

## Chapter 19

# Ecological and Public Health Effects of Microplastics Pollution



Maria Arias-Andres and Keilor Rojas-Jimenez

**Abstract** Humans and ecosystems are constantly exposed to microplastics (MP). The magnitude of contamination, their ubiquity, and high persistence over time raise serious concerns about their effects on ecosystems, wildlife, and human health. MP represent a diverse class of contaminants occurring on a continuum of sizes and in various shapes and presenting a complex composition that includes several types of polymers and several associated pollutants. In short, MP are perhaps one of the most challenging contaminants created by humankind. The effects of exposure to these pollutants are of growing concern even though the type and level of exposure and the specific risks for humans and ecosystem health have not yet been entirely determined. In this chapter, we identify critical qualitative and quantitative aspects of MP sources and exposure routes and toxicity profiles and confront them with research on MP effects and estimations of risks to human and environmental health. Finally, we highlight that some novel sources of MP contamination pose a serious risk of exposure to humans and ecosystems, such as nanoplastics and the recycled plastics incorporated into road pavements and construction.

**Keywords** Microplastics · Nanoplastics · Ingestion pathways · Exposure · Health risks · Ecological risks

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M. Arias-Andres  
Instituto Regional de Estudios en Sustancias Tóxicas (IRET), Universidad Nacional,  
Heredia, Costa Rica

K. Rojas-Jimenez (✉)  
Escuela de Biología, Universidad de Costa Rica, San Jose, Costa Rica

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## 19.1 Sources of MP Pollutants

Plastic is a material that has provided enormous benefits to modern societies. However, a substantial proportion of the plastic produced each year is improperly disposed into the environment, constituting an unprecedented pollution problem for humanity. The bulk estimate of plastic materials produced annually worldwide today is in the order of millions of tons, and it is projected to increase to the order of billions of tons by 2050 (Mbachu et al. 2020). The availability of different plastic polymer types results in a wide variety of applications, and therefore sources of MP to the environment (Jakubowska et al. 2020). The immense amount of plastic polymers produced since the 1950s, coupled with their long persistence in environmental compartments, has elicited the concept that we live in the “Plasticene” era (Haram et al. 2020).

In the environment, plastic objects such as car tires, textiles, bottles, and bags are degraded by abrasion and by the photo-oxidation of ultraviolet radiation, generating smaller fragments. If the size is less than 5 mm, they are called microplastics (Cozar et al. 2014). If it is less than 100 nm, they are called nanoplastics (Revel et al. 2018). Understanding the different MP sources is essential in prioritizing their characteristics during exposure and effects assessments and estimating toxicity risks from the data.

One of the first and more straightforward categorizations for MP regarding their source is that of “primary” or “secondary.” The first category refers mainly to those particles purposely manufactured in sizes of a few mm, and most commonly composed of polyethylene (PE), polypropylene (PP), and polystyrene (PS) (Padervand et al. 2020). The “secondary” particles often refer to those produced after fragmentation or degradation of larger plastic during their life cycle or afterward, and where other materials such as polyester, acrylic, and polyamide become relevant (Padervand et al. 2020; Adam et al. 2021).

The public has mainly associated sources of primary MP with personal care products such as toothpaste (Ustabasi and Baysal 2019), but they also form part of decorative glitters, abrasive cleaners, or industrial pellets (Yurtsever 2019). In some literature, it is noteworthy that they also include fabric fibers or tire particles released by abrasion of the materials in washing machines and roads, respectively (Waldman and Rillig 2020). Broad estimates for primary MP in the ocean are close to 30% (Adam et al. 2021). Intentional production of MP still occurs in many places, even when regions such as the European Union, the United States, Canada, New Zealand, and the United Kingdom, among others, have passed or proposed legislation banning the manufacture and sale of specific products containing microbeads (Mitrano and Wohlleben 2020). Likewise, nanoplastics are increasingly common in industrial products such as paints, adhesives, drugs, electronics, and new 3D printing technologies (Stephens et al. 2013; Koelmans et al. 2015; Lambert and Wagner 2016).

Point sources of MP to aquatic and terrestrial environments include WWTP effluents and sludges, domestic (e.g., fibers from the laundry), urban (e.g., rainwater drainages carrying litter), and industrial drainages, while others may be described as more diffuse sources such as agricultural runoff or landfills (Karbalaei et al. 2018;

Iyare et al. 2020; Sang et al. 2021). Among these diffuse sources, tires and roadways are recognized as a constant source of MP from land to freshwaters and eventually to oceans, the ultimate destiny (Siegfried et al. 2017). Plastic pollution in the oceans resulting from activities carried out at sea, such as the remains of fishing nets, represents a significant problem; however, it is much less than the volume of contamination produced by activities carried out on land (Xu et al. 2020; Wang et al. 2021).

Other novel sources of MP pollution that could be relevant for human and ecological exposure, which are until recently investigated, include the use of recycled plastic in pavement and construction (Wu and Montalvo 2021; Loria-Salazar and Gomez-Sandoval 2021; Conlon 2021).

## 19.2 Environmental Fate and Exposure to Humans and the Environment

Microplastics and nanoplastics (MNPs) represent a very diverse class of contaminants. They occur on a continuum of sizes and in a variety of shapes. Fibers are the most frequent form, followed by particles such as beads, foam, and irregular fragments (Browne et al. 2011). MNPs have a complex composition, including polymeric materials and mixtures of associated chemicals such as plasticizers and additives, increasing their polluting effect. The surfaces of MNPs are also colonized by microbial communities that form biofilms where the transfer of genes for resistance to antibiotics can occur (Arias-Andres et al. 2018, 2019).

Many methods are used to characterize MP (e.g., electron microscopy, X-rays, magnetic resonance, and chromatography coupled to mass spectrometry). However, RAMAN spectroscopy and FTIR (Fourier transform infrared spectroscopy) are among the better suited to identify polymers in environmental compartments (aquatic, terrestrial, air), biota, and food (Veerasingam et al. 2020). In general, polyethylene (PE) and polypropylene (PP) are among the most frequently found polymers in environmental samples (aquatic and terrestrial) identified by these techniques (Zhang et al. 2020c; Veerasingam et al. 2020). However, specific polymers can be relevant in certain exposure scenarios, such as polyethylene terephthalate (PET) on household dust and indoor environments (Zhang et al. 2020c).

Freshwater ecosystems differ widely in their MP concentrations according to distance and frequency of source input. However, estimates range from dozens to thousands of particles per L or m<sup>3</sup> of water, with higher concentrations found by using smaller mesh and pumps for collection (Rios Mendoza and Balcer 2019). Studies on MP exposure in groundwater are scarce, even though this environmental compartment is considered an important source of water for human consumption. However, their presence has been documented and associated with what happens on the surface (Selvam et al. 2021; Luo et al. 2021). Concentrations of MP on soil range in the mg/Kg concentrations, or from dozens to thousands of items/Kg of soil (Wang et al. 2020). Air is a much less studied compartment, but concentrations

range from a few to thousands of items per m<sup>3</sup> (Zhang et al. 2020a), and fibers seem the most relevant shape (Huang et al. 2020).

In the ocean, the final destination of a large proportion of MP, with concentrations of thousands of particles per m<sup>2</sup>, has been determined in high retention areas (Li et al. 2020). Studies on marine sediments are disproportionately from coastal areas of Europe and Asia, showing concentrations of MP in the range of dozens to thousands of particles per L or m<sup>2</sup> (Phuong et al. 2021). Still, scarce information is available from unique coastal ecosystems such as mangroves, which provide food for human populations and are crucial habitats for marine biodiversity protection and recovery (Deng et al. 2021). The fate of MP in biota (some consumed by humans) has been seen to vary according to size and shape, and in some cases, polymer type affects distribution among different biological groups (Pan et al. 2021a).

### ***19.2.1 Ingestion Pathways in Humans***

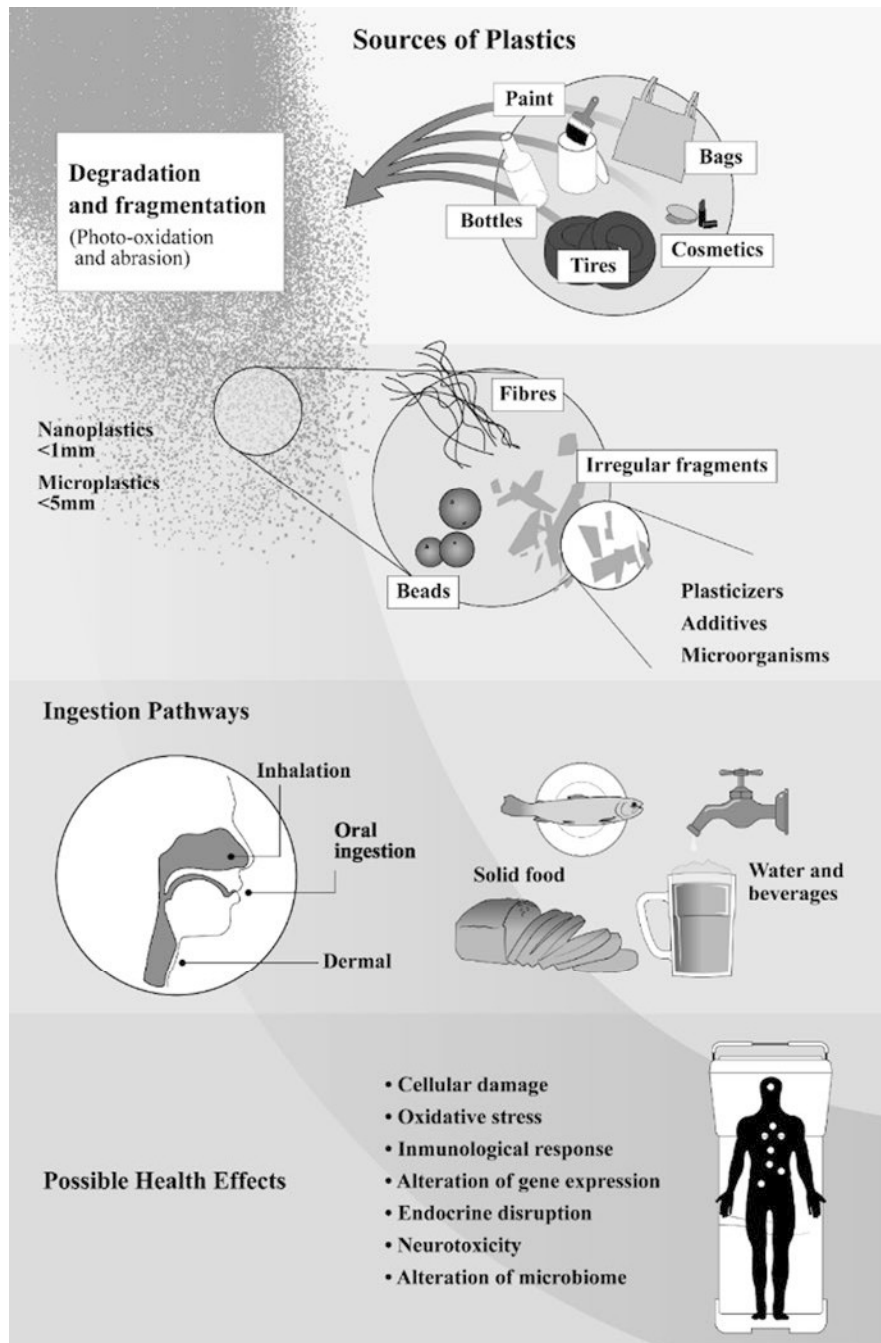
MNPs can enter the human body by inhalation, ingestion, or dermal route, directly through the skin (Fig. 19.1). Once in the body, they can accumulate and exert localized particle toxicity by inducing or increasing the immune response (Galloway 2015; Wright and Kelly 2017; Teles et al. 2020).

Microplastics are abundant in the atmosphere, especially in urban environments, and therefore can be inhaled by people. For example, atmospheric measurements determined microplastics deposition rates in Central London between 575 and 1008 particles/m<sup>2</sup>/day (Wright et al. 2020). On the other hand, studies of exposure to environmental particles among workers in the plastics and textile industry have reported lung injuries, including inflammation, fibrosis, and allergies (Wright and Kelly 2017).

The possibility of movement of the MNPs by the lung lining fluid is reduced in the upper airways, where the lining is thick. In the lungs, mucociliary clearance is likely for particles >1 µm. However, for particles <1 µm, uptake through the epithelium and its deposition in deeper parts of the lungs can be possible (Geiser et al. 2003; Ruge et al. 2013).

Oral ingestion is perhaps the primary source of entry for MNPs into the body. Evidence suggests widespread exposure to MNPs in various foods and drinking water (Catarino et al. 2018; Cox et al. 2019; Wright et al. 2020). For example, in tap and bottled water, concentrations of up to 104 particles per liter can be found (Koelmans et al. 2019). The release of particles in plastic containers containing liquids represents another source of ingestion of MNPs. These particles have even been documented in polypropylene bottles for babies (Lim 2021). Likewise, microplastics have been reported in processed foods and beverages such as sugar (Liebezeit and Liebezeit 2013), seafood (Van Cauwenberghe and Janssen 2014; Li et al. 2015), beer (Liebezeit and Liebezeit 2014), and table salt (Yang et al. 2015), among many others.

Once in the intestine, smaller particles can cross epithelial barriers. In this sense, the ingestion of MNPs of sizes between 0.1 and 10 µm may occur in the gastrointestinal tract through endocytosis by the M cells of Peyer's patches. There, M cells



**Fig. 19.1** Possible health effects of microplastics and nanoplastics (MNPs). Microplastics (<5 mm) and nanoplastics (<100 m) are generated as a result of abrasion and photo-oxidation of plastic objects such as car tires, textiles, bottles, bags, and cosmetics, which are improperly disposed of in the environment. MNPs can enter the body by inhalation, oral ingestion, and dermal routes, generating chemical, physical, and biological toxic activity. Once inside human tissues, MNPs can cause oxidative stress, immune responses, alteration of gene expression, genotoxicity, endocrine disruption, neurotoxicity, reproductive abnormalities, transgenerational effects, and behavioral abnormalities and alteration of the microbiome

can transport the particles from the gastrointestinal lumen to the lymphoid tissues of the mucosa (Mowat 2003; Wright and Kelly 2017). Likewise, it would be possible for MNPs to cross the loose junctions in the single-cell epithelial layer at the villus tips of the gastrointestinal tract, where dendritic cells can phagocytose them and transport them to the underlying lymphatic vessels and veins. MNPs can later be distributed to secondary tissues, including the liver, muscles, and (Mowat 2003; Wright and Kelly 2017).

It has been estimated that humans, on average, ingest 0.1 to 5 g of microplastics weekly through various ingestion pathways (Senathirajah et al. 2021). Many MNPs, particularly the larger ones, are excreted through the feces or after their deposition in the respiratory tract or lungs through mucociliary clearance (Wright and Kelly 2017). However, it is unknown how much of what is ingested is secreted and how much it accumulates. In this regard, although possibly a tiny part of what is ingested accumulates, the effect over time could represent an incremental risk to human health. Furthermore, it must be emphasized that human exposure to MNPs has not yet been sufficiently studied, which implies considerable uncertainty in evaluating human risk, despite its potential toxicity (Yong et al. 2020; Vethaak and Legler 2021).

### ***19.2.2 Toxicity Profile***

MNPs can exhibit a different and broader toxicity profile than other environmental particles due to their persistence, wide range of size and shapes, chemical composition, and surface charge (Wright and Kelly 2017; Ribeiro et al. 2019). Much of the research on the health effects of MNPs is based on the knowledge and lessons learned from the study of other particles, such as those associated with air pollution.

Once in contact with tissues or internalized, MNPs can cause physical, chemical, and microbiological toxicity. The toxicity effects could also be synergistic. Chemical toxicity occurs due to the leaching of endogenous additives and environmental pollutants adsorbed to the external environment. MNPs act as vectors that transfer dangerous chemicals, proteins, and toxins present in or on the particles to the human body (Hirai et al. 2011; Ribeiro et al. 2019; Koelmans et al. 2019).

When considering the entire set of substances that make up plastics, including monomers, additives, and processing aids, more than 10,000 substances have been identified. Of these, about 2400 are of potential concern due to their persistence, bioaccumulation, and toxicity (Wiesinger et al. 2021). In addition, plastics can adsorb and concentrate hydrophobic organic pollutants such as polycyclic aromatic hydrocarbons, organochlorine pesticides, and polychlorinated biphenyls (Mato et al. 2001; Ogata et al. 2009). They also accumulate heavy metals such as cadmium, zinc, nickel, and lead (Holmes et al. 2012; Rochman et al. 2014). Furthermore, the effect of chemical toxicity could be even more significant on nanoparticles, which are more effective at traversing biological membranes and have a greater surface area of chemical reactivity (Revel et al. 2018). This effect might also be enhanced by bioaccumulation.

Regarding microbiological toxicity, it has been established that MNPs can act as vectors for potential bacterial pathogens and fungi and viruses (Lu et al. 2019). Microplastic-associated microorganism communities can alter the structure of endemic communities where they are deposited, for example, the gastric mucosa of the intestine. Likewise, biofilms formed on microplastics favor horizontal gene transfer in bacterial communities, including antibiotic resistance genes (Arias-Andres et al. 2018). Therefore, MNPs can directly impact the gut microbiome, which, according to recent research, has been related to human health in multiple aspects (Fackelmann and Sommer 2019; Fournier et al. 2021; Lear et al. 2021).

In addition, nanomaterials have been attributed antimicrobial activities due to their unique physicochemical properties such as ultrasmall size, large surface area to mass ratio, high reactivity, and functionalizable structure (Shimanovich and Gedanken 2016). Therefore, it will be imperative to determine in the future if nanoplastics could have a direct toxic effect on commensal bacteria in the digestive tract and therefore cause alterations in the human microbiome.

Physical toxicity refers to the effect of the presence of the particles, as foreign agents, in the tissues. For microplastics  $<10\ \mu\text{m}$ , the translocation from the intestinal tract to the lymphatic and circulatory systems is possible, causing systemic exposure and accumulation in tissues including the liver, kidney, and brain. The translocation and accumulation could lead to oxidative stress, cytokine secretion, cell damage, inflammatory and immune reactions, and DNA damage (Yong et al. 2020).

### ***19.2.3 Possible Effects to Human Health***

The potential impact of MNPs on human health became a matter of public concern until recently, despite the evidence from ecotoxicological studies both in vivo and in vitro showing adverse effects on other organisms (Noventa et al. 2021).

As noted, MNPs enter the human body by different ingestion pathways. A large part can be excreted, but a small part remains, temporarily or permanently. As a result of the toxic activity of MNPs, either physical, chemical, or microbiological, the host cells will suffer various effects, among which oxidative stress has been noted through the generation of free radicals. Other effects of MNPs are immune responses, alteration of gene expression, genotoxicity, endocrine disruption, neurotoxicity, reproductive abnormalities, transgenerational effects, and behavioral abnormalities (Alimba and Faggio 2019; Hwang et al. 2020).

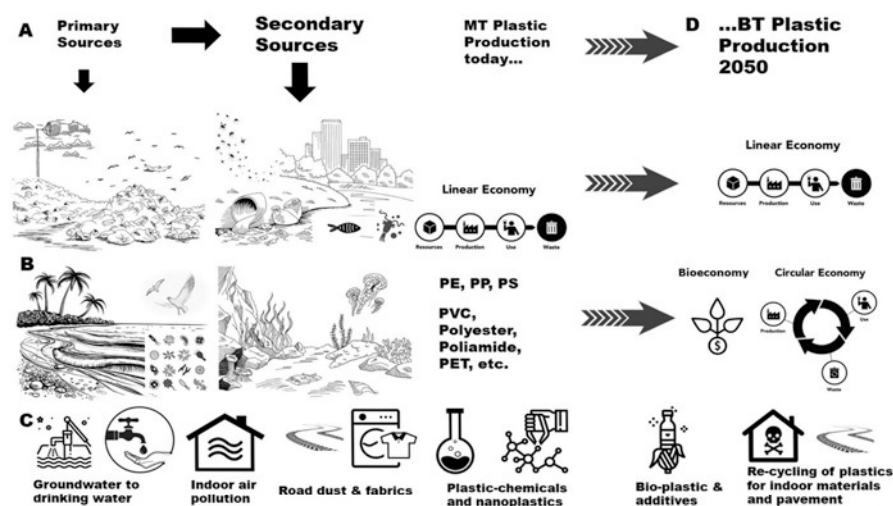
However, many aspects related to the fate and effects of MNPs on the human body are still unknown; little is known about dose-dependent effects, adsorption mechanisms through membranes, the translocation pathways to secondary tissues and organs, the impact of the cumulative effect of chronic exposure, as well as natural elimination processes (Academias 2019; Noventa et al. 2021).

**Table 19.1** Examples of methods applied to characterize ecological risks from MP in recent literature

Environmental compartment/biological group or function in effects assessed	Hazard/effects assessment	Risk characterization methods	Results	References
Coastal, continental shelf, and deep-sea areas Aquatic invertebrates, primary producers, fish, and corals	Effects on mortality, growth, development, and reproduction, and population growth	Predicted no-effect concentration (PNEC) by analysis of species sensitivity distributions (SSD) of chronic toxicity endpoints (LOEC, NOEC, EC10), to derive a hazardous concentration for 5% of the species (HC5) and using an assessment factor, for 20–300 µm sized MP vs. exposure field data	Detected MP concentrations did not exceed the derived PNEC of 12 particles/L	Jung et al. (2021)
Estuarine ecosystem	Hazard classes and categories in the EU classification and labeling (CLP) regulation based on the UN Globally Harmonized System	Hazard score (H) assigned to MP polymer and calculation of polymer composition and pollution load (PL) from exposure field data (0.3–2.5 mm MP) <sup>b</sup> Hazard level and ecological risk index calculation for single and combination of polymers	Hazard Level II for MP pollution in the estuarine ecosystem (acute toxicity, skin corrosion/irritation, serious eye damage/eye irritation, specific target organ toxicity — single exposure, hazardous to the aquatic environment, explosives <sup>ab</sup> ) “Minor” ecological risk category of studied site <sup>b</sup>	Lithner et al. (2011) Pan et al. (2021b)
Global ocean	Effects on population size (e.g., growth, reproduction, and survival)	SSD of toxicity thresholds (TT, mg/L) calculated for MP size ranges Comparing the thresholds of biological effects with the probability of exposure to those concentrations	Large MP poses a negligible global risk MP bioavailability, translocation, and toxicity increase as size decreases, and particles <10 µm are not identified by current monitoring methods	Beiras and Schönemann (2020)

Environmental compartment/biological group or function in effects assessed	Hazard/effects assessment	Risk characterization methods	Results	References
<p>Freshwater, river Algae, invertebrates, and vertebrates</p>	<p>Growth, mortality, reproduction, feeding, morphology, neurological effects, histopathology, biochemical effects, microbiota diversity, innate immune response, predatory performance, digestion, and energy production</p>	<p>PNEC by analysis of SSD of chronic toxicity endpoints (NOEC), using the HC5 as criteria and using an assessment factor, vs. exposure field data in a risk quotient (exposure/PNEC)</p>	<p>Most of the monitored sites posed negligible risks to freshwater biota, except for two sites in the urban center</p>	<p>Zhang et al. (2020b)</p>
<p>Freshwater Pelagic and benthic freshwater organisms (invertebrates, algae, plants, and fish)</p>	<p>Effects on survival, growth, reproduction, and changes in photosynthesis</p>	<p>PNEC by analysis of different percentiles of SSD using chronic toxicity endpoints (NOEC) (&gt;30% of ecotoxicological studies with MP &lt;0.45 µm Exposure probability distribution based on literature data (Europe, North America, and Asia regions) Risk characterization ratios (RCR) by comparison of probability distributions of PNEC and exposure data for each region</p>	<p>No influence of particle shape or type of polymer on the NOEC The probability distribution of the global exposure concentration overlapped to a small extent with the PNEC probability distribution. A 0.12% probability distribution calculated for the global RCR was &gt;1 but related only to exposure data from Asia</p>	<p>Adam et al. (2019)</p>

NOEC: no observed effect concentration, LOEC: lowest observed effect concentration, EC10: effect concentration to 10% of the exposed population



**Fig. 19.2** Exposure and ecological scenarios for assessing effects of MP today and in the future. (a) Today, millions of tons of plastics are produced per year, and a large proportion of MP comes from waste after using plastic objects. (b) Most effects are known for freshwater and marine species, but terrestrial compartments should be considered further. (c) Some types of environmental exposure require more attention, such as groundwater pollution and its impact on drinking water, long-term MP inhalation on indoor spaces, and effects emphasizing high and frequent exposures such as those from MP of road dust and fabrics washed at home. Further, the effect and risk assessment should focus on the smaller particles and the interaction with the large number of chemicals added to plastics. (d) In the future, billions of tons of plastic will be produced annually. If the economic model of waste production continues, an exponential increase in exposure and effects will be expected. In the scenario of a transition to a circular-like (bio)economy, new bio-based materials and additives are expected to be generated and produced. In this latter case, it will be essential to assess the toxicological profile for the new generation of materials, including toxicology regarding recycled plastic (e.g., the plastic used in pavement and the exposure to plastic-toxic substances in construction materials)

### 19.3 Ecological Risks Estimated from MP Exposure Data

The magnitude of contamination by MNPs, their ubiquity on the planet, and their high persistence over time raise serious concerns about their effects on ecosystems, wildlife, and human health. However, the type and level of exposure and the specific risks for humans are far from being elucidated (Vethaak and Legler 2021).

Information regarding toxic effects of microplastics on organisms from different ecosystems, i.e., ecotoxicological effects, increased exponentially over this decade (Anbumani and Kakkar 2018; Zhu et al. 2019). The assessments for effects include data on the traditional ecotoxicological endpoints of mortality, growth, development, reproduction, and population growth. Most of the published data is originated from aquatic species such as invertebrates, algae, plants, and fish. Accordingly, most of the ecological risk assessments (ERA), analyzing the risks of effects based on current exposure levels, were developed for aquatic environments, and many of

them with exposure data from Asia. Some examples of standard methods applied in ERA for MP are provided in Table 19.1.

The first ERA show that MP can pose toxicity risks in ecosystems but is relatively low in terms of the toxicity endpoints. However, results also indicate that underestimating MP concentrations (exposure assessment) due to size during sampling can affect the results of risk assessment characterization (Covernton et al. 2019). It is also important to consider that the assessments of effects often do not look into toxicity mechanisms, such as the production of reactive oxygen species (ROS) and immune reactions, changes in animal microbiota, or genotoxicity (Jeong and Choi 2019; Palmer and Herat 2021). In addition, MP is a source for exposure to other chemical substances, many of which are emerging contaminants with most likely long-term effects, but this is still not analyzed during ecological risk assessments (Fig. 19.2).

Chemical substances in MP include those added to plastics, those originating from plastic polymers, and others taken up by plastic in the environment (Campanale et al. 2020). For example, plastics are known to contain or absorb flame retardants, plasticizers, lubricants, and dyes that are made of organic and inorganic forms of heavy metals, different organic pigments and chromophores, salts of stearic acid, halogens such as chlorine and bromine, bisphenol A, phthalates, and pesticides, among many others (Campanale et al. 2020; Bhagat et al. 2021). Many of these substances are known or presumed to be toxic, carcinogenic, and endocrine disruptors (Mohamed Nor et al. 2021). Many additives in plastics are non-covalently added; therefore they can leach to the surrounding environment (Gewert et al. 2015).

The interaction of MP and these substances forms complex contaminants that require more sublethal and chronic ecotoxicological methods that address more complex and long-term responses (e.g., immune responses, microbiomes, and their activities). The study of these interactions is particularly important for ecological and human risk assessments intended for upcycling and recycling plastics and circular economies.

## 19.4 Conclusions

In this chapter, we analyze the sources and processes that generate MP pollution and their environmental fate. We also indicate the type and level of exposure and the specific risks for humans and the ecosystem, for example, the routes of ingestion, the toxicity profile, and possible health effects. Further research is needed to understand the toxicity, mechanisms, and long-term effects of human exposure to MP. The ecological risks associated with MP exposure also need to (1) emphasize the smaller fraction of MP, (2) provide more data regarding MP-emerging contaminant interactions, and (3) utilize more long-term, chronic, and sublethal endpoints to assess these interactions. Due to the complexity of the problems associated with MP pollution, it will be critical that research challenges will need to be addressed by multidisciplinary teams, including biologists, chemists, physicians, environmentalists,

economists, politicians, sociologists, and philosophers. Furthermore, we propose that the solution to a problem as complex as contamination by MP will be political, economic, and social rather than technical.

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