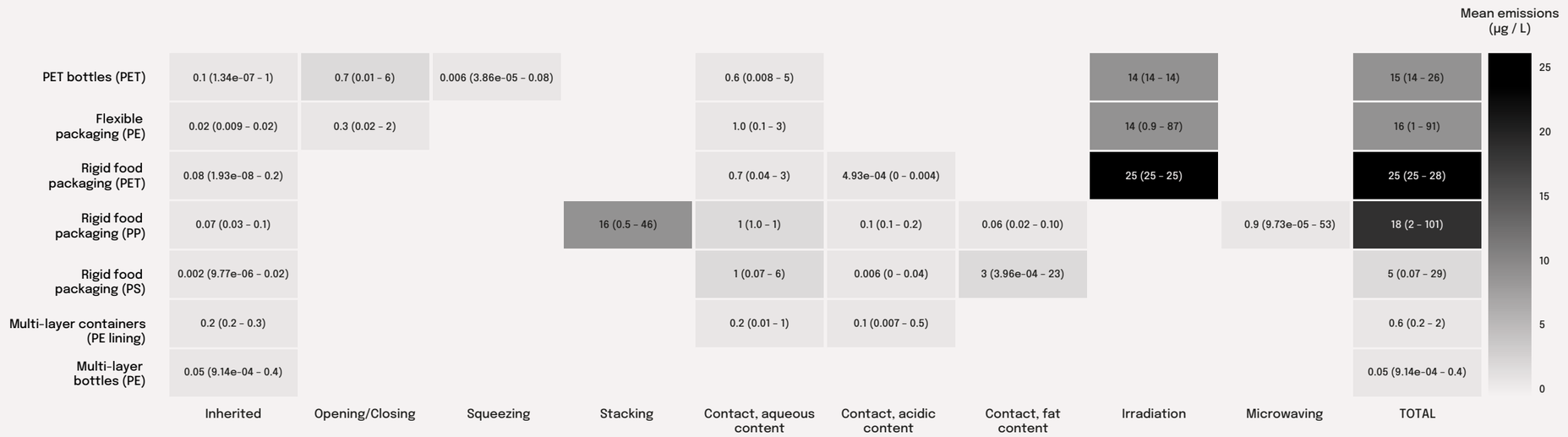
Results are then compared using a **functional unit normalised to packaging mass** (µg MNP per g of packaging). This perspective provides insight into **emission intensity relative to the amount of packaging material involved,** and supports comparison of formats with different material efficiencies and content-to-packaging ratios.

The corresponding heat map, shown in Figure 31 highlights:
- → differences in emission intensity per unit of packaging,
- → the influence of design and material properties,
- → contrasts between lightweight and more material-intensive formats.

This view complements the product-based functional unit and helps disentangle material efficiency effects from exposure-driven effects.

Figure 31. Heat map of scenario-based MNP emissions per g of packaging across packaging formats.

Results are shown for a combined case integrating low- (1/6), normal- (2/3), and high-emission (1/6) use scenarios, reflecting different intensities of use-related stress (e.g. irradiation, storage duration, and handling conditions). Values in brackets indicate the uncertainty range. Blank cells indicate that the scenario is not relevant for the given format or that no value has been reported in the literature. For contact mechanisms (aqueous, acidic, fatty), both temperature effects and product-related effects are assessed.



The relative ranking of packaging formats is broadly preserved across the two functional units, with **rigid food packaging exhibiting the highest central emission levels, flexible packaging and bottles showing intermediate values,** and **multilayer structures remaining the least emissive.**

Use-related mechanisms play a key role in shaping emission levels across both functional units. Contributions span multiple life-cycle stages, including an upstream and production-related fraction reflected in the inherited component, as well as use-phase mechanisms influenced by several interacting variables. Among these, **irradiation-driven ageing consistently emerges as the dominant contributor to elevated central values and upper-value outcomes** when applicable. Stacking represents an additional relevant contributor for specific packaging-food combinations, while other mechanisms generally contribute at lower central levels.

Expressing results per gram of packaging further highlights the role of **material-level emission intensity,** independently of packaging mass. For example, **flexible PE packaging exhibits relatively high central emission intensities when expressed per unit mass,** with a total central value of approximately **16 µg/g_pack** (range: ~1–91 µg/g), while remaining at intermediate levels when expressed per litre of packaged product. In contrast, **rigid PET food packaging shows a higher material-level intensity,** with a central value of approximately **25 µg/g_pack** (range: ~25–28 µg/g), which—combined with its higher packaging mass per unit of product—translates into substantially higher emissions per litre of packaged content.

These contrasts illustrate the combined influence of **intrinsic material emission intensity** and **packaging mass-to-product ratios** in determining overall micro- and nanoplastic (MNP) release into food and beverages. While results are presented here at the level of individual packaging formats, these intensities are subsequently scaled using quantities of packaging placed on the market to estimate **aggregate emissions under realistic consumption patterns.**

Scaling to annual global emissions (World scale)

Building on the functional unit–level results, emissions are aggregated to **annual global totals** for each packaging format. This representation highlights which packaging formats contribute most to **overall MNP emissions at the global scale,** taking into account both emission intensity and total volumes placed on the market.

Packaging	Global volume of packaging, in kilotons (Plasteax)[4]	MNP emissions per gram of packaging (µg/g)	MNP emissions, in tons
PET bottles	19,165	15 (14–26)	292 (263–498)
Flexible packaging (PE)	8,900	16 (1–91)	139 (9–812)
Rigid packaging (PET)	6,130	25 (25–28)	155 (151–173)
Rigid packaging (PP)	5,643	18 (2–101)	101 (9–567)
Rigid packaging (PS)	692	5 (0.07–29)	3 (0.05–20)
Multilayer containers (PE lining)	1,785	0.6 (0.2–2)	1 (0.3–4)
Multilayer bottles (PE)	766	0.05 (0.001–0.4)	0.04 (0.001–0.3)
Total covering 66% of global food packaging volume			**692 (433 – 2,074)**
Total extrapolated for 100% of global food packaging volume			**1,050 (657–3,146)**

Figure 32. Global volumes of selected food packaging formats (in kilotons) are based on PLASTEAX data and represent approximately 66% of total global food packaging placed on the market. Central estimates of micro- and nanoplastic (MNP) emissions per gram of packaging are reported together with their uncertainty ranges in brackets. Total MNP emissions (in tons) are obtained by multiplying format-specific emission intensities by corresponding global packaging volumes. The final two rows report (i) the aggregated MNP emissions for the packaging formats explicitly covered in this assessment (66% coverage), and (ii) an extrapolated estimate for 100% of global food packaging volume, assuming comparable emission intensities for uncovered formats. All values correspond to central estimates with associated uncertainty ranges.

When format-level emission intensities are scaled to the quantities of packaging placed on the market, results can be expressed as **annual global micro- and nanoplastic (MNP) emission fluxes** (t/year). This market-level perspective reveals how differences in both **intrinsic emission intensities** and **production volumes** jointly determine global MNP contributions from food packaging.

Based on the packaging formats explicitly analysed in this study–covering approximately **66% of the global food packaging market** according to Plasteax estimates–total global MNP emissions into food are estimated at a **central value of approximately 692 t/year,** with an **uncertainty range of 433–2,074 t/year.** These values reflect **volume-weighted emission fluxes** derived from central emission intensities per gram of packaging, rather than temporal trends or scenario progression.

Once weighted by market volumes, packaging formats with **large production volumes dominate global emission fluxes,** even when their material-level emission intensities are moderate. PET bottles, flexible PE packaging, and rigid PET food packaging emerge as the largest contributors at the global scale, together accounting for the majority of estimated emissions. In contrast, rigid PP and PS packaging contribute more modestly, **while multilayer packaging formats remain marginal contributors,** owing to both low emission intensities and smaller market volumes.

To estimate emissions for the entire food packaging sector, results were **linearly extrapolated to 100% market coverage**, assuming proportionality between packaging volumes and MNP emissions. Applying this extrapolation yields an estimated **total global MNP emission flux of approximately 1,050 t/year,** with an associated **uncertainty range of 657–3,146 t/year.** These values should be interpreted as **first order-of-magnitude estimates,** acknowledging that the remaining 34% of packaging formats not explicitly covered may exhibit different emission profiles.

Overall, these results demonstrate that **combining format-level emission intensities with realistic market volume data is essential** to assess global MNP emission fluxes from food packaging. Scaling from laboratory- and format-level intensities to market-level quantities substantially reshapes the relative contribution of different packaging formats, highlighting the dominant role of high-volume packaging systems in driving global MNP emissions into food.

Scaling to per-capita exposure (Individual scale)

Results are further scaled to **typical yearly per-capita exposure.** This analysis combines scenario-based emission estimates with global population to derive yearly per-capita exposure. The results (Figure 33) illustrates how exposure varies across packaging formats, even when global emissions are similar.

Packaging	Average consumption, in mL/person/day	Average consumption, in L/person/year	MNP emissions, in µg per L of packaging	MNP emissions, in mg/person/year
PET bottles	330	120	305 (275-520)	36 (33-62)
Flexible packaging (PE)	610	223	78 (5-456)	17 (1-101)
Rigid packaging (PET)	70	26	760 (738-844)	19 (19-22)
Rigid packaging (PP)	50	18	719 (67-4,022)	13 (1-71)
Rigid packaging (PS)	15	6	68 (1-442)	0.4 (0.01-3)
Multilayer containers (PE lining)	120	45	3 (1-10)	0.1 (0.04-0.4)
Multilayer bottles (PE)	8	3	2 (0.03-13)	0.004 (0.0001-0.4)
Total covering 66% of global food packaging volume				**87 (54 - 260)**
Total extrapolated for 100% of global food packaging volume				**131 (82-393)**

Figure 33. Estimated annual per-capita micro- and nanoplastic (MNP) exposure associated with food packaging, by packaging format and consumption profile. Exposure estimates are derived by combining format-specific MNP emission intensities per litre of packaged product with representative average consumption volumes (expressed in litres per person per year). Central values represent a weighted mix of use conditions, while values in brackets indicate the uncertainty range. Totals are reported for packaging formats covering 66% of global food packaging volumes, as well as for an extrapolation to 100% market coverage, assuming proportionality between packaging volumes and emissions.

The estimated per-capita intake of micro- and nanoplastics (MNP) from food packaging is approximately ~**130 mg/person/year,** extrapolated to 100% of global food packaging volumes. Expressed in terms of particle numbers for illustrative purposes, this corresponds to roughly **5×10^8 particles** assuming half-spherical particles with a 10 µm diameter and a density of 1 g/cm³. Depending on particle size, the plausible range spans from ~1.5×10^8 particles at 15 µm to ~4×10^9 particles at 5 µm. These estimates are indicative only and depend strongly on particle size assumptions.

When translating market-level emission fluxes into per-capita intake estimates, results indicate that MNP exposure from food packaging spans more than one order of magnitude across packaging formats, reflecting differences in both emission intensities per litre and consumption volumes. Based on the packaging formats explicitly covered in this analysis (≈66% of global food packaging volumes), the central estimate of per-capita intake is approximately 87 mg/person/year, with an uncertainty range of 54-260 mg/person/year. Linear extrapolation to full market coverage yields a **central estimate of approximately ~130 mg/person/year (82-393 mg/person/year).** For consumers with higher-than-average packaging use – such as in highly developed consumption contexts – intake may increase by multiple-fold, **potentially exceeding 1 g/person/year in worst-case conditions,** corresponding to substantially higher particle numbers.

At the level of individual packaging formats, **PET bottles represent the largest contributor to per-capita intake,** driven primarily by high consumption volumes, with a central estimate of approximately **36 mg/person/year** (range: 33-62 mg/person/year). This is followed by rigid PET food packaging at approximately **19 mg/person/year** (range: 19-22 mg/person/year) and flexible PE packaging at approximately **17 mg/person/year** (range: 1-101 mg/person/year). Rigid PP and PS packaging contribute more modestly, while **multilayer packaging formats contribute negligibly** to overall per-capita intake owing to both low emission intensities and lower consumption volumes.

These patterns mirror those observed at the global emission level, underscoring that **per-capita exposure is primarily driven by the combination of market prevalence and emission intensity.** Packaging formats that are both widely consumed and associated with moderate-to-high emission intensities dominate estimated intake, even when their per-unit emissions are not the highest.

Overall, the per-capita intake estimates provide a **first order-of-magnitude indication of potential human exposure to MNPs from food packaging,** complementing global emission flux estimates and enabling contextualisation of results at the individual scale under realistic consumption patterns.

It is worth noting that a previous study published by WWF [7] reported substantially higher estimates of human MNP intake from food, suggesting the equivalent of consuming a credit card (5 g) per week. However, these numbers appear to be overestimated.[8] Very large particle sizes were assumed (1.5 mm), which strongly increase mass due to the cubic relationship between particle diameter and weight. In contrast, our assessment accounted for particle size distributions reported in the literature, resulting in more realistic estimates of MNP intake.

CROSS-ANALYSIS TAKEAWAY

When results are compared across formats and use scenarios, a small number of packaging types and stress conditions account for a disproportionate share of potential exposure. This concentration effect means that targeted interventions can achieve meaningful exposure reduction without system-wide redesign.

(3) PERSPECTIVES

(3.11) Perspective on other packaging related sources of microplastics

This section places the results of the packaging-focused analysis in a broader **life-cycle and exposure context.** It compares micro- and nanoplastic (MNP) emissions associated with **food-contact packaging** to other major plastic- and packaging-related sources across the life cycle, including :

- → pellets emissions from food plastic packaging **production**
- → **transport-related abrasion** (tyre wear)
- → environmental leakage from **mismanaged** food plastic packaging waste,
- → and leakage from plastic **recycling processes.**

The results are shown in Figure 34. The objective is **not to establish an exhaustive or definitive ranking of sources,** but to **provide order-of-magnitude benchmarks** that help interpret the relative contribution of packaging-related emissions. Particular attention is paid to differences in **exposure routes, proximity to consumers,** and **degrees of controllability,** as these factors strongly influence the relevance of a given source for human exposure. Accordingly, this section explicitly distinguishes between **total environmental emissions** and **direct human exposure pathways,** clarifying why sources that dominate global microplastic leakage do not necessarily dominate ingestion-related exposure.

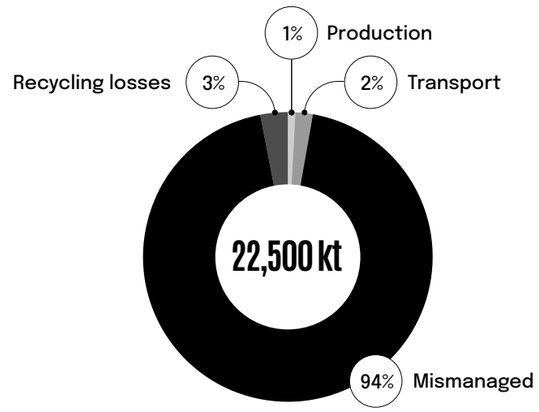


Figure 34. Order-of-magnitude comparison of environmental micro- and nanoplastic (MNP) emissions from food packaging and other major plastic- and packaging-related sources across the life cycle.

Packaging-related environmental emissions into food are estimated at approximately **1,050 t/year** (657–3,146 t/year). These fluxes are **several orders of magnitude lower** than global microplastic emissions attributed to major diffuse sources such as tyre wear, synthetic textiles, or mismanaged plastic waste, which dominate environmental leakage by mass at the global scale.

However, **mass-based comparisons alone are insufficient to assess relevance for human exposure.** Unlike diffuse environmental sources, packaging-related MNP emissions occur via a **direct exposure pathway,** with particles released **directly into food and beverages at the point of consumption.** In addition, packaging-related emissions are characterised by a **high abundance of very small particles,** for which **particle number–rather than mass–is a more relevant metric** when considering potential health implications.

Consistent with the per-capita intake analysis, an estimated ~**131 mg/person/year** of MNP intake corresponds to **hundreds of millions to several billion particles per year,** depending on assumed particle size. This highlights why **relatively modest mass fluxes from packaging can still be highly relevant from an exposure perspective,** particularly when compared with sources that dominate environmental release but contribute only indirectly to dietary intake.

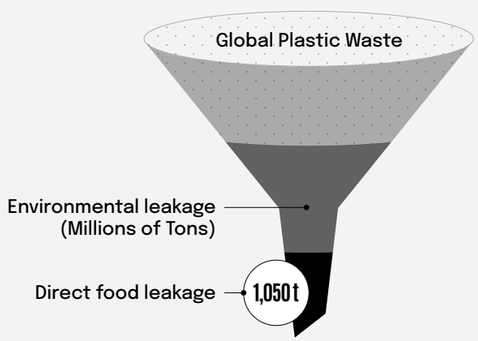
More broadly, food represents a key vector for human ingestion of microplastics, with particles originating from environmental contamination of raw materials, processing and handling, and contact with food-contact materials, including packaging. Packaging-related MNPs differ from many environmental microplastics in that they are generated **at the food–material interface,** often immediately prior to consumption, thereby limiting dilution and bypassing several environmental transport pathways.

Other plastic-related sources may nevertheless exert a **cumulative effect** on human exposure by increasing background environmental concentrations of MNP, which can subsequently enter food through secondary pathways (e.g. air deposition, water contamination, or agricultural uptake). Packaging-related emissions should therefore be interpreted **not in isolation,** but as **one controllable component within a broader, cumulative exposure landscape.**

Within this landscape, packaging-related MNP exposure occupies an **intermediate position:** it is **not dominant in terms of total environmental mass,** but it is **direct, widespread, recurrent, and comparatively actionable.** Packaging materials, designs, and use conditions are deliberately chosen, regulated, and modifiable, making packaging a **practical leverage point for exposure reduction,** even if it represents only a fraction of total microplastic emissions.

The purpose of this comparison is therefore **not to minimise packaging-related exposure by pointing to larger sources elsewhere,** but to clarify **where intervention is feasible and proportionate.** While this section positions packaging-related MNP emissions within the broader exposure landscape, it does not address health outcomes. The following section examines the **health relevance of micro- and nanoplastics,** and clarifies what can–and cannot–be concluded given current evidence.

Figure 35. Global scale: low mass, high relevance



Why 1,050 tons matters:

- → **No dilutions.** Unlike ocean plastic, these particles enter the food stream at the exact point of consumption.
- → **Source mutliplicity.** Tens of billions of packaging units act as individual emission sources.
- → **Cumulative impact.** A small release per unit x Billions of units = Massive human exposure.

(3) PERSPECTIVES

(3.12) Perspective on health relevance

Assessing the health relevance of micro- and nanoplastics (MNP) remains scientifically challenging, due to major uncertainties in hazard characterisation, exposure metrics, and dose–response relationships, particularly for nanoplastics. This section therefore does not attempt to quantify health risks or attribute disease outcomes. Instead, it adopts a comparative exposure perspective, situating packaging-related MNP exposure alongside established packaging-related health concerns, notably exposure to intentionally added substances (IAS) and non-intentionally added substances (NIAS).

The objective is not to rank risks, but to examine whether the levels, characteristics, and pathways of packaging-related MNP exposure identified in this report raise health-relevant questions comparable in nature or magnitude to those already recognised for IAS and NIAS. In doing so, the section focuses on exposure routes, metrics, and biological interaction mechanisms, rather than on disease attribution.

MNP and IAS/NIAS : shared origin and coupled exposure pathways

A key feature of packaging-related MNP exposure is that particles and chemicals originate from the same materials. MNP are generated from polymer matrices that contain complex mixtures of IAS, NIAS, degradation products, and impurities. As a result, particle exposure and chemical exposure are inherently coupled, rather than independent pathways.

This coupling has two important implications. First, exposure to MNP typically occurs concurrently with exposure to plastic-associated chemicals, rather than as a separate phenomenon. Second, MNP may act as local carriers or vectors for associated chemicals, potentially modifying exposure conditions at biological interfaces such as the gastrointestinal epithelium. In this sense, MNP do not introduce an entirely new category of concern, but rather represent a particle-mediated extension of an already complex chemical exposure landscape associated with food-contact materials.

Exposure metrics: mass versus particle number

IAS and NIAS exposure is traditionally assessed using mass-based metrics (e.g. µg/kg body weight/day), reflecting dissolved chemical concentrations. Packaging-related MNP exposure challenges this paradigm. While global mass-based emission fluxes from packaging are modest relative to major environmental sources, MNP exposure is characterised by a very high number of small particles.

Consistent with the per-capita intake analysis presented in this report, an estimated ~131 mg/person/year of packaging-related MNP intake corresponds to hundreds of millions to several billion particles per year, depending on assumed particle size. This demonstrates why particle number, size distribution, and surface properties are critical exposure descriptors, and why comparisons based solely on mass can be misleading when evaluating potential biological relevance.

Order-of-magnitude linkage to IAS/NIAS exposure. Beyond metric differences, an additional reason to consider MNP alongside IAS/NIAS is that particle exposure implies co-exposure to the chemicals present in, or associated with, the polymer matrix. For example, a study [9] suggests that an ingestion level of approximately 150 million particles, corresponding to roughly 100–200 mg of MNP mass, could be associated with an IAS/NIAS mass on the order of ~50 mg. While such a ratio does not inform toxicity or risk on its own, it provides an order-of-magnitude benchmark indicating that particle ingestion may be accompanied by non-negligible co-exposure to complex chemical mixtures, reinforcing the systemic nature of packaging-related exposure.

Biological interaction: particles versus dissolved chemicals

IAS and NIAS primarily exert biological effects through molecular interactions, including receptor binding, enzyme interference, and endocrine disruption. MNP, by contrast, may interact with biological systems through additional particle-specific mechanisms, including physical interaction with tissues, uptake by immune cells, local inflammatory responses, and particle-mediated transport of associated chemicals.

Across toxicology and particle science, there is strong evidence that particle size is a primary determinant of biological interaction. Larger microplastics tend to remain localised in the gastrointestinal tract and are largely excreted. In contrast, smaller particles are more reactive and interact more readily with biological systems. Experimental studies indicate that particles below approximately 150 µm can cross the intestinal barrier, while nanoplastics (<1 µm) are more consistently shown to enter circulation, interact with tissues, and be taken up by cells.

In this assessment, most packaging-related particles identified fall within the microplastic size range but largely below 150 µm, i.e. within size ranges compatible with uptake pathways described in the literature. In the limited number of studies detecting smaller micro- and nanoplastics, reducing analytical detection limits leads to a sharp increase in particle numbers and, despite the cubic relationship between size and mass, also to higher total mass. This indicates that small particles can dominate exposure metrics when they are captured analytically.

Uncertainty is highest precisely where potential biological relevance is greatest, namely for the smallest particles, which remain the most difficult to measure robustly.

Framing packaging-related MNP exposure requires recognising that:

- → Particle size and number are critical to understanding potential biological interaction, with smaller particles having greater potential for uptake and interaction.
- → Packaging is a direct and recurrent ingestion pathway for MNP exposure, with particle exposures spanning orders of magnitude in number and potentially interacting with co-exposed chemical contaminants.
- → Given the current limitations of toxicological evidence in humans, precautionary measures that reduce exposure – through material choice, design changes, and management of use conditions – are proportionate and consistent with established public health approaches without asserting definitive harm at this stage.

Indicative biological signals and convergence with IAS/NIAS effects

Although robust dose-response relationships are not yet available, experimental studies provide signals of biological relevance for particle exposure. For example, animal studies have shown that repeated oral exposure to microplastics at concentrations on the order of 100–1 000 µg/L can alter gut microbiota composition and induce metabolic disturbances after several weeks of exposure. While such studies cannot be directly extrapolated to human dietary exposure, they indicate that plastic particles are not biologically inert at environmentally relevant concentrations.

Notably, the biological endpoints affected in these studies—such as gut microbiota composition and metabolic regulation—are also well documented targets of IAS and NIAS exposure. This convergence suggests that MNP should not be viewed as an unrelated hazard, but rather as a complementary exposure pathway that may act on similar biological systems through different modes of action. In this context, MNP exposure may overlap with, modulate, or potentially amplify chemical-related effects, rather than replace them.

Regulatory asymmetry and knowledge gaps

A critical distinction between IAS/NIAS and MNP lies in their regulatory treatment. IAS and NIAS are, at least in principle, addressed within substance-based safety assessment frameworks, despite recognised gaps—particularly for NIAS, degradation products, and mixture effects. MNP, by contrast, fall largely outside existing food-contact material safety frameworks, even though they arise from the same materials and use conditions.

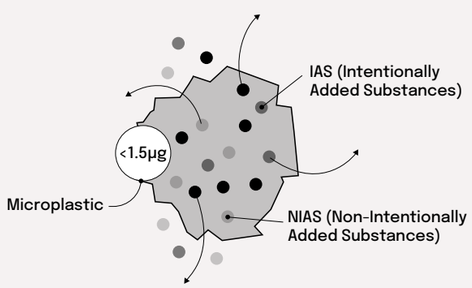
This regulatory asymmetry does not reflect an absence of potential relevance, but rather the limited suitability of current assessment frameworks to address particle-based exposure. As a result, MNP exposure represents a structural blind spot within packaging safety governance, rather than a marginal or speculative concern.

Implications for interpretation and precaution

The comparison between MNP and IAS/NIAS does not imply that particle exposure is more hazardous than chemical exposure from packaging. Instead, it highlights that packaging-related MNP exposure is direct, widespread, and recurrent, involves particle-specific interaction pathways, and originates from materials already associated with complex chemical exposure.

In such a context, uncertainty should not be interpreted as evidence of safety. Where exposure is widespread, involuntary, and plausibly relevant, precautionary approaches focusing on exposure reduction—through material choice, design, and use-condition management—are proportionate and consistent with established chemical safety principles.

Figure 36. MNPs do not travel alone



The link between physical particles and chemical toxicity

- → **The Vector Effect.** Ingesting ~131 mg of plastic implies co-exposure to tens of milligrams of associated chemicals.
- → **Biological Relevance.** Small particles can cross intestinal barriers, creating a coupled problem of physical presence + chemical cocktail.

(4)

APPENDICES – METHODS, ASSUMPTIONS, AND ANALYTICAL FRAMEWORK

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(4) APPENDIX

(4.1) Appendix 1 - Literature coverage and database

Purpose and scope

This appendix documents the scientific literature underpinning the analysis presented in the report. It provides transparency on which studies were included, what types of packaging and mechanisms were covered, and where evidence gaps remain.

The literature review focuses on experimental studies reporting the generation of micro- and nanoplastics (MNP) from packaging materials into food along its life-cycle.

Literature identification and screening

Studies were identified through:
- targeted database searches (e.g. Web of Science, Scopus),
- citation tracking from recent reviews on food-contact materials and microplastics,
- and expert knowledge within EA's plastics programme.

Studies were screened based on:
- relevance to packaging or food-contact materials,
- explicit reporting of particle generation or release,
- sufficient methodological transparency to allow interpretation.

Selection criteria:
- Particle size distribution reported, or sufficient information provided to enable particle mass estimation
- Cross-contamination explicitly assessed and controlled
- Results expressed per unit of product volume (non-exclusive criterion)
- Multiple samples tested (non-exclusive criterion)
- Multiple experimental conditions tested (e.g. temperature, repeated use cycles) (non-exclusive criterion)

Coverage overview
The reviewed literature covers:
- Packaging formats: bottles, rigid containers, flexible packaging, multilayer materials
- Polymers: PET, PP, PE, PS, and composites
- Life-cycle stages: packaging production and handling prior to product filling (inherited micro- and nanoplastics), post-filling transport, distribution, and storage of the packaging-product system, consumer use (opening and closing, routine handling, exposure to temperature changes, and light)
- Particle sizes: predominantly microplastics; limited but growing evidence on nanoplastics

Identified gaps
Coverage is uneven across packaging formats and life-cycle stages. Key gaps in the literature include:
- Limited data on nanoplastics, largely due to methodological constraints in plastic identification, characterisation, and quantification
- Inconsistent reporting metrics across studies, limiting comparability
- Scarcity of studies reporting particle mass, or providing sufficient information to enable reliable mass estimation
- Underrepresentation of certain packaging types, resulting in uneven coverage across formats (e.g. non-PET bottles, flexible packaging)

Literature database

Figure 37. Overview of reviewed studies

Authors	Year	Title	Packaging type	Mechanism tested	Number of tested samples	Particle size range	Metric	Key limitations
Ajaj et al.	2021	An Insight into the Growing Concerns of Styrene Monomer and Poly(Styrene) Fragment Migration into Food and Drink Simulants from Poly(Styrene) Packaging	Rigid PS	· Thermal stress (hot content) · Product-packaging interaction	7	5 - 100 µm	particles/cm²	average size indicated, no size distribution
Caponigro et al.	2025	Evaluating microplastic emission from takeaway containers: A Micro-Raman approach across diverse exposure scenarios	· Rigid PET · Rigid PP · Rigid PS	· Thermal stress (hot content) · Product-packaging interaction	54	5 - 100 µm	particles/container	
Chen	2023	Release of microplastics from disposable cups in daily use	· Rigid PP · Rigid PS · Rigid coated paper	· Thermal stress (hot content) · Product-packaging interaction	90	5 - 10 µm	particles/L	
Deng	2022	Microplastics released from food containers can suppress lysosomal activity in mouse macrophages	· Rigid PET · Flexible PE · Rigid PP · Rigid PS	Thermal stress (hot content)	4	200 - 800 nm	particles/mL	small number of samples
Fadare	2020	Microplastics from consumer plastic food containers: Are we consuming it?	Rigid PP	Mechanical stress (stacking)	65	10–210 nm	mg/container	
Fang	2024	Investigating microplastics and nanoplastics released from food bag ziplock using SEM and Raman imaging	Flexible PE	Mechanical stress (opening/closing)	3	1 - 20 µm	particles/mm	small number of samples
Giese	2021	A Preliminary Study of Microplastic Abrasion from the Screw Cap System of Reusable Plastic Bottles by Raman Microspectroscopy	PET bottles	Mechanical stress (opening/closing)	1	10 - 500 µm	particles/L	small number of samples
Guo	2024	Migration testing of microplastics from selected water and food containers by Raman microscopy	· Rigid PP · Rigid PET · Rigid PS	· Thermal stress (hot content) · Product-packaging interaction	6	1 - 20 µm	particles/L	33 to 50% of the particles could not be identified
Hagelskjaer	2025	Majority of potable water microplastics are smaller than the 20 µm EU methodology limit for consumable water quality	PET bottles	Inherited	10	1 - 30 µm	particles/L	
He	2021	Migration of (non-) intentionally added substances and microplastics from microwavable plastic food containers	Rigid PP	Thermal stress (microwaving)	13	1 - 50 µm	particles/L	

Authors	Year	Title	Packaging type	Mechanism tested	Number of tested samples	Particle size range	Metric	Key limitations
Hu	2022	Analysis of microplastics released from plastic take-out food containers based on thermal properties and morphology study	· Rigid PP · Rigid PS · Rigid coated paper	Thermal stress (hot content)	6	0.8 - 38 µm	particles/L	small number of samples
Huang	2022	Quantification of microplastics released from plastic food containers during rinsing and migration by pyrolysis-gas chromatography/mass spectrometry	· Rigid PP · Rigid PET · Rigid coated paper · Flexible PE	· Thermal stress (hot content) · Product-packaging interaction	10	1 - 20 µm	µg/dm²	
Kankanige	2020	Smaller-sized micro-plastics (MPs) contamination in single-use PETbottled water in Thailand	PET bottles	Inherited	95	6.5 - 100 µm	particles/L	
Kedzierski	2020	Microplastic contamination of packaged meat: Occurrence and associated risks	Rigid PS	Product-packaging interaction	12	0.8 - 100 µm	mg/kg	
Lin	2022	Detecting the release of plastic particles in packaged drinking water under simulated light irradiation using surface-enhanced Raman spectroscopy	· PET bottles · Rigid PET	Irradiation	150	100 - 1,000 nm	ng/mL	
Ossmann	2018	Small-sized microplastics and pigmented particles in bottled mineral water	PET bottles	Inherited	32	1 - 100 µm	particles/L	
Schymanski	2018	Analysis of microplastics in water by micro-Raman spectroscopy: Release of plastic particles from different packaging into mineral water	PET bottles	Inherited	22	20 - 100 µm	particles/L	
Sun	2022	The surface degradation and release of microplastics from plastic films studied by UV radiation and mechanical abrasion	Flexible PE	Irradiation	2	1 - 20 µm	particles/cm²	
Taheri	2023	Investigating the pollution of bottled water by the microplastics (MPs): the effects of mechanical stress, sunlight exposure, and freezing on MPs release	PET bottles	Inherited	23	1 - 20 µm	particles/L	
Vega-Herrera	2023	Exposure to micro(nano) plastics polymers in water stored in single-use plastic bottles	PET bottles	Inherited	20	0.7 - 200 µm	ng/L	
Winkler	2019	Does mechanical stress cause microplastic release from plastic water bottles?	PET bottles	Mechanical stress (opening/closing)	18	0.5 - 40 µm	particles/L	

Not all packaging formats and use conditions have been investigated.
Data availability is uneven across both packaging types and life-cycle or use stages, with several combinations remaining partially covered or entirely undocumented. In particular, certain use conditions (e.g. squeezing, stacking, irradiation, or contact with specific food matrices) and several packaging formats are affected by data gaps.

Figure 38. Coverage of packaging formats and use conditions in the reviewed literature

Packaging	Polymer	Inherited	Opening/ Closing	Squeezing	Stacking	Contact, aqueous content	Contact, acidic content	Contact, fatty content	Irradiation	Microwaving
PET bottles	PET	covered	covered	covered	-	covered	no data	covered	covered	-
Rigid food packaging	PET	covered	-	no data	no data	covered	covered	no data	no data	-
Rigid food packaging	PP	covered	-	no data	covered	covered	covered	covered	no data	covered
Rigid food packaging	PS	covered	-	no data	no data	covered	covered	covered	no data	-
Flexible packaging	PE	covered	covered	-	-	covered	no data	no data	covered	-
Multi-layer containers	PE lining	covered	-	no data	no data	covered	covered	no data	no data	-
Multi-layer bottles	PE	covered	no data	no data	no data	no data	no data	no data	no data	-
Flexible packaging	other polymers	no data	no data	no data	no data	no data	no data	no data	no data	no data
Bottles	other polymers	no data	no data	no data	no data	no data	no data	no data	no data	no data

(4) APPENDIX

(4.2) Appendix 2 – Harmonisation of values from literature and units conversion

This appendix describes the methodology used to harmonise quantitative data extracted from the literature and convert particle counts into comparable mass-based metrics.

Quantitative data were extracted from the literature, including particle number concentrations, particle size ranges, and their evolution across experimental conditions.

To enable comparison across heterogeneous studies, results were harmonised through two main steps:
- Conversion of particle counts into estimated mass, based on particle size and polymer density.
- Normalisation per volume of product, allowing results to be expressed on a comparable basis (µg/L).

Importance of particle size in mass evaluation
Two datasets reporting the same number of particles can correspond to orders-of-magnitude differences in mass, depending on particle size.

For illustration:
- 100 spherical PE particles with a diameter of 1 µm correspond to approximately 0.02 ng
- 100 spherical PE particles with a diameter of 100 µm correspond to approximately 20,000 ng

A 100-fold increase in particle diameter therefore results in a 1,000,000-fold increase in total particle mass, highlighting the necessity of accounting for size distributions when comparing studies.

Conversion from particle number to mass

Only studies reporting particle size distributions were retained (e.g. “50% of particles with a diameter of 5 µm, 50% with a diameter of 10 µm”). This information is required to convert particle numbers into mass while limiting uncertainties.

Total particle mass was calculated by summing mass contributions across all size classes, following this approach;

For each size class i:
- Fraction of particles in the size class (f_i)
- Total particle number (N)
- Particle volume, dependant of the particle diameter (V_i)
- Polymer density (ρ) (Figure 40)

The mass contribution of each size class is given by:

$$m_i = f_i \times N \times V_i \times \rho$$

The total particle mass is then obtained by summing across all size classes:

$$M = \sum m_i$$

Normalisation per volume of product

When quantitative results were reported in units other than per volume of product (e.g. per container, per package, or per item), results were normalised to a mass of particles per volume of product (per L) to enable comparison across studies.

Two cases were distinguished:
- Product volume reported in the study: When the volume of product per item (L/item) was explicitly provided in the original publication, this value was directly used for normalisation.
- Product volume not reported: When the product volume per container was not specified, a reasonable assumption was made based on typical packaging formats and use cases. All such assumptions are documented transparently in a dedicated assumptions table (Figure 39).

The conversion to a volume-based metric was then performed as follows:

$$M_{volume} = \frac{M_{raw}}{V}$$

where:
- M_{raw} is the total particle mass per item (µg/item),
- V is the volume of product per item (L/item),
- M_{volume} is the mass of particles expressed per unit volume of product (µg/L).

Figure 39. Assumptions on conversion factors

Packaging type	Conversion factor	Unit
Container (rigid packaging)	0.75	L/container
Cup (rigid packaging)	0.3	L/cup
Pouch (flexible packaging)	0.005	L/mm (width of pouch)
Tray (rigid packaging)	0.95	L/kg of meat
Film (flexible packaging)	0.0025	L/cm^2 (area of film)

Figure 40. Densities of polymers

Polymer	Density	Unit	Source
PS	1.05	g/cm^3	https://en.wikipedia.org/wiki/Polystyrene
EPS	0.0215	g/cm^3	https://en.wikipedia.org/wiki/Polystyrene
PP	0.9	g/cm^3	https://en.wikipedia.org/wiki/Polypropylene
PET	1.38	g/cm^3	https://en.wikipedia.org/wiki/Polyethylene_terephthalate
PE	0.92	g/cm3	https://en.wikipedia.org/wiki/Low-density_polyethylene

(4) APPENDIX

(4.3) Appendix 3 - Treatment of uncertainty

This appendix details how uncertainties in micro- and nanoplastic (MNP) emissions estimates were identified, quantified, and incorporated into the analysis.

Quantitative estimates derived from the literature are subject to multiple sources of uncertainty. For each extracted data point, three major sources of uncertainty were identified and addressed consistently:
- uncertainty in the reported values
- uncertainty in particle size, and
- uncertainty related to particle shape and volume estimation.

To ensure transparency and comparability, all results were systematically calculated and reported as **average, minimum, and maximum values,** reflecting plausible uncertainty bounds rather than statistical confidence intervals.

Uncertainty in reported study values

Most studies report particle release using either:
- a central estimate accompanied by a range (minimum and maximum), or
- a mean value with an associated variation (e.g. mean ± delta).

For each data point:
- the average value corresponds to the mean or central value reported in the study,
- the minimum value corresponds to the lowest value reported,
- the maximum value corresponds to the highest value reported.

This approach preserves the uncertainty explicitly reported in the original studies without imposing additional statistical assumptions.

Uncertainty in particle size

Particle size is often reported as a size range rather than a single value (e.g. 10–20 µm). As particle mass scales with the cube of particle size, this represents a major source of uncertainty.

To account for this:
- the average particle size was calculated as the arithmetic mean of the reported size range,
- the minimum particle size corresponds to the lower bound of the range,
- the maximum particle size corresponds to the upper bound of the range.

These three size estimates were propagated consistently through all subsequent mass calculations.

Uncertainty in particle shape and volume estimation

Most studies report particle size as an equivalent diameter, but particle **shape** is rarely characterised in sufficient detail. Particles may be spherical, elongated (e.g. filaments), or irregular, which introduces uncertainty in volume estimation.

As a reference case, the volume of a spherical particle with diameter D is given by:

$$V = \frac{4}{3} \times \pi \times \left(\frac{D}{2}\right)^3 = \frac{\pi}{6} \times D^3$$

To account for deviations from perfect sphericity, a shape correction factor (k) was applied, such that particle volume was expressed as:

$$V = k \times \varpi/6 \times D\text{^}3$$

The following values were used to represent plausible bounds:
- **Minimum:** k = 0.1 (highly elongated or flattened particles),
- **Average:** k = 0.5 (irregular but moderately compact particles),
- **Maximum:** k = 0.9 (near-spherical particles).

This approach allows particle shape uncertainty to be explicitly incorporated into the uncertainty range of mass estimates, while remaining consistent across studies.

Overall uncertainty treatment

For each data point, uncertainties related to reported values, particle size, and particle shape were combined by calculating minimum, average, and maximum estimates at each step. These bounds should be interpreted as order-of-magnitude uncertainty ranges, rather than formal statistical confidence intervals.

Why a probabilistic uncertainty approach was not applied

A fully probabilistic uncertainty analysis (e.g. Monte Carlo simulation) was not applied in this assessment for several methodological reasons.

First, the majority of reviewed studies provide very limited numbers of data points, often based on a small number of experimental replicates. Under such conditions, assuming an underlying statistical distribution (e.g. a normal distribution) is not justified and may lead to misleading representations of uncertainty.

Second, uncertainty in the literature is rarely characterised in a way that allows robust parameterisation of probability distributions. Reported information is typically restricted to ranges (minimum–maximum) or point estimates with poorly defined variability.

Third, several key sources of uncertainty—such as particle size ranges and particle shape—stem from incomplete or missing information rather than from random variability. These uncertainties cannot be meaningfully described using statistical probability distributions without making strong and arbitrary assumptions.

Finally, the purpose of this analysis is to derive order-of-magnitude estimates and comparative insights, rather than precise exposure values. A scenario-based minimum–average–maximum framework was therefore considered more appropriate, transparent, and consistent with the quality and resolution of the available evidence.

For these reasons, uncertainty was addressed through explicit uncertainty bounds rather than probabilistic modelling.

(4) APPENDIX

(4.4) Appendix 4 - Scale-up from product-level emissions to population-level intake

This appendix describes the methodological steps used to convert packaging-level emission factors into indicative global emission estimates and average per-capita intake values.

Step 1 - Conversion from product-based to packaging-based metrics

To enable aggregation at the packaging level, values expressed per volume of product (µg/L) were converted to mass of particles per mass of packaging (µg/g of packaging).

This conversion was performed using average packaging-to-product ratios, expressed as packaging mass per unit volume of product (g/L). Mean values by packaging category are reported in Figure 41.

$$MNP_{packaging} = \frac{MNP_{product}}{\text{packaging density}}$$

where:
- $MNP_{product}$ is expressed in µg/L of product,
- Packaging density is expressed in g of packaging per litre of product,
- $MNP_{packaging}$ is expressed in µg/g of packaging.

Step 2 - Mapping literature categories to Plasteax packaging data

Packaging categories covered in the reviewed studies were mapped to the corresponding categories in the Plasteax database.
The correspondence between study categories and Plasteax categories is documented in Figure 41.

Step 3 - Estimation of global packaging-related emissions

For each packaging category, the packaging-based emission factor (µg/g) was multiplied by the **total mass of packaging placed on the market,** as reported in Plasteax.

This yields an estimate of **total annual MNP emissions** associated with each packaging category at the global level.

Step 4 - Estimation of population-level intake

Total annual emissions were then divided by the global population to derive an average per-capita intake estimate, expressed as mg per person per year.

$$\text{Intake}_{per\ capita} = \frac{\text{Global emissions}}{\text{Global population}}$$

Key limitation

This scale-up approach assumes **average and homogeneous consumer use patterns** across regions. Differences in packaging usage frequency, product types, and consumption habits between regions are not explicitly accounted for. As a result, the derived per-capita intake values should be interpreted as **global average estimates,** rather than region-specific exposure assessments.

Figure 41.
Packaging mass-to-product volume ratios, category mapping used for scale-up, and total volume

Packaging	Polymer	Plasteax category	Mass to product ratios, in g/L	Volume, in kt	Food share, in %	Final volume, in kt
PET bottles	PET	PET bottles	20	21 294	90%	19 165
Flexible packaging	PE	Flexible LDPE	5	6 130	40%	8 900
Rigid food packaging	PET	Rigid food PET	30	5 643	100%	6 130
Rigid food packaging	PP	Rigid food PP	40	692	100%	5 643
Rigid food packaging	PS	Rigid food PS	15	22 251	100%	692
Multi-layer packaging	PE lining	Multi-layer LDPE	5	2 232	80%	1 785
Multi-layer packaging	PE	Multi-layer HDPE	35	958	80%	766
Total						**43 082**

Sources:
Low density polyethylene packaging market [10]
Polypropylene packaging films market [11]
HDPE packaging market [12]
Global plastic bottles market [13]

(4) APPENDIX

(4.5) Appendix 5 - Evaluation of life-cycle environmental MNP emissions from food packaging

This appendix documents the methodological approach used to estimate micro- and nanoplastic emissions released to the environment over the life cycle of food-contact packaging.

The analysis covers four potential sources of environmental MNP emissions associated with the life cycle of food packaging:
- pellet loss during polymer and packaging production,
- tyre wear emissions associated with the transport of food packaging,
- mismanaged food-contact packaging waste, and
- plastic losses during recycling processes.

All calculations were performed at an order-of-magnitude level and rely on proportional allocation approaches, as detailed below.

1. Pellet loss during production

Total pellet loss to the environment was taken from EA Global leakage assessment (figures taken from the 2025 update, not yet published), which estimates global pellet losses across all plastic applications at **808 kt/year.** To derive the contribution attributable to food-contact packaging, this total was allocated using two successive shares:
- the share of packaging applications in total plastic use, estimated at 44%;[14]
- the share of food-contact packaging within total packaging, estimated at 53%.[4]

The resulting estimate was calculated as:

$$\text{Pellet loss}_{\textit{food packaging}} = \text{Pellet loss}_{\textit{total plastic}} \times \text{Share}_{\textit{packaging in plastics}} \times \text{Share}_{\textit{food packaging in packaging}}$$

This approach assumes that pellet loss rates are proportional to production volumes across plastic applications.

2. Tyre wear emissions associated with transport

Total plastic emissions from tyre wear were taken from the EA Global Leakage Assessment,[2] which estimates global tyre-related microplastic emissions at **1,909 kt/year.**

To estimate the share attributable to food packaging transport, these emissions were scaled using the fraction of total transport activity associated with food systems.

Based on published estimates of food-related transport demand, food miles were assumed to represent 18% of total transport kilometres [15]

The resulting estimate was calculated as:

$$\text{Tyre wear}_{\textit{food packaging}} = \text{Tyre wear}_{\textit{total plastic}} \times \text{Share}_{\textit{food miles}}$$

This assumes that tyre wear emissions scale linearly with distance travelled.

3. Mismanaged food-contact packaging waste

The quantity of mismanaged food-contact packaging was taken directly from PLASTEAX packaging flow data. According to this dataset, **33% of food-contact packaging waste** is classified as mismanaged, meaning it is not adequately collected or treated and is therefore assumed to enter the environment.

No further allocation or scaling was applied.

4. Losses during recycling processes

Environmental releases associated with recycling were estimated by combining:
- the share of food-contact packaging directed to recycling, estimated at 16% (PLASTEAX), and
- representative material loss rates during recycling processes, estimated at 7% based on the EA Global Leakage Assessment.

The resulting estimate was calculated as:

$$\text{Recycling losses}_{\textit{food packaging}} = \text{Food packaging recycled} \times \text{Recycling loss rate}$$

Scope and limitations

The methodology described above provides a transparent and reproducible approach for estimating indicative environmental MNP emissions associated with food packaging across its life cycle. Results are subject to significant uncertainty due to data limitations and simplifying assumptions and are therefore interpreted strictly at an order-of-magnitude level.

(5)

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Definitions

MNP: Micro- and nanoplastics

Mechanism: Mechanical and physico-chemical processes by which MNP are generated from packaging materials.

Generation, Release, Migration, and Emissions: Quantity of MNP that form within or at the surface of packaging materials, detach from it into the surrounding medium, and are transferred into the contained food or beverage. These terms are used interchangeably throughout this report, all reported values refer exclusively to MNP effectively reaching the product.

Inert: A substance or material that does not react chemically with its surroundings under normal conditions.

Intentionally Added Substances (IAS): Chemicals deliberately incorporated into packaging materials during manufacturing, such as plasticizers, stabilizers, or colorants.

Non-Intentionally Added Substances (NIAS): Chemicals not deliberately added to packaging materials, but present as impurities, degradation products, or reaction by-products arising during manufacturing or use.

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