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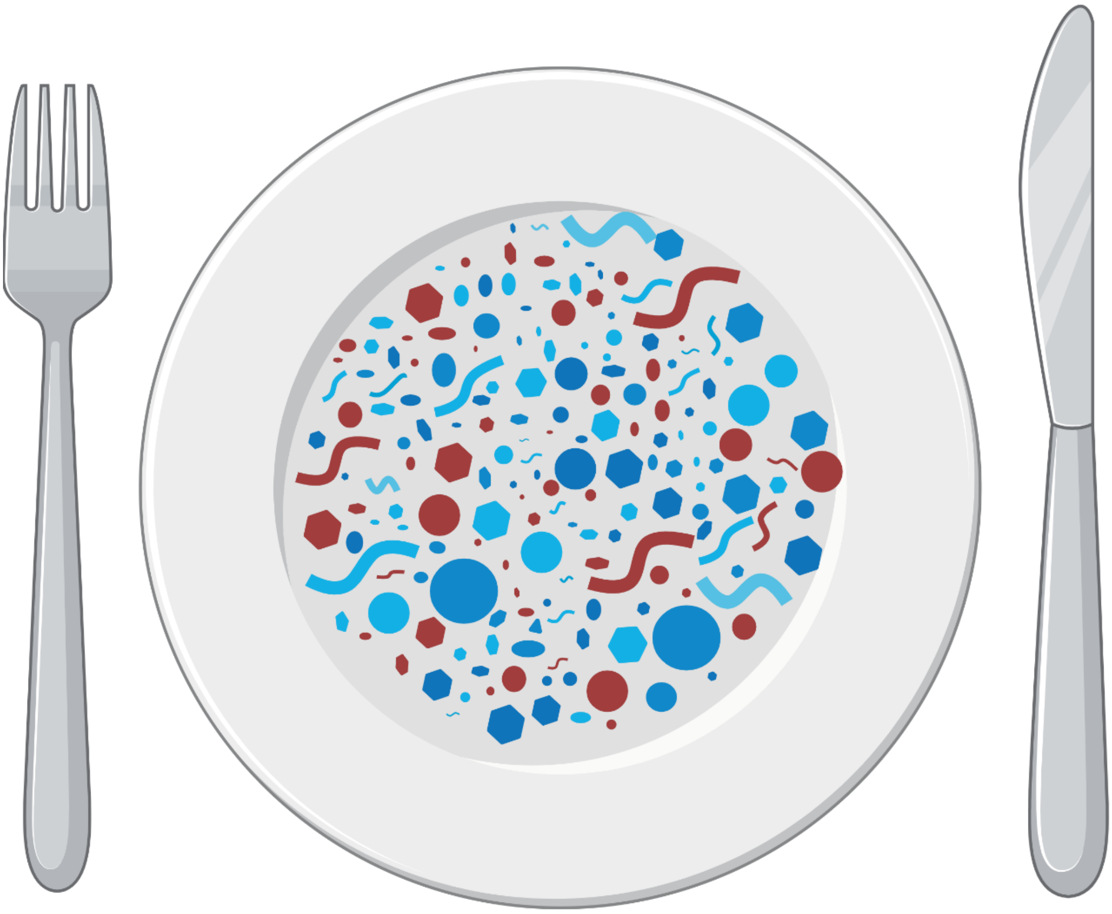
Health Food Chain Safety Environment

Blue Growth Research Lab

Analysis on the link between microplastics, the environment and public health.



Policy informing brief

Preface

This policy informing brief (PIB) has the goal to provide an overview of the current state-of-the-science regarding the link between microplastics, the environment and human health. The goal is to inform policymakers on the current knowledge gaps and formulate some recommendations. Microplastic pollution in the environment will only be described in relation to human health, more information on the current knowledge on microplastic pollution in different ecosystems, with a focus on Belgium, can be found in Devriese & Janssen, 2023.

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Summary[1]

Plastics are low-cost products with high durability and design versatility. They are omnipresent as they are adaptable to fit a vast array of applications, ranging from packaging to the automotive and construction industries. This increased use of plastic products has resulted in a thriving global plastic industry with a global production of 390.7 million ton of plastics in 2021.

Plastic, whether intentionally discarded as non-collected waste or inadvertently released? through wear and tear during use, has found its way into our environment, contributing to plastic pollution. In a toxicology framework, plastics products are often categorised based on their size, with an increased attention on microplastics, here defined as particles with sizes between 0.1 µm and 5 mm. Recently, concerns have also been raised on nanoplastics, defined as particles between 1 nm and 0.1 µm. Micro- and nanoplastics (MNP) originate either from an intentional industrial production (primary microplastics/nanoplastics) or the gradual degradation of plastics in the environment (secondary microplastics/nanoplastics). This degradation process is influenced by a complex interplay of biotic and abiotic factors, including biodegradation and photodegradation. As often misunderstood, plastics are a multidimensional group of pollutants in which each particle can be described by their own set of characteristics based on size, polymer composition, shape, surface characteristics, chemical additives, etc. This inherent heterogeneity makes microplastics pollution particularly challenging to study leading to knowledge gaps in our understanding of the microplastic pollution and the effects on the environment and human health.

Despite the existing knowledge gaps, microplastic pollution has gained attention in a number of policy initiatives on global, European, national, and regional level. These regulations have started to include or mention some critical aspects of the issue, e.g. sustainable plastic production, environmental plastic pollution and the link with human health and food safety. Despite the acknowledged link between environmental pollution and human health, and by extension food safety, little to no policy frameworks linked to human health are currently in place.

This combined with the scientific knowledge gaps, more efforts are needed on a scientific and policy level to tackle plastic pollution and move the field of MNP risk assessment forward. The goal of this policy informing brief is to provide an overview of the current state-of-the-science regarding the link between MNP, the environment and human health. Based on these recommendations are formulated to inform policymakers on the current knowledge gaps and provide stepping stones for a policy framework to tackle plastic pollution.

Most plastic is persistent, leading to accumulation in every environmental compartment; in the terrestrial (on average 6000 MP/kg soil), freshwater (0.28-1265 MP/m³), marine environment (1.5-9200 MP/m³) and the atmosphere (0-14 MP/m³). Importantly, these environmental niches, are irrefutably connected as a complex network or the 'plastic cycle', and MNPs will transmit between the compartments.

The mentioned concentrations in all compartments are based on actual observations, limited by number of samples, analytical limits, etc. Since no standardized methods are available for sampling,

[1] *On the website of FPS Health the summary can be found in Dutch and French*

extraction, and analysis of microplastics in environmental samples, a lot of variability is present between individual studies, hereby complicating the comparison of results. Moreover, the lower size limits reported research is strongly variable and depends on sampling and analytical methods used (mostly min. 25 µm, 100µm or 300µm). This has implications on the reported concentrations and hampers direct comparisons between studies. As a solution to tackle this in the future is the use of models to predict the concentration, fate and transport of MNPs. This approach could fill important knowledge gaps and improve risk assessment in time and cost-efficient manner.

When plastics enter the environment, they can act as substrates allowing an interaction with their environment mainly driven by the high hydrophobicity of plastics. Typically, two interactions are studied. First, chemicals present in the environment can adsorb to the surface of the plastic. In the Belgian part of the North Sea, a study has identified more than 200 organic compounds or compound groups on plastic debris including persistent organic pollutants, metals and pharmaceuticals. Secondly, MNP particles can interact with macromolecules and micro-organisms forming protein corona and biofilms, respectively. Microbial community can attach on plastic debris, referred to as "The plastisphere". Both these interactions can affect the fate, bioavailability, and the effects of the plastics.

Due to the wide range of microplastic pollution, humans are also exposed to MNPs via various products and pathways. The presence of MNP can be considered as an unintentional or intentionally added contaminant which can affect human safety. A few examples of products proven to contain microplastics (with variable concentrations) are fruits, vegetables, table salt, aquatic food products, drinking water, nonalcoholic beverages, alcoholic beverages, and some preliminary data exists on other food products such as sugar, honey and milk. The sources of the MNP in these products are not often very clear as MNP can originate from the food itself (e.g. water or fruit) or from processing and packaging. Due to the large amount of plastic used for packaging, these are expected to introduce extra MNP in the end-product that we consume. Furthermore, during food preparation, thermal stress could also cause the release of MNP in the food or beverage, e.g. by microwaving food in a plastic container. More recently, other manipulations such as cutting on a plastic cutting board has been also studied regarding microplastic release.

The inhalation of MNP is also a well-known pathway of human exposure with reported atmospheric microplastic concentrations are between 0 and 14 MP /m^3. First concerns were raised on occupational exposure of flock workers to atmospheric nylon fibres, showing symptoms of coughing and shortness of breath and fever, but more recently, daily exposure of lower doses has also been evaluated as a possible risk.

Several studies have attempted to estimate the daily or yearly intake of microplastics based on published concentrations using dietary consumption rates. However, due to different methodologies used in the studies measuring microplastic contamination in food, it is difficult to compare them. According to Nor et al. (2021), which was evaluated to currently be the most accurate paper, the median daily intake of microplastics for adults was calculated to be 0.6 µg or 883 microplastic per day for adults (Nor et al., 2021). It is however worth noting that the current research on microplastic contamination in food sources is limited and represents only about 25% of the food categories consumed daily. Consequently, further research is necessary to gain a better understanding of human exposure.

Humans are also exposed to plastics via personal care products. MNPs are intentionally added to personal care products in small sizes, often referred to as microbeads (1-1000 µm), microspheres (1-1000 µm), microcapsules (1-2 µm) or nanospheres (10-1000 nm). Besides the well-known scrubbing or exfoliating function, MNP are also used as thickening agents, to provide a smoother or shinier product, for controlled time release of active substances, for prolonging shelf life by trapping degradable active ingredients, regulating viscosity, as an emulsifier, opacifying agent, for 'optical blurring' effect, glitter, etc. No detailed information on the microbead quantities used in cosmetics is publicly available and thus a comprehensive estimation of the total volumes of microbeads used in cosmetic is lacking. Based on a literature search, some information could be gathered on microplastic concentrations in a few rinse-off cosmetics, which range between 6.27 to $1.4 * 10^{13}$ MP per g or mL of shower gel or facial scrub, respectively. If the emission of all rinse-off personal care products is summed, a daily gross emission of $1.32 * 10^{12}$ MP per capita per day has been estimated. Importantly, the quantities of microplastic in cosmetics are expected to decrease over the coming years due to the REACH restriction on intentionally added MNP including MNP in personal care products and other daily-use products as an emission prevention strategy.

Finally, in pharmaceutical and healthcare applications, single-use plastics are also intensively used where they have a key role in preventing contamination. The widespread use of plastics in health care, causes a microplastic exposure via enteral feeding, storage of drugs in plastic containers, inhalers, ointments and gels for wounds and intravenous infusion.

In summary, there are in general three mayor human exposure pathways described for MNPs, ingestion, inhalation, and dermal exposure via the skin. Due to the expected high exposure (linked to numerous sources), inherent uptake mechanisms in the intestines and the large total surface area of 200 m², ingestion is expected to be the primary exposure pathway. The considerable amounts of inhaled air in combination with the large alveolar surface area (ca. 150 m²), the thin tissue barrier and the increasing knowledge of MNP contamination in the air, exposure via inhalation is estimated to be the second most important exposure route. Dermal uptake of MNP via the skin is deemed to be limited due to the thick and largely impenetrable stratum corneum. However, injury to the skin could increase the exposure. In the medical sector, a fourth exposure route was proposed; uptake by infusion of pharmaceuticals by intravenous, intraosseous, intramuscular, and intradermal injections. The importance of this pathway in comparison with the previous pathways is hitherto unknown. Nonetheless, by infusion, the first tissue barrier is overcome and dispersion to various organs will become easier. This could lead to pronounced adverse health effects.

Once MNPs are taken up, they can cause direct and indirect adverse effects by cellular uptake, translocation and passing cellular barriers, with possible effects on human health.

The described indirect effects of ingestion and inhalation of MNPs are (1) interaction with the microbiome; and (2) interaction with the mucus layer. Since research on human health effects of MNP exposure has predominantly focused on the effects of cellular uptake of MNP, the indirect effects have been poorly studied. Cells can also take up the MNPs by normal cell uptake mechanisms such as endocytosis and passive diffusion.

Once taken up by the cell, the MNPS can be translocated to the bloodstream and subsequently be transported to other organs where they can accumulate or can cause cellular toxicity. Recent research has increased attention on the possible crossing of secondary tissue barriers such as the placental and blood-brain barriers. This however is currently being studied in detail to understand these processes and their possible risk better. Importantly, absorption of MNP in the tissues appears to be limited. Recent studies suggested a MNP uptake up to 7.7% of the administered dose, other MNPs can be excreted via the stool.

On cellular level, MNPs can cause toxic effects which are described to consist of oxidative stress, inflammation and genotoxicity.

Upon uptake of MNP, the cells will try to neutralize the MNPs. During that process, reactive oxygen species (ROS) are generated. The ROS production affects various cellular processes and could cause lysosomal membrane damage, mitochondrial dysfunction, genotoxicity, and apoptosis. Moreover, the cells will consider the MNPs as foreign material and thus activate the innate immune system, often observed by the stimulation of proinflammatory cytokines such as IL-6 and IL8. The internal transport towards the nuclei could subsequently cause double-strand DNA breaks leading to genotoxic effects. Based on the observed effects on cellular level, predictions can be made on possible effects for humans, where the link between microplastic and cancer or obesity has been postulated. Nonetheless, more relevant research is necessary to confidently being able to assess the risk of MNP for human health. Effect studies are currently struggling with designing relevant exposure scenario's which entail challenges on capturing the heterogeneity of plastics, with dynamic changes over time (e.g. leaching of additives and chemicals or protein corona formation).

The most prominent current research question is to know the risks for human health upon MNP exposure. However, at present, insufficient scientific knowledge is available for a reliable risk assessment. On the one hand, this is linked to a lack of profound, standardized monitoring of exposure concentrations (monitoring of MNP in the environment, the entire diet and chemical products combined with human biomonitoring). The main bottleneck to achieve this is the lack of standardized methods to measure MNPs in different matrices. On the other hand, we are currently missing relevant effect data, leading to a lack of health-based guidance values, indicating a recommended MNP intake for a certain time, identified as the second bottleneck hitherto.

Besides the recommendations for closing the scientific knowledge gaps, the MNP risks for human health should be increasingly important for the political agenda. The recommended approach for policy is two-pronged. First, short-term preventive measures linked to environmental plastic pollution, but also preliminary health-based guidance values could be defined as a precautionary measure. Secondly, a supportive policy framework, corroborated by scientific knowledge, should be developed to prevent further MNP pollution and minimize the impact on our environment and human health, now and in the future. For this framework, a holistic approach will be necessary to overcome plastic pollution where both plastic production and pollution are tackled in a parallel effort combined with considerations regarding the risk of MNP to ecosystems and human health.

The anticipated growth in plastic production suggests that (micro)plastic pollution is unlikely to diminish in the near future. Once in the environment, research has shown that plastics are persistent and can degrade into smaller, and potentially more dangerous MNP. Moreover, once MNP are released into the environment it is challenging to remove them, leading to an increased risk on adverse effects. This knowledge suggests that plastic pollution is not only a possible risk at present but it will remain relevant for years to come. This urges us to take action, both in science and policy.

Abbreviations

AOP	Adverse Outcome Pathways
ARG	Antibiotics resistance genes
BBB	Blood–brain barrier
ECHA	European Chemicals Agency
EPS	Exopolysaccharides
GIT	Gastrointestinal tract
HDPE	High-density polyethylene
KE	Key events
LDPE	Low-density polyethylene
MIE	Molecular Initiating event
MNP	Micro- and nanoplastic
MP	Microplastic
NP	Nanoplastic
PA	Polyamide
PAM	Polyacrylamide
PET	Polyethylene terephthalate
POP	Persistent organic pollutants
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride
ROS	Reactive oxygen species
WHO	World Health Organization
WWTP	Wastewater treatment plant

1. Introduction on plastic

Key highlights

- Plastics are low-cost products with high durability and design versatility.
- Micro- and nanoplastics (MNP) originate either from an intentional industrial production (primary MNPs) or due to a continuous process of degradation in the environment (secondary MNPs)
- MNPs can be categorized by size, polymer composition, shape
- Chemical additives are intentionally added to the polymer to enable processing and/or enhance certain functions. These additives can leach and pose potential threats to human health.

1.1 Plastic life cycle

Plastics are low-cost products with high durability and design versatility. The latter makes them adaptable to fit almost any requirement including various degrees of robustness and resistance against degradation (Domenech & Marcos, 2021; Van Echelpoel, 2014). They have multiple applications in industries ranging from packaging and medical applications to building and construction and the automotive industry (Domenech & Marcos, 2021). Consequently, plastic products exist in numerous shapes, colours, tensile strengths and with additives to enhance certain functions. Over 40% of the produced plastic products are designed for single-use (Geyer et al., 2017; Mason et al., 2018).

As plastic products are increasingly popular, plastic production is a globally growing industry with a yearly increase in production of 9.7 million ton since 2011. In 2020 a stagnation (375.5 million ton) was observed with a stasis in the packaging (responsible for 44% of the plastic production (Plastics Europe, 2022)) and automotive sector (responsible for 8% of the plastic production (Plastics Europe, 2022)) due to the COVID-19 pandemic (Plastics Europe, 2022). The plastic production increased again to 390.7 million ton of plastics in 2021 (Plastics Europe, 2022). As a result of the pandemic, there was an increasing demand of plastic products such as masks, gloves, packaging for take-away food etc. (European Environment Agency, 2021), explaining the sharp increase in plastic production.

The Belgian plastics industry was responsible for the production of 7.35 million ton in 2018 (most recent available data) which accounts for two percent of the global plastic production (AGORIA & Essenscia, 2019). The lifecycle of plastics, including production, use, waste, and recycling in the Belgian plastic industry, is illustrated in Figure 1. The amount of non-collected plastic waste (including litter, intentional and unintentional losses, pollution in domestic wastewater, etc.), which contribute to the plastic pollution, is difficult to measure and was estimated to be less than 10 tonnes in Belgium (Jambeck et al., 2015). Based on data from litter collection by volunteers, 2.73 kg litter per capita was collected in 2021. This is a decrease of 0.71kg litter per capita in comparison with 2019 (OVAM, 2022). The majority of collected litter were cigarette butts (44%) and soda cans (22%).

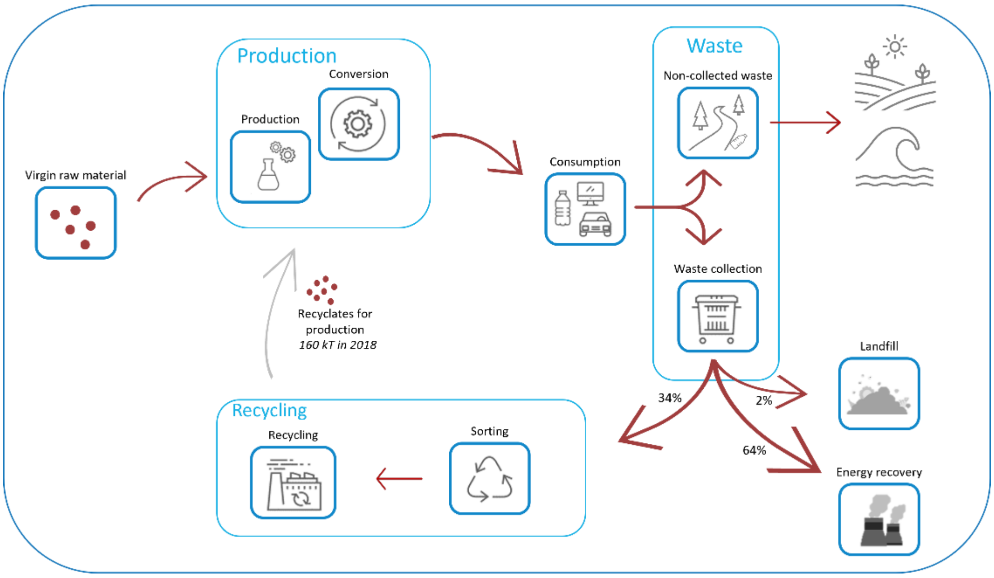

Figure 1: Schematic representation of the plastic lifecycle in Belgium including production, use, waste and recycling (based on AGORIA & Essenscia (2019))

1.2 Definition of micro- and nanoplastics

In plastic monitoring and risk assessment studies, plastic products are often categorised based on their size (Hartmann et al., 2019). In those cases, prefixes like macro, meso, micro and nano are being used. However, despite the rigorous use of this nomenclature, the scientific community has not reached an agreement on the exact definition and the used descriptions of the term microplastics are inconsistent (Figure 2) (Hartmann et al., 2019; Lusher et al., 2020).

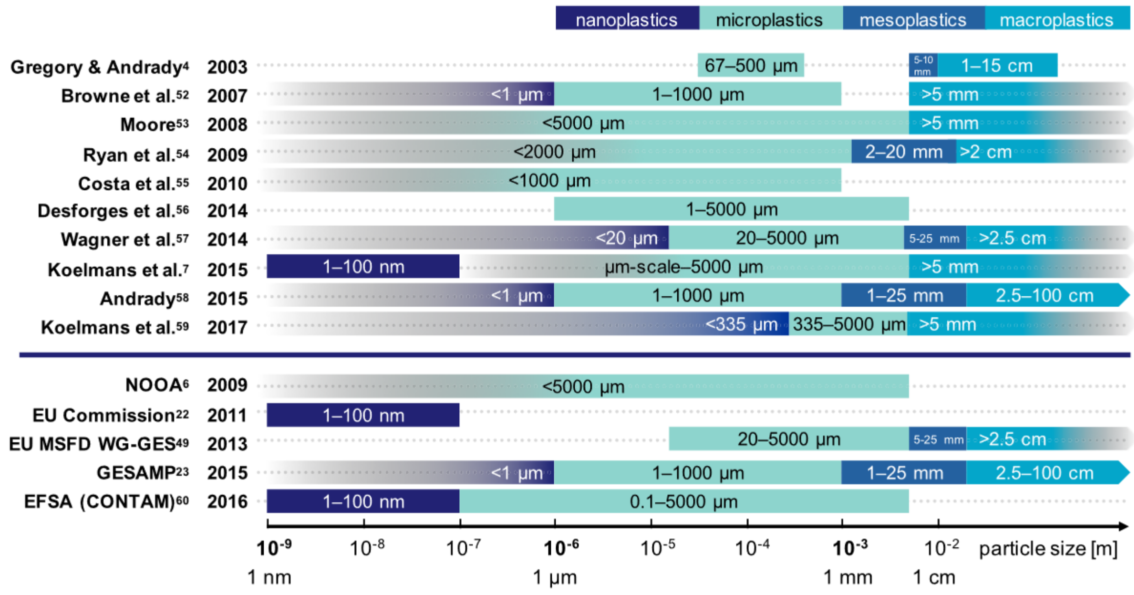

Figure 2: Some examples of inconsistent terminology used for categorization of plastic pollution based on size (Hartmann et al., 2019).

The definition for microplastic and nanoplastic used in this brief aligns with the definition as stated in the REACH restriction for intentionally added microplastics (ECHA, 2019) where microplastics are defined as particles containing solid polymer, to which additives or other substances may have been added, and where ≥ 1% w/w of particles have (i) all dimensions 0.1µm ≤ x ≤ 5mm, or (ii) a length of 0.3µm ≤ x ≤ 15mm and length to diameter ratio of >3. Consequently, all particles with dimensions smaller than 0.1 µm are defined as nanoplastics, consistent with the EU Recommendation on a Definition of Nanomaterials (European Commission, 2022). In summary, in this document following size categories are used:

- Microplastics (MP)[2]: 0.1 µm – 5mm
- Nanoplastics (NP): <0.1µm

Importantly, the term 'microplastic' or 'nanoplastic' only provides information on the size range and still includes a wide range of polymer types, morphologies, visual properties, additives, etc. Recently, more efforts are taken to include the complexity of micro- and nanoplastics (MNP) (including continuity of sizes) in the research by using distributions instead of discrete classifications (Kooi & Koelmans, 2019). Categorization, as stated by Hartmann et al. (2019), could result in the perception that items within one category have some similarities (hazardous properties or environmental behaviour), which is not necessarily the case for plastic particles. Nonetheless, particle size is currently believed to be of major ecological significance as it is one of the major factors influencing interaction between MNP and the environment (Hartmann et al., 2019). Therefore, it is assumed to largely determine the environmental fate and impact of a particle. For toxicological purposes, the categorization using size is common practice and is also followed in this brief.

[2] *In this document, we will often refer to micro- and nanoplastics (MNP) by which we intend to indicate all particles smaller than 5 mm.*

1.3 Intentionally and unintentionally produced microplastics

MNPs originate either from (intentional) industrial production (also named primary MNPs) or due to a continuous process of degradation during or after use in the environment (also named secondary MNPs) (Domenech & Marcos, 2021).

Primary MNPs are polymeric particles that are intentionally designed in micron-scale sizes and manufactured for industrial applications such as personal care products (e.g. scrubs, facial cleansers, toothpaste), air-spray media and drug carriers in medicine as well as road and shipping paints and rubber infill for synthetic sports fields (Cole et al., 2011; Gopinath et al., 2022; Lassen et al., 2015; Zhang et al., 2021).

Secondary MNPs originate from degradation and fragmentation of larger pieces of plastic during their use or after being discarded in the environment and are prone to both biotic and abiotic processes such as biodegradation, photodegradation and mechanical degradation (Cole et al., 2011). As a result of these processes, large plastic items (macroplastics) can degrade in smaller particles (Thompson et al., 2009; Van Cauwenberghe, 2016). Another class of secondary MNPS are released unintentionally during regular use of large polymer containing articles (such as tyres, synthetic textiles, detergent capsules, paints, detergent capsules).

A detailed analysis can be performed, e.g. using material flow analysis, to estimate the emission from each source to the environment. This has been done both in the Netherlands (Schwarz et al., 2022) and in Denmark (Lassen et al., 2015). Based on an analysis in Denmark, secondary microplastics form the largest fraction (99.1%, of which 60.2% from tire wear) of the total microplastic emission to the environment (Duis & Coors, 2016; Lassen et al., 2015) This was confirmed with the results of the study in the Netherlands.

1.4 Microplastic characteristics

The basic chemical structure of plastics is a chain of repeating monomers that are polymerized forming strong chemical bonds (Glaser, 2019). However, due to the variety of monomers and additives available, a nearly unlimited array of polymers can be produced, resulting in a heterogeneous group of compounds with a range of visual and physicochemical properties. The most common plastic types are listed in Table 1.

Based on differences in structure and melting point, polymers can be classified into three main categories, namely elastomers, thermosets, and thermoplastics. Elastomers are viscous and elastic (e.g. silicon, styrene-butadiene (synthetic rubber), etc.) and by definition not considered plastics. Nonetheless, in the field of plastic pollution, tire wear particles are often included as microplastics. Thermoplastics (e.g. polyethylene) are able to be remoulded under high temperature. Thermosets (e.g. PUR, epoxy resins) form a 3D-network between individual chains which makes it impossible to remould upon heating but provides them with good resistance to heat, strain and pressure (Jacobs et al., 2006).

The composition of the plastic (polymer) and addition of other chemicals (additives) will determine the physical and chemical properties of plastics (e.g. hydrophobicity, density, charge). This then influences their durability, degradation, environmental fate and their tendency to release or sorb other pollutants (Glaser, 2019; Issac & Kandasubramanian, 2021).

Table 1: Overview of common polymer types, the basic monomer, category and main uses

	Monomer	Polymer	Abbreviation	Common use
Thermoplast	Ethene	(Low density) polyethylene	(LD)PE	Plastic packaging, piping,…
	Ethene	(High density) polyethylene	(HD)PE	Plastic packaging, piping,…
	Propylene	Polypropylene	PP	Carpets, furniture, parts of car.
	Ethylene glycol + terephthalic acid	Polyethylene terephthalate	PET	Dinking bottles
	Amide	Polyamide	PA	Nylon
	Acrylamide	Polyacrylamide	PAM	Contact lenses, packaging
	Styrene	Polystyrene	PS	Isomo, isolation, packaging
	Vinyl chloride	Polyvinyl chloride	PVC	Piping
Thermoset	Siloxane	Silicone	/	Glue and basic kitchen equipment.
	Epoxide	Epoxy	/	Glue, impregnation of floors.
	(Polyfunctional) isocyanate and (polyfunctional) alcohol (polyol)	Polyurethane	PU	Car wax, isolation
Elastomer	Styrene + butadiene	Styrene-butadiene rubber	/	Tires

In addition to composition, microplastics can also exist in diverse shapes such as fibres, spheres and fragments (Enyoh et al., 2019). Definitions are provided in Table 2 (Hartmann et al., 2019).

Table 2: Microplastic shape categories based on the definitions stipulated by Hartmann et al. (2019).

Shape	Morphology
Fibre, filament	1D-thread-like structure
Fragment	2D-particles with irregular shapes
Sphere, pellet, bead	3D-particles characterized by the same distance from any point on their surface to their centre
Film	Planar plastic particles smaller in one dimension than in the other two.

1.5 Additives

As mentioned, plastics consist of their basic polymer backbone but in most cases, they contain a wide variety of chemicals. Recently, over 13,000 chemicals have been identified as being associated with plastics including plastic monomers, additives, processing aids and non-intentionally added substances (UNEP, 2023a).

Chemical additives (e.g. plasticizers, flame retardants, UV-light stabilizers, pigments) are intentionally added to the polymer to enable processing and/or enhance certain functions such as resistance to UV degradation, colour and pliability (Frøyland, 2023; Lithner et al., 2011; UNEP, 2023a). Plastics can on average contain between 7 % and 80 % of additives by mass, depending on the function of the material (Geyer et al., 2017; Hahladakis et al., 2018). These additives thus change the properties and/or durability of the end products and can be adapted to the requirements for the plastic product (Hermabessiere et al., 2017; Jeong & Choi, 2020). The non-intentionally added substances are impurities, breakdown products or by-products from the production process which can also be present in the plastic end product (Frøyland, 2023; Zimmermann et al., 2021). Thus, plastics are a complex mixture of polymers and chemicals.

Chemical additives can be subdivided into four major classes (definitions from UNEP (2023)):

- **Functional additives** influence specific properties such as stability against UV light and heat, resistance to microbes, flame retardancy, durability, softness, hardness, aesthetics, etc.
- **Colorants** give colour to the final plastic product.
- **Fillers** occupy space in plastic materials without changing the functional properties; they replace expensive resins to reduce costs.
- **Reinforcements** are used to enhance mechanical properties such as the strength and elasticity of plastics.

All four categories are widely used in common polymer types such as PE, PP, PVC, PET and a detailed overview is available in the report of UNEP (2023).

Of the 13,000 chemicals, UNEP has identified 9 groups of plastic-related chemical additives of concern[3] for human health due to their toxicity and use (Hermabessiere et al., 2017; UNEP, 2023a). In total, these groups contain more than 3,200 chemicals.

- **Flame retardants**
    - *Function*: Reduce flammability
    - *Use*: Electronic devices, vehicles, transport media, furniture, etc.
    - *Examples*: polybrominated diphenyl ethers (PBDE), hexabromocyclododecane (HBCDD), triphenyl phosphate (TPhP), etc.
    - *Described toxicity*: potential endocrine disruption, developmental neurotoxicity, carcinogenic.
- **Per- and Polyfluoroalkyl substances (PFASs)**
    - *Function:* Water/dirt repellent
    - *Use:* Lining for food containers, carpets, furniture
    - *Examples:* perfluoro carboxylic acids (PFCAs), perfluoroalkane sulfonic acids (PFSAs), etc.
    - *Described toxicity:* Neonatal mortality, carcinogenic, delays in physical development, endocrine disruption.
- **Phthalates or Phthalic acid esters**
    - *Function*: Plasticizers mainly in PVC products, fragrance
    - *Use*: vinyl flooring, personal care products, medical tubing, garden hoses, etc.
    - *Examples*: dipentyl phthalate (DPP), di(2-ethylhexyl) phthalate (DEHP)
    - *Described effect*: endocrine disruptors, reproductive disorders.
- **Bisphenols**
    - *Function*: Used as monomer for polycarbonate plastics or epoxy resins Also used antioxidant or plasticizer
    - *Use*: lining layer of aluminium cans, register receipts, personal care products
    - *Examples*: bisphenol A; other analogues: bisphenol B, bisphenol F, bisphenol S
    - *Described effects*: Endocrine disruptor, reproductive toxicity, obesity.

[3] The 10th identified group of chemicals of concern are the non-intentionally added substances, however, due to difficulties to identify and quantify these chemicals, various questions remain on their composition and toxic effects (UNEP, 2023).

- **Certain alkylphenols and alkylphenol ethoxylates (APEOs)**
  - *Function*: Antioxidants, plasticizes, stabilizer
  - *Use*: formaldehyde resins
  - *Examples*: nonylphenol ethoxylates (NPE)
  - *Described effects*: endocrine disruption.
- **Biocides**
  - *Function*: antimicrobial substances
  - *Use*: food contact material
  - *Examples*: tributyltin, 10,10'-oxybisphenoxarsine, triclosan
  - *Described effects*: antimicrobial effect, irritants, allergic contact dermatitis, etc.
- **Polycyclic aromatic hydrocarbons (PAH)**
  - *Function*: Mainly unintentionally added due to use of PAH-containing oils or carbon black
  - *Use*: direct-contact rubber consumer goods e.g. children's toys
  - *Examples*: Naphthalene, benzo[b]fluoranthene, etc.
  - *Described effects*: carcinogenic, mutagenic, toxic for reproduction.
- **UV-Stabilizers**
  - *Function*: Protection against photo-degradation
  - *Use*: used in many outdoor consumer products e.g. cars, agricultural applications, garden furniture
  - *Examples*: Benzophenones, benzotriazoles (BZTs), hindered amine light stabilizers (HALS)
  - *Described effects*: mainly ecotoxicity including estrogenic activity, liver toxicity, allergens, etc.
- **Metals and metalloids**
  - *Function*: stabilizers, colour pigments, antimicrobials, accelerators, and catalysts
  - *Use*: PUR coating
  - *Examples*: antimony, cadmium, chromium, lead, mercury, cobalt, tin, and zinc
  - *Described effects*: carcinogenic, respiratory irritation, pneumoconiosis, neurocognitive deficits, etc.

For more detailed information regarding chemical additives, we refer to the report of UNEP (2023).

Some restrictions are already in place for specific additives. As an example, the use of metals such as lead (Pb) and cadmium (Cd) as plastic additives in packaging is restricted under European Commission (EC) Directive 94/62/EC (Gopinath et al., 2022; Town et al., 2018; UNEP, 2023a).

More than 3200 chemical additives are recognized as chemicals of concern for human health due to their hazardous properties but also high persistence, bioaccumulation potential and potential long-range transport (Lithner et al., 2011; UNEP, 2023a). Generally, they have been described to cause endocrine disruption, carcinogenesis, reproductive toxicity, genotoxicity, developmental toxicity, specific organ toxicity and ecotoxicity (UNEP, 2023a).

Many additives used in plastics can end up in the environment via pathways including wastewater, runoff and atmospheric deposition (Hermabessiere et al., 2017). However, a more elaborately discussed pathway is leaching of these chemical additives from the plastic into the environment (Hermabessiere et al., 2017). As the additives are often not covalently bound to the polymer, migration from the plastic to the environment is possible. Factors that control the migration potential of these substances include the permeability of the polymer matrix, particle size, solubility, volatility of the chemical but also the temperature and composition of the surrounding medium (Hermabessiere et al., 2017; Lithner et al., 2011; Zimmermann et al., 2021).

Leaching of additives has also been described to occur in food packaging, baby teethers, children's toys, water bottles, plastic mulch, etc. (Frøyland, 2023), therefore posing a threat for human health. More than 1,000 chemicals have been described to migrate from plastic food contact materials into food or food simulants (Geueke et al., 2022). Leaching of additives has also been described in the pharmaceutical and health care sector, for example leaching of plasticizers from plastic medical devices (Gopinath et al., 2022; Panneel et al., 2023).

2. Policy framework for (micro)plastic pollution

Key highlights

- Despite the lack of standardization and existing knowledge gaps, microplastic pollution has been taken up in a number of policy measures.
- Sustainable plastic production, environmental plastic pollution and the effects on human health and food safety have all been mentioned in regulations. The latter has currently received less attention.
- Policies are formulated on a global, European and regional level.

A brief overview of existing policies at different levels is provided below and organized according to the specific problem they address (plastic life cycle, environmental plastic pollution or human health and food safety). A detailed overview of the majority of (micro)plastic related policies is provided in Supplementary file 1. Recommendations towards improved (human health) policy frameworks are provided in chapter 8.

2.1 Policies related to the life cycle of plastics (from raw materials to end of life)

Global policy framework

At a global level, some initiatives are taken up addressing single-use plastics, sustainability of plastic industry and the transboundary transport of plastic waste. As an example, UNEP launched a global campaign 'Single-use plastics: a roadmap for sustainability', including policy guidelines on regulating the production, use and recycling of single-use plastics (UNEP, 2018). In accordance with this, countries such as Denmark, Canada, Iceland, the Netherlands and Italy (Piemonte region), use deposit fee's for single-use PET bottles (Watkins et al., 2019) in order to reduce litter. The use of intentional addition of microplastics to daily-use products such as cosmetics, detergents and paints has received a lot of attention. Worldwide, there are specific actions regarding the ban on intentionally added microplastics in rinse-off cosmetics (Figure 3), however, there is no collective global action yet. However, in 2022, the UN Member States drafted the plastic pollution treaty to end plastic pollution and use through a circular economy based on eliminating waste and pollution, circulate products and regenerate nature.

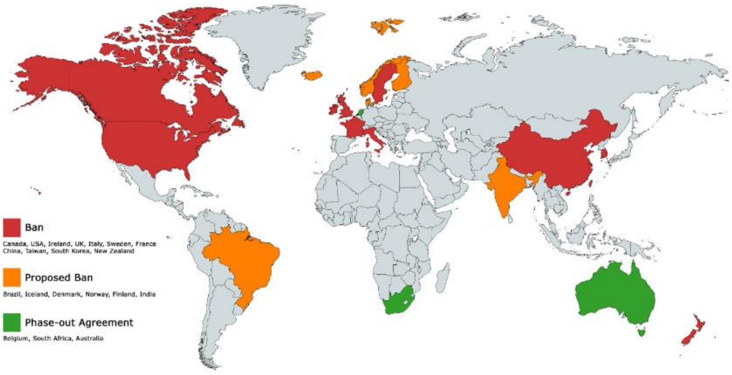

Figure 3: Map of current local policies against the use of intentionally added microplastics with a differentiation between active bans (red), proposed bans (Orange) and phase-out agreements (green). This map was created in 2021, so more recent changes are not included. Map from (Anagnosti et al., 2021)

European policy framework

Similar topics are addressed at European level with focus on single-use plastics (e.g. Single Use Plastic Directive), sustainable production and circular economy (e.g. Chemicals strategy for sustainability, European Bioeconomy) and waste management (e.g. Waste Framework Directive). The European Strategy for Plastics in a circular economy from the European Commission formulated some specific targets regarding plastic packaging: 'by 2030, all plastic packaging that is placed on the European market is either reusable or can be recycled in a cost-effective manner'. There is an ongoing initiative of the EU that aims to tackle unintentional release of microplastics into the environment.

The European Chemicals Agency (ECHA) was requested by the European commission to formulate a restriction developed under the REACH legislation on the use of intentionally added microplastics in all possible products, among others rubber infill for sport fields, personal care products and other daily-use products (ECHA, 2019). ECHA considers intentionally added microplastics as *non-threshold substances, classifying them as equivalent to PBT/vPvB (persistent, bioaccumulative, toxic/very persistent, very bioaccumulative).*(Napper et al., 2015; UNEP, 2015). Moreover it was argued that natural alternatives are available, therefore, the exclusion should be feasible (Anagnosti et al., 2021). As this is an ongoing process, there were also some concerns raised on the exclusion of water-soluble polymers[4], the lack of global action, and the challenges regarding import.

National and Regional policy framework

On both national and regional levels, several initiatives are taken related to the plastic life cycle. Since January 2022 the use of single-use plastic products such as cutlery and straws are prohibited (C-2022/20004). In 2023, this will be expanded to single-use plastic bags. In 2018, a sector agreement was published with the cosmetics industry to lower the use of intentionally added microplastics in cosmetic products and toothpaste on a voluntary basis (C-2019/404782). This agreement will be nullified when the REACH restriction will be accepted. Moreover, a discussion is ongoing on a new regulation regarding a deposit fee for PET-bottles in order to encourage recycling and reduce littering. Pending the evaluation of the current litter policy, the feasibility of implementing financial instruments such as the deposit systems was also one of the goals (nr.10) of the Flemish action plan on marine litter.

[4] *Water-soluble polymers are defined as polymers that can be dispersed, dissolved or swell in water (Nyflött et al., 2017; Rozman & Kalčíková, 2021).*

2.2 Policies related to environmental plastic pollution

Environmental plastic pollution is generally most commonly mentioned in policy frameworks (Supplementary file 1 – Based on Devriese et al. (2023)). However marine pollution is a multifaceted problem with various sources and the fact that pollution travels across territorial boundaries making it also a transboundary problem.

Global policy framework

A few relevant policy frameworks are (full list can be found in Supplementary file 1):

- **The UN Sustainable Development Goals (SDG)**
  The plastic pollution problem can be related to SDG14 – life below water; SDG 12 – Responsible consumption and production; It can also be linked to SDG 3 -Good health and well-being as our health is interlinked with the health of our environment.
- **Global plastic treaty**
  At the UNEA-5 the Member States adopted a resolution to end plastic pollution and negotiate an international legally binding agreement by 2024. They specifically highlight (in the preamble) that plastic pollution also includes microplastics. In their report, they propose a system change scenario to reach this goal (UNEP, 2023b). At UNEA-6 (2024), advances will be discussed between member states and stakeholders.

European policy framework

As on the global level, the concern on (micro)plastic releases is tangible across many EU policy strategies and policy actions are taken to tackle plastic pollution.

At the European level, following policy frameworks are, amongst others, addressing environmental plastic pollution (full list see Supplementary file 1):

- **The European Green Deal (COM (2019) 640)**
  The European Green Deal aims for a healthy and climate neutral continent. Based on the included zero environmental pollution agenda, the European Commission adopted the EU Action Plan: Towards Zero Pollution for Air, Water and Soil in 2021. This aims to reduce pollution "to levels no longer considered harmful to health and natural ecosystems, that respect the boundaries with which our planet can cope, thereby creating a toxic-free environment" (European Commission, 2021). 'The Source to Seas – Zero Pollution 2030' (SOS-ZEROPOL2030) project (EU Horizon Europe) aims to develop a holistic zero pollution framework to support the action plan.
- **Marine Strategy Framework Directive (MSFD) (2008/56/EC)**
  The MSFD describes some specific action points regarding marine litter (Descriptor 10): *'Properties and quantities of marine litter do not cause harm to the coastal and marine environment'.* Two criteria (D10C2 *Spatial distribution of micro-litter* and D10C3 *Micro-litter ingestion*) specifically apply to microplastics ('micro-litter').

In the framework of marine pollution, there are also policies developed within the Regional Sea Conventions. For the North Sea, as part of the Northeast Atlantic, OSPAR is responsible for implementing the Oslo-Paris Convention and strive for a healthy marine environment but also quality assessment and protection and conservation of the ecosystem and biodiversity. In 2022 it has adopted its second Regional Action Plan on Marine Litter.

National and Regional policy framework

At the federal level, the federal Action Plan on Marine Litter outlines 25 concrete steps that build on the initial plan developed in 2017. Its objectives are twofold by ensuring that as little litter as possible ends up in the North Sea and removing the litter already present from the North Sea. At the Flemish level, there is a Flemish action plan against marine litter that had a target to reduce the influx of marine litter from Flanders to the marine environment by 75%. To objectively measure the progress, a baseline measurement was performed between 2020 and 2022 at the request of OVAM (Everaert et al., 2022).

2.3 Policies related to microplastics and human health or food safety

In regulations and policy frameworks, such as the Farm to fork strategy from the EU Green Deal and Europe's beating cancer plan, the undeniable link between healthy planet and healthy people is recognized. This link was also acknowledge by Leticia Carvalho, head of the Marine and Freshwater Branch at UNEP who said: "The impacts of hazardous chemicals and microplastics on the physiology of both humans and marine organisms is still nascent and must be prioritized and accelerated in this Decade of Ocean Science for Sustainable Development."

Global policy framework

To our best knowledge, there are currently no global policies that specifically address the issue of microplastics in regard to human health and food safety. Nonetheless, there are some initiatives, such as the Global Coalition for Regulatory Science Research (GCRSR), under the leadership of the US Food and Drug Administration, discussing amongst others, nanoplastics as emerging pollutant (Allan et al., 2021).

European policy framework

At the European level, some policies recognize the possible effect of microplastic pollution for human health and food safety. This is, hitherto, mostly linked to drinking water (e.g. Directive 2020/2184 or the Drinking water directive) where microplastics are put on the 'watch list'. Other regulations focus on the leaching of plasticizers or other additives, for example REACH regulation No 1907/2006 and Regulation 10/2011 on food contact materials. The latter already mentioned nanoparticles but does not (yet) specifically include nanoplastics.

Moreover, a proactive approach is applied to address the issue of microplastics in food safety by funding of research projects to better understand the link between microplastics and human health. Early in 2021, the EC funded five largescale research projects under the EU Horizon 2020 research and innovation program and united them under the European Research Cluster to Understand the Health Impacts of Micro- and Nanoplastics (CUSP). The dialogue between scientists, stakeholders and policymakers within this CUSP framework will enhance the relevance and impact of the research on the future policy framework (CUSP, 2022).

National and Regional policy framework

To our knowledge, no regional policies are formulated that take into account microplastics for human health or food safety.

3. Microplastic pollution in the environment

Key highlights

- Plastic is persistent, leading to accumulation in the environment.
- General average concentrations (MP> 25µm) reported are:
  - Terrestrial environment: 6000 MP/kg soil
  - Freshwater environment: 0.28-1265 MP/m³
  - Marine environment: 1.5-9200 MP/m³
  - Atmosphere: 0-14 MP/m³

  Comparison between studies is complex due to differences in methodology and lower size limits.
- All compartments are irrefutably connected in the plastic cycle
- Increasingly, research efforts are applying a modelling approach to predict micro- and nanoplastic concentration, transport and fate.

Most plastic is persistent, leading to accumulation in virtually every environmental compartment (Andrady, 2011; Wang et al., 2021; Zhang et al., 2016). A brief overview is provided on the measured occurrence and sources of microplastics in different environments, tables with reported concentrations can be found in Supplementary file 2. For detailed information, we refer to the policy informing brief on (marine) litter and microplastics (Devriese & Janssen, 2023).

So far, no standardized methods are available for sampling, extraction, and analysis of microplastics in environmental samples. The chosen methodology can influence the results of individual studies, hereby complicating the comparison of results and introducing variability (Beiras & Schönemann, 2020; Bohdan, 2022). As a consequence, this implies that comparing results is often challenging and should be done with caution. Following the existing and emerging concerns and legislation around microplastics, more harmonized and standardised methods for microplastics monitoring in the environment are being developed in the Horizon2020 project EuroQCharm but also by international and European standardisation bodies (ISO and CEN) (See Section 8.2.1). Besides these efforts, we also need harmonized and standardized methods for monitoring MNP in food, feed, and humans.

Finally, the lower size limit reported in research is strongly variable and depends on the sampling and analytical methods used (mostly min. 25 µm, 100µm or 300µm). This has implications on the reported concentrations and hampers direct comparisons between studies:

- Depending on the lower size limit, the concentration will be different. As was already proven multiple times, the size distribution of microplastics follows a power-law function with higher concentrations in lower size ranges (Koelmans et al., 2020). Thus, studies that report a lower size range of 25µm will often report higher particle number concentrations compared to e.g. studies using manta nets with mesh size of 300 µm. Comparison between those studies is difficult.

- The concentrations never contain information on the smaller microplastics and nanoplastics as there is currently no method available to measure particle-based concentrations in environmental samples. One paper (Ter Halle et al., 2017) described the presence of nanoplastics in environmental samples measured using fractionating techniques and mass-spectrometry analysis (Pyrolysis-GC/MS). Materić et al. (2022) measured nanoplastic in polar ice using Thermal desorption – Proton Transfer Reaction – Mass Spectrometry (TD-PTR-MS). Both are mass-based methods that do not provide information on the sizes of microplastics and are not able to give information on particle-number concentrations of microplastics in samples.

For clarity, when concentrations of plastics are mentioned in this brief, it is based on the particle number concentration and not the mass-based concentration, unless stated otherwise. Secondly, no safety thresholds have been defined for microplastics in the environment, therefore, it is not yet possible to assess the environmental risk based on these concentrations.

3.1 Terrestrial environment

Concentrations

Research on microplastics concentrations in the terrestrial ecosystem is still in its infancy as these ecosystems have received less attention compared to aquatic ecosystems. A broad scale meta-analysis performed by Koutnik et al. (2021) revealed an average concentration of approximately 6000 microplastic per kg of soil (ranging between 0 to 945000 MP/kg soil), based on 196 studies worldwide. The variation on the reported particle-based concentrations is significant and could be linked to location but also to differences in methodology (Koop & van Leeuwen, 2017; Koutnik et al., 2021). The presence of earthworms has been proven to allow the transport of microplastics to deeper layers of the soil where they can interact with the biota present but it could also be a pathway of contamination of the groundwater (Rillig et al., 2017). Moreover, microplastics have been demonstrated to be taken up by the roots of plants, e.g. birch trees (*Betula pendula*) (Austen et al., 2022).

Sources

Various sources could cause microplastic contamination in the soil such as the land application of sewage sludge (Corradini et al., 2019; S. Li et al., 2018; X. Li et al., 2018), the use of compost fertilizers (Kumar et al., 2022; Weithmann et al., 2018), plastic mulching (Steinmetz et al., 2016), street run off (Piñon-Colin et al., 2020), irrigation using wastewater (Kumar et al., 2022), and atmospheric deposition (Abbasi et al., 2019). An increase in urbanization is suggested to be linked to the microplastic concentrations (Koop & van Leeuwen, 2017; Koutnik et al., 2021).

3.2 Freshwater environment

Concentrations

There is a knowledge gap on the microplastic pollution in freshwater ecosystems but concentrations in European regions varied from 0.28 to 1265 MP per m^3 (Sarijan et al., 2021). Recently, Semmouri et al. (2023) published measurements of microplastic concentrations in Flemish freshwater including a comparison with reported concentrations worldwide. Based on these results (Supplementary file 2), the measured microplastic concentrations in Flemish surface water are comparable to, among others, the Netherlands (Leslie et al., 2017), Finland (Uurasjärvi et al., 2020), and the United Kingdom (Stanton et al., 2020), but also to those measured in a river in Antarctica (González-Pleiter et al., 2019).

Sources

Via various sources, microplastics can end up in freshwater ecosystems. Examples are wastewater treatment discharge, agricultural runoff and overflow of sewage water during storm events (Forrest et al., 2022; Sarijan et al., 2021; Vercauteren et al., 2022; Vollertsen et al., 2007). Locations in regions with higher human activity are in general more likely to contain higher microplastic concentrations (Sarafraz et al., 2016). These systems are therefore suggested to be temporal sinks of microplastics (Nel et al., 2018). It is suggested that freshwater transports the microplastics towards the ocean, as the final sink. Yet, this general assumption remains to be confirmed as vertical transport of microplastics throughout the water column may lead to accumulation in freshwater sediments. Additionally, within estuaries such as the Scheldt, tidal activity may also prevent transport of microplastics to the ocean (this is being studied within PLUXIN and LABPLAS projects).

3.3 Marine environment

Concentrations

Plastic pollution in the ocean is a problem best known from the garbage patches that are found in open ocean which accumulate plastic debris at a rapid pace. The Great Pacific Garbage Patch contains on estimate 45 to 129 thousand tons of plastic in an area of 1.6 million km² (Domenech & Marcos, 2021; Lebreton et al., 2018). Microplastics are also part of these garbage patches and account for an estimated 94% of the number plastic pieces, although they only count for 8% of the total mass (Lebreton et al., 2018).

Generally, reported marine microplastic concentrations can vary greatly based on their geographical location and ecological compartment (e.g. sediment, water column, surface water) (Supplementary file 2). For example, in the Atlantic Ocean an average concentration of 1.5 MP/m³ was observed (Kanhai et al., 2017), while in the Northeastern Pacific Ocean the microplastic concentration ranged between 8 and 9200 MP/m³ (Desforges et al., 2014). The marine environment is the most studied environment for (micro)plastic pollution, this section thus only provides a very brief summary on the current state-of-the-knowledge More detailed information can be found in the policy brief by Devriese & Janssen (2023).

Sources

The ocean has for long been regarded as a major sink for microplastics and the microplastics in the marine environment are originating from both land-based (e.g. non-collected waste, waste water, run-off directly or indirectly via rivers and streams) and offshore sources (e.g. paints of ships (Gaylarde et al., 2021)). The transport of microplastic through the water column and the ocean from its entry point to its final deposition remains to be fully elucidated and plays a primordial role in identifying hotspots of microplastic pollution and environmental compartments at risk (Galgani et al., 2000).

3.4 Atmosphere

Concentrations

Comparable to the knowledge on the microplastic pollution in the terrestrial environment, research on the occurrence of microplastics in the atmosphere is quite new. This results in a limited number of scientific papers on the topic (Can-Güven, 2021). Moreover, the used methodology is often quite variable (e.g. sampling airborne microplastics or deposition) resulting in a variable reported concentration and complicating comparison between studies (Azari et al., 2023). In general, reported atmospheric microplastic concentrations are between 0 and 14 MP/m³ of air (Supplementary file 2). In case atmospheric deposition is measured, concentrations range between 2 and 1008 MP/m²/day (Supplementary file 2).

Once microplastics are in the air, they can either be transported or deposited. The observation of microplastics in remote areas, without any local point sources of plastic (e.g. pristine mountain catchment in French Pyrenees (Allen et al., 2019) or snow from the Arctic (Bergmann et al., 2019)) suggests long-distance atmospheric transport of microplastics (Bank & Hansson, 2019). Estimates indicate that microplastics can be transported over more than 1000 km (González-Pleiter et al., 2020). The surface area and density of microplastic supports these estimates (Bergmann et al., 2019; Munyaneza et al., 2022). Secondly, the airborne microplastics can also be deposited, which is believed to be an important source of microplastics in aquatic and terrestrial environments. Both dry and wet deposition is possible (Gaston et al., 2020). Dry deposition is mostly influenced by wind patterns, while precipitation is affecting the wet deposition of microplastics (Dris et al., 2017; Zhang et al., 2020)

Sources

Both indoor and outdoor airborne microplastics originate from various sources including city dust resuspension (Munyaneza et al., 2022), waste incineration (Munyaneza et al., 2022), opening of a plastic package (Sobhani et al., 2020), wear of textile garments (Belzagui et al., 2019; Dris et al., 2017), tire wear particles (Baensch-Baltruschat et al., 2020; Munyaneza et al., 2022) and sea spray aerosols (Catarino et al., 2023; Munyaneza et al., 2022; Lambert et al., *in prep*). City dust resuspension and tire wear particles are assumed to be the primary sources of atmospheric microplastic contamination (Munyaneza et al., 2022). An atmospheric transport model study suggested that roads and ocean sources contributed 84% and 11% of the microplastic deposition, while agricultural dusts and population sources contributed 5% and 0.4%, respectively.

3.5 Connection between environments

Importantly, the environmental niches, as described above, are irrefutably connected as a complex network with transmission of microplastics between air, land, water and biota that will also impact human and environmental health (Domenech & Marcos, 2021). This was described by Bank and Hanson (2019) as the 'plastic cycle' (Figure 4), i.e. *"the continuous and complex movement of plastic materials between different abiotic and biotic ecosystem compartments, including humans".* As an example, microplastic contamination in freshwater is transferred to the terrestrial environment through irrigation in agricultural practices (Domenech & Marcos, 2021; Kapp & Yeatman, 2018).

The rate of this transmission is however subjected to spatial and temporal variability (Wright et al., 2021) determined by among others weather conditions (e.g., humidity and precipitation intensity, wind speed and wind direction, etc.; (Enyoh et al., 2019; Huang, Qing, et al., 2020; Magnusson et al., 2016), topography (e.g., slope, canyons, bays, etc.; Enyoh et al., 2019), landcover type (e.g., water, snow, grassland, forest, bare soil, etc.; Klein et al., 2018) and land use (e.g., agricultural land, urban and recreational area, etc.; (Magnusson et al., 2016). This all-encompassing network indicates the broad range of human exposure pathways to MNP (Domenech & Marcos, 2021).

3.6 Future of monitoring: modelling approaches

The mentioned concentrations in all compartments are based on actual observations, limited by number of samples, analytical limits, etc.

An increasing amount of research is focussing on finding new ways to predict the concentration, fate, and transport of micro- and nanoplastics. If this can be done in a reliable way, e.g. by using a modelling approach, knowledge gaps can be filled and risk assessment could be improved in a time and cost-efficient manner. The number of publications on the modelling of concentrations of microplastics is vastly increasing over the past five years (Figure 5).

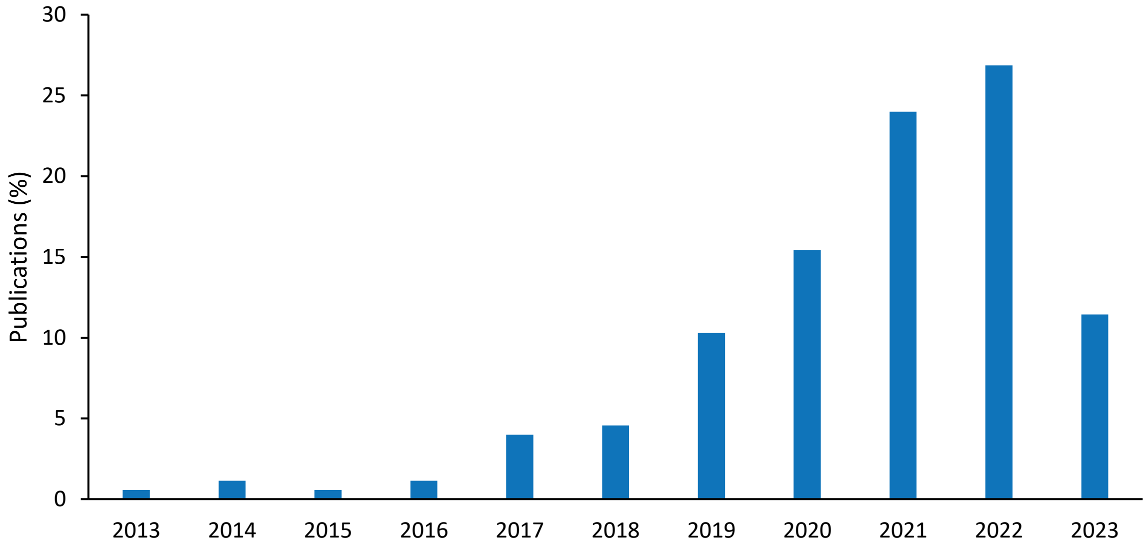

Figure 5: Overview on the number of publications on microplastic concentration modelling per academic year.

A few examples are:

- **SimpleBox4Plastic**
  As the first multimedia model linking MNP concentrations and transport across all four environmental compartments and taking into account aggregation and fragmentation by using mass balance equations (Quik et al., 2023).
- **Full Multi**
  A new, open access modelling framework for MNP fate and transport in aquatic systems (Domercq et al., 2022).

It is anticipated that optimized multimedia models will be published in the coming years.

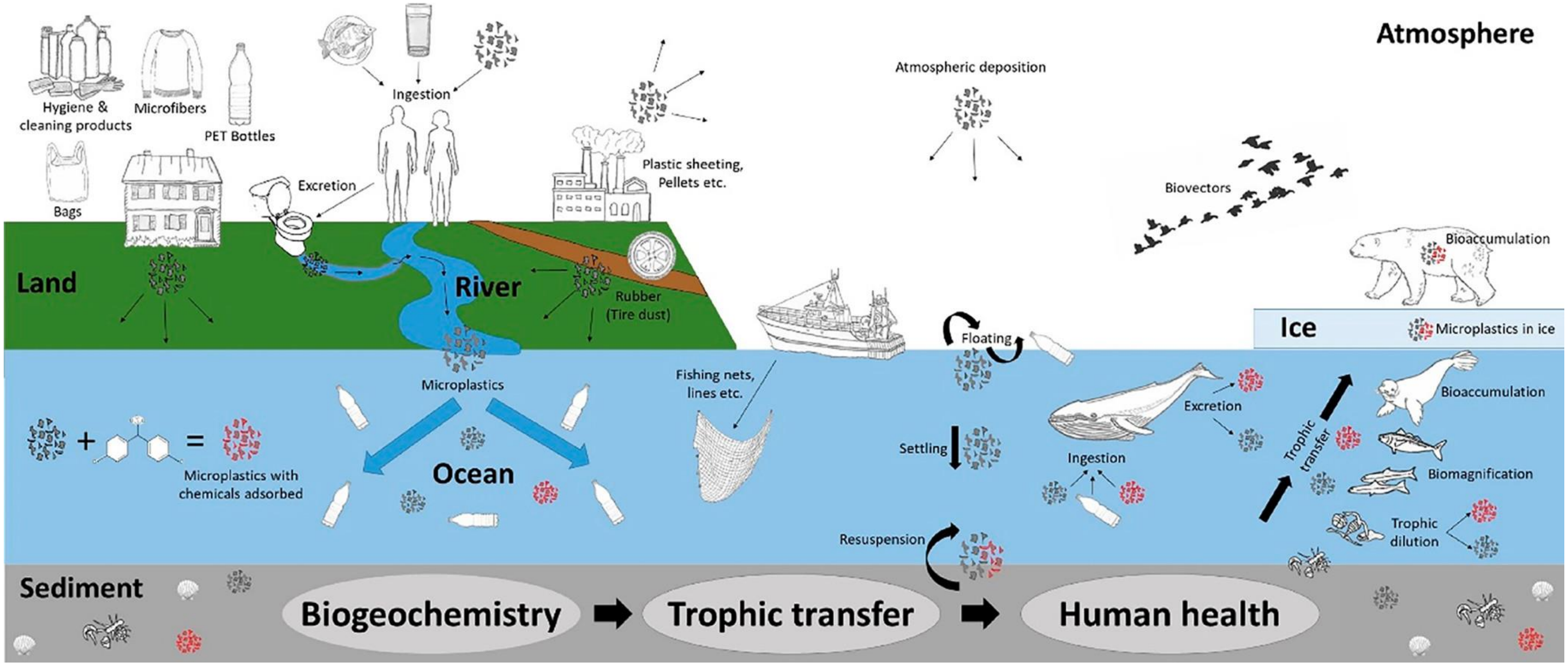

Figure 4: The plastic cycle, defined as the continuous and complex movement of plastic materials between abiotic and biotic ecosystem compartments, including humans (Bank & Hansson, 2019).

4. Interaction between micro- and nanoplastics and the environment

Key highlights

- Plastic particles can act as substrates, which can interact with their environment.
- It is known that chemicals such as persistent organic pollutants and metals in the marine environment have the potential to adsorb on plastics.
- Microbial community can attach on plastic debris, referred to as "The plastisphere".
- Immediately upon entering a biological environment, MNPs interact with macromolecules, especially proteins, and adsorb molecules on their surface, forming a protein corona

Plastic particles can act as substrates allowing an interaction with their environment mainly driven by the high hydrophobicity of plastics (Gauquie et al., 2015). Typically, two interactions are studied: (1) adsorption of chemicals and (2) interaction with macromolecules and micro-organisms.

4.1 Adsorbed chemicals

It is known that all organic matter in the environment has the potential to adsorb hydrophobic organic compounds from environmental matrices. Microplastics are no exception (Devriese et al., 2017; Koelmans et al., 2016).

The process of adsorption is defined as the chemicals present in the environment binding to the surface of the plastics. On the other hand, penetration or diffusion of chemicals into the plastic is called absorption (Gopinath et al., 2022). Based on conducted research, electrostatic bonding, hydrogen bonding, hydrophobic interaction, van der Waals interaction and π-π interactions are the predominant sorption mechanisms (Gopinath et al., 2022). Chemicals are subject to partitioning, i.e. the distribution of chemicals among phases or compartments, across water, sediment, biota, air and plastics (Koelmans et al., 2016). Under certain conditions, the sorbed pollutants can desorb, i.e. release from the plastics (Devriese et al., 2017; Gopinath et al., 2022)

Gauquie et al. (2015) identified more than 200 organic compounds or compound groups on plastic debris collected in the Belgian part of the North Sea. Amongst those, we can find:

- **Chemicals of concern persistent organic pollutants (POPs)**
  As an example, polychlorinated biphenyls (PCBs) are found, even though they were banned in the 1980's (Devriese et al., 2017). Other examples are polycyclic aromatic hydrocarbons (PAH)

and organochlorine pesticides (Gauquie et al., 2015). Importantly, some of these substances, like PAHs can also be present in the virgin plastic product (Gauquie et al., 2015).

- **Metals**
  Metals such as aluminium, iron, cadmium, lead and zinc are found to have strong adsorption capacity to plastics (Gauquie et al., 2015). Some metals are also used as stabilizers in plastics, although the use of lead and cadmium additives is now restricted in Europe (Town et al., 2018).
- **Pharmaceuticals**
  Anticancer, antineoplastic, anticonvulsants, psychotic and anaesthetic drugs have been described to sorb to medical plastic devices. Examples are benzocaine, vitamin A, propranolol. An extensive list can be found in Gopinath et al. (2022). This absorption results in a significant loss of therapeutic potential of pharmaceuticals (Gopinath et al., 2022).

Measured concentrations on microplastic particles from the environment range between 0.1-45,000 ng/g (Table 3), however, the dynamic sorption/desorption processes, result in complex interactions that can rapidly change (Gauquie et al., 2015).

Table 3: A non-exhaustive list of measured chemical concentrations on microplastic fragments found in the environment. Importantly, it is often not specified if reported concentrations are total concentrations (plastic particle and adsorbed chemicals) or concentrations of adsorbed chemicals extracted from the surface.

Chemical group	Chemical	Concentration	Reference
Persistent organic pollutants	16 EPA-PAHs	1076–3007 ng/g	(Antunes et al., 2013; Hirai et al., 2011; Mizukawa et al., 2013)
	P 7 OSPAR-PCBs	31 to 236 ng/g	
	Polycyclic aromatic hydrocarbons (PAHs)	up to 45,000 ng/g	
	Polychlorinated biphenyls (PCBs)	up to 450 ng/g	(Antunes et al., 2013; Hirai et al., 2011; Karapanagioti et al., 2011; Mizukawa et al., 2013)
	Organochloride pesticides (OCPs)	200 ng/g	
Metals	Al, Fe, Cu, Pb and Zn	up to 300 µg/g	(Holmes et al., 2012)
	Cd, Cr, Co, Ni	up to 80 ng/g	
Plastic additive	Bisphenol A	up to 35 ng/g with outliers up to 700 ng/g	(Hirai et al., 2011; Rochman et al., 2014)
	PBDEs	between 0.1 and 400 ng/g with outliers up to 9900 ng/g	
	Alkylphenols	up to 3940 ng/g	

The sorption/desorption processes can be influenced by properties of the plastics (surface roughness and charge, size, porosity and degradation), properties of the chemicals (e.g. hydrophobicity, solubility, polarity, charge) and environmental conditions (e.g. pH, salinity, temperature, dissolved organic matter). As an example, physical and chemical weathering of the plastics can increase the surface area and create new sorption sites for pollutants. Additionally, the surface often becomes negative charged and thus stimulating electrostatic interactions (Gauquie et al., 2015; Town et al., 2018).

The adsorption/absorption processes have sparked questions on the role of plastics in the transport of such chemicals in the environment, but also, microplastics can be a vector for chemicals, including hazardous pollutants, for both environmental and human health exposure through desorption after ingestion (Gopinath et al., 2022; Koelmans et al., 2016) (Section 7.5). Importantly, microplastics are not the only particles present in the environment, therefore the relative contribution of microplastics in the transfer of hazardous chemicals is subjected to discussion, and according to some sources not as important as other transport routes such as suspended organic particulates or natural diet and prey items (Koelmans et al., 2016).

4.2 Interaction with macromolecules and micro-organisms

4.2.1 Biological macromolecular interactions

Immediately upon entering a biological environment, MNPs interact with macromolecules, especially proteins, and adsorb molecules on their surface, forming a protein corona (Gopinath et al., 2022; Kopac, 2021). The MNPs adsorb the proteins via Van der Waals force, electrostatic or hydrophobic attraction (Gopinath et al., 2022).

The interactions are driven both by particle (charge, size, surface functionality and hydrophobicity) and protein characteristics (e.g. histidine and tyrosine establish strong interactions) (Gopinath et al., 2022).

The formation of a protein corona follows different steps. It initially starts with a primary cluster of proteins that are weakly bound to the MNP surface with noncovalent interactions, called the soft corona. Subsequently, the weakly adsorbed proteins will be replaced with more tightly bound molecules forming a hard corona (Kopac, 2021). Moreover, protein-protein interactions can occur resulting in a multi-layered corona or aggregation of MNPs with protein coronas (Gopinath et al., 2022).

4.2.2 Biofilm formation

Bacterial communities are known for their adaptability, allowing them to quickly colonize diverse ecological habitats, including artificial sources such as microplastics (Oberbeckmann et al., 2014). The microbial community forming on plastic debris, including on microplastics, is often referred to as the “plastisphere” (Zettler et al., 2013).

Succession of biofilm

Plastics undergo rapid coverage (within minutes) by hydrophobic inorganic and organic matter, known as the "conditioning film" (Oberbeckmann et al., 2015) or "eco-corona" (Galloway et al., 2017; Junaid & Wang, 2021). This process alters the hydrophobicity of the microplastics and facilitates microbial colonization (Galloway et al., 2017; Wright et al., 2020).

The initial biofilm formed consists of pioneer bacteria, such as Gammaproteobacteria and Alphaproteobacteria, which attach reversibly to the surface of microplastics (Figure 6) (Du et al., 2022). Through attachment, these pioneer bacteria further decrease the surface hydrophobicity (Tu et al., 2020) and promote stronger biofilm adhesion to the microplastics by secreting extracellular polymeric substances (EPS). This facilitates further colonization (Kumar et al., 2020). Moreover, pioneer bacteria experience minimal competition, which results in extensive coverage of the plastic surface (Dang &

Lovell, 2016). The initial biofilm becomes detectable within one week (De Tender et al., 2017; Wright et al., 2020).

The secondary colonizing bacteria play a crucial role in the irreversible attachment of the biofilm to the surface of microplastics through active mechanisms such as pili, adhesion proteins, and EPS (Dussud et al., 2018). The composition of this secondary colonization can be influenced by the pioneer bacterial composition (Rummel et al., 2017). Limited resources and space during secondary colonization will lead to niche divergence and reduced competition (Wright et al., 2020). The formation of the secondary biofilm typically becomes detectable after several months (De Tender et al., 2017; Wright et al., 2020).

This mature biofilm increases further in complexity producing a self-made matrix rich in EPS that offers protection against predation (Sionov & Steinberg, 2022; Vestby et al., 2020). A biofilm is a complex, three dimensional organization of bacteria (Preda & Săndulescu, 2019). Secondary metabolites are also produced, facilitating bacterial communication (quorum sensing) and exhibiting antimicrobial effects for competing bacteria (Miller & Bassler, 2001; Sionov & Steinberg, 2022).

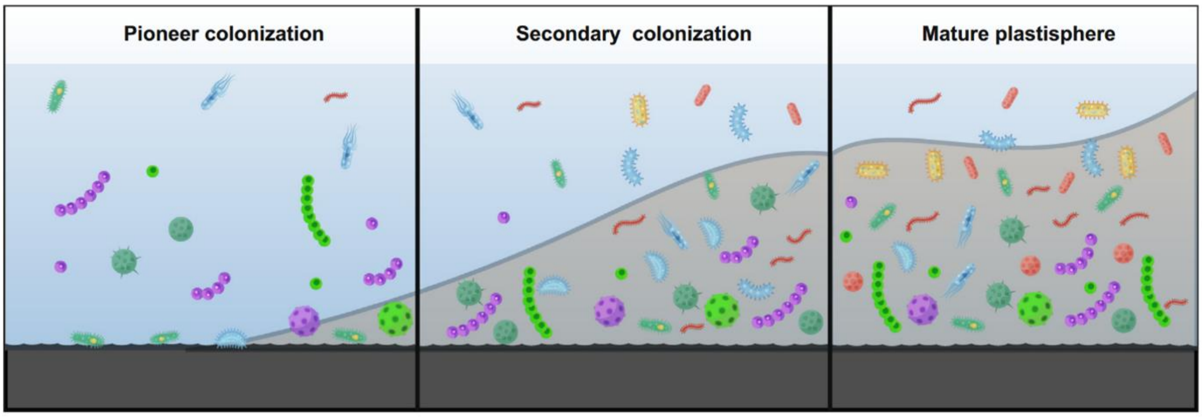

Figure 6: Visualization of the steps of biofilm formation on a plastic surface (dark grey) in contact with water with various bacterial species. The bacteria produce exopolysaccharides (EPS; light grey) that form a matrix for the biofilm and increases adherence to the plastic surface (adapted from Du et al. 2022).

Biofilm composition

In the North Sea, several studies found bacteria that comprised the plastisphere: Flavobacteriaceae, Cryomorphaceae and Saprospiraceae (plastics sampled at the sea surface) (Oberbeckmann et al., 2016), Alpha- and Gammaproteobacteria (plastics sampled on the seafloor) (De Tender et al., 2017) and Proteobacteria, Nitrospira, Planctomycetacia, Caldilineae and Acidimicrobiia (plastics sampled in the water column) (Kirstein et al., 2018). Moreover, over the past years, different studies confirmed the presence of pathogens within the plastisphere (Khalid et al., 2021; Kirstein et al., 2016; Wu et al., 2019). For example, the potentially pathogenic *Vibrio* sp. was found on microplastics in marine environments in several studies (e.g. Foulon et al., 2016; Kirstein et al., 2016; Zettler et al., 2013). This plastisphere composition is dependent of several environmental as well as non-environmental parameters (Oberbeckmann et al., 2018).

The biofilm composition in other environments (e.g. freshwater, terrestrial, wastewater effluents,…) are not yet characterized. Also, biofilm formation and composition in relation to the human microbiome has not been studied, to the best of our knowledge.

Plastisphere – specific biofilm on plastic material

This plastisphere community composition can vary compared to other types of substrates. For example, differences between inert surfaces, such as microplastics, and natural surfaces, like wood pellets and cellulose, were found (Oberbeckmann et al., 2018; Ogonowski et al., 2018). Microbial communities on inert particles and in the bulk seawater were also found to distinctively diverge from each other (Dang & Lovell, 2016). Moreover, biofilm communities on PS substrates exhibited significantly higher diversity compared to those on PE substrates (Parrish & Fahrenfeld, 2019).

This is possibly due to the different nutritional conditions and unique niches possible in biofilms (Dang & Lovell, 2016). However, it has been shown that there is no significant difference in the microbial community between plastics and other inert surfaces such as glass (Oberbeckmann & Labrenz, 2020). It has been observed that the rough and irregular surfaces of plastics can offer additional colonization sites for biofilm communities (Amaral-Zettler et al., 2021; Parrish & Fahrenfeld, 2019).The release of plastic additives from different types of plastics can also impact the biodiversity and structure of the biofilm, causing plastic-specific differences.

Effect of biofilm formation

The presence of a biofilm can have effects on the bioavailability of plastic particles as the biofilm can increase the density of microplastics. This could make them negatively buoyant inducing sinking behaviour (Amaral-Zettler et al., 2021). This leads to a higher bioavailability of microplastics in the whole water column and benthic zones for a variety of organisms (Li et al., 2018).

A biofilm can contain pathogenic species causing possible increased exposure to pathogens via concentration of pathogens on plastic surfaces. Furthermore, it can influence the transport and dispersion of such pathogens. The biofilm is an adaptation of bacteria to survive in certain environments and be more resilient, leading to longer survival (Preda & Săndulescu, 2019). Additionally, by inclusion of possible pathogens in a biofilm, they can evade the host's immune system and thus cause more severe infections (Preda & Săndulescu, 2019)

Bacteria present in the biofilm can also communicate with each other using quorum sensing, this can lead to an increased virulence of bacteria through metabolic changes of the bacteria (Preda & Săndulescu, 2019). Moreover, they can exchange genes. Recently, scientists have noticed that microbial communities colonized on plastic tend to carry substantial amounts of antibiotics resistance genes (ARG), which can be transferred to new (potentially pathogenic) bacterial species. Therefore, MNPs can be vectors for the spread of ARG (Arias-Andres et al., 2018; Zettler et al., 2013). Importantly, the importance of MNPs in the spread of pathogens or ARGs in comparison to other (natural) particles is yet unknown.

5. Human exposure to microplastic

Key highlights

- Humans are exposed to microplastics via various products including
  - Food such as fruits, vegetables and table salts
  - Beverages such as drinking water and beer
  - Medicine
  - Personal care products
- The air that we breath is also an important source of micro-and nanoplastic exposure.
- Furthermore, wrapping or preparation of food can cause additional microplastic exposure

Humans are exposed to microplastics via various products (such as food and beverages, food packaging and personal care products) and pathways (e.g. indoor and outdoor air pollution) (Figure 7). The presence of microplastics can be considered as an unintentional or intentionally added contaminant which can affect human safety (EFSA, 2016; Hantoro et al., 2019).

5.1 Microplastic exposure via food and beverages

The state-of-the-art knowledge on microplastic exposure via various food products will be discussed below.

5.1.1 Fruits and vegetables

As the presence of microplastics in soils was demonstrated, there is also a concern for food safety since microplastics can be taken up by plants which could introduce microplastics in the human food chain. Particularly as fruit and vegetables form an important component of a balanced diet and the WHO recommends a daily intake of 400 g fruits and vegetables excluding starch-products such as potatoes, which could be a concern (WHO, 2023).

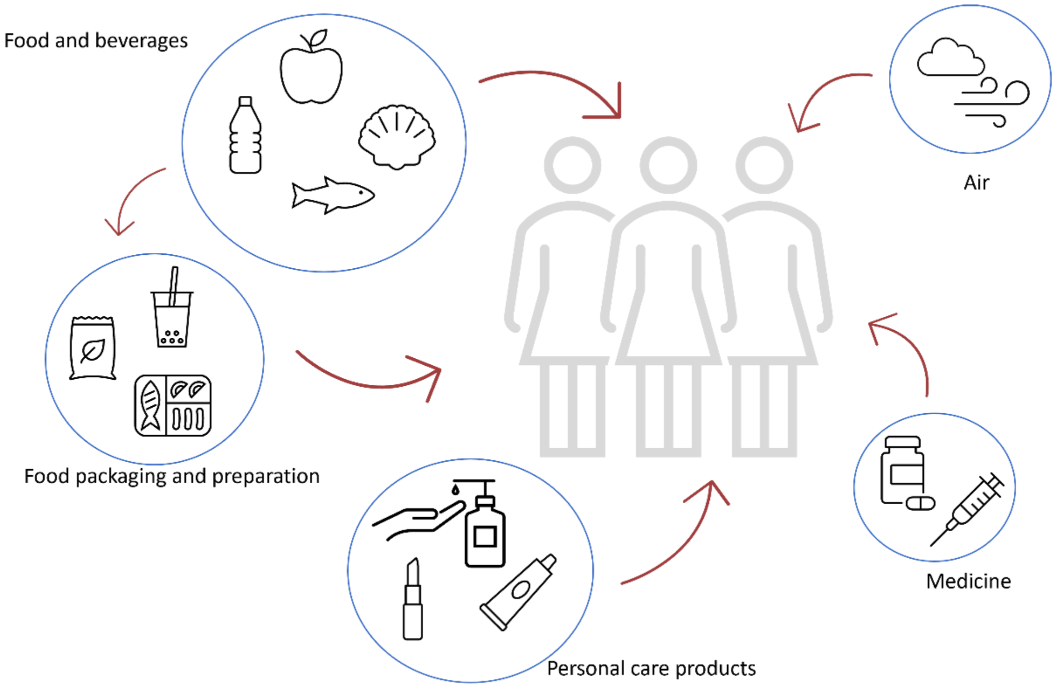

Figure 7: Schematic overview of diverse types of products and pathways by which humans are exposed to microplastics.

Occurrence of microplastic in fruits and vegetables

Only a limited number of studies have reported the uptake and distribution of MNPs in edible plants. Li et al. (2020) showed the uptake of nanoplastics (polystyrene and polymethylmethacrylate; 0.2 µm) by crop plants wheat (*Triticum aestivum*) and lettuce (*Lactuca sativa)* in an experimental setting. Based on their analyses, the nanoplastics were subsequently transported to the shoots of the plants, indicating that edible parts of plants could receive nanoplastics via contaminated soil (Li et al., 2020).

A study in India demonstrated the presence of microplastics, mainly nylon, PE and PS, in grapes (*Vitis vinifera),* bananas (Musa paradisiaca), brinjal (*Solanum melongena*) and potatoes (*Solanum tuberosum*) (Rajendran et al., 2022). However, the concentrations that were observed were not reported. The only study reporting concentrations of microplastics found in fruits and vegetables thus far is the publication of Oliveri Conti et al. (2020) who determined the microplastic concentration in carrots (*Daucus carota*), lettuce (*Lactuca sativa*), broccoli (*Brassica oleracea* var. *italica*), apples (*Malus domestica*) and pears (*Pyrus communis*) (Oliveri Conti et al., 2020) (Table 4).

The fruits (apples and pears) generally contained the highest amounts of microplastics in comparison with the studied vegetables. It is hypothesized that the high vascularization of the fruit pulp, the bigger size and complexity of the root system and the age of the vegetation (tree vs. plant) could explain the observed difference (Oliveri Conti et al., 2020). In general, root properties, xylem properties, growth rate, transpiration, water and lipid fractions, tonoplast potential, plasma membrane potential and the pH of vacuoles and cytoplasm could influence the uptake of pollutants, including microplastics (Trapp, 2000). Moreover, the size, the surface charge, morphology and the polymer type seems to impact the uptake (Dietz & Herth, 2011; Lian et al., 2021; Taylor et al., 2020; Yin et al., 2021). However, more research is necessary.

Table 4: Overview of reported microplastic (MP) concentration in fruits and vegetables

Country	Name of fruit/vegetable	Uptake (Y/N)	Concentration MP (MP/g)	Reported median size (µm)	Author
India	Grapes (*Vitis vinifera*)	Y	Not mentioned	2	(Rajendran et al., 2022)
India	Banana (*Musa paradisiaca*)	Y	Not mentioned	10	(Rajendran et al., 2022)
India	Brinjal (*Solanum melongena*)	Y	Not mentioned	10	(Rajendran et al., 2022)
India	Potato (*Solanum tuberosum*)	Y	Not mentioned	2	(Rajendran et al., 2022)
Italy	Carrot (*Daucus carota*)	Y	126,150 ± 80,715	1.51	(Oliveri Conti et al., 2020)
Italy	Lettuce (*Lactuca sativa*)	Y	50,550 ± 25,011	2.52	(Oliveri Conti et al., 2020)
Italy	Brocoli (*Brassica oleracea* var. *italica*)	Y	101,950 ± 44,368	2.10	(Oliveri Conti et al., 2020)
Italy	Potato (*Solanum tuberosum*)	Not reported	Not reported	Not reported	(Oliveri Conti et al., 2020)
Italy	Apple (*Malus domestica*)	Y	195,500 ± 128,687	2.17 µm	(Oliveri Conti et al., 2020)
Italy	Pear (*Pyrus communis*)	Y	189,550 ± 105,558	1.99	(Oliveri Conti et al., 2020)
Not reported	Cucumber (*Cucumis sativus* L.)	Not reported	Not reported		(Li et al., 2020)
Not reported	Lettuce	Y	Not reported		(Li et al., 2020)
The Netherlands	Wheat plant (T*riticum aestivum*)	Not reported	Not reported		(Qi et al., 2018)

Sources of microplastic in fruits and vegetables

Sources of plastic pollution in agriculture are described in literature. The importance of each of these sources is however not yet clear and should be studied further. The EU Horizon 2020 project PAPILLONS studies the sources, behaviour and ecological effects of micro- and nanoplastics in agricultural soils resulting from the use of agricultural plastics. Some possible sources are the use of plastic products during cultivation (e.g. plastic mulch films, row covers (e.g. Hachem et al., 2023)), irrigation with microplastic contaminated water (e.g. Tadsuwan & Babel, 2021), fertilization (e.g. control-release fertilizers (Bian et al., 2022; Trenkel, 1997)) and atmospheric fall-out (Domenech & Marcos, 2021; Enyoh et al., 2019).

Once MNPs are present in the agricultural fields, the limited available research indicates that MNPs are capable to be taken up by the roots and transported to leaves and fruits of the plants, based on possible uptake of nanoparticles (Dietz & Herth, 2011). For the uptake via the roots, MNP's will first adhere to the rhizophere (containing root cap mucilage), based on hydrophobic interactions (R. Kumar et al., 2022). Subsequently, cellular uptake will occur via the cell-wall pores (uptake is limited by size) (e.g. Enyoh et al., 2019; Jiang et al., 2019; Yin et al., 2021), crack-entry pathway[5] (e.g. Kumar et al.,

[5] *Crack-entry pathway: Using disruptions in the epidermal cell layers of the roots resulting from the emergence of developing lateral roots, aging, or damage.*

2022; L. Li et al., 2020), endocytosis (R. Kumar et al., 2022; Z. Li et al., 2020) or aquaporins[6] (Zhou et al., 2021). Depending on the cellular uptake mechanism, MNPs can be transported via different mechanisms including the apoplastic and the xylem transport system (Taylor et al., 2020).

5.1.2 Table salt

Commercial table salt is the main source of sodium in a human diet. This table salt can be derived from the marine environment, salt lakes or from wells or rocks (Jin et al., 2021). In the framework of microplastic contamination, salt is an intensively studied food source due to its clear link with the marine environment (Domenech & Marcos, 2021).

In the overall production procedures of table salt, saltwater is transferred to evaporation ponds where it undergoes concentration through exposure to sunlight and wind. As a result, the salt gradually concentrates and forms crystals on the surface of the crystallizers. These crystals are carefully collected through a controlled and enclosed gathering process. Subsequently, the salt undergoes physical treatments before being prepared for packaging (Gündoğdu, 2018). The crystals can be harvested and processed either mechanically or manually (Devriese et al., 2017).

Microplastic concentration in table salt

Microplastics have been identified in commercial salts worldwide (Jin et al., 2021), reported concentrations can be found in Supplementary file 3 (Table S3.1). Lee et al. (2019) stated that 94% of salt products tested worldwide contain microplastics (Lee et al., 2019). Reported concentrations range mostly between 0 and 806 MP/kg salt (Supplementary file 3, Table S3.1). A few higher concentrations are reported in China (max. 1,674 MP/kg salt (Kim et al., 2018)), India (max. 1,900 MP/kg salt (Yaranal et al., 2021); 1,633 MP/kg salt (Nithin et al., 2021)), Indonesia (13,629 MP/kg salt (Kim et al., 2018)), and Croatia (max. 19,800 MP/kg salt (Renzi, Grazioli, et al., 2019)) (Supplementary file 3). Generally, studies show high variability (both in one study and between studies) in microplastic concentrations (Domenech & Marcos, 2021; Lee et al., 2019) with generally higher reported microplastic concentrations in Asian countries (Karami et al., 2018; Kim et al., 2018). Even in Europe, Renzi et al (Renzi, Grazioli, et al., 2019), found striking differences between salts from Italy (22-594 MP/kg salt) and Croatia (0.07-0.20 MP/kg salt) (Supplementary file 3).

In terms of polymer composition, PE, PP and PET are generally described as the most common polymer types found in table salts (e.g. Gündoğdu, 2018; Kapukotuwa et al., 2022; Yang et al., 2015) and fibres are generally the dominant shape (e.g. Kapukotuwa et al., 2022; Nithin et al., 2021). The latter was not confirmed in the work of Rakib and colleagues who found more fragments (48%) compared to fibres (15%) (Rakib et al., 2021).

Source of microplastics in table salt

The origin of microplastic contamination in sea salt can be attributed to numerous factors. Firstly, the origin of the salt seems to be the most dominant source of microplastic contamination and thus linked to seawater pollution (Yang et al., 2015). Based on the most commonly used production process (evaporation of seawater) it is evident that microplastic contamination present in the water can be trapped between the salt crystals during the evaporation process (Gündoğdu, 2018; Lee et al., 2019; Yang et al., 2015). Microplastic concentrations found in sea salt (generally 0-806 MP/kg) are usually higher compared to lake salts (1-462 MP/kg). Rock and well salt concentrations, which are often collected underground, are even lower (generally 0-204 MP/kg) (e.g. Gündoğdu, 2018; Jin et al., 2021; Kim et al., 2018; Lee et al., 2019). This corroborates the reasoning that the origin of the salt could be

[6] *Aquaporins are membrane channels that facilitate the transport of water and small molecules.*

an important source of the microplastic contamination. Moreover, as these salts are mostly harvested in open air, atmospheric deposition can also occur (Lee et al., 2019).

Additionally, contamination of salt can occur throughout the production process and subsequent stages such as transportation, intermediate storage, packaging, and repackaging (Devriese et al., 2017). The harvested salt is cleaned, dewatered, milled, dried, sieved, sorted, and packed, which could all be possible sources of contamination. However, based on the current literature, the industrial processes of salt production seem to be able to remove the contamination at least partly based on higher microplastic contamination in raw salt (e.g. Nithin et al., 2021) and traditionally (manually) processed salt with less thorough cleaning steps (Devriese et al., 2017).

As research showed that microplastic contamination found in the salt often doesn’t match with possible plastic packaging (polymer type and shape), it appears that the packaging has a minimal impact on the microplastic contamination of table salt (Devriese et al., 2017; Fadare et al., 2020).

5.1.3 Aquatic food products

Due to the ingestion of microplastics by aquatic organisms, these particles also find their way into food products intended for human consumption including fish, bivalves and crustaceans (Devriese & Janssen, 2023; Jin et al., 2021). Since seafood is an important food source, concerns exists on the human exposure to microplastics via the consumption of seafood (Hantoro et al., 2019). Three recent and very comprehensive review articles are published describing and listing all relevant data on microplastic contamination in aquatic food products. For detailed information including specific concentrations, we refer the readers to Domenech & Marcos, 2021; Hantoro et al., 2019; Jin et al., 2021, containing data on bivalves, crustaceans and fish.

Concentration of microplastics in fish

The microplastic contamination in commercial fish species has been studied and confirmed (Jin et al., 2021). Microplastics are found in both pelagic and demersal commercially important fish species although in some cases the latter tend to show higher microplastic concentrations compared to pelagic species (Hantoro et al., 2019; Lusher et al., 2013).

Reported average microplastic concentrations in fish are:

- Between 0 and 42 MP/animal corresponding to 0 and 25.9 MP/g (Hantoro et al., 2019)
- Between 0.2 and 20 MP/animal (Jin et al., 2021)
- Between 0.002 – 0.052 MP/g (Domenech & Marcos, 2021)

Differences between data could be explained by differences in methods, species, or geographical locations.

Importantly, research shows that microplastic are mainly found in the gastrointestinal tract of fish and to a lesser extent (and presumably in a negligible amount) in the edible filet (De Witte et al., 2021; Hantoro et al., 2019; Jin et al., 2021). Hence, degutting minimizes the direct human exposure to microplastic via fish consumption (Hantoro et al., 2019). Some smaller fish species, such as anchovies (*Engraulis encrasicolus;* 8-23 MP/animal) and sardines (*Sardina pilchardus;* 3-15 MP/animal), are nonetheless eaten as a whole and thus microplastic exposure will occur (Hantoro et al., 2019; Renzi, Specchiulli, et al., 2019).

Concentration of microplastics in shellfish

Microplastics are prevalent in various shellfish species, including bivalves and crustaceans. Extensive research has primarily concentrated on the blue mussel (*Mytilus edulis*) and oyster (*Crassostrea gigas*). Additionally, commercially significant crustaceans such as brown shrimp (*Crangon crangon*), Norwegian lobster (*Nephrops norvegicus*), and crabs (*Carcinus maenas* and *Eriocheir sinensis*) have also been observed to ingest microplastic (Hantoro et al., 2019).

Reported concentrations in bivalves range from 0 to 10.5 MP/g (M. Jin et al., 2021), 0.15 – 6.7 MP/g (Domenech & Marcos, 2021) and 0.2 – 13.1 MP/g (Hantoro et al., 2019). Hence a concentration between 0 and 13.1 MP/g can be expected in bivalves.

In crustaceans, reported ranges are 0.07-1.5 MP/g (Domenech & Marcos, 2021) and 0.18-10.9 MP /g (Hantoro et al., 2019). Thus, corresponding to a general range between 0.07 – 10.9 MP /g.

Filter feeding, the feeding behaviour of e.g. bivalves, oysters, and clams, could result in higher concentrations of microplastics taken up as it is a non-selective feeding strategy, making them more prone to ingesting microplastics (Wesch et al., 2016).

As in fish, microplastics are mostly found in the gastrointestinal tracts of the shellfish. However, as most of the bivalves and some of the crustaceans such as shrimp are eaten as a whole, the direct human microplastic exposure through consumption of shellfish is larger compared to that of fish (Jin et al., 2021). Nonetheless, the exact impact of consumption of crustacean species on our total microplastic exposure is debated (De Witte et al., 2021).

Generally, polymer types encountered in seafood are PP, PE, PS, and PET. In terms of the morphology, fibres are the most abundant particle throughout all samples, followed by fragments (Teng et al., 2019).

Sources of microplastics in seafood

Seafood microplastic contamination is correlated with pollution in the environment. This is confirmed by the link between microplastic concentration and feeding strategies as described before for demersal fish and filter feeding strategies (Hantoro et al., 2019).

5.1.4 Drinking water

Drinking water has been extensively studied in the framework of microplastic pollution, focussing both on bottled water and tap water (and the entire drinking water production chain). As mentioned before, characterization and quantification of microplastic in drinking-water is limited by the lack of standardized methods, which also limits comparability of studies (WHO, 2022). A detailed overview of reported concentrations of microplastics in drinking water can be found in Supplementary file 3.

Concentration of microplastic in drinking water

Depending on the type of water (bottled or tap) concentrations are variable. For bottled water, concentrations generally are reported between 6 and 6269 MP/L, with slight differences depending on the material of the container and measured size ranges (Supplementary file 3, Table S3.2). For raw and treated water in drinking water treatment plants, concentrations between 0 and 628 MP/L are reported, with some outliers of on average 6614 ± 1132 MP/L (Wang et al., 2020). Household tap water contains between 0.05-18 MP/L, with the exception of a few higher reported concentrations (up to approximately 400 MP/L). Some concern has been raised on the studies with high reported microplastic concentrations, since it can be questioned if the observed particles are really plastic (WHO, 2022).

General trends observed is that microplastic contamination in bottled water is higher compared to tap water and the source of the water (groundwater or surface water) also influences the microplastic contamination (Semmouri et al., 2022).

Sources of microplastics in drinking water

Microplastic contamination in drinking water can originate from the environment. This is corroborated by the observation that groundwater seems to be well protected against microplastic contamination in comparison to surface water sources of drinking water (Semmouri et al., 2022). Moreover, bottled water in glass containers also contains microplastics (Kankanige & Babel, 2020; Schymanski et al., 2018).

5.1.5 Nonalcoholic beverages

Thus far, only limited information is available for microplastic exposure through nonalcoholic beverages (excluding drinking water). Nonetheless, these beverages are consumed by humans in rather large amounts, with an estimated consumption of 235.4 L per capita of nonalcoholic beverages in 2021 (Crosta et al., 2023; Shruti, Pérez-Guevara, Elizalde-Martínez, et al., 2020).

The limited reported data indicates that the microplastic concentration in nonalcoholic beverages (excluding drinking water) ranges between 0 and 9.94 MP/L (Table 5). The reported findings seem to indicate that the microplastics contamination are likely to vary (Crosta et al., 2023; Shruti, Pérez-Guevara, Elizalde-Martínez, et al., 2020). Various shapes have been described although fibres seem to be largely present in these beverages (Crosta et al., 2023; Shruti, Pérez-Guevara, Elizalde-Martínez, et al., 2020).

Table 5: Overview of data regarding the microplastic concentration in nonalcoholic beverages (excl. drinking water).

Author	Year	Country		Concentration MP / L
(Shruti, Pérez-Guevara, Elizalde-Martínez, et al., 2020)	2020	Mexico	Cold tea	1-6
			Soft drink	0-7
			Energy drink	0-6
(Crosta et al., 2023)	2023	Italy	Soft drink	9.94 +/- 1.84
		Italy	Cold tea	7.11 +/- 2.62

Sources of microplastic contamination in nonalcoholic beverages

Nonalcoholic beverages are made of water of multiple sources combined with non-water ingredients such as sugar, fruit or tea (Shruti, Pérez-Guevara, Elizalde-Martínez, et al., 2020). The latter are products of the agricultural industry. Both the water and additions are possible sources of microplastic (Shruti, Pérez-Guevara, Elizalde-Martínez, et al., 2020). Next to that, the possibility of microplastics contamination can be attributed to several factors associated with the operation and production processes (e.g. improper cleaning) in the beverage industry and the packaging material (Crosta et al., 2023; Shruti, Pérez-Guevara, Elizalde-Martínez, et al., 2020).

5.1.6 Alcoholic beverages

Microplastic concentration in alcoholic beverages

Only a limited number of studies on the microplastic content of alcoholic beverages are available (Table 6), mainly focusing on beer. Reported concentrations range between 4.05 and 47 microplastics/L. Liebezeit and Liebezeit (2013) reported 82.67 MP/L although the quality of their methodology has been questioned (Lachenmeier et al., 2015).

Table 6: Overview of reported microplastic (MP) concentrations in alcoholic beverages.

Author	Year	Country	Beverage	Concentration MP / L
(Kosuth et al., 2018)	2018	Canada	Beer	4.05
(Wiesheu et al., 2016)	2016	Germany	Beer	10.10
Liebezeit and Liebezeit (Liebezeit & Liebezeit, 2013)	2014	Germany	Beer	82.67
(Diaz-Basantes et al., 2020)	2020	Ecuador	Craft beer	32
		Ecuador	Industrial beer	47
(Shruti, Pérez-Guevara, Elizalde-Martínez, et al., 2020)	2020	Mexico	Beer	0-28
(Prata et al., 2020)	2020	Italy	White wine	2563-5857*

**Optical methods used which does not allow for identification of microplastics leading to a possible overestimation*

Sources of microplastics in alcoholic beverages

Studies on the source of microplastic contamination in beer are currently missing but product processing and the brewing process might influence the contamination (Kosuth et al., 2018). Beer production does include a microfiltration step to remove yeast cells, presumably removing microplastic contamination in raw materials (Lachenmeier et al., 2015).

5.1.7 Other food products

In addition to the described foods and beverages, microplastics have been found in some other food sources such as honey (Mühlschlegel et al., 2017), canned sardines (Karami et al., 2018), vinegar (Makhdoumi et al., 2021), milk (Kutralam-Muniasamy et al., 2020) and chicken meat (Huang, Chapman, et al., 2020).

Moreover, in some other food sources, particle contamination (e.g. sugar (Liebezeit & Liebezeit, 2013)) or chemical migration from plastic packaging (e.g. cereal (García Ibarra et al., 2019)) has been determined but microplastic contamination was not yet studied in those food sources.

5.2 Microplastic release linked to wrapping or preparation of food

In the section before, we discussed the microplastic contamination present in various food items. As noted, the sources of the MNP are not often very clear as MNPs can originate from the food itself (e.g. water or fruit) or from processing and packaging. Due to the large amount of plastic used for packaging or kitchen utensils, these are expected to introduce extra MNPs in the end-product that we consume.

Importantly, all these observations are limited by the analytical possibilities, as such, little to no information is possible on the smallest nanoscale particles, with exemption of a few SEM images suggesting the production of smaller particles.

5.2.1 Contact between food and plastic packaging

Food is very often stored in plastic packaging due to its benefits in terms of food preservation, easy transport and storage (Cella et al., 2022; Jadhav et al., 2021). However, the mere contact between food and plastic packaging could cause migration of microplastics to the food.

Migration of other non-plastic components of packaging to the food product has been described before (Guerreiro et al., 2018; Lee, 2010; Sanches Silva et al., 2007). As this is a relevant matter for human health, strict regulations exist on the composition of the packaging and migration of compounds must be monitored (Cella et al., 2022; Guerreiro et al., 2018). However, as the polymers are considered chemically inert, the legal migration tests only consider low molecular weight (<1kD) compounds such as the additives or monomers. Moreover, often chromatography or mass spectrometry-based methods are used with a prior filtration step (Cella et al., 2022). This filtration step hinders the detection of the migration of microplastic particles in the food and only limited amount of information is available on this matter (Cella et al., 2022). To the best of our knowledge, only one study described the migration of microplastics to food. Kedzierski et al (2020) observed the presence of microplastic of expanded PS food tray present in chicken meat with concentrations from 4.0 to 18.7 MP/kg packaged meat. However, other studies describe the presence of microplastics in plastic food containers without reporting migration to the food (Du et al., 2020; Fadare et al., 2020).

5.2.2 Opening plastic food package

When opening a plastic food package, it often causes mechanical stress to the material which could produce MNPs. Sobhani et al. (2020) described that various ways of opening plastic packages (scissoring, tearing, cutting with a knife or twisting) could cause the generation of 0.46-250 MP/cm.

One of the most-studied cases in this category is the microplastic generation while opening a plastic bottle with the typical cap-bottleneck system. Recent papers have proven the friction between the bottle (made of polyethylene, PE) and the bottleneck (made of polyethylene terephthalate, PET) is a source of microplastics (Winkler et al., 2019). Importantly, it seems that the repeated open-and-closing of the cap is the main contributor to the microplastic production with a clear difference in microplastic particles after 1 and 100 times opening and closing (Winkler et al., 2019)(Figure 8). However, the microplastic particles that are produced due to this friction are assumed to have negligible contribution on the total concentration of microplastic in bottled water (Winkler et al., 2019, 2022). It is assumed that the majority of the microplastic particles will already be present in the water bottles before opening, which has been observed to be linked to the industrial capping procedure in the bottling factories (Weisser et al., 2021).

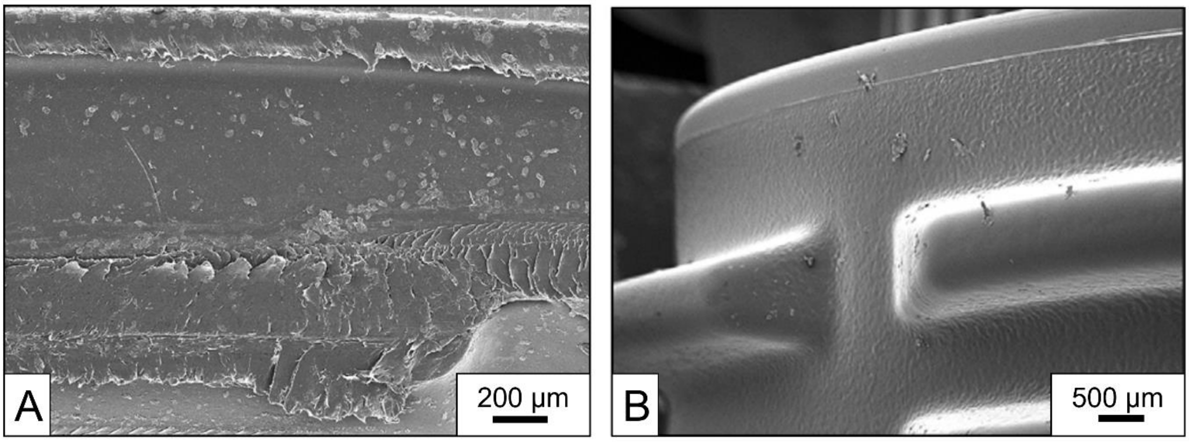

Figure 8: SEM images showing the microplastic particles produced by one hundred times opening/closing treatment of a cap (A) and bottleneck (B). Derived from (Winkler et al., 2019).

5.2.3 Food preparation

During food preparation, thermal stress is exerted onto the plastic packaging which has been confirmed to release MNPs in the food or beverage. Examples are preparing a cup of tea with teabags made from nylon or PET (Afrin et al., 2022; Cella et al., 2022; Hernandez et al., 2019), cooking rice in PE cooking bags (Cella et al., 2022) or using single-use plastic cups or containers for hot liquids or food (either plastic containers or other material with a PE coating) (Deng et al., 2022; Hee et al., 2022; Liu et al., 2021; Ranjan et al., 2021). Moreover, Deng et al. (2022), reported that repeated heating of PET and PP food containers resulted in increasing release of microplastic, indicating possible higher exposure when using reusable plastic containers (Deng et al., 2022). Recently, a study was published that reported high microplastic contamination in infant feeding bottles, mainly linked to thermal stress via sterilization processes (Li et al., 2020; Su et al., 2022). In all those cases, it was proven that the thermal stress from the heat caused an increase in microplastic concentration. Importantly, the quality of some of these studies is discussed (e.g. Busse et al., 2020). When looking into new research, attention must be paid to the analytical technique used and whether this technique can provide information on plastic concentration or only on particles (e.g. Busse et al., 2020).

Thermal stress due to freezing has been reported to induce microplastic contamination as observed in ice-cubes bags (Cella et al., 2022; Shruti et al., 2023). However, heating tends to release more microplastics compared to cold thermal stress (Hee et al., 2022; Zhou et al., 2023)

5.2.4 Other influencing parameters

Generally, the release of microplastics during contact, manipulation or preparation of the food container can be dependent on various polymer- and food-specific characteristics. As an example, Du et al. (2020) studied take-out food containers of various polymer types and observed a difference in their risk for microplastic release linked to the loose structure and rough surface of PS containers causing the highest amounts of microplastic release (Du et al., 2020). The hardness of a polymer can also affect the release as was demonstrated with the friction between the cap (PE, 65 Shore D (ASTM, 2015)) and bottleneck (PET 85 Shore D (ASTM, 2015)) where the latter is more resilient against mechanical abrasion (Winkler et al., 2019). Other factors affecting the migration of microplastics are the thickness of the packaging (Sobhani et al., 2020), the contact time (Zhou et al., 2023) and the single- or repeated use (Deng et al., 2022; Winkler et al., 2019). It can however be suspected that other factors, such as the acidity of the food could also impact the release of microplastics, as was already proven for leaching of other additives (Makhdoumi et al., 2021). More research is warranted to further study these processes and help to design food packaging options with reduced risk of microplastic exposure.

As more research is being published, a better estimate of sources of microplastic contamination in human food becomes possible. More recently, abrasions between plastic objects during cooking, such as stirring in Teflon coated non-stick pot (Luo et al., 2022) or slicing food on a plastic cutting board (Habib et al., 2022; Yadav et al., 2023), are also observed to cause microplastic contamination of food. The research is however still too limited to draw strong conclusions.

5.3 Microplastic exposure via air

First concerns were raised on occupational exposure of flock workers to atmospheric nylon fibres, showing symptoms of coughing and shortness of breath and fever (Burkhart et al., 1999). Although inhalation is a well-known pathway of exposure to micro- and nanoplastics in humans, few studies have addressed this concern.

5.3.1 Microplastic concentration in air

Microplastic concentration in air was already discussed in Section 3.4. As a recap, reported atmospheric microplastic concentrations are between 0 and 14 MP /m³. A lot of variability is observed when comparing research linked to geographical and methodological differences (Zhang et al., 2020). In occupational exposures (e.g. synthetic textile industry, flock industry and vinyl chloride and PVC industry), concentrations as high as 39.9 mg/m³ respirable dust has been reported (Burkhart et al., 1999) causing interstitial lung disease and inflammatory responses. In this context, the concentration of inhaled microplastic fibres is evidently expected to be much higher compared to normal exposure.

Fibres are the most commonly described microplastic shape found in atmospheric samples (Can-Güven, 2021; Dris et al., 2015; Zhang et al., 2020). Higher levels of fibres were reported in indoor air (5.4 fibres/m³) than outdoor air (0.9 fibres/m³), presumably as a result of the dilution of outdoor levels due to rainfall and wind (Can-Güven, 2021). Based on the gathered data, PA, PE, PP and PS were the most prevalent in atmospheric samples (Can-Güven, 2021). Information on the possible sources of microplastic contamination in air can be found in Section 3.4.

5.4 Estimated daily intake via ingestion and inhalation

The question of human exposure to microplastics, specifically "To how much MNPs are we exposed?", remains unanswered. Several studies have attempted to estimate the daily or yearly intake of microplastics based on published concentrations using dietary consumption rates. However, due to different methodologies used in the studies measuring microplastic contamination in food, it is difficult to compare them. Furthermore, the quality of reported data varies, with often lacking information on polymer types. Moreover, the overall amount of data is limited and often relying on a small number of repeated measurements. Finally, biomonitoring data in humans is lacking (with exception of some first studies for microplastic detection in human blood and stool (Leslie et al., 2022; Schwabl et al., 2019)). These elements stress the need for the necessary caution in interpretation and/or comparison of data and the need for broad (bio)monitoring studies.

It is worth noting that the current research on microplastic contamination in food sources is limited and represents only about 25% of the food categories consumed daily, as reported by the World Health Organization (WHO, 2022). Consequently, further research is necessary to gain a better understanding of human exposure.

Nevertheless, some calculations have been performed based on the available data. Nor et al. (2021) presented a probabilistic approach for assessing human exposure to microplastics. They considered nine food sources (fish, molluscs, crustaceans, tap water, bottled water, salt, beer, milk) and air, which represent approximately 20% of the human diet (WHO, 2022). By applying this probabilistic approach, inconsistencies in the reported data are addressed, resulting in a more reliable estimate of human exposure. This method is different to earlier work of Cox et al. (2019) that also reported on the consumption of microplastics by humans but based on the reported concentrations as such therefore introducing more variability and uncertainty. According to Nor et al. (2021), the median daily intake of microplastics for adults was calculated to be 0.6 µg or 883 microplastic per day for adults (Nor et al., 2021).

5.5 Microplastic exposure via personal care products

Plastics are widely used in personal care products and the use of these products can be a source of environmental microplastic pollution and additional route of exposure to MNPs.

5.5.1 Microplastics in personal care products

Microplastics are intentionally added to personal care products in small sizes, often referred to as microbeads (1-1000 µm), microspheres (1-1000 µm), microcapsules (1-2 µm) or nanospheres (10-1000 nm) (UNEP, 2015). Microplastics can be added to a vast array of personal care products such as toothpaste, shower gel, shampoo, face wash, nail polish, body lotion, sunscreen and makeup (UNEP, 2015). Based on their intended use, they are often categorized into rinse-off and leave-on cosmetics. Depending on the polymer type and characteristics (size, shape, composition), the microplastics can exert multiple functions. Besides the well-known scrubbing or exfoliating function, microplastics are also used as thickening agents, to provide a smoother or shinier product, for controlled time release of active substances, for prolonging shelf life by trapping degradable active ingredients, regulating viscosity, as an emulsifier, opacifying agent, for 'optical blurring' effect, glitter, etc. (UNEP, 2015).

Approximately 93% of these used beads are polyethylene beads (Gouin et al., 2015). Generally, microbeads in cosmetics are mainly larger than 420 µm (70%) (Gouin et al., 2015), although the sizes of microbeads will be in concordance with their intended function. For example, microbeads in facial cleansers are 2 to 4 times smaller compared to the microbeads in body scrubs (Fendall & Sewell, 2009; Napper et al., 2015), while in toothpastes microbeads are even smaller (Verschoor et al., 2014). Beads smaller than 60 µm are generally not suited as a scrubbing agent (Beach, 1972). Nonetheless, some smaller particles, nanoparticles, have been found in scrubs which are believed to not be intentionally added but created due to breaking down of the microbeads during preparation or usage causing shear stress forces (Enfrin et al., 2020; Hernandez et al., 2017).

Another commonly used category of polymers in cosmetics are water-soluble polymers (WSP), with an estimated production of several million ton in Europe (Rozman & Kalčíková, 2021). This is a form of plastic pollution which is often overlooked by scientists and policymakers due to their lack of a defined size scale (Mondellini et al., 2022; Rozman & Kalčíková, 2021). WSPs are defined as polymers that can be dispersed, dissolved or swell in water (Nyflött et al., 2017; Rozman & Kalčíková, 2021). They account for 6% of the global polymer market and are used in personal care products (Mondellini et al., 2022; Rozman & Kalčíková, 2021). Examples are Poly(vinyl pyrrolidone) (PVP), polyacrylic acid (PAA), Poly(vinyl alcohol) (PVOH) and poly(ethylene glycol) (PEG) (Mondellini et al., 2022). PAAs, used as crosslinked homopolymers, are the most commonly used WSPs in personal care products and cosmetics (Mondellini et al., 2022; Plastic Soup Foundation, 2022; Rozman & Kalčíková, 2021). By changing the pH of the fluid, the polymers become gels and therefore can be used as thickeners for creams (Patil et al., 2022).

WSP are generally considered as a low-concern chemical (ECHA, 2019; Rozman & Kalčíková, 2021), however their use in cosmetics is similar as for solid microplastics, so they will end up in the wastewater and the environment where they could pose a risk, similar to microplastics (Plastic Soup Foundation, 2022; Rozman & Kalčíková, 2021). Despite their wide applications, information on the production, environmental concentration, fate and (eco)toxicity of these polymers is lacking (Mondellini et al., 2022; Rozman & Kalčíková, 2021).Therefore, more information should be gathered on these WSPs in order to assess their possible risk in a scientifically sound way.

Microplastic concentrations

No detailed information on the microbead quantities used in cosmetics is publicly available and thus a comprehensive estimation of the total volumes of microbeads used in cosmetic is lacking (Anagnosti et al., 2020). The most precise numbers are from 2012, where it was reported that 4360 tonnes of microplastics were used in cosmetic products across Europe (including Norway and Switzerland) (Gouin et al., 2015).

It was mentioned in some reports and scientific publications that shower gel can contain as much plastic by weight as their plastic container, however this was not documented to date (Anagnosti et al., 2020). Generally, it is estimated that 0.05 % to 12% of the final product can be intentionally added microbeads (Gouin et al., 2015; Habib et al., 2020) and Gouin et al. (Gouin et al., 2015) estimated an amount of 0.6% of microbeads present in skin cleansing products. Based on a literature search, some information could be gathered on microplastic concentrations in a few rinse-off cosmetics (Table 7), which range between 6.27 to 1.4 * 10^{13} MP per g or mL of shower gel or facial scrub, respectively. Importantly, the quantities of microplastic in cosmetics are expected to decrease over the coming years due to the REACH restriction (Section 5.5.2) (Anagnosti et al., 2021; Dauvergne, 2018).

It must be noted that this analysis is based on publications from different countries, time points, products, and conditions. All these differences could explain the observed variation but also complicate generalization.

Pathway of primary microplastics in the environment

For studying the fate of microplastics from cosmetics in the environment, a distinction is often made between rinse-off cosmetics (such as toothpaste, face scrub) and leave-on cosmetics (such as body lotion, lipstick) (Anagnosti et al., 2021), as both have different usages and thus their pathways to the environment are assumed to be different. Microplastics present in rinse-off cosmetics all end up in the wastewater as they are intended to be washed off immediately after use (Anagnosti et al., 2021). Leave-on cosmetics are intended to stay longer on the body after which they can be washed off or removed with a tissue or cotton pad. The latter usually ends up in the collected waste fraction and will be incinerated or transported to landfills (Anagnosti et al., 2021). In case the leave-on cosmetic is washed off (but not immediately after use), between 15 and 90% of the microplastics are expected to end up in the wastewater (ECHA, 2019). For the rinse-off cosmetics, 95% is expected to end up in the wastewater.

Table 7: Overview of reported microplastic (MP) concentrations in rinse-off personal care products.

Product	Reported concentration	Reference
Facial scrub	1.4 ± 0.3 * 10^{13} MP /g	(Enfrin et al., 2020)
	3 x 10^{11} MP /g	(Hernandez et al., 2017)
	20,860 MP /g	(Cheung & Fok, 2017)
	1,810,730 MP /100mL	(Kalčíková et al., 2017)
	11,776-36,636 MP /g	(Praveena et al., 2018)
Shower gel	6.27 MP /g	(Lei et al., 2017)
Facial cleanser	0.09-0.1 g MP /mL	(Chang, 2015)
	919-18,906 MP /mL	(Napper et al., 2015)
	8.03 MP /g	(Lei et al., 2017)
	124 MP /mg	(Jemec Kokalj et al., 2018)
	NA	(Fendall & Sewell, 2009)
Toothpaste	0.25-4.17 g MP /10g	(Ustabasi & Baysal, 2019)
	2,500 MP /g	(Carr et al., 2016)
	327-832 MP /g	(Madhumitha et al., 2022)
	19,543-52,342 MP /g	(Praveena et al., 2018)
Body scrub	8,966 MP / g	(Guerranti et al., 2019)
	5,279,660 MP/100mL	(Kalčíková et al., 2017)

Once the microplastics enter the wastewater, they can be transferred to a wastewater treatment plant (WWTP) or end up directly in the environment (in the absence of WWTP or via overflows). If the wastewater passes an active WWTP, we know a large microplastic fraction (up to 97.5% reported in Flanders (Vercauteren et al., 2022)) will be retained in the WWTP and captured mainly in the sludge fraction. Approximately 53 % of the sludge produced in the European Union is used as biosolids in agriculture (ECHA, 2019; Zubris & Richards, 2005), hence, the captured fraction can be re-introduced in the terrestrial environment. Moreover, despite the high retention rates, still large quantities of microplastics can end up in the environment due to the high amounts of wastewater produced daily (Vercauteren et al., 2022).

Daily emission of microplastics to wastewater via rinse-off personal care products

To estimate the quantities of microbeads that end up in the environment in Europe, some calculations were made based on the limited reported data on microplastic in rinse-off cosmetics (Table 8). Literature was gathered on amount of product (g) used per day (either provided in literature or calculated from frequency of use (based on exposure modelling; Ficheux et al., 2015) and amount (g) per application (Cheung & Fok, 2017)). This was combined with the reported microplastic concentrations in the products (Table 7 and (Gouin et al., 2015)). Based on this information the daily microplastic emission per capita could be estimated (Table 8). For shaving cream and hair dye, no information was available on microplastic contamination, these are thus not taken into account.

As an example, on average 2.09 g toothpaste is used per day per capita (Hall et al., 2007). Toothpaste contains on average 18,558 MP per g (Table 8) leading to a daily emission of 38.82 MP per day per capita. If the emission of all rinse-off personal care products is summed, a daily gross emission of 1.32 * 10^{12} MP per capita per day is calculated. The majority of the emission originates from the use of facial and body scrub, which is not used by every person necessarily. If these sources are not included, the daily emission is estimated to be 38,826 MP per European citizen per day.

Table 8: Estimation of the daily emission of microplastic through the use of personal care products

Product	Exposure route	Application site	Exposure type	Amount used per day per capita	Estimated MP contamination	Emission (MP per capita per day)
Facial scrub	Dermal	Face, periocular	Rinse-off	0.46 g	2.86E+12 MP/g	1.32E+12
Body scrub	Dermal	Body	Rinse-off	2.60 g	30,881 MP/g	80,290.6
Facial cleanser/Face wash	Dermal	Face, periocular	Rinse-off/Leave on	0.28 mL	10438.01 MP/mL	2.9
Shower gel	Dermal	Body	Rinse-off	2.50 mL	6.89 MP/mL	0.02
Liquid hand soap	Dermal	Hand	Rinse-off	0.87 mL	0.60%	0.0
Shampoo	Dermal	Scalp, neck, hands	Rinse-off	6.03 g	0.60%	0.0
Toothpaste	Oral/dermal	Perioral, mucous membranes	Rinse-off	2.09 g	18,558 MP/g	38,823.3
Daily gross emission per capita						**1.32E+12**

5.5.2 Restriction on intentionally added microplastics

As mentioned before (Section 2.1), ECHA prepared a restriction on intentionally added microplastics including microplastics in personal care products and other daily-use products (Supplementary file 4) as an emission prevention strategy (ECHA, 2019). The restriction has been adopted by the European Commission on the 25th of September 2023.

The value of this ban on intentionally added microplastics is:

1. Elimination at the source as there is no effective method to retrieve them from the environment once they are dispersed (Cheung & Fok, 2017; Napper et al., 2015; UNEP, 2015).
2. There are natural alternatives therefore, this exclusion is feasible without increasing costs (Anagnosti et al., 2021).

Some comments or concerns that have been raised:

3. The definition of microplastics as posed by ECHA in the REACH restriction, quite unmistakably, specifies solid plastics (ECHA, 2019). Some parties are convinced that ECHA undermines its own proposal by exempting engineered nanoplastics, water-soluble, liquid and biodegradable polymers (Plastic Soup Foundation, 2022). The latter are a concern as the degradability are seldomly occurring in relevant environmental situations in comparison to laboratory circumstances (e.g. temperatures). Water-soluble and liquid polymers are currently exempted from the restriction proposal due to their undefined sizes, however, as mentioned before, adverse effects are possible although they are underrepresented in scientific research.
4. The REACH restriction and other active bans on intentionally added microplastics do not explicitly state a restriction on manufacturing, only on placing on the market. Therefore, multinational companies may still produce and sell cosmetics in markets that have not enacted any bans (Anagnosti et al., 2021; Habib et al., 2020).
5. The microplastic pollution via intentionally added microplastics is a transboundary issue and thus requires actions at global scale. However, we are currently far from a global phase-out of intentionally used microplastics (Anagnosti et al., 2021).
6. A long transition period is provided. Rinse-off products will be exempted for four years, leave-on products for six years. Make-up products will even be exempted for 12 years. Several other products are also temporarily exempted (rubber infill, medical devices, fertilizers, etc.). This, according to some parties, allows ongoing microplastic release in the environment (Anagnosti et al., 2021).

5.6 Microplastic exposure via medicine

In pharmaceutical and healthcare applications, single-use plastics are intensively used. Plastic products, particularly single-use plastics, have already played a significant role in preventing contamination and the spread of infections in the healthcare system over the past five decades. They are increasingly used for the storage of pharmaceutical formulations (such as plastic bags and containers) and for the application of medications (through administration sets) (Gopinath et al., 2022). The COVID-19 pandemic has further exacerbated the use of single-use plastics as a preventive measure against virus transmission, particularly in clinical settings and during the treatment of infected individuals (Haque et al., 2021). Consequently, there has been a significant surge in the global generation of single-use medical plastic waste (Hu et al., 2022).

The widespread use of plastics in health care, causes a microplastic exposure via ingestion (enteral feeding, storage of drugs in plastic containers), inhalation (e.g. inhalers and respiratory devices), dermal contact of damaged skin (e.g. ointments and gels for burn wounds, ulcers and skin diseases), and injection (e.g. intravenous infusion) (Gopinath et al., 2022). The latter bypasses the normal barriers in the human body and introduces contaminants directly into the blood where it can interact with erythrocytes, leucocytes but also be transported to other organs (Section 6.4). The concentration of plastics that enter the body via pharmaceuticals or medical treatments (e.g. via infusion or dialysis) is still unknown. Publications report the contamination with plasticizers (Gopinath et al., 2022), but micro- and nanoplastics contamination is also expected to occur.

The most commonly used plastic polymers in the administration sets and packaging (primary and secondary) of pharmaceuticals are plasticized polyvinyl chloride (PVC), polypropylenes (PP), polyethylene terephthalate (PET), polyolefin (PO) and polysulfone (PSU) (Gopinath et al., 2022).

6. Pathways for human micro- and nanoplastic uptake

Key highlights

- The most important human exposure pathways are
    - Ingestion
    - Inhalation
    - Dermal contact

  A possible new exposure pathway is via infusion during medical procedures.

In general, three mayor human exposure pathways are described for MNPs. Oral inhalation might occur next to ingestion or dermal absorption by the skin (Figure 9).

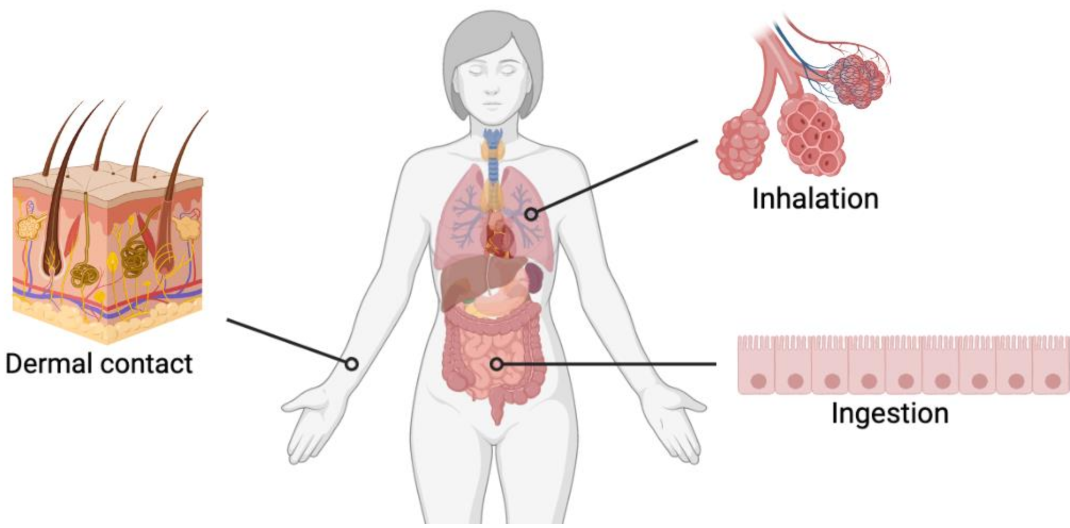

Figure 9: The three major human exposure pathways for microplastics

6.1 Ingestion

6.1.1 Entry route

When microplastics are ingested, they will end up in our gastrointestinal tract (GIT) which is responsible for the breakdown, digestion, and absorption of food. They will follow the same route as the food matrix and will thus be subjected to the same mechanical and chemical digestive processes (Figure 10):

1. Mouth:
    a. Mechanical digestion via chewing
    b. Chemical digestion via enzymes present in the saliva
2. Oesophagus
    a. Mechanical movement through muscular contractions called peristalsis.
3. Stomach
    a. Chemical digestion via gastric juices containing enzymes and acids to break down proteins.
4. Small intestine
    a. Mechanical movement through peristalsis
    b. Chemical digestion via pancreatic fluids and bile to break down carbohydrates, proteins, and fats.
5. Large intestine
    a. Mechanical movement through peristalsis
6. Rectum
    a. Storage of faeces until defecation, no digestive processes

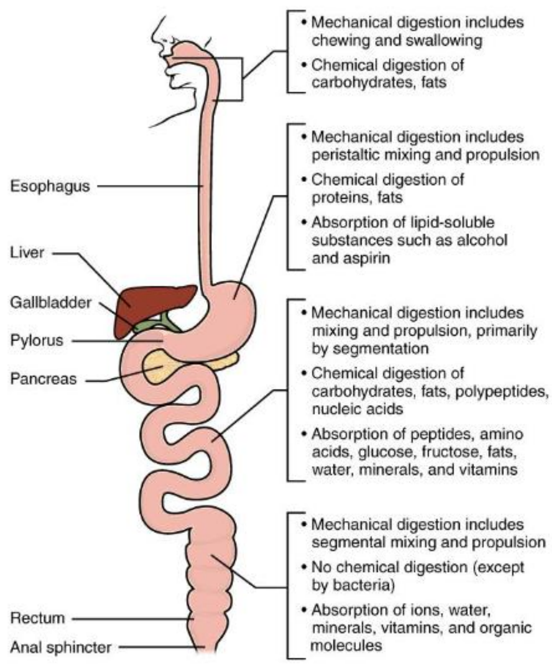

Figure 10: Schematic overview of gastrointestinal tract with corresponding digestive processes.

Ingestion and accumulation of micro- and nanoplastics in the GIT has been demonstrated in a wide range of aquatic organisms (Lehner et al., 2019). As the main absorption of nutrients, water and electrolytes is occurring in the small, and to a smaller extent in the large intestine, those are the presumed entry routes for microplastics into our bloodstream.

Once in the intestine, the microplastics will interact with the mucus layer and the epithelial cells lining the intestines. Importantly, the mere presence of MNPs in the GIT could exert indirect effects (on microbiome and mucus) without the uptake of the particles (Section 7.1).

6.1.2 Importance

Due to the expected high exposure (linked to numerous sources), inherent uptake mechanisms in the intestines and the large total surface area of 200 m², the GIT is expected to be the primary exposure site for microplastics (Lehner et al., 2019).

6.2 Inhalation

6.2.1 Entry route

Once micro- or nanoplastics are inhaled, they will first interact with the nasal mucosa where they can be trapped. Via mucociliary clearance the trapped particles can end up in the GIT (Porfiryeva et al., 2021). If the micro- and nanoparticles get through and reach the lung tissue, they again face the extensive defence systems of the lung including mucociliary clearance in the upper airways and macrophage clearance in the lower airways and alveoli (Borm & Kreyling, 2004). The latter is quite sensitive for size and shape as longer fibres are not taken up by alveolar macrophages (Borm & Kreyling, 2004).

In comparison with the GIT, a very thin tissue barrier (<1µm) is lining the alveoli (Figure 11) to ensure a close link between the alveoli and the capillary surface for oxygen diffusion (Gehr et al., 1978). This small barrier allows nanosized particles to penetrate into the capillary blood system more easily and be transferred to other organs (Lehner et al., 2019).

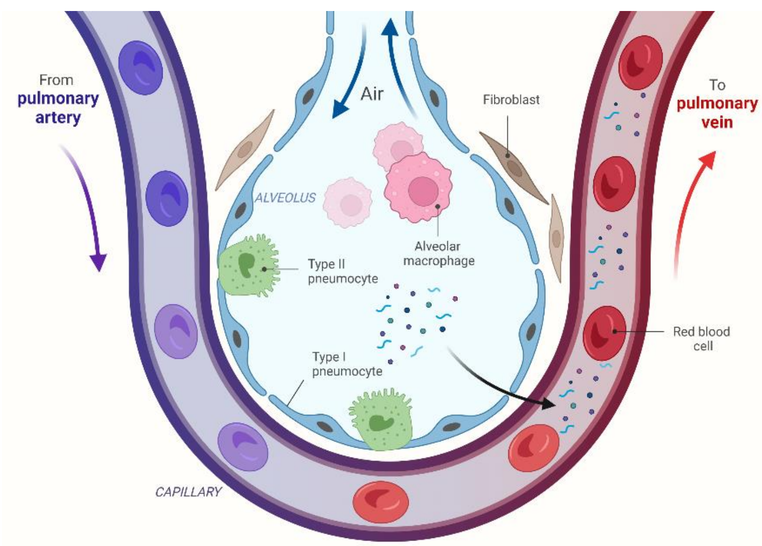

Figure 11: Uptake of small micro- or nanoplastic particles in the alveoli and their transport in the blood.

6.2.2 Importance

Due to the large amounts of air inhaled daily, the large alveolar surface area (ca. 150 m^2), the thin tissue barrier and the increasing knowledge of MNP contamination in the air, exposure via inhalation is estimated to be the second most important exposure route (Lehner et al., 2019).

Moreover, in occupational settings, exposure via inhalation could be of higher importance. For flock workers, high exposure to nylon fibres has been described (Burkhart et al., 1999).

6.3 Dermal contact

6.3.1 Entry route

The most important physical barrier of the skin is the stratum corneum (Lehner et al., 2019). Due to the hydrophobicity of plastics, the uptake of microplastic is not expected. Generally, it is hypothesized that only particles smaller than 100 nm can cross this skin barrier in healthy skin (Bouwstra et al., 2001). However, Campbell et al. (2012) observed that polystyrene particles between 20 and 200 nm could only penetrate maximally 3 µm in the stratum corneum.

A possible alternative dermal entry routes is via the hair follicles (Schneider et al., 2009), which was observed in porcine skin with fluorescent polystyrene particles (20 nm), however penetration in deeper skin tissue was again not observed (Alvarez-Román et al., 2004). Similar observations were reported by Vogt et al. (Vogt et al., 2006) who observed some polystyrene particles (40 nm) in perifollicular tissue (i.e. the tissue surrounding the follicle) (Figure 12). Other alternative uptake pathways are injured skin areas and possible subsequent uptake by Langerhans cells, important immune cells present in the skin (Vogt et al., 2006). UV is known to affect the integrity of the skin barrier due to disturbed expression of proteins involved in tight-junctions (Zonula occludens-1, claudin-1, and occludin) (Mortensen et al., 2021). This has been proven to increase the penetration of nanoparticles in the skin (Mortensen et al., 2021). Also wounds on the skin (burn wounds, skin ulcerations) could increase MNP exposure and subsequent uptake (Gopinath et al., 2022).

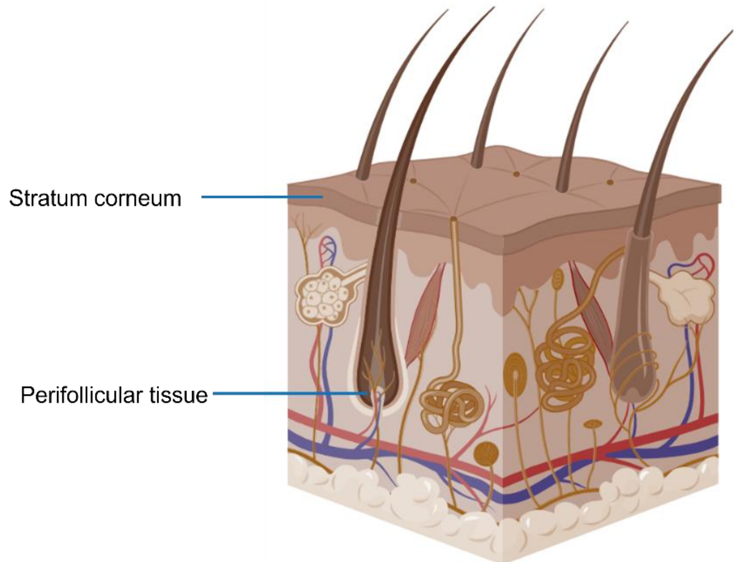

Figure 12: Possible routes for dermal exposure of micro- and nanoplastics.

Moreover, urea glycerol and α-hydroxyl acids and chemical penetration enhancers, ingredients of skin lotions and other personal care products, were shown to enhance nanoparticle penetration(Jatana et al., 2016; Lane, 2013) Nonetheless, their effect on the dermal uptake of nanoplastics has not been proven.

6.3.2 Importance

Generally, due to the stratum corneum, the uptake of MNP via the skin is deemed to be limited. However, injury to the skin could increase the exposure (Gopinath et al., 2022).

6.4 New exposure route: infusion

6.4.3 Entry route

In the medical sector, a fourth exposure route was proposed; uptake by infusion of pharmaceuticals by intravenous, intraosseous, intramuscular and intradermal injections (Gopinath et al., 2022). The plastic products used for infusion therapy (tubes, IV-bags, syringes, etc.) may release MNPs (Gopinath et al., 2022). Leaching of chemical additives has already been reported (Panneel et al., 2023).

6.4.2 Importance

The importance of this pathway in comparison with the previous pathways is hitherto unknown. Nonetheless, by infusion, the first tissue barrier is overcome and dispersion to various organs will become easier. This could lead to pronounced adverse health effects.

7. Effects of microplastic on human health

Key highlights

- Once plastics are taken up, they can cause various direct and indirect adverse effects, including:
  - Indirect effects on microbiome and mucus production
  - Cellular uptake mainly via endocytosis
  - Translocation to the bloodstream and passing cellular barriers such as the blood-brain and placental barrier
  - Toxic effects of exposure linked to cellular effects and whole organism effects.
    - The main toxicity mechanism of microplastics on cellular level was revealed as oxidative stress, genotoxicity and inflammation

Once microplastics are taken up, they can cause direct and indirect adverse effects by cellular uptake, translocation and passing cellular barriers, with possible effects on human health.

7.1 Indirect effects

Once MNPs are present in the GIT or lungs, they can cause indirect effects via (1) interaction with gut microbiome[7]; and (2) interaction with the mucus layer (Figure 13). Since research on human health effects of micro- and nanoplastic exposure has predominantly focused on the effects of cellular uptake of MNP, the indirect effects have been poorly studied.

In the lumen of the gut and lungs, there is a vast microbiome present containing over 10 trillion microorganisms that assist in the digestion of our food (gut) or regulating immunity (lungs). Based on *in vivo* experiments, changes in gut microbiome diversity and functionality (i.e. gut microbiome dysbiosis (Brüssow, 2020)) (Figure 13) has been observed as a response to microplastic (merely PS, also PE) ingestion in animal species such as zebrafish (*Danio rerio*) (Jin et al., 2018), soil springtail (*Folsomia candida*) (Ju et al., 2019; Martens et al., 2018), Medaka (*Oryzias melastigma*) (Kang et al., 2020) and mice (Li et al., 2020). To our best knowledge, no information is available on the indirect effect of MNP on the lung microbiome.

Secondly, based on research conducted with non-plastic nanoparticles, it can be expected that the mucus layer, which serves as a crucial protective barrier, has the potential to capture particles. Moreover, the

[7] *The gut microbiome is the community of microorganisms that are found in the gastrointestinal tract.*

presence of these particles may influence the mucus layer by inducing alterations in its composition or promoting an increase in mucus production (Figure 13) (Brun et al., 2014; Chen et al., 2011; Jeong et al., 2009; Talbot et al., 2018). Changes in mucus production or composition have been linked to colitis-associated colon cancer, alcoholic liver diseases and inflammatory bowel disease (Bergstrom et al., 2016; P. Hartmann et al., 2013; Johansson et al., 2014). In the lungs, hypersecretion of mucus can cause chronic bronchitis, a type of chronic obstructive pulmonary disease, and infection and inflammation (Fahy & Dickey, 2010).

Both indirect effects of the presence of MNPs in the gut lumen or lungs have not yet been elucidated and more research is thus warranted.

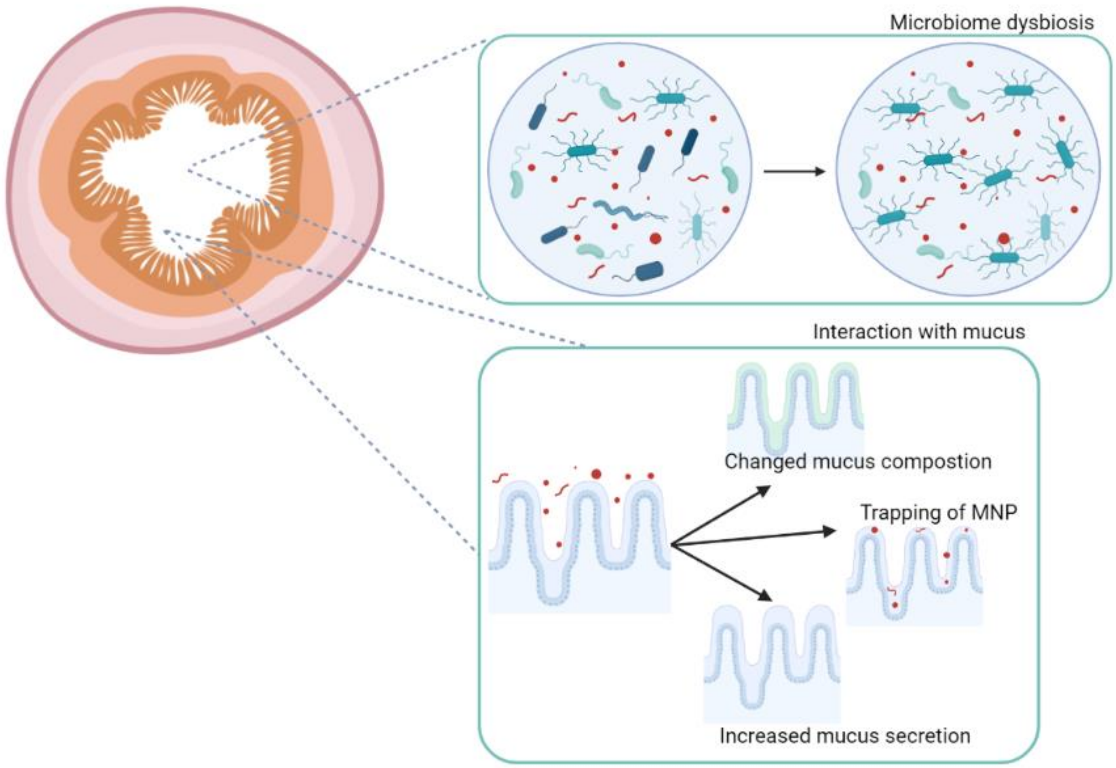

Figure 13: Effect pathways by the presence of MNP in the gut.

7.2 Cellular uptake

The MNPs present in the GIT or lungs can be taken up by the cells. This can happen using existing uptake mechanisms, although endocytosis and passive diffusion are the main uptake routes:

1. **Endocytosis**
   Endocytosis, the process by which cells take up plasma membrane components, fluid, solutes macromolecules and particulate substances (Alberts et al., 2022). The material is enclosed by a small portion of the plasma membrane and forming an endosome. Different forms of endocytosis exist, of which a few are also relevant for MNP uptake (Figure 14): Clathrin-dependent endocytosis; Caveolae-dependent endocytosis; Micropinocytosis; Phagocytosis. The latter mainly occurs in specific cell-types (e.g. macrophages) (Hua & Wang, 2022). For the uptake of nanoplastics, clathrin- and caveloa-dependent endocytosis (reported for MNP between 20 and 200 nm) is assumed to be the major uptake pathway. As for small microplastics, micropinocytosis (reported for MNP between 49 nm and 1 µm) and phagocytosis (reported for MNP between 50 nm and 5 µm) are important (Hua & Wang, 2022).

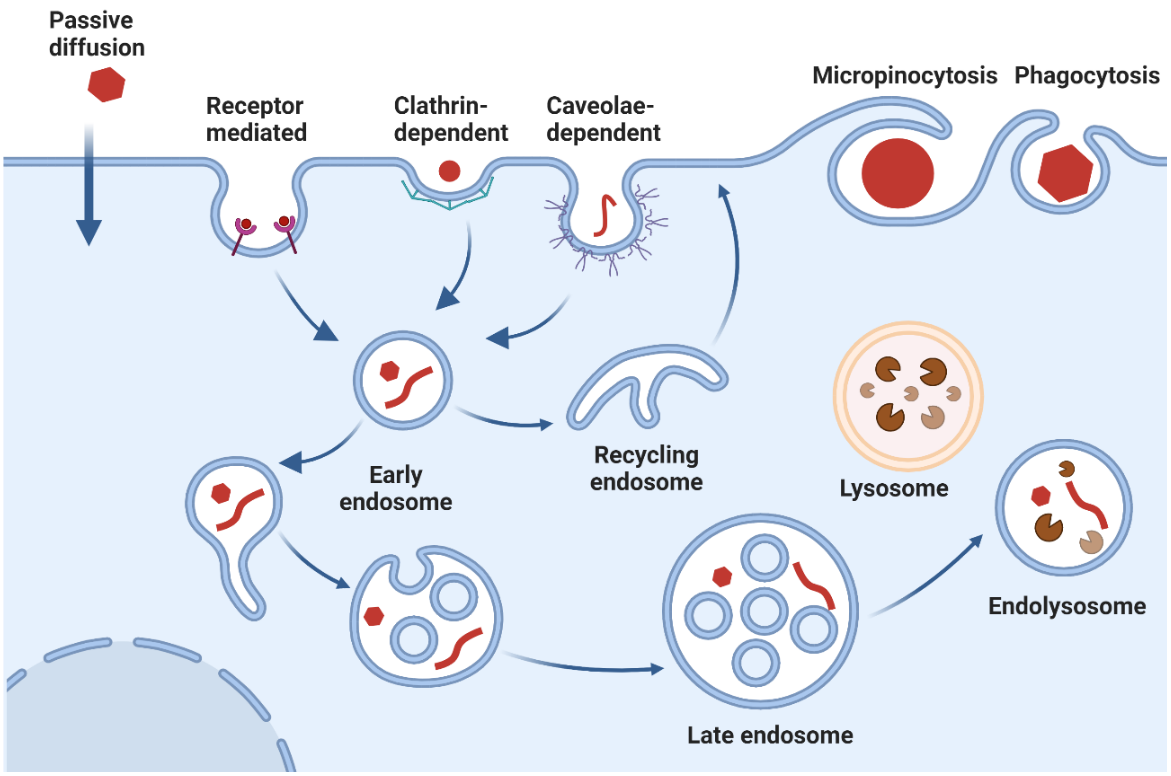

Figure 14: Cellular uptake mechanisms for micro- and nanoplastics.

2. **Passive diffusion**
   Both micro- and nanoplastics could enter the cells by passive diffusion, which is dependent on the surface properties of the cell membrane. The hydrophobicity of the particles plays a role in this process as hydrophobic MNPs interact with the inner hydrophobic core of the bilayer and thus penetrate the membrane. This process is already reported for MNPs between 1.3 and 100 nm) (Hua & Wang, 2022).

Besides these, channel- or transport-protein-mediated uptake have been described (Lehner et al., 2019). Moreover, transport in between the cells has also been described (Van Cauwenberghe, 2016). Both are assumed to be less common. Diseases affecting the permeability of the GIT, such as inflammatory bowel disease, could lead to higher susceptibility to MNP uptake and translocation (Science for Environment Policy, 2023).

Generally, the uptake kinetics of MNPs can be influenced by many factors amongst which:

- **Cell type**
  Uptake mechanism of red blood cells is assumed to be passive diffusion as for other human cells (e.g.Caco-2) energy dependent mechanisms are presumably dominant. Moreover, it is possible that one cell type uses multiple uptake pathways simultaneously (Lehner et al., 2019).
- **Size of the particle**
  Both uptake and translocation are size dependent with larger particles having lower chances for uptake (Lee et al., 2023).
- **Polymer type**
  A recent study of Stock et al. (2021) observed polymer-specific cellular uptake where 1-4 µm PE microplastics were transported in higher amount then PS particles of same size.
- **Shape of the particle**
  Rod-shaped PS nanoplastics entered easier into cells than spherical nanoplastics indicating that the shape influences the cellular uptake of nanoplastics (Hua & Wang, 2022).
- **Surface charge**
  A positive surface charge of nanoparticles often results in increased cytotoxicity and cellular uptake by unspecific binding to negatively charged sugar moieties on the cell surface, whereas negatively charged particles impair endocytosis due to repulsive interactions (Lehner et al., 2019).
- **Biocorona**
  Microplastics with a biocorona often interact differently with the cells sometimes resulting in receptor-mediated endocytosis and increased translocation (Lehner et al., 2019).

Once taken up by the cell, the MNPS can be translocated to the bloodstream and subsequently be transported to other organs (Section 7.3) or can cause cellular toxicity (Section 7.4). Importantly, absorption of MNP in the tissues appears to be limited. Recent studies suggested a micro-and nanoplastic uptake up to 7.7% of the administered dose (V. Stock et al., 2021). As proven by the microplastics present in human stool samples, at least part of the ingested particles will be eliminated from the body (Schwabl et al., 2019).

7.3 Translocation

7.3.1 Transportation in bloodstream

Once MNPs succeeded to overcome the primary cellular barrier, they are translocated to the bloodstream. In a recent study, MNPs were detected in blood. Of the 22 studied donors, 77% carried a quantifiable mass of microplastics (Leslie et al., 2022). It remains to be determined whether microplastics are present in the plasma or are carried into the bloodstream by specific cell types (Leslie et al., 2022). Red blood cells lack endocytic uptake mechanisms, nonetheless, cellular uptake has been described for polystyrene (<200 nm) and suggested to be based on passive diffusion (Rothen-Rutishauser et al., 2006). By the internalization of MNPs into the red blood cells MNPs could evade rapid clearance by the liver and spleen, commonly referred to as the cellular hitchhiking mechanism. This consequently extends the residence time within the circulatory system (Lehner et al., 2019).

The blood functions as a transport pathway throughout the human body, and thus the MNPs can be transported within the blood. The fate of the MNPs in the bloodstream should be studied further. Once they are in the blood they can be transported and bioaccumulate in organs (Section 7.3.2) or cross secondary tissue barriers (Section 7.3.3). Either way, the physical sizes of capillaries (5-8 µm) will limit the circulation of these particle sizes in the micro-vessels (Leslie et al., 2022). Moreover if particles are present, they might impact microvascular fluid dynamics (Leslie et al., 2022).

7.3.2 Bioaccumulation in organs

Bioaccumulation of small polystyrene micro-particles in the liver, kidney and gut was observed after oral administration in mice *in vivo* (Deng et al., 2017; Lu et al., 2018). In zebrafish (*Danio rerio*) and red tilapia (*Oreochromis* Spp.), the PS microplastic accumulation is calculated using a toxicokinetic/toxicodynamic model based on the ratio between removal and absorption, leading to the conclusion that microplastics could potentially bioaccumulate in the gut, gills, liver and brain (González-Acedo et al., 2021).

7.3.3 Breaching secondary tissue barriers

Secondary barriers able to be reached via the bloodstream include the placental and blood−brain barrier. Recently, information on the crossing of MNPs of both barriers has been published.

1. **Placental barrier**
   The placenta, a vital organ for a growing foetus, regulates the link between the foetal and maternal environment acting as a crucial interface (Ragusa et al., 2021). Microplastics have been detected in human placenta, both on the foetal and maternal side, in one recent publication (Ragusa et al., 2021). A small amount of microplastic particles were found in six placentae from uneventful pregnancies. Using a human placental perfusion model, the permeability was also demonstrated for polystyrene beads between 50 and 240 nm (Wick et al., 2010). Both studies show preliminary results and preventing contamination is challenging in the described setups, therefore more research is necessary.
2. **Blood-Brain barrier (BBB)**
   The BBB is a highly selective barrier regulating the uncontrolled diffusion of molecules into the brain for protection. A few *in vivo* studies have observed the crossing of the BBB by PS nanoparticles (20 nm) after injection (Lehner et al., 2019; Yang et al., 2004). The study of Kopatz et al. (2023) however pinpointed the important role of a biomolecular corona for this process. No behavioural effects were observed in the presence of 25 and 50 nm in brain of rats (Rafiee et al., 2018).

7.4 Effects of micro-and nanoplastic exposure

The main toxicity mechanisms of microplastics on cellular level has been suggested to consist of oxidative stress, inflammation and genotoxicity (Jeong & Choi, 2020).

1. **ROS production and oxidative stress**
   Upon uptake of MNP, the cells will try to neutralize the MNPs. During that process, reactive oxygen species[8] (ROS) are generated as a product of NADPH-oxidase or other enzymatic reactions in form of superoxide and hydrogen peroxide (Hu & Palić, 2020). In normal circumstances, ROS is eliminated by antioxidants such as superoxide dismutase and catalase to maintain the cellular redox homeostasis[9]. However, with the excess ROS production, the antioxidation capacity is unable to keep up and cells will experience oxidative stress (Hua & Wang, 2022). The ROS production affects various cellular processes and could cause lysosomal membrane damage, mitochondrial dysfunction and apoptosis (Hua & Wang, 2022).
2. **Inflammation**
   MNPs are considered as foreign material by the cells and thus activate the innate immune system, often observed by the stimulation of proinflammatory cytokines such as IL-6 and IL-8 which has been demonstrated in various cell lines (lung (Brown et al., 2001) and gastric cells (Forte et al., 2016)) (González-Acedo et al., 2021; Lehner et al., 2019). This activation induces inflammation or mediates oxidative stress (Lehner et al., 2019).
3. **Genotoxicity**
   Genotoxicity as a result of MNP exposure can be exerted in two ways. First, a direct contact between small nanoplastics, transported into the nuclei, can cause double-strand DNA breaks. Secondly, indirect exposure to MNP induced changes in replication and repair capacity and increased ROS production (González-Acedo et al., 2021).

Other effects are described in literature (e.g. effects on cytoskeleton and endoplasmic reticulum (Hua & Wang, 2022)), however only fragmentary data report these effects and thus more research is needed. Moreover, it is somewhat challenging to pinpoint the cytotoxic effects of MNP due to their heterogeneity and the often unrealistic exposure scenario's (high concentration, acute exposure). The dose-response relationship still requires further study. Therefore, more research efforts are necessary to understand the impact of MNP properties on the toxic effects and study realistic MNP exposure across the entire dose response curve.

Mechanistic relationships between toxicity endpoints have been discussed using the concept of Adverse Outcome Pathways (AOP) (Hu & Palić, 2020). In two independent studies, ROS production was pinpointed as the Molecular Initiating event (MIE)[10] (Hu & Palić, 2020; Jeong & Choi, 2020). A proposed AOP for MNP is depicted in Figure 15 and based on key events (KE)[11] linked to the MIE at molecular, cellular, organ/tissue and individual/population level. Based on the AOP (Figure 15), possible individual effects are behavioural changes, developmental impairment, and growth inhibition.

[8] *Reactive oxygen species: A "free radical" is an individual atom or a cluster of atoms possessing one or more unpaired electrons, exhibiting a significant potential to cause reactions, including oxidative chemical reactions. Within biological systems, numerous radicals arise from oxygen and are commonly known as reactive oxygen species (ROS) (M. Hu & Palić, 2020).*

[9] *Homeostasis is the tendency towards a stable equilibrium.*

[10] *A Molecular Initiating Event (MIE) is the initial interaction between a molecule and a biomolecule.*

[11] *A Key Event (KE) is described as a biological state being observed or measured.*

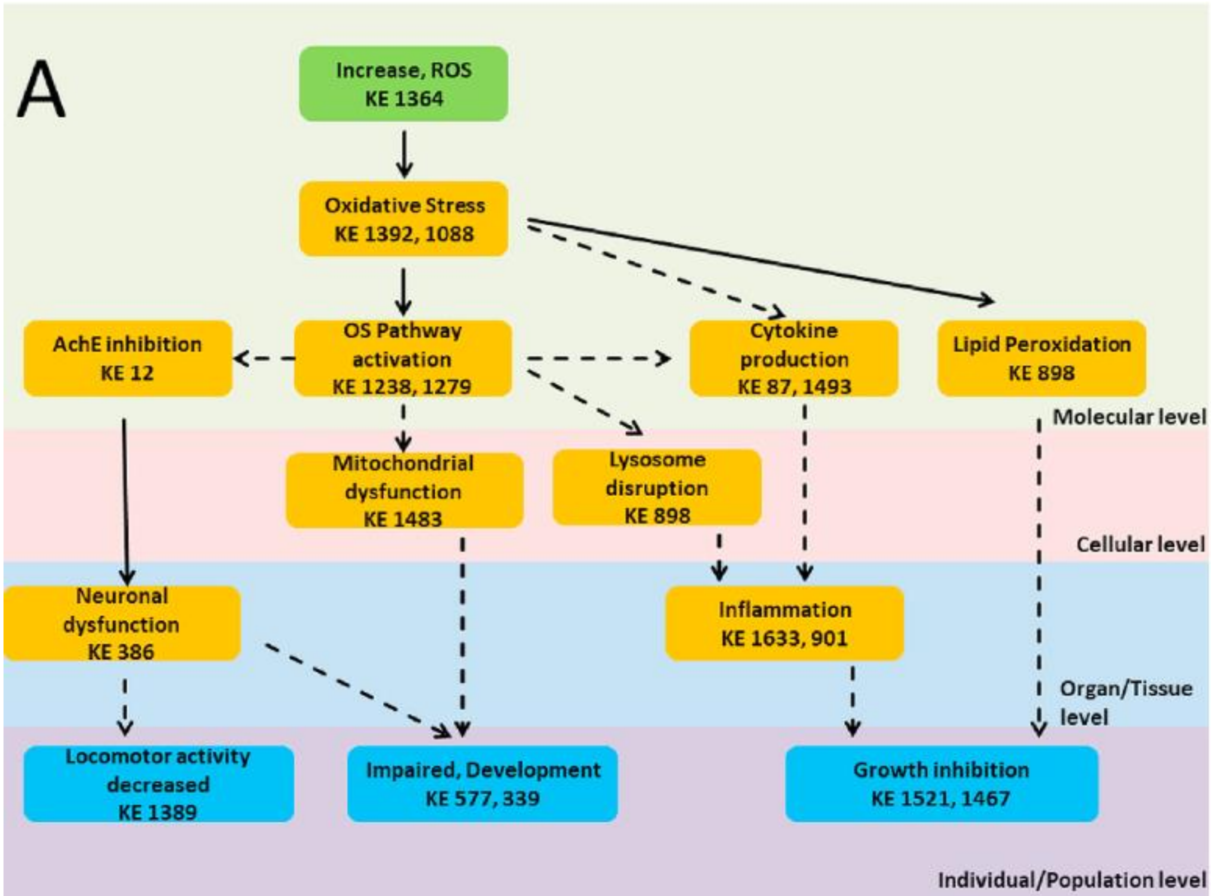

Figure 15: Suggested adverse outcome pathway for microplastics with Reactive Oxygen Species (ROS) as the first key event (KE) (Hu & Palić, 2020).

Besides these effects, some others have been described. Here we would like to highlight the following two possibly linked effects:

- **Link between microplastic and cancer**
  As ROS production is put forward as the molecular initiating event of MNP toxic effects, it has been hypothesized that cellular uptake of MNPs could pose a potential risk for the development of cancer (Nam, 2011; Science for Environment Policy, 2023). Oxidative stress, and thus the presence of ROS, promotes the growth and proliferation of cancer cells by interfering in the DNA replication and repairing capacities (Lee et al., 2023; Poillet-Perez et al., 2015). This was observed in some studies where PS nanoplastics exacerbated the cell proliferation of cancerous cells (Science for Environment Policy, 2023). However, definite proof is still lacking and data is merely scattered to this day. More research is needed to elucidate the link between microplastic and cancer.
- **Link between plastic and obesity**
  Among the various toxic effects reported in laboratory animals from exposure to microplastics and plastic additives, the disruption of adipogenesis and lipid metabolism through the activation

of peroxisome proliferator-activated receptors suggests that MNPs and their additives are potential obesogens (Kannan & Vimalkumar, 2021). Moreover, the maternal transfer of microplastics can change lipid metabolism of the developing foetus. Importantly, these are preliminary findings and elaborated research is necessary to support these findings.

7.5 Factors affecting effects

7.5.1 Particle characteristics

Currently, we are far from capturing the heterogeneity of MNPs in the human health effect studies (and environmental effect studies by extension). As often misunderstood, plastics are a multidimensional group of pollutants with different sizes, materials, shapes, surface characteristics and additives (Figure 16) (Science for Environment Policy, 2023; WHO, 2022). All these characteristics can affect the bioavailability, cellular uptake, cellular effects of MNPs and thus influence the whole organism effects. As stated by Bucci and Rochman (2022) this pollutant requires a multidimensional framework for assessing risk, which currently hampered by analytical limitations and limited reporting of MNPs properties used in effect studies (Science for Environment Policy, 2023; WHO, 2022).

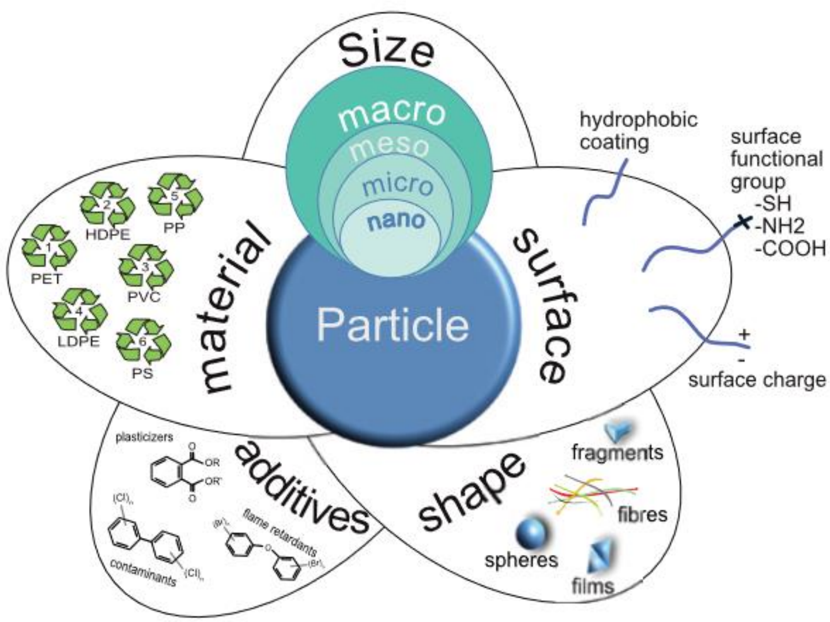

Figure 16: Micro- and nanoplastic properties that might affect human exposure and effects including polymer types (Polyethylene terephthalate (PET), high density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), low density PE (LDPE) and polystyrene (PS)), size, surface characteristics, additives, and shapes (WHO, 2022).

7.5.2 Additives

Leaching of additives can lead to increased or changed toxicity upon exposure. The following endpoints were assessed in relation to the leached plastic chemicals: baseline toxicity, cytotoxicity, oxidative stress, endocrine activity, genotoxicity and mutagenicity, effects on inflammatory processes, and effects on metabolic signal pathways (Frøyland, 2023). Jeong and Choi (2020) pinpointed an AOP of chemical additives, leading to ROS as being the MIE, and observed effects on lipid metabolism, inflammation and effects on energy metabolism (Figure 17). These toxicity mechanisms thus largely correspond to the main toxicity mechanisms of microplastics (Jeong & Choi, 2020). More research is needed to fully elucidate the importance of chemical additives in the microplastic toxicity, thus stressing the need for a more holistic approach.

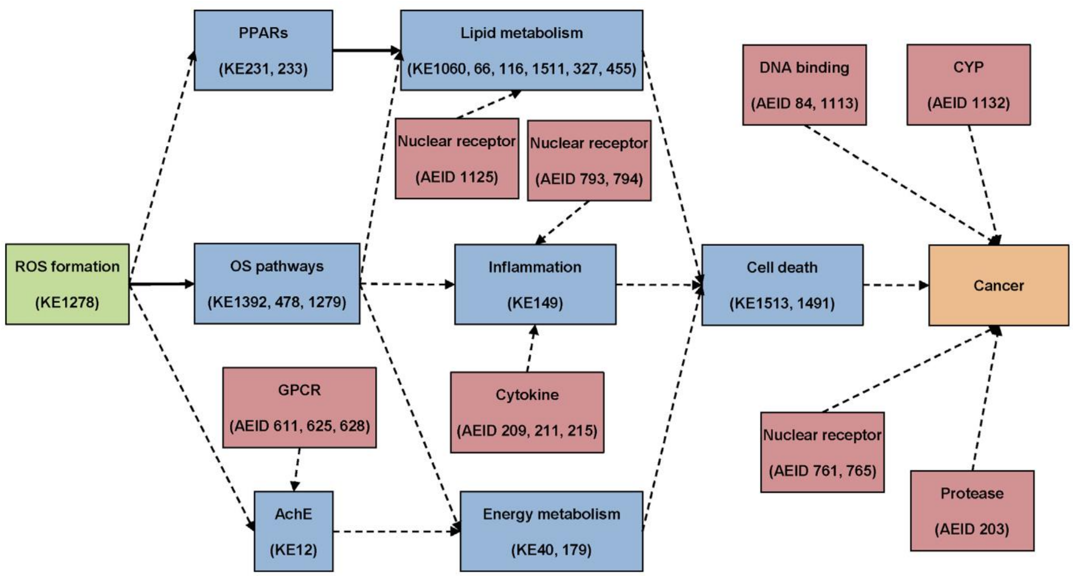

Figure 17: The adverse outcome pathway based on the toxicity mechanisms of chemical additives (Jeong and Choi, 2020).

7.5.3 Chemicals

Generally, it was hypothesized that microplastics are a vector and source of chemical pollutants to marine organisms and humans. The theory was that the adsorbed chemicals on the microplastics can desorb rapidly in the acidic gut and lysosomal environments and thus provide an extra contaminant exposure route (Devriese et al., 2017; Gopinath et al., 2022; Koelmans et al., 2016). The opposite mechanism, a cleaning effect was also suggested (similar to consuming non-digestible fat as treatment for dioxin poisoning) although never proven for the sorbed chemicals on plastics (Devriese et al., 2017). Possible, but not necessarily proven, mechanisms of interactions are summarized in the figure below (Figure 18).

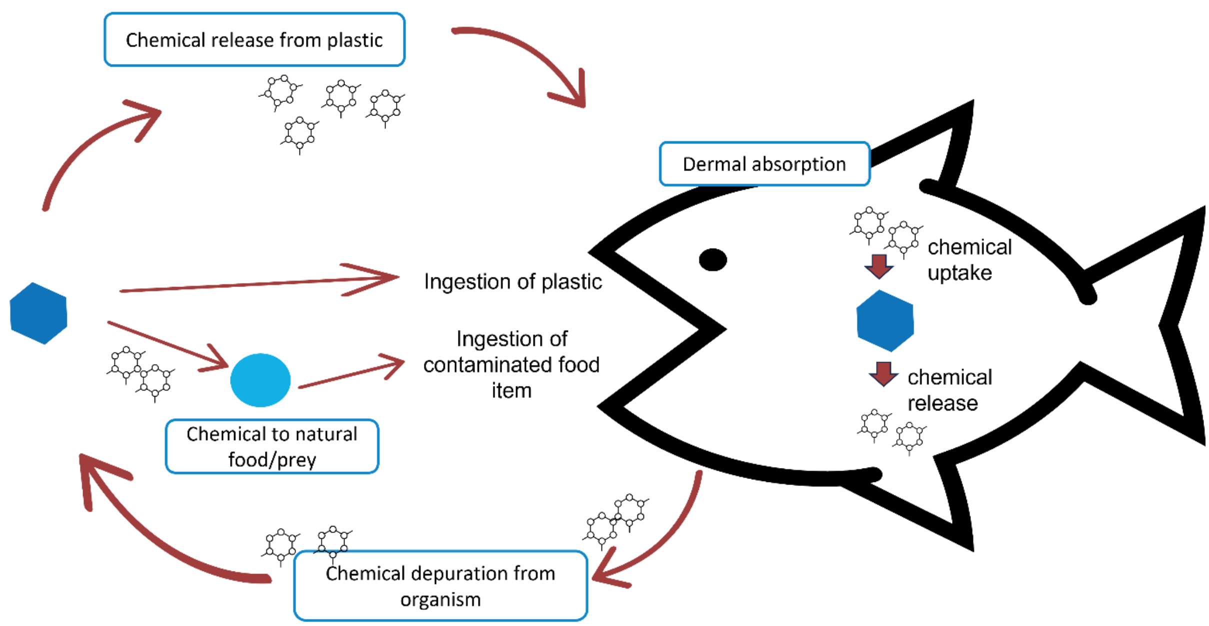

Figure 18: Potential mechanisms of interaction between microplastics additives and aquatic organisms (based on Koelmans et al., 2016).

Discussions are ongoing whether microplastic are indeed a substantial source of these toxic chemicals. Despite the high affinity of chemicals for plastics, the relative low concentration of plastics in comparison to other carrier media such as water, suspended organic particulates, black carbon, or natural prey items, urges to question the relative importance of microplastics. In a study on MNP in food, EFSA concluded that the contribution of microplastics as carriers for both additives and chemicals is very small compared to the overall exposure (EFSA, 2016). This is based on current knowledge the case for both aquatic animals and humans and but can also be dependent on the trophic level as a result of biomagnification (Diepens & Koelmans, 2018). The human model of Nor et al. (2021) confirmed that chemical leaching from microplastic would not substantially affect the background chemical concentration in the gut originating from food (Nor et al., 2021). One parameter of concern that should be studied further are the small sizes of the nanoplastics which increases the surface to volume ratio and thus sorption capacity.

In conclusion, additives are more likely to contribute to the toxicity of microplastics than adsorbed chemicals from the environment (Koelmans et al., 2016)

7.5.4 Biocorona

The rapid formation of a protein corona on the MNPs surface through interaction with the biological environment, can cause a different effect compared to a pristine MNP (without any additional corona). A few reported differences between pristine microplastics and microplastics with a protein corona are:

- **Biological identity**
  The protein corona can mask the presence of a MNP and could mislead the cells in responding to a biological macromolecule instead of a foreign MNP particle. This biocorona can hide the particles from the immune system and prolongs the persistence of MNPs in the organisms (Gopinath et al., 2022; Kihara et al., 2021).
- **Interaction with the cells**
  The presence of a corona alters the interaction between cells and the MNP (Kihara et al., 2021). However, the scientific results on the effect of the corona on the uptake are inconsistent. In some cases it is argued that the protein corona causes recognition and thus increasing uptake of the MNPs in the cell, on the other hand decreased uptake has been described as well (Gopinath et al., 2022; Kopatz et al., 2023; Obst et al., 2017). Recently, it has been observed that the protein corona aided the crossing of the blood-brain barrier by allowing diffusion of the protein-covered nanoplastics into the membrane (Kopatz et al., 2023). Importantly, the effect of the protein corona on cellular uptake is likely influenced by the type of proteins present (Kopac, 2021). More research is thus warranted.
- **Cellular toxicity**
  Some differences have been described when the cytotoxicity of pristine MNPs was compared to protein covered MNPs. However, here again, results show inconsistencies ranging from greater to milder or no toxicity at all (Kihara et al., 2021; Vela et al., 2023). More research is again needed to elucidate these effects.
- **Changes in the bioavailability of the MNP**
  Protein-protein interactions can cause agglomeration of protein-covered MNPs, hereby reducing the fraction of MNPs available for uptake (Gopinath et al., 2022; Kopac, 2021). This has been observed by experiments using simulated digestive fluids. The digested PS nanoplastics had higher tendency to agglomerate (Vela et al., 2023).
- **Effects on the proteins**
  The proteins can also be affected by their adsorption on the MNP by influence of the structure and changed biochemical properties (Kopac, 2021).

These, for now scattered, results indicate the importance of taking the interactions with the environment into account for assessing the adverse effects of MNP.

8. Towards relevant human health risk assessment and appropriate mitigation measures

Key highlights

- The most urgent research question is to know the risks for human health upon micro- and nanoplastic exposure
- However, at present, insufficient scientific knowledge is available for a reliable risk assessment.
- The two main scientific bottlenecks are identified as:
  - Lack of standardized methods
  - Lack of safety thresholds
- The scientific knowledge should stimulate the development of a holistic policy framework focusing on production, pollution and risk assessment.

The anticipated growth in plastic production (Statista, 2023) suggests that (micro)plastic pollution is unlikely to diminish in the foreseeable future (Figure 19) (Lau et al., 2020). Even under the best case scenario, a vigorous system change scenario to reduce plastic pollution, the influx of plastics into the environment is still predicted to accumulate (Lau et al., 2020). Once in the environment, research has shown that plastics are persistent and can degrade into smaller, and potentially more dangerous micro- and nanoplastics. Moreover, once microplastics are released into the environment it is challenging to remove them[12], leading to an increased risk on adverse effects (Anagnosti et al., 2021). This knowledge suggests that plastic pollution is not only a possible risk at present, but it will remain relevant for years to come. This urges us to take action, both in science and policy.

[12] *Currently, there are some methods to remove microplastics, especially the larger particles, from aqueous matrices. However, these techniques are currently applied on a local and limited scale. More development is needed to improve the efficiency and economic feasibility of these techniques (Moulaert et al., 2021).*

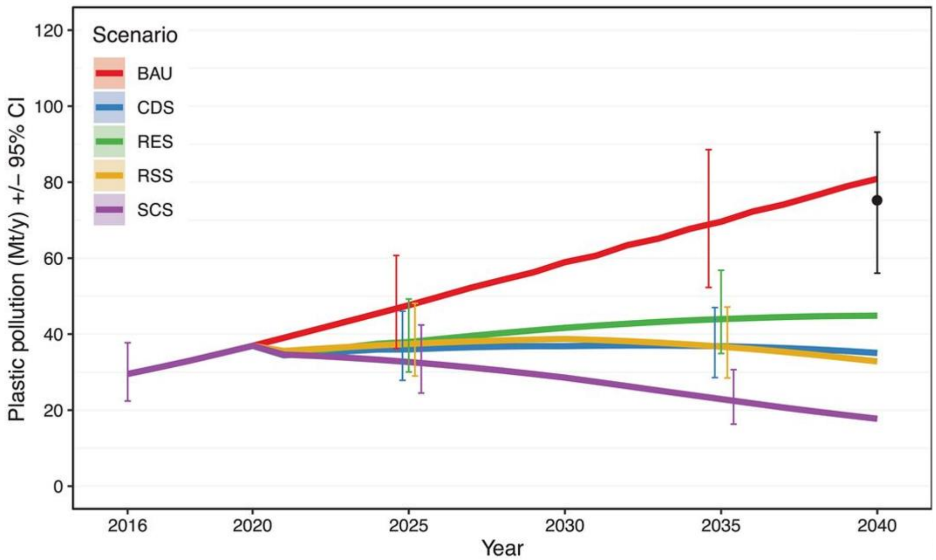

Figure 19: Prediction of annual rates of plastic production in the future under different scenarios: Business as usual (BAU), Collect and Dispose scenario (CDS), Recycling scenario (RES), Reduce and Substitute scenario (RSS), and System Change scenario (SCS). Graph from (Lau et al., 2020).

8.1 The goal: relevant human health risk assessment and mitigation measures

The most prominent current research question is to know the risks for human health upon micro- and nanoplastic exposure (via various pathways, Chapter 5). This goal is not only driven by scientific curiosity, but it is supported by a general public concern on the effects of micro- and nanoplastic pollution on the environment and human health (Catarino et al., 2021).

From a toxicological viewpoint, assessing a risk requires information on both the exposure concentrations and the expected effects when exposed to these concentrations (ECHA, 2016). Both exposure and effect data can be used to characterize risks and initiate appropriate mitigation measures to reduce the risk for human health (Figure 20). Those mitigation measures should be based on science and supported by a relevant policy framework. Nonetheless, the currently available scientific evidence on the persistence, fragmentation, harmfulness, omnipresence and increasing concentrations could be sufficient to justify preventive measures addressing plastic pollution (including microplastics) in the framework of the precautionary principle (e.g. Rethink plastic, 2022).

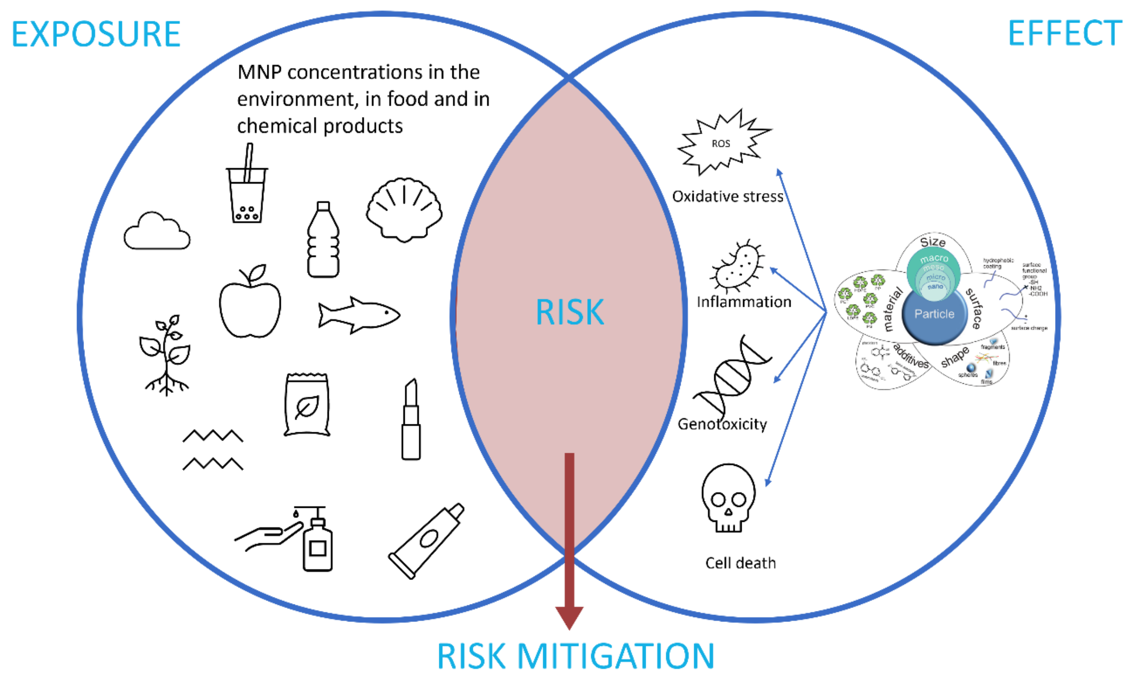

Figure 20: Risk assessment framework for human health effects of micro- and nanoplastic (MNP) including a profound monitoring of exposure concentrations (including concentrations in food, chemical products, and the environment) and a reliable study on effects with respect to the heterogeneity of microplastics (with varied sizes, shapes, surface characteristics, etc.).

Below we will discuss both the scientific needs (Section 8.2) and propose the key stepping stones towards a supportive policy framework (Section 8.3) for human health risk upon micro- and nanoplastic exposure.

8.2 Current scientific needs

As summarized in this brief, a lot of research has been performed on microplastic concentrations and on the human health effects upon exposure. However, at present, insufficient scientific knowledge is available for a reliable risk assessment. On the one hand, this is linked to a lack of profound, standardized monitoring of exposure concentrations (monitoring of MNP in the environment, the entire diet and chemical products combined with human biomonitoring[13]). The main bottleneck to achieve this is the lack of standardized methods to measure MNPs in different matrices. On the other hand, we are currently

[13] *"Human biomonitoring involves measuring concentrations of environmental contaminants, and/or their metabolites, in human tissues or body fluids, such as blood, amniotic fluid, breast milk, saliva, hair or urine sources" (Science for Environment Policy, 2023).*

missing relevant effect data, leading to a lack of health-based guidance values[14], indicating a recommended intake for a certain time period. This is identified as the second bottleneck hitherto.

8.2.1 Bottleneck 1: the lack of standardized methodology

As the lack of standardization amongst studies results in the generation of incomparable data (N. B. Hartmann et al., 2019), a large scientific effort is currently ongoing to develop standardized methods for microplastic sampling and analysis. Various international and European projects or bodies are working on developing standardized methods for MNP, amongst others:

- The Horizon2020 project EuroQCharm is working on developing standardized operating procedures for monitoring of microplastic in the marine environment.
- COST PRIORITY action, a science and technology research network has organized a round table on microplastic research standardization.
- JRC is currently working on the development of a methodology to measure microplastic in drinking water according to Directive (EU) 2020/2184, in collaboration with ISO/TC 147/SC 2/JWG 1 (see below)
- The ANDROMEDA project focuses on analytical methods for quantification of MNP in marine environments.
- International Organization for Standardization (ISO)
  - Following technical committees are in start-up/active in developing standards on sampling, analysis, and reporting of microplastics in the environment:
    - Textiles – Microplastics from textile sources (ISO/TC 38/WG 34)
    - Textiles – Environmental aspects (ISO/TC 38/WG 35)
    - Plastics – Environmental aspects (ISO/TC 61/SC 14)
    - Plastics – Characterization of plastics leaked into the environment (including microplastics) and quality control criteria of respective methods (ISO/TC 61/SC 14)
    - Rubber and rubber products - Environmental aspects (ISO/TC 45/WG 16)
    - Water Quality – Plastics (including microplastics) in waters and related matrices (ISO/TC 147/SC 2/JWG 1)
    - Water Quality – Sampling for microplastic particles and fibres (ISO/TC 147/SC 6/WG 16)
- European Committee for Standardisation (CEN)
  - Following technical committees are in start-up/active in developing standards on sampling, analysis, and reporting of microplastics in the environment.
    - Plastics – Environmental aspects (CEN/TC 249/WG 24)
    - Environmental characterization of solid matrices – microplastics (CEN/TC 444/WG6)

We refer to Devriese and Janssen (2023), a more exhaustive list of current projects (with Belgian project partners) working on methodology for environmental microplastic monitoring methods.

[14] *Health-based guidance values a science-based recommendation for the maximum (oral) exposure to a substance that is not expected to result in an appreciable health risk, taking into account current safety data, uncertainties in these data, and the likely duration of consumption (Committee et al., 2021).*

Together with a standardized methodology, standardized reporting guidelines and quality criteria should be pursued to improve the quality of the research and increase the reproducibility and comparability. Plastic is omnipresent therefore inducing a high risk of sample contamination during processing and analysis (e.g. Wesch et al., 2017). To avoid misinterpretation of results, analysis of blanks, recovery percentage of the techniques used, size detection limits, etc. should be reported (Cowger et al., 2020; Schwaferts et al., 2019).

Microplastic methodology

For microplastics, a fairly large suite of methods are available to analyse their presence in different matrices. There are a multitude of protocols containing specific methods adaptable to specific research questions (Schwaferts et al., 2019). Many parties strive for harmonization of these methods, however it is important that the choice of the method should align with the research question that is being asked (Mitrano et al., 2023). Moreover, the harmonization should not hamper the development of new approaches (Mitrano et al., 2023).

As for now, a methodological gap exists for small microplastics and nanoplastics, although some methods have the potential to be adapted to this size range in combination with other techniques often used for nanoparticle research (Schwaferts et al., 2019). However, as these are not yet fully pinpointed, we will focus on the methods available for microplastic.

Generally, the analysis of microplastics exists of three major steps:

1. Sample collection (not included in this brief, a few relevant sources are: Adomat & Grischek (2021); Campanale et al. (2020); F. Stock et al. (2019); Zheng et al. (2021))
2. Extraction of microplastic from the matrix
3. Morphological characterization and/or chemical identification of microplastics

Extraction of microplastics from the matrix

In order to analyse the microplastics, they need to be extracted from the sample matrix and the origin and composition of the matrix determines the complexity of the process. Following steps can be included (Schwaferts et al., 2019):

- **Digestion**
  The organic matrix like tissue, organisms or natural organic matter has to be removed from the sample to allow further analyses. Commonly used digestives are either acid (e.g. 65% nitric acid (HNO_3), 30% hydrogen peroxide (H_2O_2)), alkaline (potassium hydroxide (KOH)) or enzymatic (e.g. Proteinase K) (Schwaferts et al., 2019).
- **Density separation**:
  Fluids with high density (e.g. NaCl and NaI (1.6 g / cm^3)) induces the plastic particles to float and matrix with higher densities such as sediment particles to sink inducing a separation of both and an ultimately cleaner sample.
- **Filtration**
  To concentrate and purify the sample and focus on a specific size class the sample can be filtered using a membrane filter. These are commercially available with various pore sizes. The filter material used should be attuned to the full protocol.

For the extraction of small microplastics and nanoplastics, the masses are expected to be exceptionally low which results in constraints of the current techniques linked to the low particle size and low particle masses. Therefore, in the extraction protocol, it is assumed a pre-concentration and specific separation techniques will be needed to enhance the analysis (Schwaferts et al., 2019). For pre-concentration of the sample, techniques such as (ultra)filtration, centrifugation and evaporation can be used. Separation of the nanoplastics from the matrix could be done by using Field Flow Fractionation (FFF) or chromatographic techniques (Schwaferts et al., 2019). FFF technique is often suggested to be useful for separation of nanoplastics from their matrix. A physical force is used to separate particles, based on size or mass, as they flow through a channel (Science for Environment Policy, 2023). For more information on the differences between existing technologies for microplastics and possibilities for nanoplastic research, we refer to the work of Schwaferts et al. (2019).

Morphological characterization and chemical identification

Depending on the required information, morphological characterization and/or chemical identification is performed on the purified sample.

Morphological characterization aims mainly at identifying the particle size and shape but sometimes also surface charge, aggregation behaviour and surface morphology are measured. For this, techniques such as light scattering methods or electron microscopy are often used (Schwaferts et al., 2019).

Chemical identification of microplastics can be done in many ways:

- **Microscopy - based methods**
  Nile red staining is known to bind to plastics based on hydrophobic interactions. This has been used before to separate plastics from non-plastic particles. More recently, it was discovered that Nile red can interact differently with different polymer types and using a combination of Nile red staining and machine learning can provide a cost- and time effective method to characterize microplastics (Meyers et al., 2022). A proposed analytical workflow using this technique is depicted below (Figure 21).

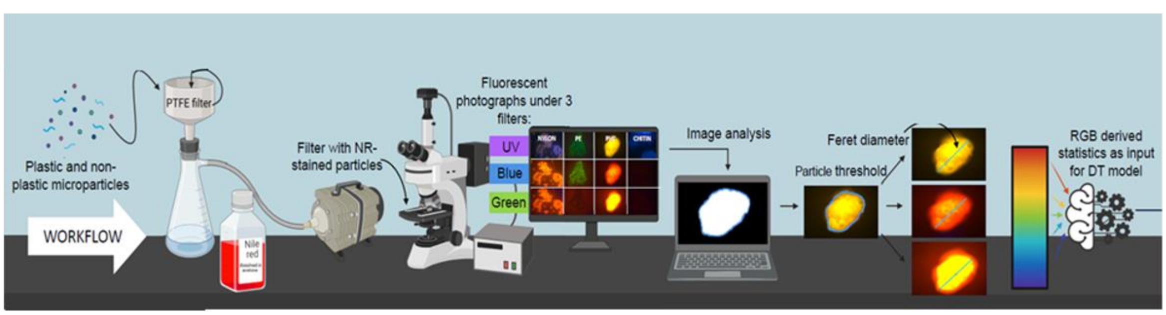

Figure 21: Semi-automated, high-throughput analytical workflow using a combination of Nile red staining and machine learning technique, developed in the ANDROMEDA project (Meyers et al 2022).

- **Spectroscopy**
  The most commonly used spectroscopic technique is Fourier-transformed infrared (FTIR) spectroscopy in which infrared irradiation causes vibrational transitions resulting in changed absorbances. The latter can be captured in an absorbance spectrum used to identify the polymer

type. Moreover, ageing can be observed using the carbonyl index, calculated based on these spectra. Often, FTIR is combined with a microscope to allow basis morphological analysis (Schwaferts et al., 2019).

Raman spectroscopy uses the scattering of laser light resulting in a vibrational fingerprint spectrum which can be used for polymer identification. Both techniques have size detection limits due to analytical constraints. Raman spectroscopy can analyse particles up to 1µm and FTIR until 10µm (Schwaferts et al., 2019).

In this field, Laser Direct Infrared (LDIR) is also gaining attention in its abilities to identify and quantify microplastics (e.g. Ourgaud et al., 2022).

- **Mass spectrometry-based techniques**

  Mass spectrometric polymer identification is commonly used to provide mass information on the plastics. Importantly, no information of particle size can be obtained from bulk sample analysis. Known methods are pyrolysis gas chromatography/mass spectrometry (GC/MS) using thermal degradation with subsequent separation using GC and characterization using MS (Schwaferts et al., 2019). The downside of this technique is the limit of detection which is assumed to be too high for the smaller nanoplastics. Other mass-spectrometry based methods are MALDI-TOF-MS and ICP-MS (Velimirovic et al., 2021), which are also explored for microplastic research.

- **Others**

  Hyperspectral imaging uses analysis of material-specific wavelengths to characterize plastics, amongst others. This has been successfully used to detect 52 nm PS nanoplastics in the brain of carp (Mattsson et al., 2017). Hyperspectral imaging is currently also applied for remote sensing monitoring of macrolitter in the environment (Lordache et al., 2022).

The cost-effectiveness of different methods is also very important and is currently being studied as part of the ANDROMEDA project (Kopke et al., 2023).

The selected method must be ‘fit-for-purpose’, thus tailored to the research question being asked and depend on the matrix, the aimed minimum size, the need of detailed morphological characterization or chemical information, etc. as no method is capable to measure all characteristics (Mitrano et al., 2023). Therefore, decision trees (Figure 22) could help to guide policymakers and scientists to select the state-of-the-art methods based on the scientific question that needs to be answered (e.g. necessity of morphological information of the particles). A first non-exhaustive and preliminary decision tree (for food samples, environmental samples, and human samples) was constructed based on the current scientific knowledge and in-house experience. The preliminary interactive app can be found via: https://maaikevercauteren.shinyapps.io/DecisiontreeMNP/. The development of such trees could support decision making and standardizing methodologies.

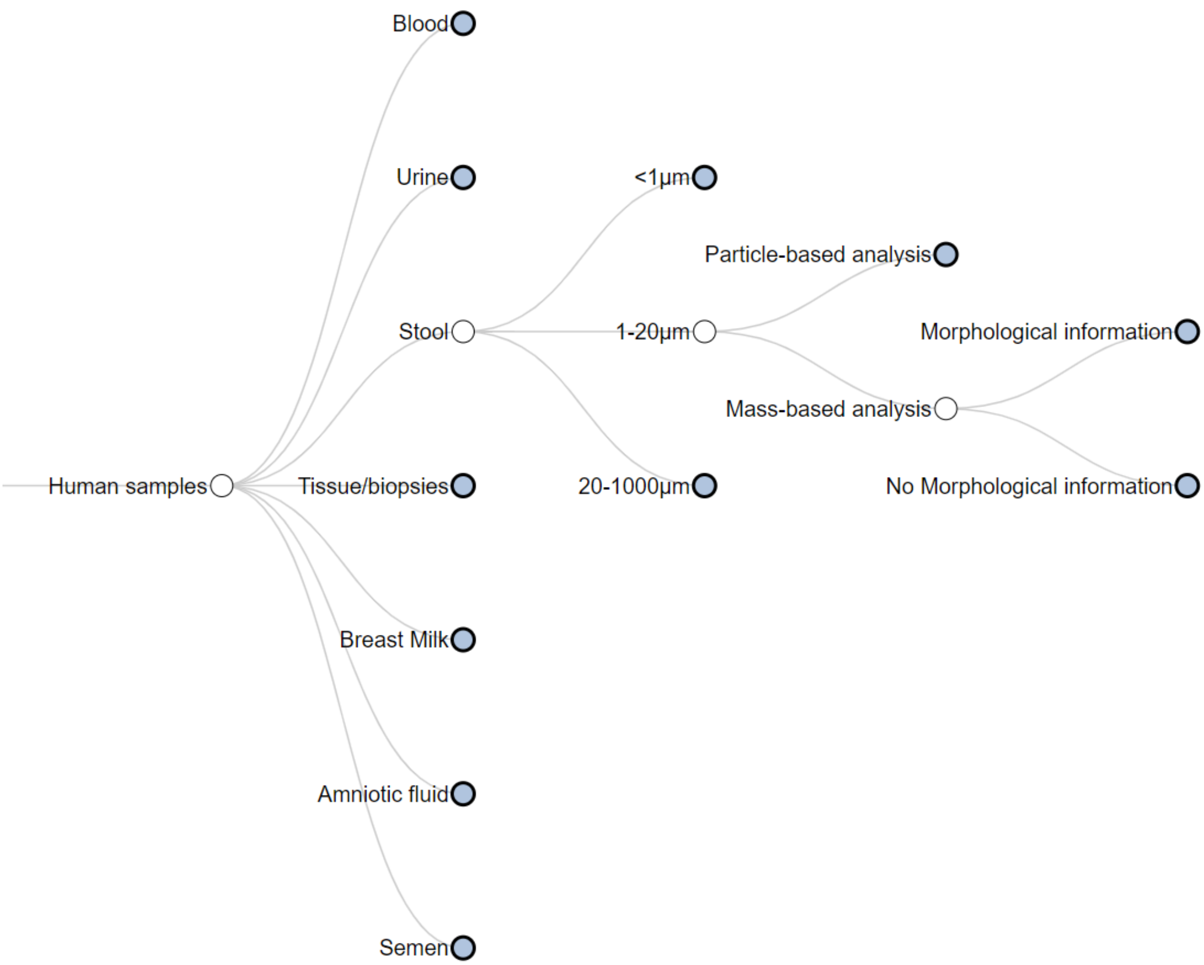

Figure 22: Example of the preliminary interactive app with a decision three to help policy makers and scientist select the best methods to extract and analyse their samples based on the matrix and the required particle information.

8.2.2 Bottleneck 2: Lack of health-based guidance values

Despite the high research effort, we are currently not yet able to correctly assess the human health effects of micro- and nanoplastics exposure. As a consequence, no health-based guidance values have been developed for MNPs. Various knowledge institutes are working towards this risk assessment frameworks for MNPs. The JPI Oceans project RESPONSE is currently developing a risk assessment framework for marine ecosystems and the CUSP consortium is focusing on a risk assessment framework for human health including amongst others the IMPTOX project with a focus on allergic diseases, PlasticsFatE on additives and contaminants, AURORA project on early life health impacts of micro- and nanoplastics.

The lack of knowledge on the effects are linked to four main challenges that are recommended to be taken into account in future scientific studies (Science for Environment Policy, 2023):

- **The plastic continuum**
  Plastics are a large group of pollutants variable in sizes, shapes, surface functionalities, polymer types, additives, … Moreover, plastics continuously change under the influence of degradation processes and interactions with the environment. Thus, each micro- or nanoplastic particle will possess its own set of characteristics. This complexity is, hitherto, not included in the scientific research. Furthermore, it is until now unknown which of these particle characteristics would play a role in exerting toxic effects.
- **Relevant exposure scenarios**
  The focus of current effect studies has been pointed towards short-term effects following a single exposure with often high MNP concentrations. However, if compared to human exposure, it is more likely that we are repeatedly exposed to low doses of MNP concentrations with possible longer-term effects. Switching the research focus towards more relevant exposure scenarios to assess these effects, would challenge us to increase the complexity of the models used (e.g. move to co-culture systems and using stem cell-based models) and the measured endpoints for better insights and easier extrapolation on these expected but more subtle effects. Moreover, predictive modelling tools such as AOPs could be explored to assess different exposure scenarios and organism level effects based on observed cellular changes.
  Evidently, to ensure relevant exposure scenarios, we would need more information on relevant exposure concentrations and morphological characteristics of these plastics for human exposure pathways. The first and second identified bottlenecks are therefore inherently linked and should be tackled simultaneously.
- **Holistic approach**
  A more holistic approach could help to include the possible chemical toxicity (related to leaching of additives) and/or the combined stress of plastic pollution and other stressors (e.g. climate change) (Everaert et al., 2020; Koelmans et al., 2016, 2022). Furthermore, the biological interactions (e.g. formation of biofilm corona on the plastic surface) should be included to shed a light on the relevant exposure and effects. Moreover, in this framework, work on environmental effects or effects of other particles (e.g. nanomaterials) could shed a light on possible important pathways and effects and should therefore be used to the best extend, keeping in mind the inherent complexity of plastics.
- **High quality research**
  Similar as described before on the monitoring studies, more focus is needed for the quality of the research data. Some quality criteria are recently proposed for microplastic effect studies (de Ruijter et al., 2020). Moreover, more caution should be taken when using commercially available plastics, e.g. provide adequate controls to account for possible confounding effects linked to fluorescence label leakage (Catarino et al., 2019) and use of reference particles to account for particle effects in itself.

All these challenges affect the comparability, reproducibility and the relevance of the performed laboratory experiments (SAPEA, 2019; Science for Environment Policy, 2023). With a clear focus on these challenges, we can move towards a relevant human health risk assessment for exposure to MNP.

8.3 Stepping stones to advance policy

Microplastic pollutions is getting more attention, not only in the public and scientific fields, but the problem is also increasingly important on the political agenda (See Chapter 2). However, despite the accepted link between environmental pollution and human health (and linked food safety), little to no policy frameworks linked to human health are currently in place (See Chapter2) and no health-based guidance values have been described for MNPs.

The approach for policy should be two-pronged:

1. Short-term preventive measures linked to environmental plastic pollution but also preliminary health-based guidance values could be defined as a precautionary measure (Hantoro et al., 2019; Rethink plastic, 2022).
2. A supportive policy framework, corroborated by scientific knowledge, should be developed to prevent further microplastics pollution and minimize the impact on our environment and human health, now and in the future. For this framework, a holistic approach will be necessary to overcome plastic pollution where both plastic production and pollution are tackled in a parallel effort combined with considerations regarding the risk of MNP to ecosystems and human health:
    a. **Focus on overproduction of plastics and the unsustainable design of plastic products.** With a decrease in plastic production and use (reduce) and an increase in recycling rates and better waste management, the general plastic pollution can be tackled. Examples are the ban on single-use plastics, Plastic Bag Directive, restriction on intentionally added microplastics etc. Plastic should be safe by design to minimize release in relevant human health settings.
    b. **Environmental pollution of both macro- and microplastic should be addressed simultaneously.** Even if direct emissions to the environment were completely prevented, the MNP concentrations will continue to increase due to the further degradation of current plastic pollution (Rethink plastic, 2022). Clean-up actions and technologies would help to achieve this goal (Moulaert et al., 2021). Furthermore, knowledge on the transport of plastics through the water column and the final sink remain to be fully elucidated. This however plays a primordial role in identifying hotspots of plastic pollution and environmental compartments at risk as well as the development of suitable remediation technologies (Galgani et al., 2000).
    c. **Establishing safety thresholds for MNP exposure.** Plastic pollution should be considered in the framework of risk characterization and mitigation. Despite actions to reduce pollution (precautionary measure), more information is needed on the risk of MNP for environmental and human health in order to ensure proper mitigation measures when certain safety thresholds are met. This to ensure humans and organisms in the environment are not exposed to levels of MNPs that may be hazardous to health.

In general, it remains however crucial to formulate clear targets for all three pillars of the relevant policy framework (Devriese et al., 2023), supported by scientific evidence, as this can expedite informed decision-making processes. Moreover, in order to monitor progress and effectiveness of taken measures, a comparison between the prior situation and the situation after the execution of the measure is used. However, in most cases, a baseline measure is often missing that will hinder an objective evaluation of mitigating measures.

9. Supplementary information

Health Food Chain Safety Environment

Blue Growth Research Lab

Supplementary file 1: Detailed (but non-exhaustive) overview of (micro)plastic related policies

	Competent authority	Document name	Year	Targets
Environmental plastic pollution				
Global	UNESCO	Ramsar Convention	1971	Article 3. Each Contracting Party shall arrange to be informed at the earliest possible time if the ecological character of any wetland in its territory and included in the List has changed, is changing or is likely to change as the result of technological developments, pollution, or other human interference. Information on such changes shall be passed without delay to the organization or government responsible for the continuing bureau duties specified in Article 8.
	IMO	UNCLOS -Part XII: Section 5 International Rules and National Legislation to prevent, reduce and control pollution of the marine environment	1982	Article 192 - General obligation: States have the obligation to protect and preserve the marine environment. Article 194 - Measures to prevent, reduce and control pollution: of the marine environment 1. States shall take, individually or jointly as appropriate, all measures consistent with this Convention that are necessary to prevent, reduce and control pollution of the marine environment from any source, using for this purpose the best practicable means at their disposal and in accordance with their capabilities, and they shall endeavour to harmonize their policies in this connection. 2. States shall take all measures necessary to ensure that activities under their jurisdiction or control are so conducted as not to cause damage by pollution to other States and their environment, and that pollution arising from incidents or activities under their jurisdiction or control does not spread beyond the areas where they exercise sovereign rights in accordance with this Convention. 3. The measures taken pursuant to this Part shall deal with all sources of pollution of the marine environment.
	COP	Jakarta Mandate: Conservation and sustainable use of marine and coastal biological diversity	1995	Programme element 1. Implementation of integrated marine and coastal area management (IMCAM). Operational objective 1.2: To promote the development and implementation of IMCAM at the local, national, and regional level. Activities (d): To promote action to reduce and control sea-based sources of pollution;

	Competent authority	Document name	Year	Targets
Global	UNEP	Honolulu Strategy: A Global Framework for Prevention Management of Marine Debris	2011	The Honolulu Strategy is a framework for a comprehensive and global collaborative effort to reduce the ecological, human health, and economic impacts of marine debris worldwide. This framework is organized by a set of goals and strategies applicable all over the world, regardless of specific conditions or challenges. The Honolulu Strategy specifies three overarching goals focused on reducing threats of marine debris: Goal A: Reduced amount and impact of land-based litter and solid waste introduced into the marine environment Goal B: Reduced amount and impact of sea-based sources of marine debris including solid waste, lost cargo, ALDFG, and abandoned vessels introduced into the sea Goal C. Reduced amount and impact of accumulated marine debris on shorelines, in benthic habitats, and in pelagic waters
	UN	Rio + 20 Declaration	2012	124. We stress the need to adopt measures to significantly reduce water pollution and increase water quality, significantly improve wastewater treatment and water efficiency and reduce water losses. In order to achieve this, we stress the need for international assistance and cooperation. 158. We recognize that oceans, seas and coastal areas form an integrated and essential component of the Earth's ecosystem and are critical to sustaining it, and that international law, as reflected in the United Nations Convention on the Law of the Sea, provides the legal framework for the conservation and sustainable use of the oceans and their resources. We stress the importance of the conservation and sustainable use of the oceans and seas and of their resources for sustainable development, including through their contributions to poverty eradication, sustained economic growth, food security and creation of sustainable livelihoods and decent work, while at the same time protecting biodiversity and the marine environment and addressing the impacts of climate change. We therefore commit to protect, and restore, the health, productivity and resilience of oceans and marine ecosystems, and to maintain their biodiversity, enabling their conservation and sustainable use for present and future generations, and to effectively apply an ecosystem approach and the precautionary approach in the management, in accordance with international law, of activities having an impact on the marine environment, to deliver on all three dimensions of sustainable development. 163. We note with concern that the health of oceans and marine biodiversity are negatively affected by marine pollution, including marine debris, especially plastic, persistent organic pollutants, heavy metals, and nitrogen-based compounds, from a number of marine and land-based sources, including shipping and land run-off. We commit to take action to reduce the incidence and impacts of such pollution on marine ecosystems, including through the effective implementation of relevant conventions adopted in the framework of the International Maritime Organization (IMO), and the follow-up of the relevant initiatives such as the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities, as well as the adoption of coordinated strategies to this end. We further commit to take action to, by 2025, based on collected scientific data, achieve significant reductions in marine debris to prevent harm to the coastal and marine environment.

	Competent authority	Document name	Year	Targets
	UNEP	First session of United Nations Environment Assembly (UNEP/EA.1)	2014	The United Nations Environment Assembly, Recalling the concern reflected in the outcome document of the United Nations Conference on Sustainable Development, entitled "The future we want",1 that the health of oceans and marine biodiversity are negatively affected by marine pollution, including marine debris, especially plastic, persistent organic pollutants, heavy metals and nitrogen-based compounds, from numerous marine and land-based sources, and the commitment to take action to significantly reduce the incidence and impacts of such pollution on marine ecosystems,
	UN	SDG 14: Life below water	2015	14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution
Global	UNEP	Second session of United Nations Environment Assembly (UNEP/EA.2)	2016	94. The representative of Norway said that his government pledged $1 million to UNEP to support strategic action to combat marine litter and microplastics. 3. Welcomes the activities of the relevant United Nations bodies and organizations, including the Food and Agriculture Organization of the United Nations and the International Maritime Organization, which act in coordination with the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection and the Global Partnership on Marine Litter to prevent and reduce marine litter and microplastics; encourages the active contribution of all stakeholders to their work; and acknowledges the importance of cooperation and information sharing between the United Nations Environment Programme, the Food and Agriculture Organization and the International Maritime Organization, as well as the cooperation under the Global Partnership on Marine Litter, on this matter; 42. Following the work of the drafting group, at its 7th meeting, on the evening of 27 May, the Committee approved a draft resolution on marine plastic litter and microplastics for consideration and possible adoption by the Environment Assembly.
	G20	Group of 20 Action Plan on Marine Litter	2017	The G20 recognizes the urgent need for action to prevent and reduce marine litter in order to preserve human health and marine and coastal ecosystems and mitigate marine litter's economic costs and impacts. We stress the direct relationship between the challenge of marine litter, environment, human health, economic development, social well-being, biodiversity, and food security. Realizing the global nature of the challenge of marine litter, the G20 will work together to promote and initiate measures and actions at local, national, and regional levels to prevent and reduce marine litter. We recognize that the lack of effective solid waste management, wastewater treatment and storm water systems, and unsustainable production and consumption patterns, are primary land-based sources and pathways of marine litter. Taking into account the need for comprehensive multi-stakeholder involvement, we as the G20 acknowledge the role of non-state actors and further encourage private sector engagement and the development of environmental protection solutions to reduce marine litter.

	Competent authority	Document name	Year	Targets
Global	IMO	Guidelines for the implementation of MARPOL Annex V	2017	All other garbage including plastics, synthetic ropes, fishing gear, plastic garbage bags, incinerator ashes, clinkers, cooking oil, floating dunnage, lining and packing materials, paper, rags, glass, metal, bottles, crockery and similar refuse: Discharge prohibited
	IMO	Strategic Plan for the London Protocol and London convention	2017	The Strategic Plan was adopted on 18 October 2016 by the thirty-eighth Consultative Meeting of Contracting Parties to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (London Convention), and the eleventh Meeting of Contracting Parties to the 1996 Protocol to the London Convention, 1972 (London Protocol).* The Strategic Plan is intended to facilitate the implementation of the London Protocol and the London Convention in order to contribute to the prevention of marine pollution and to advance the 2030 Agenda for Sustainable Development. This Strategic Plan sets out the strategic directions and targets that London Protocol and London Convention Parties are working to achieve by 2030. It is intended to serve as an overarching tool to guide, focus, and prioritize the work of the Parties and to communicate their shared objectives to the outside world. Strategic Direction 4: Identify and address emerging issues in the marine environment within the scope of the London Protocol and/or London Convention 4.1 Identify and evaluate emerging trends and risks to the marine environment based on best available scientific evidence 4.2 Respond as appropriate to newly identified risks to the marine environment taking into account recommendations from the London Protocol and London Convention Scientific Groups
	IMO	LONDON Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972"	1972	Contracting Parties shall individually and collectively protect and preserve the marine environment from all sources of pollution and take effective measures, according to their scientific, technical, and economic capabilities, to prevent, reduce and where practicable eliminate pollution caused by dumping or incineration at sea of wastes or other matter. Article 2. Where appropriate, they shall harmonize their policies in this regard.
	IMO	IMO Action Plan to address marine plastic litter from ships	2018	1. Reduction of marine plastic litter generated from, and retrieved by, fishing vessels.2. Reduction of shipping's contribution to marine plastic litter, 3. Improvement of the effectiveness of port reception and facilities and treatment in reducing marine plastic litter, 4. Enhanced public awareness, education and seafarer training, 5. Improved understanding of the contribution of ships to marine plastic litter, 6. Improved understanding of the regulatory framework associated with marine plastic litter from ships, 7. Strengthened international cooperation, 8. Targeted technical cooperation and capacity-building
	FAO	Voluntary Guidelines for the marking on Fishing Gear FAO	2018	The Voluntary Guidelines for the Marking of Fishing Gear are a tool to contribute to sustainable fisheries and to improve the state of the marine environment by combatting, minimising, and eliminating abandoned, lost or otherwise discarded fishing gear (ALDFG) and facilitating the identification and recovery of such gear.

	Competent authority	Document name	Year	Targets
	UNEP	Third session of United Nations Environment Assembly (UNEP/EA.3)	2018	1. Stresses the importance of long-term elimination of discharge of litter and microplastics to the oceans and of avoiding detriment to marine ecosystems and the human activities dependent on them from marine litter and microplastics; 2. Urges all actors to step up actions to "by 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution"; 3. Encourages all member States, based on best available knowledge of sources and levels of marine litter and microplastics in the environment, to prioritize policies and measures at the appropriate scale to avoid marine litter and microplastics from entering the marine environment;
	UNEP	UNEP/GPA/IGR.4/6 Bali Declaration on Protection of the Marine Environment from Land-based Activities	2019	1. Agree to continue work on: (a) Enhancing the mainstreaming of the protection of coastal and marine ecosystems, especially from the environmental threats caused by increased nutrients, wastewater, and marine litter and microplastics;
	UNEP	Fourth session of United Nations Environment Assembly (UNEP/EA.4)	2019	(i) We will improve national environmental monitoring systems and technologies, including for air, water and soil quality, biodiversity, deforestation, marine litter, and chemicals and waste, and we encourage the development of national environmental data management capacities.
			2019	1. Calls upon Member States and other actors at the local, national, regional and international levels, including in the private sector, civil society and academia, to address the problem of marine litter and microplastics, prioritizing a whole-life-cycle approach and resource efficiency, building on existing initiatives and instruments, and supported by and grounded in science, international cooperation and multi-stakeholder engagement;
			2019	2. Requests the Executive Director of the United Nations Environment Programme, subject to the availability of resources and benefiting from the work of existing mechanisms, to immediately strengthen scientific and technological knowledge with regard to marine litter, including marine plastic litter and microplastics

	Competent authority	Document name	Year	Targets
Global	UN	Resolution adopted by the General Assembly on 8 December 2020, Sustainable fisheries, including through the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, and related instruments	2020	- Concerned that marine pollution from all sources constitutes a serious threat to human health and safety, endangers fish stocks, marine biodiversity and marine and coastal habitats and has significant costs to local and national economies, - Recognizing that marine debris is a global transboundary pollution problem and that, owing to the many different types and sources of marine debris, different approaches to its prevention and removal are necessary, including the identification of such sources and environmentally sound techniques for its removal, - Recognizing also that the majority of marine debris, including plastics and microplastics, entering the seas and oceans is considered to originate from land-based I63sources,sources,
			2020	216. Urges all States to implement the 1995 Global Programme of Action for the Protection of the Marine Environment from Land-based Activities36 and to accelerate activity to safeguard marine ecosystems, including fish stocks, against sources of land-based pollution, including plastics and excess nutrients, and physical degradation, taking into account the increase in oceanic dead zones;
	UN	Resolution adopted by the General Assembly on 31 December 2020. Oceans and the law of the sea	2021	225. Encourages States to further develop partnerships with industry and civil society to raise awareness of the extent of the impact of marine debris on the biological diversity, health and productivity of the marine environment and consequent economic loss and to cooperate with other States, industry and civil society, as appropriate, on environmentally sound and cost-effective measures to prevent and reduce, as appropriate, marine debris and microplastics in the marine environment, including through strengthened cooperation under the Global Partnership on Marine Litter;
	UNEP	Fifth session of United Nations Environment Assembly (UNEP/EA.5)	2022	3. We are ready to do our utmost to end plastic pollution worldwide, and we welcome the decision by the Environment Assembly to establish an intergovernmental negotiating committee towards an international legally binding instrument on plastic pollution.

	Competent authority	Document name	Year	Targets
			2022	5/14. End plastic pollution: towards an international legally binding instrument 3. Decides that the intergovernmental negotiating committee is to develop an international legally binding instrument on plastic pollution, including in the marine environment, henceforth referred to as "the instrument", which could include both binding and voluntary approaches, based on a comprehensive approach that addresses the full life cycle of plastic, taking into account, among other things, the principles of the Rio Declaration on Environment and Development, as well as national circumstances and capabilities, and including provisions:
Global	Intergovernmental Oceanographic commission/ UN	[Mid Term Strategy 2022-2029 /ocean decade]()	2022	Through international cooperation, IOC aspires to build and apply scientific knowledge to achieve the following High-Level Objectives (HLOs), with particular attention to ensuring that all Member States have the capacity to meet them: 1. Healthy ocean and sustained ocean ecosystem services; 2. Effective warning systems and preparedness for tsunamis and other ocean-related hazards; 3. Resilience to climate change and contribution to its mitigation; 4. Scientifically founded services for the sustainable ocean economy; and 5. Foresight on emerging ocean science issues The Decade will be guided by a vision of "the Ocean we need for the future we want," namely: ~ a clean ocean where sources of pollution are identified, reduced, or removed;
				(d) Continued efforts to combat pollution from nutrients, wastewater, and marine litter and microplastics from land-based sources in an integrated manner, and the inclusion of the land/sea and freshwater/seawater interfaces in action plans for addressing marine litter, wastewater, and nutrients;
				(l) We will address the damage to our ecosystems caused by the unsustainable use and disposal of plastic products, including by significantly reducing the manufacturing and use of single-use plastic products by 2030, and we will work with the private sector to find affordable and environmentally friendly alternatives.
				20. We commit ourselves to safeguarding life under water and restoring a clean, healthy, resilient and productive ocean capable of providing food and sustainable livelihoods and storing carbon, and we will do so by strengthening efforts to protect, conserve and sustainably manage our oceans, seas, lakes, rivers and coastal ecosystems while acting to prevent pollution, including eutrophication and plastic pollution, and to prevent sea level rise, ocean warming and acidification by keeping our efforts in line with the Paris Agreement and the 2030 Agenda for Sustainable Development. We look forward to the organization of the second United Nations Ocean Conference in Lisbon in 2022 and the United Nations Water Conference in New York in 2023.

	Competent authority	Document name	Year	Targets
	IMO	Convention of the High Seas	1958	Article 25. All States shall cooperate with the competent international organizations in taking measures for the prevention of pollution of the seas or air space above, resulting from any activities with radioactive materials or other harmful agents.
Europe	DG ENV	Directive 91/271/EEC on Urban wastewater treatment Directive	1991	Ongoing review (SWD (2022) 541) of the Directive is tackling the issue of wastewater treatment of micro-pollutants, including micro-plastics
	DG ENV	Water Framework Directive WFD 2000/60/EC on establishing a framework for Community action in the field of water policy	2000	Ongoing review (COM (2022) 540) of the Directive aiming to include microplastics
Europe	DG ENV	MSFD Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy, as amended by Directive (EU) 2017/845	2008	Properties and quantities of marine litter do not cause harm to the coastal and marine environment.
	DG ENV	Commission Decision EU 2017/848 Laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment	2017	Descriptor 10: Properties and quantities of marine litter do not cause harm to the coastal and marine environment. Criteria for micro-litter: D10C2 – Primary: The composition, amount and spatial distribution of micro-litter on the coastline, in the surface layer of the water column, and in seabed sediment, are at levels that do not cause harm to the coastal and marine environment Member States shall establish threshold values for these levels through cooperation at Union level, taking into account regional or subregional specificities. D10C3 – Secondary: The amount of litter and micro-litter ingested by marine animals is at a level that does not adversely affect the health of the species concerned. Member States shall establish threshold values for these levels through regional or subregional cooperation.

	Competent authority	Document name	Year	Targets
	EU	Fertilising Products Regulation	2019	This directive has its aim to guarantee the functioning of the internal market while ensuring that EU fertilising products on the market fulfil the requirements providing for a high level of protection of human, animal, and plant health, of safety and of the environment.
				By 16 July 2024, the Commission shall assess biodegradability criteria for polymers referred to in point 2 of component material category 9 in Part II of Annex II and test methods to verify compliance with those criteria and, where appropriate, shall adopt delegated acts pursuant to paragraph 1 which lay down those criteria. Such criteria shall ensure that: (a) the polymer is capable of undergoing physical and biological decomposition in natural soil conditions and aquatic environments across the Union, so that it ultimately decomposes only into carbon dioxide, biomass and water; (b) the polymer has at least 90 % of the organic carbon converted into carbon dioxide in a maximum period of 48 months after the end of the claimed functionality period of the EU fertilising product indicated on the label, and as compared to an appropriate standard in the biodegradation test; and (c) the use of polymers does not lead to accumulation of plastics in the environment.
Europe				The aerobic composting shall consist of controlled decomposition of biodegradable materials, which is predominantly aerobic, and which allows the development of temperatures suitable for thermophilic bacteria as a result of biologically produced heat. All parts of each batch shall be either regularly and thoroughly moved and turned or subject to forced ventilation in order to ensure the correct sanitation and homogeneity of the material. During the composting process, all parts of each batch shall have one of the specified temperature-time profiles. The compost shall contain: (a) no more than 6 mg/kg dry matter of PAH16 (5); (b) no more than 3 g/kg dry matter of macroscopic impurities above 2 mm in any of the following forms: glass, metal or plastics; and (c) no more than 5 g/kg dry matter of the sum of the macroscopic impurities referred to in point (b).From 16 July 2026, the presence of plastics above 2 mm within the maximum limit value referred to in point (b) shall be no more than 2,5 g/kg dry matter. By 16 July 2029, the limit-value of 2,5 g/kg dry matter for plastics above 2 mm shall be re-assessed in order to take into account the progress made with regards to separate collection of biowaste.

	Competent authority	Document name	Year	Targets
	EU	Zero pollution action plan	2021	The Commission adopted the EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil' on 12 May 2021. The plan sets out the overarching vision that by 2050, pollution is reduced to levels no longer considered harmful to health and natural ecosystems. To achieve this, it defines a number of zero pollution targets for 2030, namely reducing: • by more than 55 % the health impacts (premature deaths) of air pollution; • by 30 % the share of people chronically disturbed by transport noise; • by 25 % the EU ecosystems where air pollution threatens biodiversity; • by 50 % nutrient losses, the use and risk of chemical pesticides, the use of the more hazardous ones, and the sale of antimicrobials for farmed animals and in aquaculture; • **by 50 % plastic litter at sea and by 30 % microplastics released into the environment**; • significantly total waste generation and by 50 % residual municipal waste.
	DG ENV	SWD (2022) 541 on proposal for a Directive concerning urban wastewater treatment	2022	Further reduce nutrient (N and P), micro-pollutants and microplastic pollution as well as 'remaining sources' of pollution from urban sources (cf. COM (2022) 540).
	DG ENV	COM (2022) 540 on proposal for amending Directive 2000/60/EC, 2006/118/EC, and 2008/105/EC	2022	Ex-post evaluations/fitness checks of existing legislation: Improving the existing guidelines for Effect-Based Methods and developing a harmonised methodology for monitoring microplastics will simplify Member States' work in these areas.
				Preferred option to improve digitalisation, administrative streamlining, and risk management in the area of water pollution: Develop a harmonised measurement standard and guidance for microplastics in water as a basis for MS reporting and a future listing under EQSD and GWD.
				WFD ANNEX VIII - INDICATIVE LIST OF THE MAIN POLLUTANTS: point 10 ('Materials in suspension') is replaced by the following: 'Materials in suspension, including micro/nanoplastics'.
				Amendment proposal to Directive 2006/118/EC: Add Article 6a:"... As soon as suitable monitoring methods for micro-plastics and selected antimicrobial resistance genes have been identified, those substances shall be included in the watch list..."
Europe				Amendment proposal to Directive 2008/105/EC: Article 8b is amended to: 1) improve the monitoring and review cycle of the Watch List mechanism, setting a three year instead of the current two-year cycle. "..."; 2) allow including micro-plastics and selected antimicrobial resistance genes in the next Watch List, subject to suitable monitoring and analysis methods being identified, with input from ECHA
				Further reduce nutrient (N and P), micro-pollutants and micro-plastics pollution as well as 'remaining sources' of pollution from urban sources (cf. SWD (2022) 541)

	Competent authority	Document name	Year	Targets
	EC	Conference on the future of Europe - Report on the final outcome (May 2022)	2022	Proposal 2.7: 'Protect water sources and combat river and ocean pollution, including through researching and fighting microplastic pollution ...'
	DG ENV	COM (2018) 28 A European Strategy for Plastics in a Circular Economy	2018	Action to curb microplastics pollution: Evaluation of the Urban Wastewater Treatment Directive: assessing effectiveness as regards microplastics capture and removal (ongoing)
	EC, Secretariat-General	COM (2019) 640 The European Green Deal	2019	The Commission will adopt in 2021 a zero-pollution action plan for air, water, and soil, proposing measures to address pollution from urban runoff and from new or particularly harmful sources of pollution such as micro plastics and chemicals, including pharmaceuticals
	EU	Regulation (2020/740) on tyre Labelling	2020	The abrasion of tyres during use is a significant source of microplastics, which are harmful to the environment and human health. The Commission's Communication 'A European Strategy for Plastics in a Circular Economy' therefore mentions the need to address the unintentional release of microplastics from tyres, inter alia through information measures such as labelling and through minimum requirements for tyres. Linked to tyre abrasion is the concept of mileage, namely the number of kilometres a tyre will last before it needs to be replaced because of tread wear. In addition to tyre abrasion and tread wear, the lifespan of a tyre depends on a range of factors, such as the wear resistance of the tyre, including the compound, tread pattern and structure, road conditions, maintenance, tyre pressure and driving behaviour.
				Once reliable, accurate and reproducible methods to test and measure tyre abrasion and mileage are available, the Commission should assess the feasibility of adding information on tyre abrasion and mileage to the tyre label. When proposing a delegated act to add tyre abrasion and mileage to the tyre label, the Commission should take that assessment into account, and should collaborate closely with industry, relevant standardisation organisations, such as the European Committee for Standardization (CEN), the United Nations Economic Commission for Europe (UNECE) or the International Organisation for Standardisation (ISO), and representatives of other stakeholders interested in the development of suitable testing methods. Information on tyre abrasion and mileage should be unambiguous and should not negatively affect the clear intelligibility and effectiveness of the tyre label as a whole towards end-users. Such information would also enable end-users to make an informed choice with regard to tyres, their lifespan and the unintentional release of microplastics. This would help protect the environment and at the same time allow end-users to estimate the operating costs of tyres over a longer period.

	Competent authority	Document name	Year	Targets
Europe	DG ENER	Regulation 2020/740 of the EP on the labelling of tyres with respect to fuel efficiency and other parameters	2020	Mention of microplastics with respect to the inclusion of abrasion and mileage information to the tyre label.
	DG RTD	European Missions: Restore our Ocean and Waters by 2030 (Implementation Plan)	2021	Reduce by at least 30% microplastics released into the environment by 2030 (cf. COM (2020) 400)
	DG ENV	COM (2021) 400 -Pathway to a Healthy Planet for All EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil	2021	The EU should reduce plastic litter at sea by 50% and microplastics released into the environment by 30% by 2030 (cf. Implementation Plan of Mission Restore our Oceans and Waters)
				The upcoming review of the Urban Wastewater Treatment Directive 91/271/EEC will, in synergy with the evaluation of the Sewage Sludge Directive 86/278/EEG, help to increase the ambition level to remove nutrients from wastewater and make treated water and sludge ready for reuse, supporting more circular, less polluting farming. It will also address emerging pollutants such as microplastics and micropollutants, including pharmaceuticals
	DG ENV	SWD (2021) 141 on Towards a monitoring and outlook framework for the zero-pollution ambition	2021	Expand the monitoring scope for pollutants and explore the possibilities of monitoring microplastic pollution in rivers and marine environments by 2022.
	EU	Horizon Europe Mission on Ocean and Waters	2021	The objective of the Mission is to restore the health of the EU's Ocean and waters by 2030. Specifically, this Mission's objective is to restore the health of our ocean and waters by reaching the European Green Deal targets for biodiversity, zero pollution and decarbonisation with greenhouse gas emissions reduction for 2030, across the ocean, seas, and waters, thereby addressing the three principal drivers of degradation.
				2. Prevent and eliminate pollution of our ocean, seas, and waters, in line with the EU Action Plan Towards Zero Pollution for Air, Water and Soil: a. Reduce by at least 50% plastic litter at sea. b. Reduce by at least 30% microplastics released into the environment. c. Reduce by at least 50% nutrient losses, the use and risk of chemical pesticides

	Competent authority	Document name	Year	Targets
	DG ENV	COM (2022) 156 on proposal for amending 2010/75 and 1999/31/EC	2022	Proposal: Micro-plastics emissions would be reduced by 9%, mainly though actions on improved management of rain waters (to be in place by 2040).
	EU	Industrial Emissions Directive	2010	(2) In order to prevent, reduce and as far as possible eliminate pollution arising from industrial activities in compliance with the 'polluter pays' principle and the principle of pollution prevention, it is necessary to establish a general framework for the control of the main industrial activities, giving priority to intervention at source, ensuring prudent management of natural resources and taking into account, when necessary, the economic situation and specific local characteristics of the place in which the industrial activity is taking place. The Commission shall establish guidance on 4. Chemical industry; 4.1. Production of organic chemicals, such as: (h) plastic materials (polymers, synthetic fibres, and cellulose-based fibres)
Regional	OSPAR	The second OSPAR Regional Action Plan on Marine Litter	2022	Strategic Objective 4: Prevent inputs of and significantly reduce marine litter, including microplastics, to reach levels that do not cause adverse effects to the marine and coastal environment with the ultimate aim of eliminating inputs of litter.
	Vlaamse overheid	Vlaams actieplan voor marien zwerfvuil		By 2025, the influx of litter from Flanders into the marine environment will have been reduced by 75%".
Human health and Food safety				
Europe	EU	Regulation (EU) 10/2011 regarding materials intended to come into contact with food	2011	This Regulation is a specific measure within the meaning of Article 5(1) of Regulation (EC) No 1935/2004. This Regulation should establish the specific rules for plastic materials and articles to be applied for their safe use and repeal Commission Directive 2002/72/EC of 6 August 2002 on plastic materials and articles intended to come into contact with foodstuffs.
				This Regulation shall apply to materials and articles which are placed on the EU market and fall under the following categories: (a) materials and articles and parts thereof consisting exclusively of plastics; (b) plastic multi-layer materials and articles held together by adhesives or by other means; (c) materials and articles referred to in points a) or b) that are printed and/or covered by a coating; (d) plastic layers or plastic coatings, forming gaskets in caps and closures, that together with those caps and closures compose a set of two or more layers of different types of materials; (e) plastic layers in multi-material multi-layer materials and articles. Plastic materials and articles shall not transfer their constituents to food simulants in quantities exceeding 10 milligrams of total constituents released per dm2 of food contact surface (mg/dm2). 2. By derogation from paragraph 1, plastic materials and articles intended to be brought into contact with food intended for infants and young children, as defined by Commission Directives 2006/141/EC (1) OJ L 401, 30.12.2006, p. 1. and 2006/125/EC (2) OJ L 339, 6.12.2006, p. 16., shall not transfer their constituents to food simulants in quantities exceeding 60 milligrams of total of constituents released per kg of food simulant.
	EU	REACH Regulation (EC) No 1907/2006	2006	The purpose of this Regulation is to ensure a high level of protection of human health and the environment, including the promotion of alternative methods for assessment of hazards of substances, as

	Competent authority	Document name	Year	Targets
				well as the free circulation of substances on the internal market while enhancing competitiveness and innovation.
				Article 6.3: Any manufacturer or importer of a polymer shall submit a registration to the Agency for the monomer substance(s) or any other substance(s), that have not already been registered by an actor up the supply chain, if both the following conditions are met: (a) the polymer consists of 2 % weight by weight (w/w) or more of such monomer substance(s) or other substance(s) in the form of monomeric units and chemically bound substance(s); (b) the total quantity of such monomer substance(s) or other substance(s) makes up 1 tonne or more per year.
				Restrictions for use of phtalates (DEHP, DBP BBP) in materials in concentration > 0.1 %
	DG ENV	Directive 2020/2184 on the quality of water intended for human consumption	2020	By 12 January 2024, the Commission shall adopt delegated acts in order to supplement this Directive by adopting a methodology to measure microplastics with a view to including them on the watch list
				The Commission shall, no later than 12 January 2029, submit a report to the EP and EC on the potential threat to sources of water intended for human consumption from microplastics
	EU	Drinking water directive	2020	Directive 98/83/EC set the legal framework to protect human health from the adverse effects of any contamination of water intended for human consumption by ensuring that it is wholesome and clean. This Directive should pursue the same objective and should improve access to such water for all in the Union.
Europe	EU	Drinking water directive	2020	In order to address growing public concern about the effects of emerging compounds, such as endocrine-disrupting compounds, pharmaceuticals and microplastics, on human health through use of water intended for human consumption, and to address new emerging compounds in the supply chain, a watch list mechanism should be introduced in this Directive.
				Member States should pay particular attention in their risk assessment to microplastics and endocrine-disrupting compounds, such as Nonylphenol and Beta-estradiol, and should, where necessary, require water suppliers to also monitor and, where necessary, carry out treatment for those and other parameters included in the watch list if considered a potential danger to human health.
				The purpose of better consumer knowledge of relevant information and improved transparency should be to increase citizens' confidence in the water supplied to them, as well as in water services, and should lead to an increased use of tap water as drinking water, which could contribute to reduced plastic usage and litter and greenhouse gas emissions, and a positive impact on climate change mitigation and the environment as a whole.
				6. By 12 January 2024, the Commission shall adopt delegated acts in accordance with Article 21 in order to supplement this Directive by adopting a methodology to measure microplastics with a view to including them on the watch list referred to in paragraph 8 of this Article once the conditions set out under that paragraph are fulfilled.

	Competent authority	Document name	Year	Targets
	DG ENV	COM (2021) 400 -Pathway to a Healthy Planet for All EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil	2021	As from January 2023, the revised Drinking Water Directive (EU) 2020/2184 will provide higher human health protection thanks to more stringent water quality standards, tackling pollutants of concern, such as endocrine disruptors and microplastics
Plastic life cycle and economy				
Global	G7	Ocean plastic Charter	2018	We, the Leaders of Canada, France, Germany, Italy, the United Kingdom, and the European Union, commit to move toward a more resource-efficient and sustainable approach to the management of plastics. We will work to mobilize and support collaborative government, industry, academia, citizen, and youth-led initiatives. We also recognize the need for action in line with previous G7 commitments and the 2030 Agenda, which sets a global framework for sustainable development
Global	UNEP	Basel Convention on control of transboundary movements of hazardous wastes and their disposal (Amendment to Annex I and III)	2019	In 2019, the fourteenth meeting of the Conference of the Parties adopted further amendments to Annexes II, VIII and IX to the Convention by amending or inserting entries on plastic waste. The entries in the Plastic Waste Amendments to Annexes II, VIII and IX to the Convention become effective as of 1 January 2021.
Europe	EU	Single Use Plastics Directive (EU) No 2019/904	2019	The objectives of this Directive are to prevent and reduce the impact of certain plastic products on the environment, in particular the aquatic environment, and on human health, as well as to promote the transition to a circular economy with innovative and sustainable business models, products and materials, thus also contributing to the efficient functioning of the internal market. This Directive applies to the single-use plastic products listed in the Annex, to products made from oxo-degradable plastic and to fishing gear containing plastic
Europe	EU	Waste Framework directive	2008	This Directive lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use.
Europe				Member States shall take measures, as appropriate, to promote the re-use of products and preparing for re-use activities, notably by encouraging the establishment and support of re-use and repair networks, the use of economic instruments, procurement criteria, quantitative objectives, or other measures. Subject to Article 10(2), by 2015 separate collection shall be set up for at least the following: paper, metal, plastic, and glass.

	Competent authority	Document name	Year	Targets
Europe	EU	Waste Framework directive	2008	In order to comply with the objectives of this Directive, level of resource efficiency, Member States shall take the necessary measures designed to achieve the following targets: (a) by 2020, the preparing for re-use and the recycling of waste materials such as at least paper, metal, plastic and glass from households and possibly from other origins as far as these waste streams are similar to waste from households, shall be increased to a minimum of overall 50 % by weight; (b) by 2020, the preparing for re-use, recycling and other material recovery, including backfilling operations using waste to substitute other materials, of non-hazardous construction and demolition waste excluding naturally occurring material defined in category 17 05 04 in the list of waste shall be increased to a minimum of 70 % by weight.
Europe	DG ENV	COM (2018) 28 A European Strategy for Plastics in a Circular Economy	2018	By 2030, all plastics packaging placed on the EU market is either reusable or can be recycled in a cost-effective manner.
Europe				Actions to monitor and curb marine litter more effectively: Improve monitoring and mapping of marine litter, including microplastics, on the basis of EU harmonised methods from 2018 onwards
Europe				Action to curb microplastics pollution: Start the process to restrict the intentional addition of microplastics to products via REACH (ongoing)
Europe				Action to curb microplastics pollution: Examination of policy options for reducing unintentional release of microplastics from tyres, textiles and paint [e.g. including minimum requirements for tyre design (tyre abrasion and durability if appropriate) and/or information requirement (including labelling if appropriate), methods to assess microplastic losses from textiles and tyres, combined with information (including possibly labelling)/minimum requirements, targeted research and development funding] (ongoing)
Europe				Action to curb microplastics pollution: Development of measures to reduce plastic pellet spillage (e.g. certification scheme along the plastic supply chain and/or Best Available Techniques reference document under the Industrial Emissions Directive) (Q1 2018 onwards)
Europe	EU	Bioeconomy Strategy	2018	The European bioeconomy is one of the EU's largest and most important sectors encompassing agriculture, forestry, fisheries, food, bioenergy, and bio-based products with an annual turnover of around 2 trillion euro and employing around 18 million people. The bioeconomy contributes to the UN Sustainable Development Goals and to the EU target of restoring at least 15% of degraded ecosystems by 2020. Example: up to 12 million ton of plastic are dumped in our oceans every year, but with the help of bioeconomy this amount can be reduced by 90% by 2025.
Europe				A renewed and strengthened EU industrial base and modernised primary production. Deploying the bioeconomy across Europe with bio-based innovation will modernise agriculture, aquaculture, fisheries, and forestry, and will renew industries. Example: Avoiding food waste can save up to €143 billion annually. Agri-food waste can be turned into biodegradable plastic for food packaging.

	Competent authority	Document name	Year	Targets
	DG ENV	Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment	2019	Microplastics do not fall directly within the scope of this Directive, yet they contribute to marine litter and the Union should therefore adopt a comprehensive approach to that problem. The Union should encourage all producers to strictly limit microplastics in their formulations.
	DG ENV	COM (2020) 98 Circular Economy Action Plan	2020	In addition to measures to reduce plastic litter, the Commission will address the presence of microplastics in the environment by: Restricting intentionally added microplastics and tackling pellets taking into account the opinion of the European Chemicals Agency.
Europe	DG ENV	COM (2020) 98 Circular Economy Action Plan	2020	In addition to measures to reduce plastic litter, the Commission will address the presence of microplastics in the environment by: Developing labelling, standardisation, certification, and regulatory measures on unintentional release of microplastics, including measures to increase the capture of microplastics at all relevant stages of products' lifecycle.
				In addition to measures to reduce plastic litter, the Commission will address the presence of microplastics in the environment by: Further developing and harmonising methods for measuring unintentionally released microplastics, especially from tyres and textiles, and delivering harmonised data on microplastics concentrations in seawater.
				In addition to measures to reduce plastic litter, the Commission will address the presence of microplastics in the environment by: Closing the gaps on scientific knowledge related to the risk and occurrence of microplastics in the environment, drinking water and foods.
				Key actions: Restriction of intentionally added microplastics and measures on unintentional release of microplastics by 2021
	EU	Chemicals strategy for sustainability	2020	In line with the European Green Deal, the strategy strives for a toxic-free environment, where chemicals are produced and used in a way that maximises their contribution to society including achieving the green and digital transition, while avoiding harm to the planet and to current and future generations. It envisages the EU industry as a globally competitive player in the production and use of safe and sustainable chemicals.
				The Comission will support investments in sustainable innovations that can decontaminate waste streams, increase safe recycling, and reduce the export of waste, in particular plastics and textiles.
	DG MARE	COM (2021) 240 on a new approach for a sustainable blue economy in EU. Transforming the EU's Blue Economy for a Sustainable Future	2021	The Commission will take action to restrict intentionally added micro-plastics and develop labelling, standardisation, certification, and regulatory measures on the unintentional release of micro-plastics, including measures to increase the capture of micro-plastics at all stages of the product lifecycle

	Competent authority	Document name	Year	Targets
	DG ENV	COM (2022) 141 from the EC on: EU Strategy for Sustainable and Circular Textiles	2022	The Commission plans to address the different lifecycle stages at which synthetic fibres are shed into the environment by a set of prevention and reduction measures, notably through binding design requirements to be introduced under the Ecodesign for Sustainable Products Regulation, as well as under the forthcoming Commission initiative to address the unintentional release of microplastics in the environment, to be presented in the second half of 2022.
Regional	Belgium	Sectoraal akkoord van 9 januari 2018 ter ondersteuning van het vervangen van microplastics in consumptieproducten	2019	Vervanging van “plastic microbolletjes” in cosmetische producten die worden af-, uit- of weggespoeld en mondverzorgingsproducten
	Belgium	Koninklijk besluit betreffende producten voor eenmalig gebruik en ter bevordering van herbruikbare producten	2022	

Supplementary file 2: Overview on measured microplastic concentration in freshwater systems (Table S2.1), marine environment (Table S2.2) and in the atmosphere (Table S2.3).

Table S2.1: Overview of the current literature on microplastic (MP) concentrations in freshwater systems

	Location	River/lake	Minimum MP concentration (MP/L)	Max. MP concentration (MP/L)	Mean MP concentration (MP/L)	Reference
Europe	Hungary	Several rivers	0.0035	0.032	0.014	(Bordós et al., 2019)
	Amsterdam, The Netherlands		0.048	0.19	0.10	(Leslie et al., 2017)
	Kalavesie, Finland	Lake Kelavesie	NA	0.25	0.17	(Uurasjärvi et al., 2020)
	United Kingdom	Trent, Leen and Soar	0.019	0.083		(Stanton et al., 2020)
	Flanders, Belgium	Several rivers	0	1.11	0.48	(Semmouri et al., 2023)
	Wuhan, China	Wuhan lake	1.7	8.9		(Q. Wang et al., 2017)
	Pearl river, China	Pearl river	0.38	7.9		(Lin et al., 2018)
	Danjiangkou, China	Danjiangkou reservoir	0.015	0.47		(Di et al., 2019)
	Suzhou en Huangpu river, China	Suzhou en Huangpu River	1.8	2.4		(W. Luo et al., 2019)
	Taihu lake, China	Taihu lake	0.5	3.1		(L. Su et al., 2018)
	Guangxi, China	Lijiang river	0.00013	0.0015	0.00067	(L. Zhang et al., 2021)
Australia	Victoria, Australia	Victoria river	0.11	0.72	0.40	(Nan et al., 2020)
Antarctica	Byers Peninsula, Antarctica	Byers Peninsula	0.00000047	0.0000015	0.00000095	(González-Pleiter et al., 2020)

America	Gallatin, USA	Gallatin River Watershed	0	67.5	1.2	(Barrows et al., 2018)

Table S2.2: Occurrence of microplastics (MP) in the marine environment (Adapted from Wang et al., 2021)

	Location/Region	Sample type	Concentration	Unit	Reference
Asia	Yellow sea, China	Seawater	0.117-0.506	MP/m³	(T. Wang et al., 2018)
	Bohai Sea, China	Seawater	0.33	MP/m³	(W. Zhang et al., 2017)
	Yangtze Estuary System, China	Seawater	0.167	MP/m³	(Zhao et al., 2014)
	Beibu Gulf, China	Sediment	5020-8720	MP/kg	(Qiu et al., 2015)
	Mangrove habitats, Singapore	Sediment	12-62.7	MP/kg	(Mohamed Nor & Obbard, 2014)
	Coastal beaches, India	Sediment	45-220	MP/kg	(Tiwari et al., 2019)
Europe	France, Belgium, The Netherlands	Seawater	400	MP/m³	(Van Cauwenberghe et al., 2015)
		Sediment	6	MP/kg	(Van Cauwenberghe et al., 2015)
	Gulf of Lion, Mediterranean Sea	Seawater	6000-1000000	MP/km²	(Schmidt et al., 2018)
Africa	Southeastern Coastline, South Africa	Seawater	275.9-1215	MP/m³	(Nel & Froneman, 2015)
		Sediment	688.9-3308	MP/m²	(Nel & Froneman, 2015)
North America	Northeastern Pacific Ocean	Seawater	8-9200	MP/m³	(Desforges et al., 2014)
	Halifax harbor, Canada	Sediment	2000-8000	MP/kg	(Mathalon & Hill, 2014)
	East coast of Vancouver Island, Canada	Seawater	659.9	MP/m³	(Collicutt et al., 2019)
South America	Goiana Estuary, Brazil	Seawater	0.26	MP/m³	(Lima et al., 2014)
	Guanabara Bay, Brazil	Seawater	1.4-21.3	MP/m³	(Olivatto et al., 2019)
	Kingston Harbour, Jamaica	Seawater	0-5.73	MP/m³	(Rose & Webber, 2019)
Oceania	Sea ports in Australia	Sediment	83-350	MP/kg	(Jahan et al., 2019)
	Beach, New Zealand	Sediment	459	MP/m³	(Bridson et al., 2020)

Others	Atlantic Ocean	Seawater	1.15	MP/m³	(Kanhai et al., 2017)
	Arctic Ocean	Seawater	0-7.5	MP/m³	(Kanhai et al., 2017)
	Black Sea	Seawater	600-1200	MP/m³	(Aytan et al., 2016)

Table S2.3: Occurrence of microplastics (MP) in the atmosphere.

	Year	Country	Specific location	Origin	Concentration MP	Author
Atmospheric concentrations	2019	Arctic	Arctic snow	Outdoor	0-14.4 MP/m³	(Bergmann et al., 2019)
	2019	China	Shanghai	Outdoor	0-4.18 MP/m³	(K. Liu, Wang, et al., 2019)
	2019		West Pacific Ocean	Outdoor	0-1.37MP/m³	(K. Liu, Wu, et al., 2019)
	2019	Iran	Asaluyeh	Outdoor	0.3-1.1MP/m³	(Abbasi et al., 2019)
	2021	Spain	Urban environment	Outdoor	13.9MP/m³	(González-Pleiter et al., 2020)
	2021	Spain	Rural environment	Outdoor	1.5MP/m³	(González-Pleiter et al., 2020)
	2017	France		Indoor	1.64-4.8MP/m³	(Dris et al., 2017)
	2018	Turkey		Outdoor	1.64-4.9MP/m³	(Tunahan Kaya et al., 2018)
	2018	Turkey		Bus terminal	1.64-4.10MP/m³	(Tunahan Kaya et al., 2018)
Atmospheric deposition	2016	France		Outdoor	2-355 MP/m²/day	(Dris et al., 2015)
	2017	China	Dongguan	Outdoor	175-313MP/m²/day	(Cai et al., 2017)
	2017	China	Yantai	Outdoor	max. 602MP/m²/day	(Q. Zhou et al., 2017)
	2019	Germany		Outdoor	137-512MP/m²/day	(M. Klein & Fischer, 2019)
	2019		Pyrenees	Outdoor	365 MP/m²/day	(Allen et al., 2019)
	2020	England	London	Outdoor	575-1008 MP/m²/day	(S. L. Wright et al., 2021)

Supplementary file 3: Overview of reported concentrations of microplastics in food and beverages: Salt (Table S3.1) and drinking water (Table S3.2)

Table S3.1: Overview of reported microplastic (MP) concentration in table salt.

	Country	Year	Origin	Concentration (MP / kg)	Reference
Africa	Cameroun	2021	Not reported	0-0.33	(Fadare et al., 2021)
	Ghana	2021	Not reported	0-0.33	(Fadare et al., 2021)
	Kenya	2021	Not reported	0	(Fadare et al., 2021)
	Malawi	2021	Not reported	0	(Fadare et al., 2021)
	Nigeria	2021	Not reported	0-0.33	(Fadare et al., 2021)
	South Africa	2021	Not reported	0-1.33	(Fadare et al., 2021)
	South Africa	2017	Sea salt	4	(Karami et al., 2017)
	Uganda	2021	Not reported	0	(Fadare et al., 2021)
	Zimbabwe	2021	Not reported	0	(Fadare et al., 2021)
Asia	China	2015	Lake salt	43-364	(D. Yang et al., 2015)
	China	2018	Lake salt	28	(Kim et al., 2018)
	China	2015	Rock salt	7-204	(D. Yang et al., 2015)
	China	2018	Rock salt	0-14	(Kim et al., 2018)
	China	2015	Sea salt	550-681	(D. Yang et al., 2015)
	China	2018	Sea salt	120-718	(Kim et al., 2018)
	China	2018	Sea salt	0-1674	(Kim et al., 2018)
	China, Taiwan	2019	Not reported	9.77	(H. Lee et al., 2019)
	India	2021	Sea salt	230-575 **	(Vidyasakar et al., 2021)
	India	2018	Sea Salt	56-103	(Seth & Shriwastav, 2018)
	India	2018	Sea salt	32-366	(Kim et al., 2018)
	India	2020	Sea salt	35-72	(Sathish et al., 2020)

	India	2020	Well salt	2-19	(Sathish et al., 2020)
	India	2020	Rock salt	200-400	(Yaranal et al., 2021)
	India	2020	Sea salt	1400-1900	(Yaranal et al., 2021)
	India	2021	Sea salt	467-1633 **	(Nithin et al., 2021)
	India	2021	Sea salt	115-505 **	(Vidyasakar et al., 2021)
	Indonesia	2018	Sea salt	13629	(Kim et al., 2018)
	Iran	2017	Lake salt	1	(Karami et al., 2017)
	Japan	2017	Sea salt	1	(Karami et al., 2017)
	Korea	2018	sea salt	98-232	(Kim et al., 2018)
	Malaysia	2017	Sea salt	0-2	(Karami et al., 2017)
	Sri Lanka	2022	Rock salt	64	(Kapukotuwa et al., 2022)
	Sri Lanka	2022	Sea salt	11-193	(Kapukotuwa et al., 2022)
	Thailand	2018	Sea salt	70-402	(Kim et al., 2018)
	Turkey	2018	Lake salt	8-102	(Gündoğdu, 2018)
	Turkey	2018	Rock salt	6-19	(Gündoğdu, 2018)
	Turkey	2018	Sea salt	16-84	(Gündoğdu, 2018)
	Vietnam	2018	Sea salt	76-88	(Kim et al., 2018)
Australia	Australia	2017	Sea salt	0-9	(Karami et al., 2017)
	Australia	2018	Sea salt	46	(Kim et al., 2018)
	New Zealand	2017	Not reported	1	(Karami et al., 2017)
Europe	Belgium	2017	Sea salt	0-805	(L. Devriese et al., 2017)
	Bulgaria	2018	Sea salt	12	(Kim et al., 2018)
	Croatia	2018	Sea Salt	13900-19800 (>500μm) *	(Renzi & Blašković, 2018)
	Croatia	2019	Sea salt	0.07-0.20	(Renzi, Grazioli, et al., 2019)
	Croatia	2018	Sea salt	58	(Kim et al., 2018)
	France	2017	Sea salt	0-2	(Karami et al., 2017)
	France	2018	Sea salt	0	(Kim et al., 2018)
	Italy	2018	Rock salt	80	(Kim et al., 2018)
	Italy	2018	Sea Salt	22-594 (>500μm)*	(Renzi & Blašković, 2018)
	Italy	2018	Sea salt	4-30	(Kim et al., 2018)

	Italy	2019	Sea salt	0.17-0.32	(Renzi, Grazioli, et al., 2019)
	Portugal	2017	Sea salt	0-10	(Karami et al., 2017)
	Spain	2017	Sea salt	50-280	(Iñiguez et al., 2017)
	Spain	2017	Well salt	115-185	(Iñiguez et al., 2017)
	UK	2018	Sea salt	136	(Kim et al., 2018)
North America	US	2018	Rock salt	5	(Kim et al., 2018)
	US	2018	Sea salt	32	(Kim et al., 2018)
South America	Brazil	2018	Sea salt	24	(Kim et al., 2018)
	Senegal	2018	Lake salt	462	(Kim et al., 2018)
	Senegal	2018	Sea salt	48	(Kim et al., 2018)
Global		2018	Sea salt	46.7-806	(Kosuth et al., 2018)

**The authors indicated possible overestimation due to analytical methods, therefore the data of particles > 500 µm is provided here*

*** recalculated from originally reported concentrations*

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Table S3.2: Overview of reported microplastic (MP) concentration in drinking water.

	Country	Source (Tap/bottled)	Detailed info	MP/L (average)	Lower size bound (µm)	Reference
Africa	Uganda	Tap	NA	3.92	100	(Kosuth et al., 2018)
Asia	China	Tap	DWTP – raw water	6614 ± 1132	1	(Z. Wang et al., 2020)
	China	Tap	DWTP – treated water	930 ± 72	1	(Z. Wang et al., 2020)
	China	Tap	NA	0.7 ± 0.6 (0.3–1.6)	10	(M. Zhang et al., 2020)
	China	Tap	NA	343.5	1	(Shen et al., 2020)
	China	Tap	NA	13.23	NA	(Chu et al., 2022)
	China	Tap	NA	440 +- 275	1	(Tong et al., 2020)
	China	Tap	NA	0.64 +-0.46	10	(M. Zhang et al., 2020)
	India	Tap	NA	6.24	100	(Kosuth et al., 2018)
	Indonesia	Tap	NA	3.23	100	(Kosuth et al., 2018)
	Korea	Bottled	NA	6–58	15	(E.-H. Lee et al., 2021)
	Lebanon	Tap	NA	6.64	100	(Kosuth et al., 2018)
	Saudi Arabia	Tap and bottled	NA	2.1 ± 5.0 (0.99–26)	25	(Almaiman et al., 2021)
	Thailand	Bottled	Glass bottle	26.0 ± 2.0	6.5	(Kankanige & Babel, 2020)
	Thailand	Bottled	Glass bottle	12.0 ± 1.0	6.5	(Kankanige & Babel, 2020)
	Thailand	Bottled	Reusable bottle	118 ± 88	6.5	(Kankanige & Babel, 2020)
	Thailand	Bottled	Reusable bottle	14 ± 14	6.5	(Kankanige & Babel, 2020)
	Thailand	Bottled	Reusable bottle	50 ± 52	6.5	(Kankanige & Babel, 2020)
	Thailand	Bottled	Single-use plastic bottle	81.0 ± 3.0	6.5	(Kankanige & Babel, 2020)
	Thailand	Tap	NA	0.6 (range,0.24–1.00)	50	(Chanpiwat & Damrongsiri, 2021)
Australia	Australia	Tap	Tap from groundwater sources	38 ± 8 (16-97)	NA	(Samandra et al., 2022)
Eu	Belgium	Tap	DWTP - Groundwater	0	25	(Semmouri et al., 2022)

	Belgium	Tap	DWTP – Surface water	0.02	25	(Semmouri et al., 2022)
	Belgium	Tap	DWTP	0.05	25	(Semmouri et al., 2022)
Europe	Belgium	Tap	NA	0.01 + -0.02	25	(Semmouri et al., 2022)
	Czech Republic	Tap	DWTP – raw and treated water	628	1	(Pivokonsky et al., 2018)
	Czech Republic	Tap	DWTP – raw and treated water	338	1	(Pivokonsky et al., 2018)
	Czech Republic	Tap	DWTP – raw and treated water	369	1	(Pivokonsky et al., 2018)
	Denmark	Tap	Tap from groundwater sources	0.2	100	(Strand et al., 2018)
	Denmark	Tap	Tap	0.8	100	(Strand et al., 2018)
	Denmark	Tap	Tap	0	100	(Strand et al., 2018)
	Denmark	Tap	Tap from groundwater sources	0.312	100	(Strand et al., 2018)
	Denmark	Tap	NA	<LOD	100	(Strand et al., 2018)
	England	Tap	DWTP – raw water	4.9	25	(Ball et al., 2019)
	England	Tap	DWTP – treated water	0.0011	25	(Ball et al., 2019)
	England	Tap	NA	7.73	100	(Kosuth et al., 2018)
	France	Tap	NA	1.82	100	(Kosuth et al., 2018)
	Germany	Bottled	Beverage carton	11	20	(Schymanski et al., 2018)
	Germany	Bottled	Glass bottle	3074–6292	1	(Oßmann et al., 2018)
	Germany	Bottled	Glass bottle	50	20	(Schymanski et al., 2018)
	Germany	Bottled	Reusable bottle	4889	1	(Oßmann et al., 2018)
	Germany	Bottled	Single-use plastic bottle	2649	1	(Oßmann et al., 2018)
	Germany	Bottled	Reusable bottle	118	20	(Schymanski et al., 2018)
	Germany	Bottled	Single-use plastic bottle	14	20	(Schymanski et al., 2018)
	Germany	Tap	Tap from groundwater sources	0.0007	20	(Mintenig et al., 2019)
	Germany	Tap	NA	0.91	100	(Kosuth et al., 2018)
	Germany	Tap	NA	<LOD	10	(Weber et al., 2021)
	Iceland	Tap	DWTP - Groundwater	0.12	27	(McQuilkin et al., 2020)
	Iceland	Tap	DWTP – Surface water	0.22	27	(McQuilkin et al., 2020)
	Ireland	Tap	NA	1.83	100	(Kosuth et al., 2018)

	Italy	Bottled	NA	5.42 x 10^7	0.5	(Zuccarello et al., 2019)
	Italy	Bottled	NA	148 ± 253	3	(Winkler et al., 2019)
	Italy	Tap	NA	0	100	(Kosuth et al., 2018)
Europe	Norway	Tap	DWTP - Groundwater	<LOQ	60	(Uhl et al., 2018)
	Norway	Tap	DWTP – Surface water	<LOQ	60	(Uhl et al., 2018)
	Norway	Tap	NA	<LOQ	60	(Uhl et al., 2018)
	Slovakia	Tap	NA	3.83	2.5	(Kosuth et al., 2018)
	Sweden	Tap	DWTP – Surface water	0.174	6.6	(Kirstein et al., 2021)
	Switzerland	Tap	NA	2.74	100	(Kosuth et al., 2018)
South-America	Ecuador	Tap	NA	4.02	100	(Kosuth et al., 2018)
North America	Cuba	Tap	NA	7.17	100	(Kosuth et al., 2018)
	Mexico	Tap	NA	18 +- 7	500	(Shruti, Pérez-Guevara, & Kutralam-Muniasamy, 2020)
	USA	Tap	Tap water from groundwater wells	2.8	NA	(Panno et al., 2019)
	USA	Tap	NA	9.24	100	(Kosuth et al., 2018)
Global		Bottled	NA	315	100	(Mason et al., 2018)
		Bottled	NA	10.4	100	(Mason et al., 2018)
		Tap	NA	39 ± 44 (1.9–225)	NA	(Mukotaka et al., 2021)

Supplementary file 4: Microplastics in daily-use product

Besides their use in personal care products, microplastics are also intentionally added to various other daily-use products such as detergents, maintenance products, medicinal products for both human and veterinary use, food complements, paints, and adhesives (non-exhaustive list) (ECHA, 2019). The use of microplastics in these products is provided in Table S4.1. Not much information is available on the concentrations of intentionally added microplastics in these products.

Table S4.1: Overview of uses of microplastic in daily-use products (excluding cosmetic products) (ECHA)

Product group	Brief details of use and technical function(s)
Detergents and maintenance products	Microplastics are used in detergents and maintenance products to provide a range of functions, including as abrasives, fragrance encapsulations, pacifying agents, and anti-foam agents. They can be used in surface cleaning products, fabric softeners, dishwashing liquids, waxes, and polishes.
Agricultural and horticulture	Microplastics are used in controlled-release formulations (CRF) for fertilisers and plant protection products (typically as microencapsulation), as fertiliser additives (e.g. anti-caking agents) and as soil conditioners. Similar to microencapsulation, seed coating involves the deposition of polymeric material on seeds such that coated seeds may be considered microplastic particles as they fall below the upper size limit of 5 mm.
Medical devices and in vitro diagnostic medical devices	Microplastics have various functions in medical devices (MD) and in vitro diagnostic medical devices (IVD MD). Microplastics in medical devices are used as polymeric filters, adsorber and absorber granulates and in ultrasound devices. Microplastics, often with inorganic (e.g. iron oxide) cores and chemically functionalised surfaces, are ubiquitous as reagents in IVD medical devices and are essential in all automated IVD tests conducted worldwide. Microplastics are also frequently used in the manufacturing of IVD reagents and devices (e.g. chromatography columns used to purify antibodies).
Medicinal products for human and veterinary use	In medicinal products, microplastics are the backbone of many ‘controlled-release’ medicines: in contrast to immediate release, these formulations can deliver drugs with a delay after its administration (delayed release), or for a prolonged period of time (extended release), or to a specific target organ in the body (targeted release dosage). Controlled-release mechanisms allow to protect the active substance from the physiological environment (e.g. enzymes, pH), to control its release at a specific predetermined rate in specific location/organ. In addition, microplastics can be used for their taste masking function. In medicinal products, microplastics are often classified as excipients, but they can also be authorised as an active pharmaceutical ingredient (API).
Food complement and medical food	Similarly, to the medicinal products use, microplastics are used in the formulation of food complements (e.g. vitamins) as ‘controlled-release’ agent, and to hide unpleasant taste.
Paints, inks and other coatings	Microplastics are an integral part of polymer dispersion binders in water-based paints and coatings, where they are present to coalescence into films (film-forming function). Microplastics are also used as speciality additives in architectural and industrial coatings (wood, plastic, metal). Microplastic additives enhance properties like matting, abrasion resistance, scratch resistance, mark resistance and side sheen control. In addition, they are used to add texture and structure to surfaces. Microplastics are also used in combination with metallic pigments to achieve a sparkle effect by controlling pigment orientation. They are also used in antifouling paints.
Oil and gas	Microplastics are used as additives in drilling and production chemicals (lubricants, friction reducing agents, antifoam agents, demulsifiers).
Plastics	Microplastics are used as speciality additives in thermoplastic masterbatches and engineered materials as light diffusion agents, anti ‘blocking’ agents and to introduce surface structure. Pre-production plastic (resin) pellets (also called ‘nurdles’) that are used as raw materials in extrusion / moulding processes in article production, by nature of their size, are also microplastics.

Technical ceramics	Microplastics are used as a pore forming additive to achieve the correct size and number of pores in porous ceramics. According to industry stakeholders these materials are combusted as part of the production process.
Media for abrasive blasting	Plastic granules are used to remove difficult contaminants e.g. paint, plastics, rubber and adhesive from plastic tools and dies etc. The underlying surface is normally not affected by the blasting as the different plastic materials are somewhat softer than those made of minerals or metal. The material of the granules vary depending on the wanted features; they may consist of poly methyl metacrylic polymer, melamine, urea formaldehyde, urea amino polymers or poly amino nylon type. The granulate size ranges from 0.15-2.5 mm and the relative density is > 1000 kg/m3, indicating they will not float.
Adhesives	The intentionally added microplastics can be used as a spacer in adhesives and metallic plated microplastic particles can be used in conductive adhesives in electronics.
3D printing	Polymeric materials are used in Fused Deposition Modelling (FDM) printers for consumers. These printers are smaller than industrial ones and can be bought by private consumers to print smaller objects.
Printing inks	The toner in laser printing is mostly made of granulated plastic to make the powder electrostatic.

In the above-mentioned uses, water-soluble polymers are also intensively used and do not fall under any current restriction or regulation. They are used for (Rozman & Kalčíková, 2021):

- Paints, coatings, fertilizers: as a dispersing agent - polyethylene oxide (PEO), polypropylene oxide (PPO) polyethylene glycol (PEG)
- Agriculture: conditioners for soil to prevent erosion - polyacrylamide (PAM)),
- Waste-water treatment: flocculants in the treatment process (PAM and polyethylene imide (PEI)
- Textile industry: surface modifications – PEG
- Pharmaceuticals: (polyvinylpyrrolidone (PVP) and PEO),

Pathway in the environment

Depending on the use of the product, the pathway into the environment can be variable between disposal via the waste water, via municipal waste or direct release into the environment (ECHA, 2019). The use of the product will determine the pathway and concentrations released in the environment. As an example, the acrylate or polyester particles used for abrasive blasting will most likely end up in the wastewater (Sundt et al., 2014). In comparison, only 1.5% of the microplastics in paints are assumed to be released down-the-drain at the point of use (ECHA, 2019).

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