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Chapter 2

Plastic litters and public health

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Table of Contents

2.1 SOURCES, OCCURRENCE, FRAGMENTATION AND DEGRADATION OF PLASTIC LITTERS

2.1.1 Entry routes into the environment and food chain

When plastics enter the environment as macro- or microplastic (MP), they break into small particles over time, contaminating all areas of the environment (air, water, and soil), accumulating in food chains, releasing toxic additives or concentrating additional toxic chemicals in the environment, and rendering them bioavailable for direct or indirect human exposure.

Plastic litter is ubiquitous in the environment in various sizes. As a result, the health effects and exposure routes of plastic pollution depend on the sizes ranging from 'nano-particles' to 'macroplastics.'

'Macroplastics' are generally defined as plastic items larger than 5 mm.
'Microplastics' are generally recognized as synthetic organic polymer particles less than 5 mm at their longest point.
'Nanoplastics' are generally defined as plastic items with sizes between 1 and 100 nm.

- **Macroplastics**
  Macroplastics can be distributed in aquatic, terrestrial and atmospheric environments via different transport routes such as wind and water currents (Lechthaler *et al.*, 2020). The details of transport paths of macroplastics in different environmental compartments are provided in Chapter 4.

  The majority of micro-plastics discovered in the ocean are 'original consumer items.' The plastic items that reach the environment are listed in a recent collection of the top 20 most prevalent products detected in six separate worldwide sets of coastal data. Food and beverage packagings (such as wrappers), bottles and bottle caps, straws, stirrers, lids, cutlery, containers, cups, and plates account for 75% of the items on the list. The

remaining items include smoking-related items (cigarette butts, packaging, and lighters), as well as bags, balloons, diapers, condoms, tampons, and six-pack holders.

- **Microplastics**
  Microplastics (MPs) that enter the environment can be defined as both 'primary and/or secondary microplastics.'
  - *Primary MPs* are defined as MP produced as 'original products in micro-sizes'. This includes pre-production plastic in the form of powders and pellets (5 mm in size) used in producing plastic consumer products. MPs are leaked from processing and transportation facilities, mostly as a result of poor housekeeping standards during the shift from rail, truck, and storage sites to processing facilities. Microbeads, which are found in hand cleansers, face cleansers, and toothpaste, are another form of primary MPs.
  - *Secondary MPs* are the 'degraded plastic pieces of larger consumer products.' Common MPs reported in many studies on shoreline litter are degradants of textile fibers and particles from automobile tires which originally are macro-sized plastic products.

  Studies have shown that MP particles are commonly found in personal care products, accounting for a range between 0.05% and 12% of the ingredients. As a result, many countries such as the United States, Canada, Australia, the United Kingdom, New Zealand, Taiwan, and Italy now have banned the primary MPs in production of personal care products.
- **Nanoplastics**
  Nanoplastics are being more widely used in paints, adhesives, medicines, electronics, and 3D printing. These are then released into the environment as primary nanoplastics products. Secondary nanoplastics result from continued degradation of MPs, similar to the secondary MP process.

2.1.2 Plastic litter in the environment and food chains

2.1.2.1 Numbers and characteristics of plastic litter in the food chains

It has been commonly reported recently that humans are becoming exposed to plastic pollution. The abundance and concentration of plastic litter found in different places are key factors causing adverse impacts on human health via the food chain. According to recent research findings, 'humans can easily be exposed to micro and nanoplastics in three ways: drinking contaminated water, consuming contaminated food and breathing polluted air' (WHO, 2019). All kinds of plastics, namely macro-, micro- and nano-plastics can be found in the environment and the food chain.

2.1.2.2 Numbers and characteristics of MPs (MaP)

As macroplastics occur and accumulate in different environmental compartments, their numbers and concentrations significantly lead to different levels of health risk. In the case of macroplastics, concentration in the environment can be found in freshwater, marine, and terrestrial environments. An estimated 1.15–2.41 million tons of plastic waste depending on waste

management, population density, and hydrological information was reported in 2017 alone (Lechthaler *et al.*, 2020).

Moroever, it has been reported that 91% of mismanaged plastic waste in the African and Asian continents were transported and accumulated along waterways, making rivers the main input path leading plastic waste into the oceans as shown in Table 2.1 (Lechthaler *et al.*, 2020).

Table 2.1 Abundance of MPs in freshwater.

Environment	Environmental Compartments	Study Area (Year)	Average MP Concentration/ Input/Year	References
Freshwater	River and sea	Italy; the Tiber (2018)	87 600–438 000 items	Crosti *et al.* (2018)
		South-East: Vietnam, Indonesia, Thailand, Malaysia (2019)	8.76–87.60 million items	van Calcar and van Emmerik (2019)
		Europe: Italy, The Netherlands, France (2019)	0.88–876 million items	van Calcar and van Emmerik (2019)
		France; the Rhone the Seine (2019)	0–175 200 items 0.93–1.40 million items	Van Emmerik *et al.* (2019)
		Vietnam; the Saigon River (2018)	7500–13 700 tons	Van Emmerik *et al.* (2019)
		Black Sea (2014)	1533 tons	Lechner *et al.* (2014); Lechthaler *et al.* (2020)
		The North Sea by; the Elbe the Ems the Weser (2020)	 Up to 451 tons Up to 1.60 tons Up to 6.30 tons	Schöneich-Argent *et al.* (2020)
		The ocean; Discharging by two Catalan rivers, Llobregat and El Beses (2020)	0.40–0.60 tons	Schirinzi *et al.* (2020)
		Switzerland; the Rhine (2020)	0.88–0.66 million items	Vriend *et al.* (2020)
	Lakes	Switzerland; six lakes	1800 items/km^2	Faure *et al.* (2015); Lechthaler *et al.* (2020)

2.1.2.3 Numbers and characteristics of MPs

MPs enter the human body through the water we drink, the food we eat, and the air we breathe, according to a WHO report released in 2019 (Figure 2.1). MPs' presence in numerous environmental compartments, such as water, soil, air, and organisms, increases the number of possible routes by which humans and animals are exposed. This could link to potential sources of transportation pathways and its adverse effects on animals and human health.

- **MPs in tap water**

The presence of MPs in the water sources of water supply (surface water, reservoir, dam, etc.) resulted in the abundance of MPs in tap water. Several investigations have confirmed the contamination of MPs in tap water worldwide (Figure 2.2). Previous studies (as summarized in Table 2.2) investigated 159 tap water samples from 14 countries, half of which were developed countries and half were developing countries. The results showed 81% of all samples contain a range of 0–61 particles/L of MPs with an average of 5.45 particles/L. In particular, tap water in the US was found to contain the highest average (9.24 particles/L), while the four countries with the lowest averages were all from the European Union countries. As a result, water from more developed countries had a greater average density (6.85 particles/L) than that from developing countries (4.26 particles/L). The tap water analysis revealed 83% contamination, with microfibers accounting for 98% of the particles. Figure 2.3 shows the examples of anthropogenic particles found in tap water samples from the Indian subcontinent and the US.

- **Drinking water**

Studies of MPs contamination in treated tap water and drinking water and its potential impact on human health have recently grown in number. MPs found in drinking water are a silent problem that threatens people's health globally. MPs in commercially bottled water have been reported to be two times more abundant than MPs found in tap water.

A study found that over 90% of the world's most popular bottled water brands contain MPs. With these findings, the World Health Organization (WHO) has emphasized the potential risks of MPs in drinking water. According to the McCarthy (2018) study, 259 bottles bought in 8 different countries, including China, Brazil, India, Indonesia, Mexico, Lebanon, Kenya, Thailand, and the United States, across 11 leading brands were examined.

The results showed that the water in the 242 bottles was found to contain an average of 325 MP particles/L, while only 17 bottles were confirmed to be plastic-free (Figure 2.4). Thus, MP contamination was found in over 93% of the bottled water samples. A bottle of Nestlé Pure Life, for instance, contained almost 10 000 particles of MPs, while Bisleri, Gerolsteiner, and Aqua bottles all had significant quantities (Mason *et al*., 2018). The bottled water was found to be 93% contaminated, with 13% of the particles classified as microfibers. Polypropylene, nylon, and PET were among the plastics found in the bottled water samples. Furthermore, the study revealed that fragments were the most

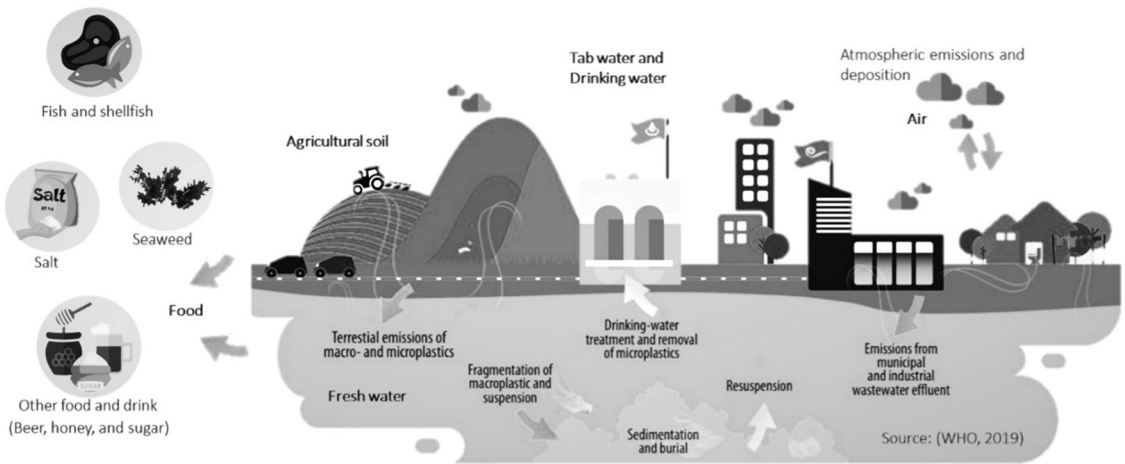


Figure 2.1 MP entering the human body through the water we drink, the food we eat, and the air we breathe (*Source*: adapted from WHO, 2019).

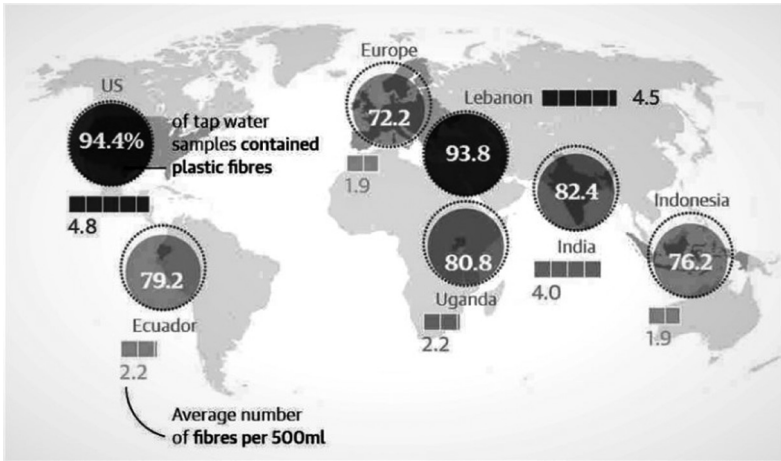


Figure 2.2 Percent of tab water samples contaminated with MPs by country (*Source*: Picó & Barceló, 2019).

Table 2.2 MPs concentration in tap water.

Country/Sources	Number of Samples	MPs Concentration (Particles/L)[a]
Cuba	1	7.17 ± 0.00
Ecuador	24	4.02 ± 3.20
England	3	7.73 ± 4.76
France	1	1.82 ± 0.00
Germany	2	0.91 ± 1.29
India	17	6.24 ± 6.41
Indonesia	21	3.23 ± 3.48
Thailand	NA	0.56 ± 0.24
	6	0.62 ± 0.38
Ireland	1	1.83 ± 0.00
Lebanon	16	6.64 ± 6.38
Slovakia	8	3.83 ± 4.47
Switzerland	2	2.74 ± 3.87
Uganda	26	3.92 ± 3.17
USA	33	9.24 ± 11.8
Bottled water	3	3.57 ± 1.79

Note: For countries with only one sample, the density of anthropogenic debris is provided as the mean with no values given for min., max., or standard deviation.
Source: Kosuth *et al.* (2018); Chanpiwat and Damrongsiri (2021).

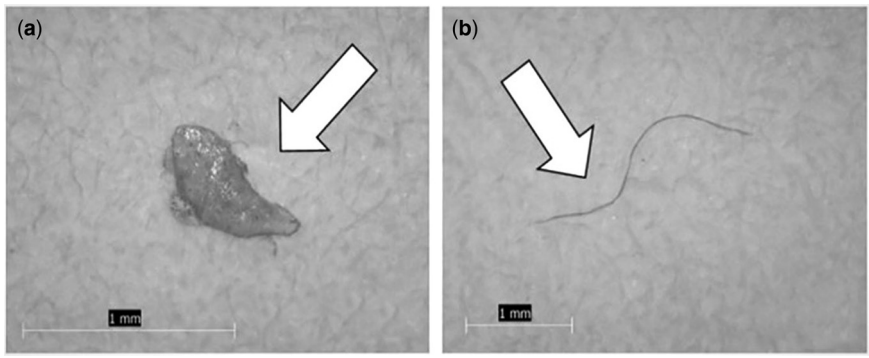


Figure 2.3 Tap water particles. Examples of anthropogenic particles found in tap water: (a) fragment, 1 mm in length from the Indian subcontinent; (b) fiber, 2.5 mm in length from the U.S. tap water sample (*Source*: Kosuth *et al.*, 2018).

common MPs form detected in bottled water samples (65%), which were likely produced by a different source of contamination than tap water. Polypropylene was the most popular polymeric material for particles bigger than 100 m (54%), which is similar to the most common plastic used for bottle caps. Nestle Pure Life water, which can be purchased on Amazon.com, had the highest average MP density, at 2247 particles/L. The number and properties of MPs can be linked to their origins and possible effects on ecosystems and human health. Despite the lack of proof that consumption of these MPs might cause health concerns, it has lately been a source of concern.

- **Food**

MPs and associated hazardous compounds in plastic food packaging and drinking water are significant sources of food contamination. However, contamination extends beyond packaged food; natural food chains are also a source of contamination. Both sea-based and land-based food chain contamination requires more research.

- **Fish and Shellfish**

Many studies have investigated the impact of plastics in the ocean. MPs have been found in more than 690 marine species, ranging from small zooplanktons to vast marine animals. Many commercially significant species have also been confirmed to be contaminated with plastic particles. The majority of MP ingestion in humans comes from 'seafood' species that are consumed entirely, such as mussels, oysters, shrimp, crabs, and some small fish. MP contamination of seafood may not be limited to ingestion of the species mentioned above; it is possible that other seafood, such as fish muscle tissue, may be contaminated either within the organism or during preparation (Figure 2.5 and Table 2.3).

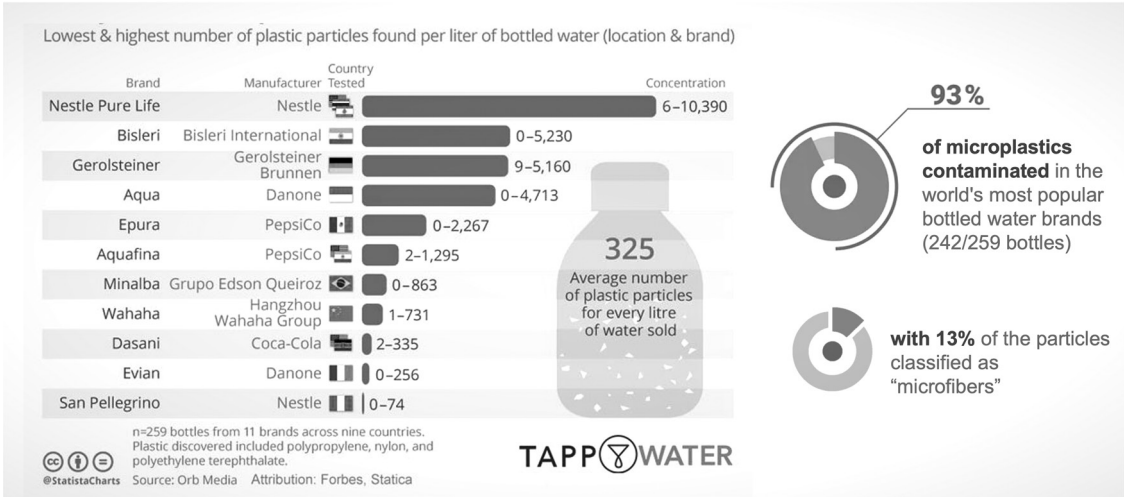


Figure 2.4 Study finds MPs in 93% bottled water (*Source*: adapted from McCarthy, 2018).

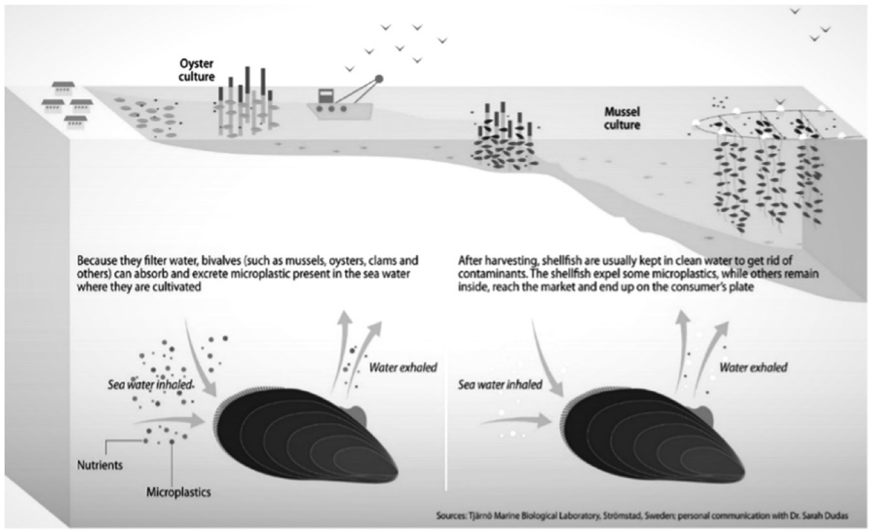


Figure 2.5 An example of how MPs could end up on a consumer's plate (*Source*: Smith *et al.*, 2018).

Table 2.3 Examples of MPs in the environment and food chain (MPs in animals and seafood).

Study Area	Animal	Figure	PS Size (μm)	LC_{50}* (Items/ind.)	Reference
Marine Science Department, Chulalongkorn University	Juvenile tiger shrimp (*Penaeus monodon*)		<30 30–300 300–1000	25 19 19	Phothakwanpracha *et al.* (2021)
Maptaphut, Rayong province	Blue swimming crab		PET, PP, PS, Polyester, Nylon	1.30	Fangsrikum *et al.* (2021)
	Goldstripe sardinella		PET, PE, PP, Nylon	3.90	
	Silver sillago		PET, Polyester, Nylon	1.88	
	Green mussels		PET, PE, PP,	0.75	

*Lethal concentration fifty; LC_{50} (More detail of LC_{50} is described in 1.3.5: Ecotoxicological Assessment of Microplastics.)

- **Seaweed**

MP particles often attach to the surface of edible seaweed species at high exposure levels, indicating that humans can be exposed to MP through eating seaweed (*Fucus vesiculosus*). The quantity of MP particles was reduced by 94.5% after a thorough wash before using the seaweed for cooking. In China, MPs have been detected in both final commercial seaweed nori products and intermediate products (*Pyropia* spp.) at different processing stages (Figure 2.6). In commercially packaged nori, polyester is the most common MP component. The most common polymer found in factory-processed nori is polypropylene (Table 2.4).

- **Salt**

MPs have been detected in rock salt and sea-salt samples, indicating that there is a high background level of plastic pollution in both marine and terrestrial ecosystems (Figure 2.7). MP contamination in packaged salt and other food products packaged in plastic can also occur during processing and packing. A case study of commercial sea salt from various salt-producing regions was conducted using 12 brands of commercial sea salt. It was found that the MP concentrations of the brands sampled ranged from 46.7 to 806 particles/kg, with a mean of 212 particles/kg (Table 2.5). The color distribution of particles was found that blue and red/pink were prominent colors among all samples (Figure 2.8).

- **Beer**

A study (Kosuth *et al.*, 2018) sampled 12 brands of beer in the USA and found that MPs were detected in all samples with the average particle count for each brand ranging from 0 to 14.3 particles/L, with a mean of 4.05 particles/L (Table 2.6). The vast majority (98.4%) of the 189 particles found were fibers, whereas the remaining were fragments. The fibers measured 0.98 mm on average, with a range of 0.1–5 mm (Figure 2.9). Nine of the 12 beer samples included one or more particles in the second filtration phase, totaling 17 particles among all the samples. In Figure 2.10, blue was the most prominent color among the 189 particles, followed by red/pink and brown, all of which were detected in tap water sample also collected in the study. Although anthropogenic particles were found in both the municipal tap water and the beers sampled, there seemed to be no correlation between the two.

2.1.2.4 Case studies of small MPs and nanoplastic contaminations

The small micro- and nanoplastic contaminations were commonly observed in the environments or in daily used products. Several previous case studies reported and highlighted the contaminations of MPs in the atmosphere, food packaging chemicals and receptors of plastics in the environment and food chains.

- **MPs in the atmosphere**

Because of their small size and low density, MPs are potentially transferred to air and are easily transported by wind. Compared to MPs in other ecosystems,

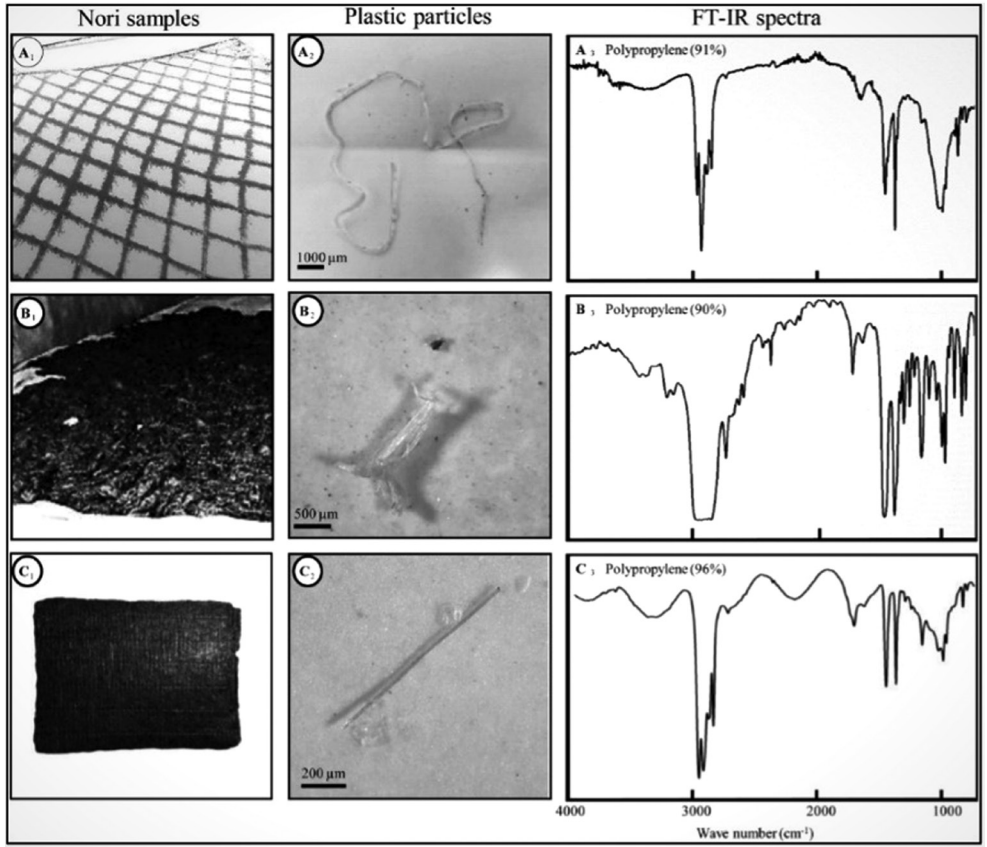


Figure 2.6 MPs in nori samples from factory-processed with optical microscopy and μ-FT-IR spectroscopy. Nori samples in the first column (A_1, B_1, C_1) were photographed from a nori farm site, a nori processing factory, and a dried nori product, respectively. Optical photographs in the second column (A_2, B_2, C_2) showed the plastic particles isolated from different sources to their left ones, and the third column (A_3, B_3, C_3) displayed FT-IR spectra of the corresponding particles to their left ones (*Source*: Li *et al.*, 2020).

Table 2.4 MPs in commercial seaweed nori (*Pyropia* spp.)

Sample	The Abundance of MPs, Items/g (dw)	MPs Size, mm	MPs Shape	Types of MPs	Color of MPs
Twenty-four brands of commercially packaged nori in China	0.9–3.0 (average: 1.8 ± 0.7)	0.11–4.97 (median size: 1.13)	Fiber (85.2%)	Polyester (18.9%)	Blue-green (41.4%)
Factory-processed nori	10–2.8 (average: 1.8 ± 0.6)	0.07–4.74 (median size: 0.85)	Fiber (64.8%)	Polypropylene (16.3%)	Blue-green (48.1%)

MPs in the air can be directly and continuously inhaled into the human body, posing serious health risks.

To date, only a few studies have examined the presence of MPs in the atmosphere. In a study conducted in Greater Paris, MPs were detected in air fallout for the first time, with an average of 118 particles/m^2/day (Dris *et al.*, 2015). More than 90% of the MPs found were fibers, with 50% of them being longer than 1000 μm. Dris *et al.* (2016) also examined two sites in Paris, reporting that air fallout fibers were present with the concentrations of 110 ± 96 (urban site) and 53 ± 38 (sub-urban site) particles/m^2/day (29% MPs). The authors suggested that the variance in MP concentrations in air fallout between the two sites was due to the density of the surrounding population. Dris *et al.* (2017), in their study conducted in Paris, found that indoor fiber concentrations (4.0–59.4 fibers/m^3, 33.3% MPs) were greater than outdoor fiber concentrations (0.3–1.5 fibers/m^3). MPs are continuously generated by indoor furniture, cleaning practices and activities, and lower rates of indoor air renovation may result

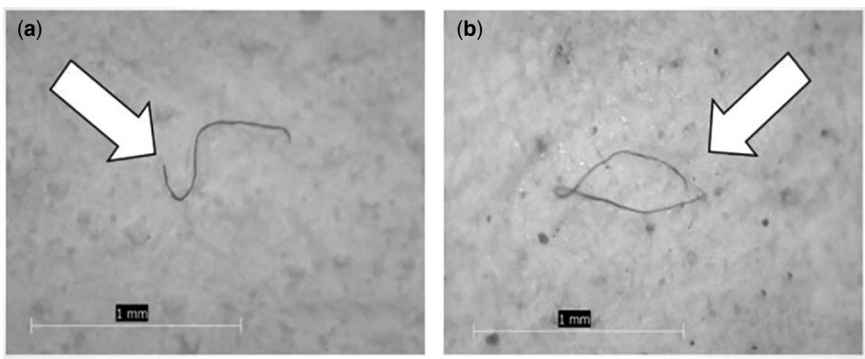


Figure 2.7 Sea-salt particles. Examples of particles found in sea salt: (a) fiber, 1 mm in length from the Pacific Ocean sourced sea salt; (b) fiber, 1.5 mm in length from the Atlantic Ocean sourced sea salt (*Source*: Kosuth *et al.*, 2018).

Table 2.5 Summary of sea-salt results.

Salt ID	MPs Concentration (Particles/kg)[a]
North Sea salt	66.6 ± 3.61
Celtic Sea salt 1	113 ± 1.53
Celtic Sea salt 2	187 ± 8.19
Sicilian Sea salt	220 ± 2.31
Mediterranean Sea salt 1	133 ± 3.06
Mediterranean Sea salt 2	133 ± 4.16
Utah Sea salt	113 ± 2.08
Himalayan Rock salt	367 ± 12.7
Hawaiian Sea salt	46.7 ± 0.58
Baja Sea salt	173 ± 3.79
Atlantic Sea salt	180 ± 4.16
Pacific Sea salt	806 ± 15.3

in high concentrations of indoor MPs, but the dilution of the air outdoors can greatly reduce MP concentrations.

Cai *et al.* (2017) investigated three sample sites in Dongguan, China and found that the average concentration of MPs in the atmosphere was 367 particles/m^2/day. Twenty-three percent of the MPs found were fibers, while

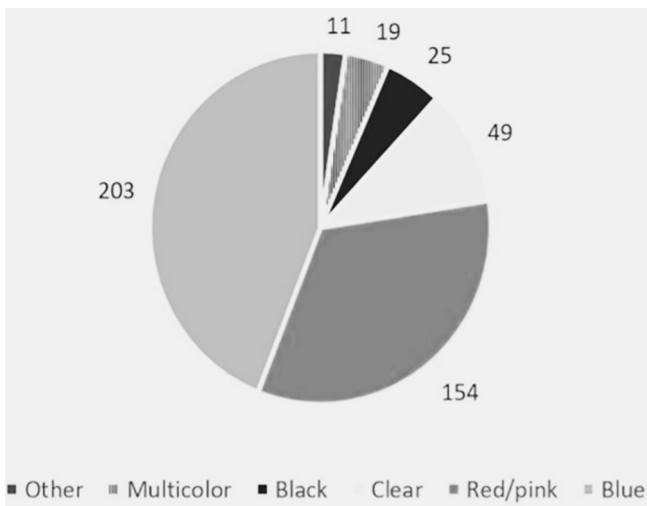


Figure 2.8 Sea salt particle colors. The color distribution of particles was extracted from 12 brands of sea salt (*Source*: Kosuth *et al.*, 2018).

Table 2.6 Comparison of MP particle count in beer and its corresponding municipal tap water.

Municipality	Number of Particles in Tap Water (Particles/L)	The Average Number of Particles in Beer (Particles/L)
Duluth, Minnesota	1	2.76
Milwaukee, Wisconsin	3	1.30
Chicago, Illinois	2	14.3
Holland, Michigan	2	2.30
Alpena, Michigan	1	1.30
Buffalo, New York	1	3.00
Clayton, New York	1	8.00

Note: ($r = 0.016$), which would seem to indicate that any contamination within the beer is not just from the water used to brew the beer itself.

84.6% of all other forms (films, bits, and foams) (Cai *et al.*, 2017). According to Liu *et al.* (2019b), atmospheric MPs may be detected throughout Shanghai, with a mean concentration of 1.421.42 particles/m^3. The lowest concentration was discovered near the sea due to dispersion of MPs by the water or delivery onto land by winds, as well as a lack of significant sources of fibers. MP concentrations were found to be greater at 1.7 m above ground level in the city than they were at 80 m. However, owing to wind mixing in the troposphere, no significant differences in concentrations were identified between the two sites.

Klein and Fischer (2019) reported that during December 2017 and February 2018, a median of 275 particles/m^2/day of MPs were detected in atmospheric fallout in Hamburg, Germany, and fragments (95%) were the most common shape of MPs. Abbasi *et al.* (2019) investigated microfibers in Asaluyeh County, Iran and reported that the number of microfibers/m^3 ranged from 0.3 to 1.1.

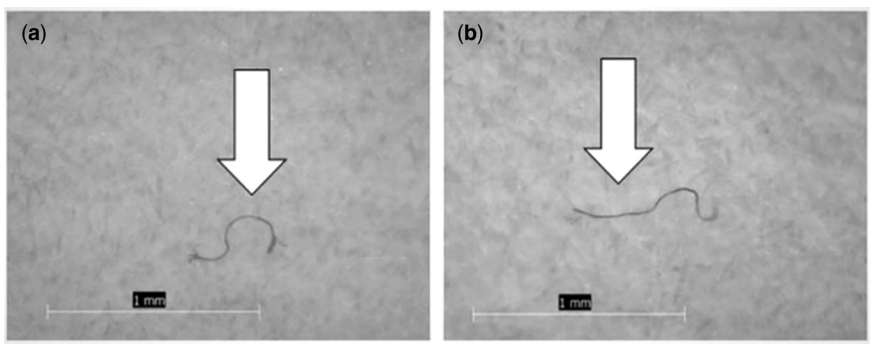


Figure 2.9 Beer particles. Examples of particles found in beer: (a) fiber, 0.75 mm in length from brewery drawing water from Lake Ontario; (b) fiber, 1 mm in length from brewery drawing water from Lake Erie (*Source*: Kosuth *et al.*, 2018).

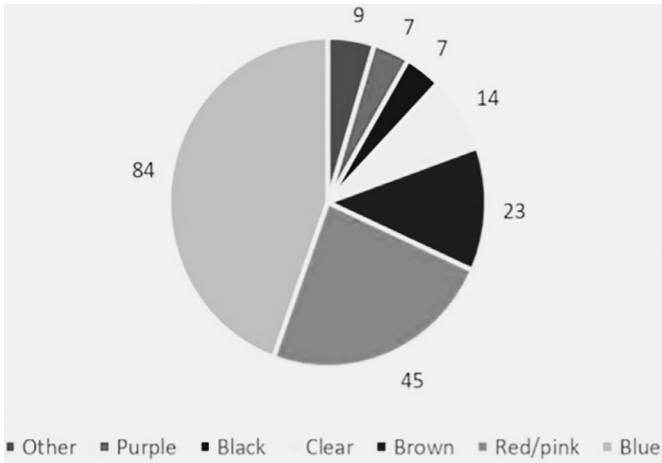


Figure 2.10 Beer particle colors. Color distribution of particles extracted from 12 brands of beer (*Source*: Kosuth *et al.*, 2018).

Allen *et al.* (2019) recently published an observation of atmospheric MP deposition in a remote, pristine mountain watershed French Pyrenees that is difficult for humans to access and far away from significant populations or industrial hubs. They found that the average MPs deposition found at this remote site was 365 ± 69 particles/m^2/day, which was comparable to the average concentrations observed in Paris and Dongguan city if only fiber were included. Chen *et al.* (2020) found that MPs remained in the atmosphere and were transmitted over a long distance. Table 2.7 shows the summary of the afore-mentioned study findings.

- **Food packaging chemicals**

Recent research findings revealed that the 'major source of human exposure to contaminants associated with plastic' is chemical migration from food packaging into food and beverages. With acidic or alkaline foods and UV radiation or heat coming into contact with some plastic polymers, plastic degradation can occur and toxic monomers such as styrene are released. Plastic additives are a varied group of compounds that serve a variety of functions. Since they are not strongly bonded to the substance, these additives are another typical source of chemicals leaching into food. Chemical migration and leakage are further enhanced by non-intentionally added substances (NIAS) such as impurities, side products, and contaminants. To prevent food from spoiling, food packaging additives are intended to migrate out of the package for this purpose. According to a case study at Italian state schools where school meals were investigated (Cirillo *et al.*, 2011), plasticizers are easily absorbed by food and beverages. The packaging raised the average phthalate concentrations by more than 100%.

Table 2.7 Abundance of airborne MPs in some cities and regions.

Location	Average Concentration	Shape	Size, μm	Colors	Polymer Types	Reference
Paris	118 no./m²/day	Fiber, fragment	100–5000	N/A	N/A	Dris *et al.* (2015, 2016, 2017)
Paris	110 ± 96 no./m²/day (urban) 53 ± 38 no./m²/day (sub-urban) 29% MPs	Fiber	50–5000	N/A	N/A	Dris *et al.* (2016)
Paris	5.4 no./m³ (outdoor) 0.9 no./m³ (indoor) 33% MPs	Fiber	50–3250	N/A	PA, PP	Dris *et al.* (2017)
Dongguan	36 ± 7 no./m²/day.	Fiber, fragment, film, foam	<00–4200	Blue, red, yellow, white, black	PE, PP, PS	Cai *et al.* (2017)
Yantai	400 no./m²/day	Fiber, fragment, film, foam	50–3000	White, black, red, transparent	PET, PE, PVC, PS	Qian *et al.* (2017)
Shanghai	1.42 ± 1.42 no./m³	Fiber, fragment, granule	23–5000	Blue, black, red, transparent, brown, green, yellow, gray	PET, PE, PES, PAN, PAA, EVA, RY, EP, ALK	Liu et al. (2019a, 2019b, 2019c)
Hamburg	275 no./m²/day	Fragment, fiber	63–5000	N/A	PE, EVAC, PTFE, PVA, PET	Klein and Fischer (2019)
Pyrenees	365 no./m²/day	Fiber, fragment, film	50–2600	N/A	PS, PP, PE, PET	Allen *et al.* (2019)

- **Receptors of plastics in the environment and food chains**

In addition to sources and pathways, receptors are a significant aspect of consideration of the impact assessment models. Here, fauna and flora are regarded as receptors as well as consequences on the ecosystem and economy. Based on the sources and pathways, the receptor analysis shows the further consequences and implications and thus fills the data for a holistic view of MPs in the environment. In addition to the environmental impact, the extent to which the economy is affected, which is often neglected, also becomes clear.

2.2 FRAGMENTATION AND DEGRADATION OF PLASTIC LITTER

2.2.1 Definition of plastic fragmentation and degradation

One of the main reasons contributing to the occurrence of MPs in the environment is the extensive breakdown and fragmentation of plastics.

Weathering-related degradation results in a 'progression of changes' that includes loss in mechanical integrity, embrittlement, further degradation and fragmentation (Harshvardhan & Jha, 2013).

Fragmentation is most likely to occur at 'advanced stages of degradation' well beyond embrittlement for most plastics, mainly due to exposure to solar UV radiation (Andrady, 2011).

Biodegradation of plastic occurs at a very slow rate; for instance, a study revealed that only 1–1.7% decrease in mass was observed in laboratory-accelerated degradation of PE over a 30-day duration by microorganisms isolated from marine waters (Harshvardhan & Jha, 2013).

Complete degradation refers to the 'destruction of the polymer chain and its complete conversion into small molecules' such as carbon dioxide or methane (also called mineralization process). The process is distinct from degradation which refers to as **an alteration in the plastic's properties** (e.g., embrittlement, discoloring) or its chemistry (Figure 2.11).

2.2.2 Influence of plastic fragmentation and degradation on its adverse effects

- **Size reduction**

Size reduction of many types of plastics ranging from macroplastics to small nanoplastics can occur in the environment under optimum conditions of degradation (photodegradation by UV, mechanical degradation, biodegradation, etc.). The reduced size contributes to the environmental distribution rate, and impacts on ecosystems and human health. Larger MPs (2–5 mm) may take longer to pass through organisms' stomachs and may remain in the digestive system, potentially extending the exposure time resulting in a higher amount of toxins absorbed (Rochman, 2015). Plastics with a diameter of nanometers can easily penetrate through cell membranes and accumulate inside living cells (Gilliber *et al.*, 2019) (Figure 2.12).

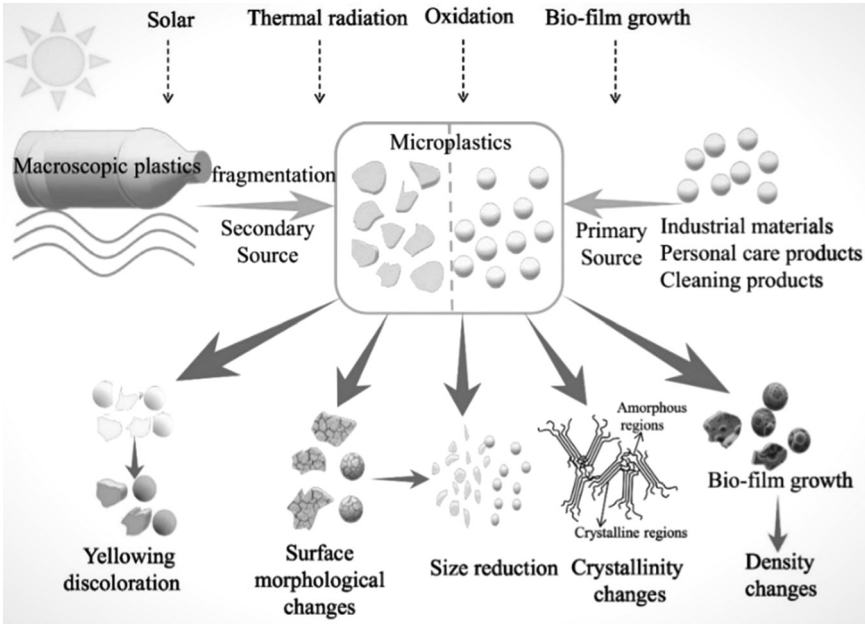


Figure 2.11 Property changes in plastic after degradation (*Source*: Guo *et al.*, 2019).

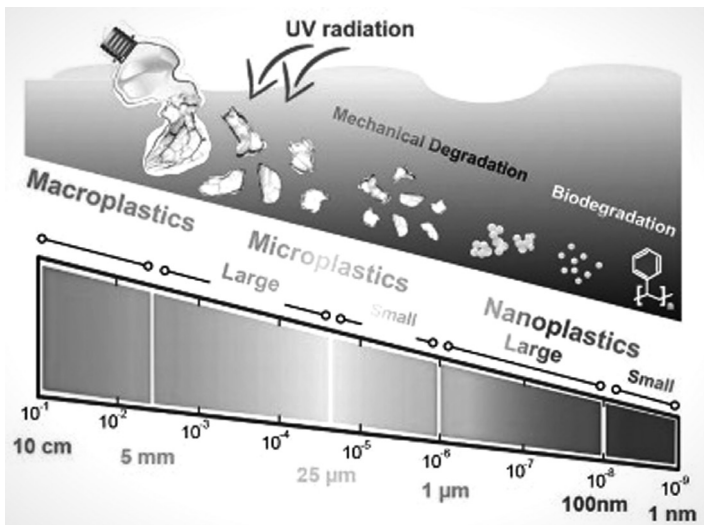


Figure 2.12 Degradation flow and size-based definition of plastics (*Source*: Gilliber *et al.*, 2019).

- **Surface morphological change**

The increased specific surface area of MPs caused by fragmentation provides for better contact with water/sediment, resulting in faster chemical leaching or sorption rates and more space for biofouling. Degradation is defined as any change in the physical or chemical properties of a polymer caused by chemical, physicochemical (photodegradation, thermal degradation, mechanical degradation), or biological processes. Hydrolysis and oxidation are the most common polymer degradation mechanisms, which can be influenced by chemical or biological factors, some examples of which are the number of polymer branches, the molecular weight, the hydrophobicity/hydrophilicity ratio, the crystallinity, and the shape of the polymer. Based on the given factors, PVC is most susceptible to degradation, followed by HDPE and PE. (Figure 2.13) (Fotopoulou & Karapanagioti, 2015).

- **Surface area and porosity**

With the erosion of polymers, the specific surface area of plastics, mainly PET and PVC, increases. The pore volume of polymers is altered in numerous ways depending on their original condition, which results in different erosion processes and attributes after erosion. PET is more sensitive to biodegradation and the development of a biolayer that may interact with contaminants due to its increased specific surface area (Figure 2.14).

2.3 BIOACCUMULATION AND BIOMAGNIFICATION

2.3.1 Definition of bioaccumulation and biomagnification

Bioaccumulation refers to the accumulation and concentration of contaminants in organisms. Bioaccumulation is the sum of all absorption and loss processes, including respiratory and dietary intake and losses through egestion, passive diffusion, metabolism, transfer to offspring, and growth. As a result, bioaccumulation encompasses the more specialized bioconcentration and biomagnification processes (Figure 2.15). Bioconcentration is the process of chemicals being directly partitioned between water and the organism, resulting in higher concentrations in the latter. Biomagnification occurs when the feeder takes up contaminants in the diet, resulting in larger quantities in the feeder than in the diet. As a result of biomagnification, chemical concentrations rise along with trophic position in the food chain.

Direct uptake from water occurs through respiration, whereas indirect uptake occurs through food. Respiration, metabolism, egestion and growth dilution are examples of loss mechanisms. From the water to animals, bioaccumulating pollutants rise by more than 5000 times. As the total biomass per trophic level in the food chain declines (but the contaminants remain), contaminant concentrations rise as the food chain progresses (Borgå, 2013). MPs can reach the food chain and be transported between trophic levels, indicating bioaccumulation and biomagnification (Figure 2.16).

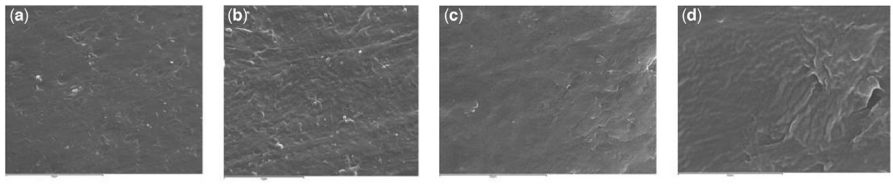


Figure 2.13 The surface topography of virgin plastic pellets from SEM for (a) high-density PE pellets enlarged 1000 times (note the gray scale bar at the bottom of the image; scale bar 60 μm), (b) high-density PE pellets enlarged 5000 times (scale bar 10 μm), (c) low-density PE pellets enlarged 1000 times (scale bar 60 μm), (d) low-density PE pellets enlarged 5000 times (scale bar 10 μm) (*Source*: Fotopoulou & Karapanagioti, 2012).

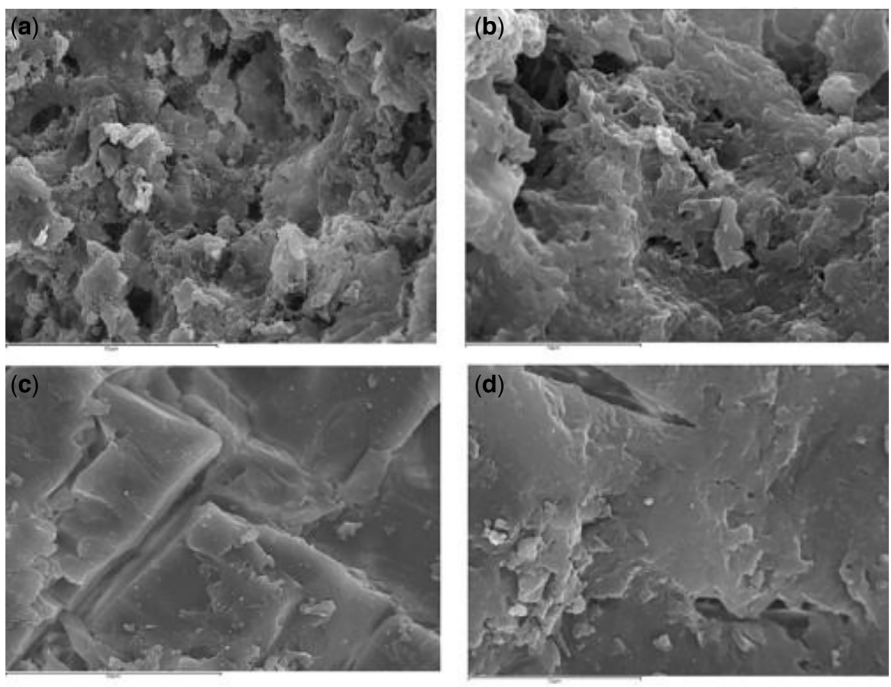


Figure 2.14 The surface topography of eroded plastic pellets from SEM for (a) PE pellets enlarged 1000 times (note the gray scale bar at the bottom of the image; scale bar 60 μm), (b) PE pellets enlarged 5000 times (scale bar 10 μm), (c) PP pellets enlarged 1000 times (scale bar 60 μm), (d) PP pellets enlarged 5000 times (scale bar 10 μm) (*Source*: Fotopoulou & Karapanagioti, 2012).

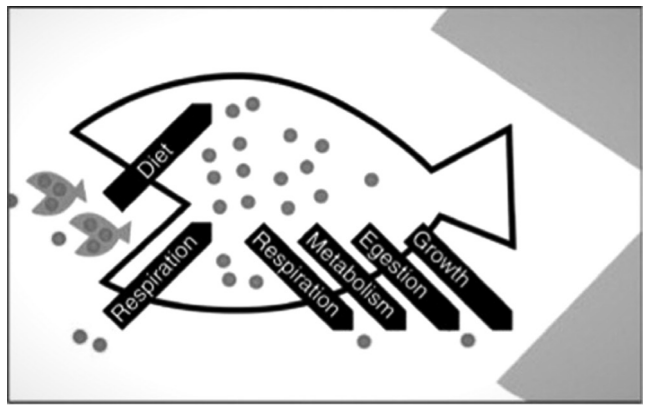


Figure 2.15 Bioaccumulation of contaminants (dots) to an organism (fish) as a net result of uptake and loss processes (arrows) (*Source*: Borgå, 2013).

2.3.2 Bioaccumulation of plastics in the food web

2.3.2.1 Bioaccumulation of plastic particles in environmental media and food webs

Plastic particles interact with marine organisms at all levels of the food chain in various ways. Bioaccumulation of plastic particles is a process that is based on an organism's ability to take plastic particles into its body through an exposure pathway. MP can be consumed directly or indirectly by organisms and remain in the body (e.g., on external appendages; Cole *et al*., 2013) and/or be absorbed (i.e., taken up by the organisms into the body through cell membranes). MP absorption is observed in phytoplankton (Bhattacharya *et al*., 2010; Long *et al*., 2015). MPs can be taken up through the gills during the ventilation process, as seen in crabs (Watts *et al*., 2014).

Over a hundred marine species have reportedly consumed MPs directly as food or accidentally capturing them while feeding and/or mistaking them for prey (Farrell & Nelson, 2013; Lusher, 2015).

Adverse physiological and biological effects of MPs have been reported in several invertebrates depending on the 'size of MPs,' with smaller sizes having more cellular impacts (Figure 2.17). Although it has been commonly reported that plastics are easily ingested and ejected in the micro-meter range, further research is necessary to confirm the contamination of more organisms and the effects of MP uptake and retention.

2.3.2.2 Amount and concentration of accumulated plastic particles in the food web through predation

Few studies have investigated the amount of MPs in tissues or blood fluid of organisms collected in the environment. Evidence for internal MP exposure is mainly limited to filter-feeding mussels and sediment-feeding polychetes, as seen in Table 2.8.

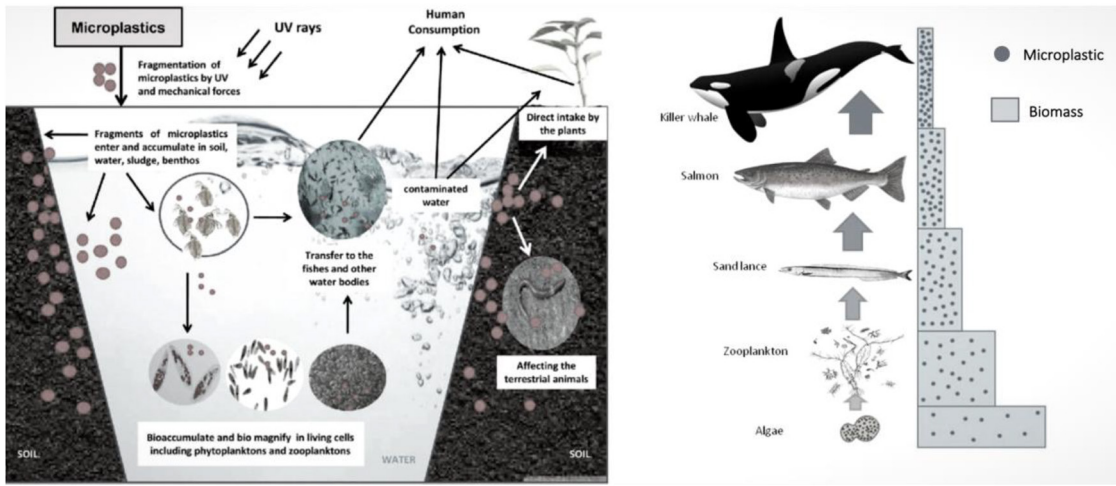


Figure 2.16 Possible bio-accumulation and bio-magnification of MP in our environment (*Source*: Adapted from Miraj *et al.*, 2021).

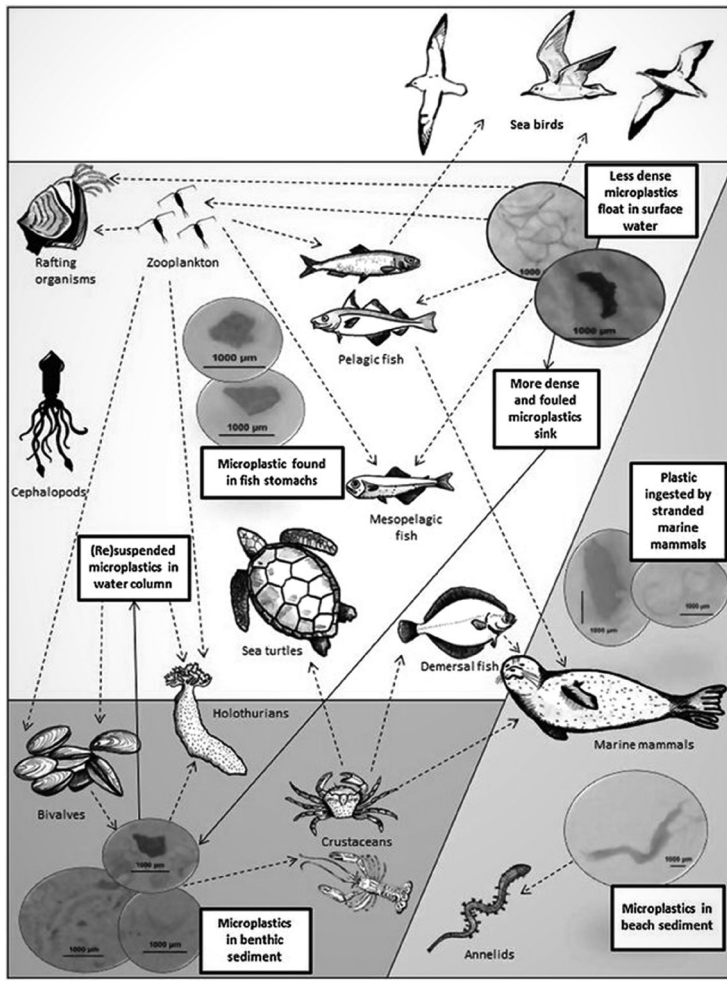


Figure 2.17 MP interactions with physical and biological matrices in the marine environment. Solid arrows represent environmental links (i.e., how MPs may transfer between sediment and water) and dashed arrows represent biological links (i.e., how MPs may transfer among trophic levels) (*Source*: Lusher, 2015).

2.3.2.3 Bioaccumulation of absorbed contaminants carried by plastic fractions (a case study of POPs)

Plastics, being hydrophobic, tend to 'absorb hydrophobic persistent organic pollutants' (POPs) such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) while circulating in marine and other water bodies, resulting in increasing potential threats associated with accumulated pollutants.

Table 2.8 MP uptake and transition into tissues, cells and organelles of marine animals.

Species	Plastic Type and Size	Exposure Pathway	Accumulated Organelles	Average Concentration	References
 ***Mytilus edulis***	Microscopic polystyrene particles (3 and 9.6 μm)	Ingestion	Accumulated in the gut, then translocated to the circulatory system within 3 days and were taken up by hemocytes	NA	Browne *et al.* (2008)
 **Marine mussels (a species used for human consumption)**			Accumulated in the gut, then moved from the gut to the circulatory system and was retained in the tissues	-4.5 ± 0.9 particles in their tissue -5.1 ± 1.1/100 L of extracted hemolymph	Van Cauwenberghe *et al.* (2013)
 **Lugworms**			Accumulated in the gut and retained in the tissues	19.9 ± 4.1 particles in their tissue and coelomic fluid	
 **Marine mussels**	HDPE powder (>0–80 μm)	Ingestion	Intracellular uptake into the digestive tubules and accumulation inside of lysosomes coincides	NA	von Moos *et al.* (2012)
 **Shore crab (*Carcinus maenas*)**	Fluorescently labelled polystyrene microspheres (8–10 μm)	Inspiration across the gills	Retained within the body tissues of the crabs for up to 14 days following ingestion and up to 21 days following inspiration across the gill	NA	Watts *et al.* (2014)

POPs are a type of very toxic chemical pollution that has been identified as a severe global threat to human health and ecosystems. Because of their potential hazards, POPs are subject to limitations and bans under the Stockholm Convention on Persistent Organic Pollutants. Plastic additives (softeners and flame retardants) recognized by the international community as POPs include short-chain chlorinated paraffin (SCCPs), polybrominated diphenyl ethers (PBDEs), nonylphenols, octylphenols, and per- and polyfluoroalkyl substances (PFAS). Specifically, POPs are lipophilic and are absorbed in fatty tissues through the process of bioaccumulation. These POPs can remain intact for exceptionally long periods or many years with the half-life varying from days to years. In living organisms, including humans, POPs can be found at high concentrations and are linked to cancer, reproductive harm, or other diseases.

In water, accumulated contaminants can exhibit up to 100 times higher concentration compared to their background levels. When ingested, some of these compounds have been found to desorb into the tissues of marine organisms. MP ingestion is possibly a significant source of organic pollution exposure for aquatic species. Desorption rates can reach up to 30 times greater in the intestinal environment of warm-blooded species (38°C, pH 4) than in aquatic systems. As a result, MPs may be more relevant than previously considered in mammals, including humans. However, it is questionable how much plastic debris contaminated with accumulated pollutants contributes to the body burden (the total amount of hazardous chemicals in the body). Furthermore, environmental factors such as pH, temperature can affect the absorption–desorption rate and pathway of pollutants, which can be both MPs, the pollutants themselves and other substances absorbed on MPs, in organisms as shown in Figure 2.18.

2.3.2.4 Amount and concentration of absorbed contaminants carried by plastic fractions (a case study of POPs)

The amount and concentration (C) of absorbed contaminants carried by plastic fractions to other phases/organisms can be determined by the following equation:

$$K = \frac{C_{\text{biota}}}{C_{\text{microplastic}}} \tag{2.1}$$

where K is partitioning coefficient, C_{biota} is the concentration of an absorbed contaminant in the organism/biota and $C_{\text{microplastic}}$ is the concentration of an absorbed contaminant on the MP surface.

As shown in Figure 2.19, the levels of DDT accumulated in the tissues of living organisms proceed up the food chain from producers to consumers. The DDT quantity in the tissues of the heron at the base of the food chain is approximately 1 million times higher than the DDT concentration in the water (Yu *et al.*, 2019)

2.3.3 Biomagnification of plastic litter in the food web

2.3.3.1 Transfer of plastic particles to the food web

MP particles may be transferred through the food web as predators consume prey. As the producer and primary consumer, all 10 zooplankton taxa examined

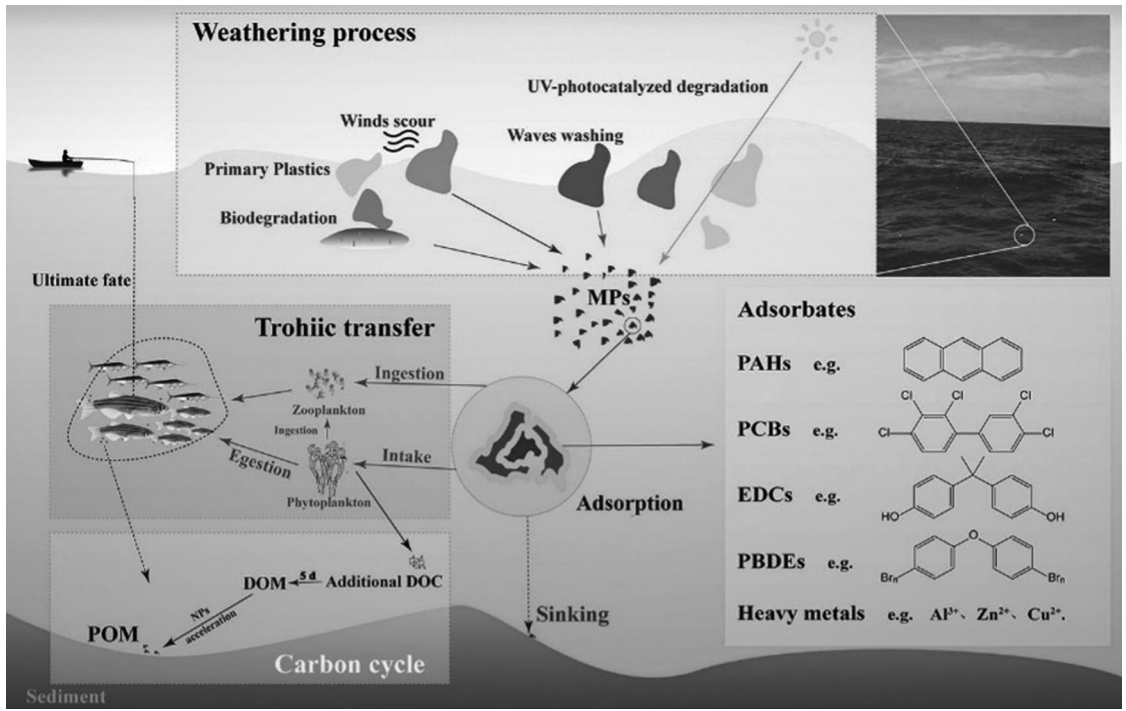


Figure 2.18 Effects of environmental factors on the properties and absorption behavior of MPs and normal contaminants (*Source*: Yu *et al.*, 2019).

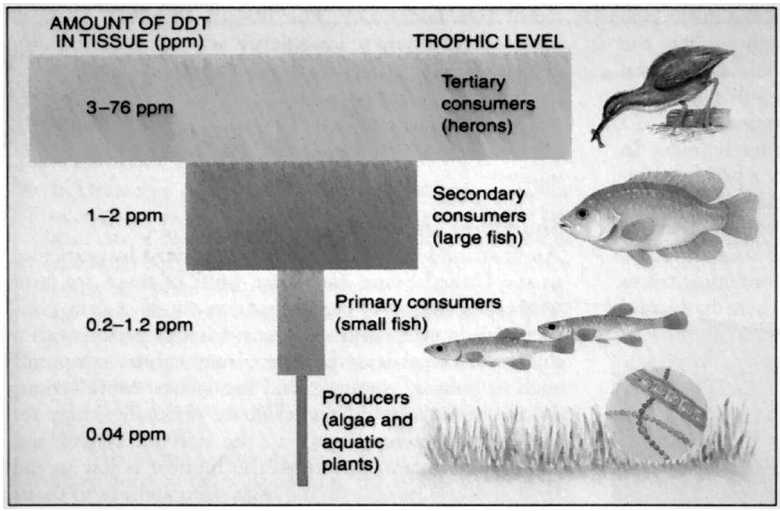


Figure 2.19 Level of DDT concentrates on the tissues of various organisms along the food chain from primary producers to top consumers (*Source*: Walsh *et al.*, 2008).

from the Baltic Sea ingested 10 μm polystyrene microspheres in a laboratory feeding experiment. Microparticles found in zooplankton were transferred after mysid shrimps consumed them, indicating that MPs can be spread along the food chain (Setälä *et al.*, 2014).

Consequently, at the upper level, the crabs (*Carcinus maens*) were fed mussels (*Mytilus edulus*) that had been exposed to 0.5 m polystyrene microspheres. As a result, MPs were found in crabs' stomachs, hepatopancreas, ovaries, and gills, with the highest concentration detected 24 hours after feeding. After 21 days, the crabs had excreted nearly all of the ingested MPs (Farrell & Nelson, 2013). In a similar study, Lusher *et al.* (2013) found MP particles in the gastrointestinal tracts (GITs) of 36% of 504 individual fish collected from the English Channel, confirming ingestion of MPs in prey species in the environment. Murray and Cowie (2011) also found MPs (mainly plastic strands) in the stomach contents of 62% of Norwegian lobsters (*Nephrops norvegicus*) collected from the Clyde Sea, and confirmed that plastic fibers remained in the GI tract of the lobsters.

2.3.3.2 Transfer of absorbed contaminants carried by plastic fractions (a case study of POPs)

POPs are widely present in the environment in all regions of the world. POPs can magnify up to 70 000 times the background level with high persistence ability and transmission rate. Organisms at the top of the food chain bear the greatest POPs concentration. Successive release over time results in the ubiquitous presence of POPs. A serious problem can occur when plastic particles absorb POPs, stay in the organism's cell, and desorb toxic substances over time. Moreover, POPs absorbed particles can transfer to the next generations during pregnancy and breastfeeding.

POPs can enter and contaminate fetuses of humans and other mammals before birth and can also be passed on to infants through breastmilk. POPs are extremely harmful to a developing fetus, causing health problems such as neurological diseases and deficits that last an entire life of a child. POPs are seriously harmful to infants, children, women, those who are malnutrition, and those who have a weakened immune system, such as the sick or elderly. Children due to their lower body weight or lower immune response are more susceptible to POPs than adults since they are exposed to higher amount of pollutants when compared to adults.

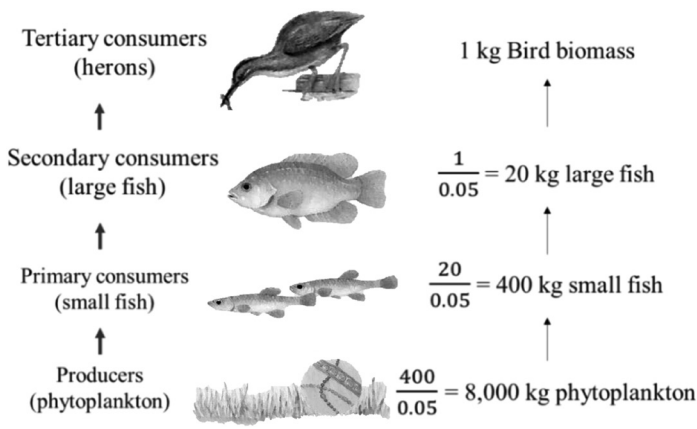
Example of transfer of absorbed contaminants carried by plastic fraction

In terms of the aquatic food chain;

$$y = 0.05\left[\frac{\text{mg Biomass}}{\text{mg Substrate utilized}}\right]$$

Notice: 5% of biomass produced from consuming 1 mg of substrate utilized (Burian *et al.*, 2020).

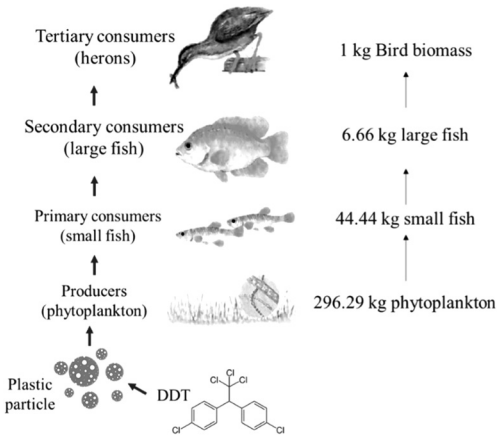
To produce 1 kb of bird biomass, birds need to consume at least 8000 kg of phytoplankton



Question: To supply a certain biomass for human beings, how much phytoplankton should be produced? And if plastic particles accumulate in phytoplankton, how many plastic particles are transferred to a higher level in the food chain, like humans?

Example 1: Aquatic food chains include plankton, smelt, trout and birds. Assume yield coefficients at each level to be 0.15 and that 95% of the pollutant is transferred to the next level up the food chain. Assume that DDT has a plastic particle to plankton partition coefficient ($K_{pt/p}$) of 250 000 and 100% desorption into plankton cell. If the concentration of DDT in the plastic particle is 1.0 ppt, estimate DDT concentration at each level.

Solution 1:



$$K_{pt/p} = \frac{C_{plankton}}{C_{plastic}} = 250\,000$$

$= 1.0$ ppt, $y = 0.15$ mg/kg

*95% magnification

$$C_{pt} = (2.5 \times 10^5)(1 \times 10^{-12})$$

$$= 0.25 \times 10^{-6} \text{ or } 0.25 \text{ ppm}$$

Weight of DDT in plankton;

$$= 296.29 \times 0.25 \text{ ppm}$$

$$= 74 \text{ mg}$$

Organisms/ Predators	Accumulated Concentration of DDT	Accumulated Weight of DDT (mg)	Amount Transferred (mg)
Bird	$\frac{63.5 \text{ mg}}{1 \text{ kg}} = 63.5$ ppm	63.5 ppm × 1 kg = 63.5	60.3
Large fish	$\frac{66.8 \text{ mg}}{6.66 \text{ kg}} = 10.02$ ppm	10.02 ppm × 6.66 kg = 66.8	63.5
Small fish	$\frac{70.3 \text{ mg}}{44.44 \text{ kg}} = 1.58$ ppm	1.58 ppm × 44.44 kg = 70.3	66.8
Phytoplankton	0.25 ppm	74	70.3
Plastic particles	1.0 ppt		

Example 2: Hexachlorobenzene (HCB) is a plastic particle for plankton partition coefficient ($K_{pt/p}$) of 200 000; a plankton to smelt magnification factor of 7.5; and a smelt to lake trout magnification factor of 3.5. If the concentration of HCB in plastic particles is 1.0 ppt, will either fish exceed the fish consumption standards?:

5 ppm for general consumption
1 ppm for pregnant and nursing women

Solution 2:

$$K_{pt/p} = \frac{C_{plankton}}{C_{plastic}}; \quad C_{plankton} = [2 \times 10^5][1 \times 10^{-12}] = 0.2 \times 10^{-6} \text{ or } 0.2 \text{ ppm}$$

$$\frac{C_{smelt}}{C_{plankton}} = 7.5; \quad = 7.5 \times 0.2 = 1.5 \text{ ppm}$$

$$\frac{C_{trout}}{C_{smelt}} = 3.5; \quad = 3.5 \times 1.5 = 5.25 \text{ ppm}$$

Interpretation:

- Lake trout exceeds general consumption standards and both species exceed the standard for pregnant and nursing women.
- Both could easily argue based on uncertainty.

2.3.3.3 Lifetime and excretion pathway

The presence of MPs in organisms indicates recent exposure to these particles. MPs either accumulate or are excreted after being ingested into the body (hemolymph or tissues) depending on the size, shape, and composition of the particles. If MPs accumulate, chemical and/or physical effects are likely to occur and remain over time. If excreted, these side effects should be eradicated throughout the healing and repair phase. After a single particular exposure, MP concentrations in the hemolymph rise at a specific time (which varies by species, plastic type, and exposure time) and subsequently decrease in abundance (Browne *et al.*, 2008; Farrell & Nelson, 2013). The amount that is removed or transferred to other organ systems or tissues is unknown. According to a study of von Moos *et al.* (2012), the elimination of MPs from the digestive tubules after a period of 12–48 hours, and a shift of HDPE particles into the newly formed connective tissue (fibrosis) around the tubules, indicate a repair mechanism of injured tissue, as shown in a study in mussels after acute exposure to HDPE (0–80 μm size range) for 12 h followed by regeneration in plastic-free seawater. Similar studies with PVC MPs demonstrated particle retention in the stomach for up to 12 days, with smaller particles retaining longer than bigger particles.

2.4 ECOLOGICAL TOXICITY OF PLASTICS

2.4.1 Fundamentals of toxicology and the environment

In conventional terms, toxicology can be defined as the scientific study of the effects of toxicants on biological systems, which can be humans, animals, and other living organisms. Toxicological research has significantly contributed to an understanding of the basic mechanisms on how contaminants and/or pollutants cause adverse effects and health impacts. More recently, toxicology has been considered as 'the study of all the negative effects of chemicals and physical agents interacting with living organisms.' (Costa & Teixeira, 2014).

A study of the effects of poisons revealed poisonous substances can be produced by plants (phytotoxins), animals (zootoxins), or bacteria (bacteriotoxins). The specific chemical substances produced and released by poisonous living organisms are defined as 'toxicant'. On the other hand, an anthropogenic and/or man-made substance that is not normally found in the body is known as 'xenobiotic' (Gupta, 2020).

The amount of an agent or chemical offered to an animal, or a human, is referred to as a 'dose'. In this context, a response refers to an observation or effect detected in an animal or a human during or after exposure to the agent. Exposure refers to an instance when an animal or a human comes into contact with or is exposed to an agent or chemical (dose). The concept of exposure is determined by the routes of exposure, the frequency of exposure, and the duration of exposure

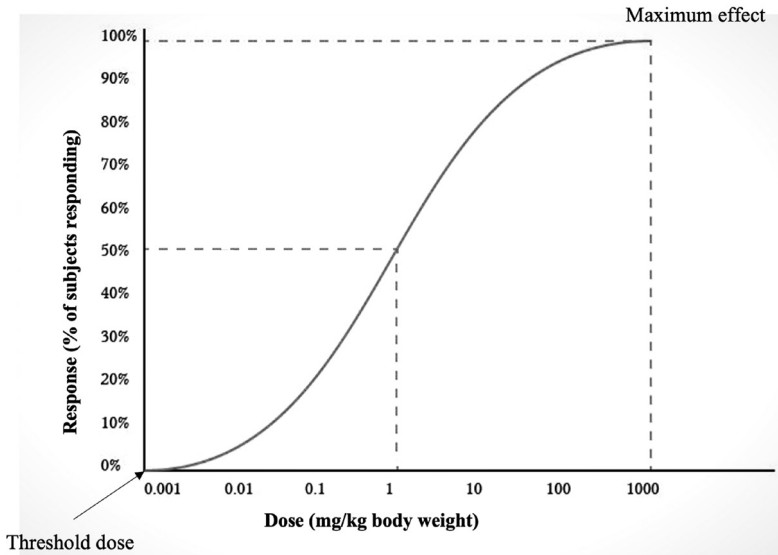


Figure 2.20 Dose–response relationship; threshold dose is the lowest dose at which a drug effect is seen, maximum effect is the maximum effect achievable by that dose (*Source*: adapted from Yartsev, 2015).

(acute vs. chronic) (WHO, 2019). However, routes of exposure can be classified into four pathways, including ingestion (water and food), absorption (through skin), injection (bite, puncture, or cut) and inhalation (air). The exposure route of greatest concern for humans is inhalation. Exposure to any substance in a specific concentration (dose) can cause a distinct response. The relationship is defined as 'dose–response relationship' (Figure 2.20). Exposure duration and frequency are also important factors in determining dosage. Acute exposure is defined as a single exposure lasting less than 24 hours. Repeated exposures are classified as: sub-acute – repeated for up to 30 days; sub-chronic – repeated for 30–90 days; and chronic repeated for over 90 days.

The fundamental premise of toxicology is an individual's reaction to a dosage. The variety of responses among organisms that get the same dose of chemical is due to individual susceptibility. In all cases concerning chemicals, including those involving medicine and coffee, dose and individual susceptibility play a role. Individual susceptibility and variability, such as age, sex, individual variability, genetic variations, and species differences, distinguish a poison from a remedy.

2.4.2 Ecological toxicity and impacts of plastics

The effects of MPs exposure have been investigated at several levels of biological organization, ranging from the gene to the population level, providing a lot of information on organism interactions, exposure pathways, and biological consequences. However, most studies on the impact of MPs have focused on biological responses, and data on population and ecological levels is still

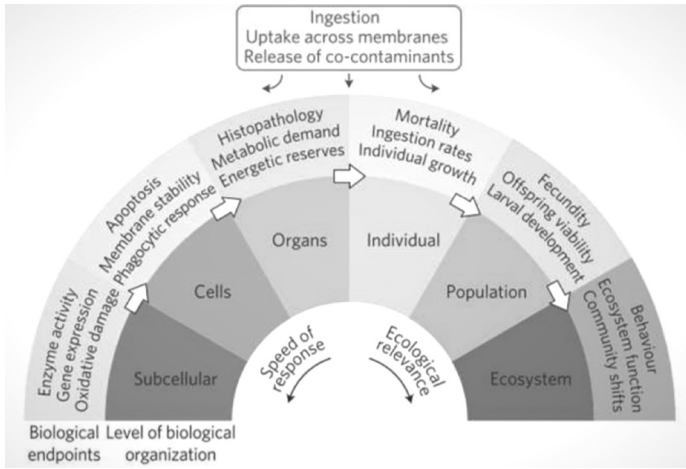


Figure 2.21 Schematic representation of impacts associated with MPs exposure across different levels of biological organization (*Source*: Ašmonaitė & Almroth, 2018).

limited. The adverse effects of direct MP exposure on organisms, including the consequences, are briefly described here. While particle characteristics (size, shape, polymer), chemical exposure (leachates or sorbed environmental contaminants), and exposure possibilities (exposure routes, concentrations, etc.) all have an impact on biological effects, the importance of aspects for mediating biological effects is also discussed in this report. MPs are ingested by fish, and their consumption can interfere with biological processes such as gastrointestinal function inhibition, as well as producing obstructions and causing feeding impairment (Figure 2.21).

2.4.3 Differential risk of marine litter interactions across the oceanic gradient

Aquatic population that live in environments where hydrographic patterns such as coastal systems or mesoscale oceans combine food and floating plastics (Pichel *et al.*, 2007). Surprisingly, one of the first field observations of this occurrence occurred from the Humboldt Current System (HCS) off Chile's central coast, where Bourne and Clark (1984) saw planktivorous seabirds feeding on a coastal front that also had a substantial concentration of floating plastics.

Even though floating trash volumes are lower than those in the fresh waters, these interactions are prevalent in the productive upwelling systems of the eastern boundary currents (for a summary, see Scales *et al.*, 2014) and present a massive risk to marine vertebrates.

Marine productivity is low in the ocean, particularly in the oligotrophic subtropical zones, and is often concentrated above seamounts or around marine habitats. Some species are at high risk of harmful interactions with floating plastics if these islands are within the area of the subtropical gyres' trash accumulation zones (Figure 2.22).

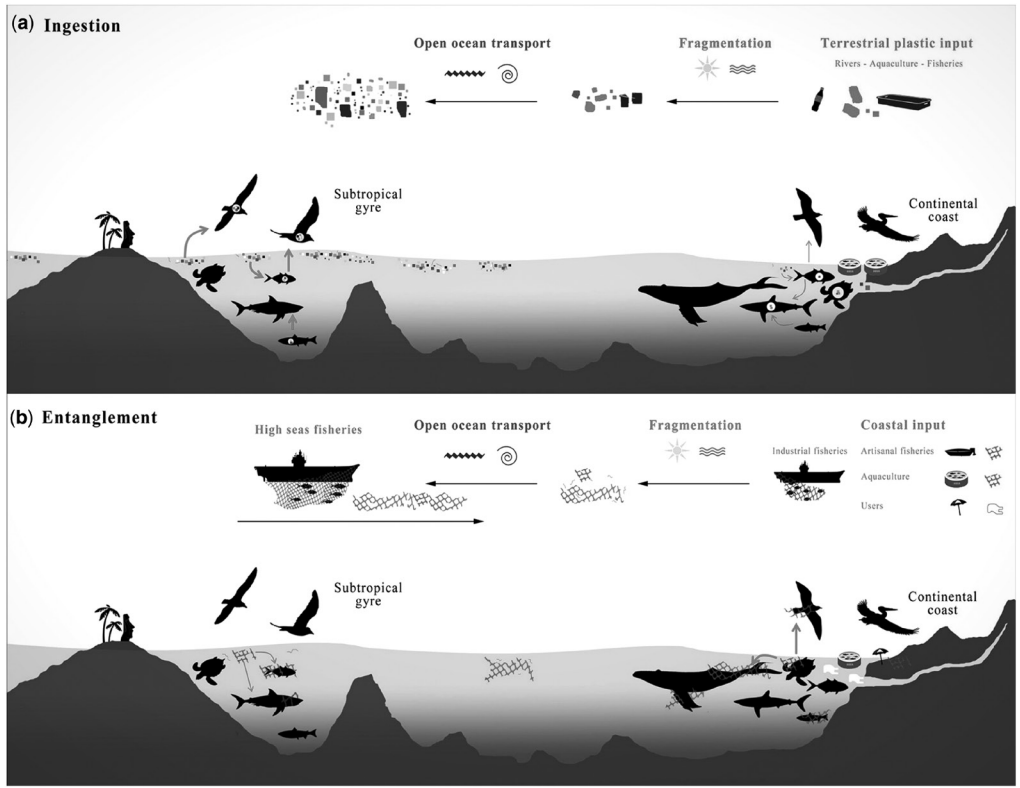


Figure 2.22 Conceptual model of (A) ingestion and (B) entanglement by marine vertebrates with anthropogenic marine plastics, highlighting the litter sources and abiotic processes (upper part of figures) and the interactions with marine invertebrates (bottom part of figures) (*Source*: Thiel *et al.*, 2018).

2.4.4 Toxicity of plastic and carried substance in aquatic life

MPs have been detected in the intestines of benthic invertebrates, fish, and larger mammals at various trophic levels, and the ingested MPs are transferred along the food chain, causing concerns about the threat to aquatic biota. MP particles that have dispersed in aquatic, terrestrial, and atmospheric ecosystems have a high bioavailability for various species, resulting in higher ecological toxicity than macroplastics. As a result of interference with fecundity, mortality and the dosage–effect relationship with physiological stress, including behavioral alterations, immune responses, abnormal metabolism, and changes in energy budgets, both direct and indirect evidence for the adverse effects of MPs have been found.

2.4.4.1 Heterogeneity of physicochemical properties

MPs' physicochemical properties are employed as the core information in toxicological investigations.

2.4.4.2 Physical properties

Bioavailability, a significant indicator of MPs' potential impact on various species, is determined by the pollutant's characteristics and the organisms' foraging habits. Unlike most selective foragers, species with general feeding patterns and prey capture mechanisms (e.g., predators that simply identify food from other objects based on a few criteria) are more likely to consume MPs that look like their normal prey (Peters *et al.*, 2017).

Physical properties influence the morphology and mobility of MPs in the aquatic environment, affecting bioavailability by modifying dispersion throughout the aquatic environment, resembling natural substances and causing different levels of physical damage to organisms. The size, color, density, and shape of MPs are the most explored physical properties, and each contributes differently to the serious implications.

- **Particle size**

MPs are about the same size as sand grains, microalgae and plankton, and are consumed by a variety of aquatic species, particularly nonselective foragers (Baldwin, 1995). Kpkalj *et al.* (2018) found that the rate of MP uptake by *Daphnia magna* is proportional to particle size, and the number of daphnids having MPs in their guts falls as the average particle size increases. The most common size of MPs consumed by daphnids was less than 100 μm, which corresponds to its size preference for food. Fernández (2001) revealed that *Artemia franciscana*, due to its smaller food feeding preferences (50 μm) than daphnids, on the other hand, consumed fewer MP particles under the same MP exposure settings. Ory *et al.* (2017) found that most ingested MPs by the amberstripe scad *Decapterus muroadsi* (Carangidae) fish are typically 1.3–0.1 mm in size, similar to their prey. Resulting from consumption, particle size is an important factor in influencing the ability of MPs to translocate throughout an organism's body. Browne *et al.* (2008) found that the smaller MPs (3.0 μm) translocate more easily and readily within *Mytilus edulis* than the bigger particles (9.6 μm).

- **Particle shape**

Another important property in determining the interaction of polymeric particles with biological systems is the shape of particles (Wright *et al.*, 2013). Particles with a more irregular or needle-like shape may attach more readily to internal and external surfaces and have a greater effect in both cases. To illustrate this, Au *et al.* (2015) examined the impact of particle shape on the amphipod *Hyalella azteca* and found that polypropylene (PP) fibers were more hazardous than PP beads, illustrated in Table 2.9. Hua *et al.* (2014) also found that when zebrafish embryos were tested for mortality and hatching inhibition, zinc oxide nano-sticks caused more toxicity than nanospheres. Several relevant research or investigation studies on the particle toxicology and its impact (Besseling *et al.*, 2014; Farrell & Nelson, 2013; Lee *et al.*, 2013; Rosenkranz *et al.*, 2009; Setälä *et al.*, 2014) are summarised in Table 2.9.

- **Surface area**

The surface area is a significant characteristic since it increases as particle size decreases; hence, nanoscale particles can have greater effects. Although the surface area is not commonly reported in MPs research, it can be determined for primary micro-beads using spherical equivalent diameter, but this can result in an overestimation for irregularly shaped secondary MPs. For example, La Rocca *et al.* (2015) discovered that using geometrical estimates to estimate the surface area of nanoscale soot particles can result in a sevenfold overestimation of the surface area, requiring the application of a particle shape factor for adjustment.

- **Polymer crystallinity**

Because the crystalline region includes more ordered and strongly structured polymer chains, crystallinity is an important polymer characteristic. Physical properties such as density and permeability are changed, which affect hydration and swelling behaviour. Environmental MPs' crystallinity will change over time as they degrade. As the MP reduces in size, preferential breakdown in the amorphous portion of the polymer causes the overall crystallinity to rise (Gopferich, 1996). Crystallites will form as a result, and their toxicity may differ from that of the original MPs. Changes in crystallinity will affect the physical (surface area, particle shape, particle size, and density) and chemical (leaching of additives, adsorption of contaminants) aspects of environmental MPs, influencing ingestion rates and effect outcomes.

2.4.4.3 Chemical properties

- **Polymer types and additives**

Leaching of chemicals such as residual monomers, starting ingredients, solvents, catalysts, and additives (e.g., antioxidants, colors, biocides, plasticizers) introduced during compounding and processing can induce plastic-related toxicity (Andrady, 2015). Several monomers and additives used in the manufacturing of different plastic types have well-known toxicity

Table 2.9 Toxicity of different MP sizes, particle types and observed responses.

Organism	Particle Type	Main Findings	Reference
Hyallela azteca	Polyethylene MPs (powder; size: 10 and 27 μm) Polypropylene fibers (secondary; length 20–75 μm; dia. 20 μm)	Fibers were found to be more toxic than particles with 10-d LC_{50} of 71.43 fibers/ mL compared to 4.64×10^4 particles/mL.	Au *et al.* (2015)
Tigriopus japonicus	Polystyrene microspheres Size: 0.05, 0.5, and 6 μm	6 μm beads did not affect the survival over two generations, 0.05 and 0.5 μm beads caused increased toxicity and impacts on survival and development in the F_1 generation at 9.1×10^{11} and 9.1×10^8/mL	Lee *et al.* (2013)
Daphnia magna	Polystyrene carboxylated microspheres Size: 0.02 and 1 μm	Demonstrated ingestion of both bead sizes, but the 20 nm beads were retained to a greater degree within the organism	Rosenkranz *et al.* (2009)
Daphnia magna	Polystyrene microspheres Size: 70 nm	Reduction in body size and lower reproduction at concentrations ≥30 mg/L (using a nominal density of 1.05 g/cm³ this equals 74.3 billion particles/L)	Besseling *et al.* (2014)
Eurytemora affinis *Neomysis integer*	Polystyrene microspheres Size: 10 μm	Potential of transfer from meso- to macro- zooplankton at concentrations of 1000, 2000, and 10 000 particles/ mL	Setälä *et al.* (2014)
Mytilus edulis *Carcinus maenas*	Polystyrene microspheres Size: 0.5 μm	The number of MP in the haemolymph of the crabs was highest at 24 h (15 033/mL), and was almost gone after 21 days (267/mL).	Farrell and Nelson (2013)
Zebrafish embryos (*Danio rerio*)	Uncoated zinc oxide nanospheres (43 nm), nanosticks (150 nm), and cuboidal particles (900 nm)	Zinc oxide nanosticks induced higher toxicity than nanospheres and cuboidal particles for mortality and hatching inhibition endpoints.	Hua *et al.* (2014)

characteristics. Depending on how a chemical is compounded within a polymer matrix, the environmental release of additives from plastic materials and other plastic-associated chemicals can occur at any stage of the lifetime (Lambert *et al.*, 2014). Low molecular weight additives, for example, are only weakly entrenched in the polymer matrix and move quickly. Flame retardants from television housings and other electronic items (Deng *et al.*, 2007; Kim *et al.*, 2006), lead from unplasticized PVC pipes (Al-Malack, 2001), nonylphenol from food contact materials (Fernandes *et al.*, 2008), extractable PET cyclic and linear oligomers from bottles and food trays (Kim & Lee, 2012), and antimony leaching from PET water bottles are just a few additives released from consumer electronics (Keresztes *et al.*, 2009; Shotyk & Krachler, 2007; Westerhoff *et al.*, 2008). Overall, physical parameters such as the pore width of a polymer structure and the molecular size of the monomer and additives used will affect the rates at which residue monomers and additives leach (Gopferich, 1996). The relevance of leachable chemicals in terms of MP hazard potential is defined by their concentration in the parent material, partitioning coefficient, and the age and degree of degradation of a specific MP. For example, an older MP may have a higher degree of crystallinity, which means less leaching.

- **Surface chemistry**

The surface chemistry of environmental MPs will also change as they age. The plastic surface will be affected by photo and oxidative degradation processes that create new functional groups through interactions with OH radicals, oxygen, nitrogen oxides, and other photo produced radicals (Chandra & Rustgi, 1998). An increase in chemical reactions causes a plastic's surface to crack, exposing new surfaces to additional degrading processes (Lambert *et al.*, 2013). These processes may weaken the plastic surface, causing more microscopic particles to be released upon ingestion, increase chemical leaching, and increase gut retention times by forming more angular-shaped particles, distinguishing environmental MPs from primary micro-beads. However, it is unknown if these changes in surface chemistry are important determinants of toxicity in realistic exposure scenarios in the environment (Figure 2.23).

2.4.5 Ecotoxicological assessment of MPs

There are a variety of creatures that can be utilized in MPs ecotoxicological assessments; nevertheless, marine (micro)organisms were used in almost 75% of the research. Fish, mollusks, small and big crustaceans, annelids, mammals and echinoderms, birds and cnidarians, sponges, reptiles, and rotifers are commonly used as testing species. Small crustaceans predominate among creatures evaluated in a laboratory, but fish are commonly utilized in in-situ studies. Spherical particles, threads, and pieces are the most researched MPs shapes. Although PE and PS are the most studied MPs (because of their widespread prevalence in aquatic environments), ecotoxicological effects of other MPs such as PP, PES/PET, PVC, polyamide, acrylic, polyether, cellophane, and polyurethane have also been investigated. Small crustaceans predominate among creatures evaluated in a laboratory, but fish is commonly utilized in in-situ studies (Figure 2.24).

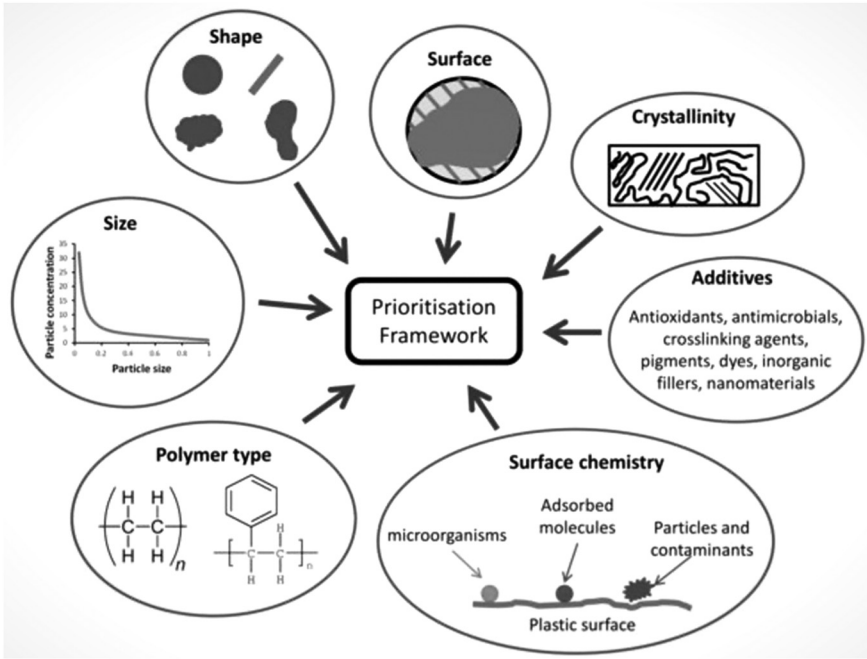


Figure 2.23 Different MP physical and chemical properties to be considered in a prioritization framework (*Source*: Lambert *et al.*, 2017).

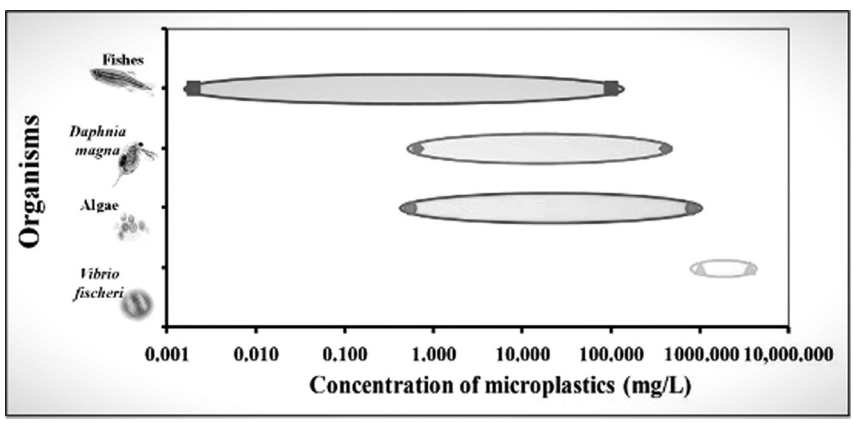


Figure 2.24 Range of ecotoxicological concentrations for different organism levels (*Source*: Miloloža *et al.*, 2021).

2.5 EFFECTS OF MPS ON HUMAN HEALTH

The rise in plastic production, use, and consumption has raised concerns about the potential impacts on human health and environment since at least the 1970s and with growing frequency and urgency over the last two decades. For most of this period, attention has focused on human health exposures to specific plastic precursors or additives, and among specific populations, for example, workers exposed to benzene, infants exposed to phthalates and other plastic additives, or consumers exposed to bisphenol A in food packaging. To date, discussion of plastic's health and environmental impacts has usually focused on specific moments in the plastic life cycle: during use and after disposal. However, the lifecycle of plastics and their related human health impacts extend far beyond these two stages in both directions: upstream, during feedstock extraction, transport, and manufacturing, and downstream, when plastics reach the environment and degrade into micro- and nano-plastics.

Although it is generally believed that plastic polymers are lethargic and of little concern to public health, different types of additives and the residual monomers possibly retained from these polymers are responsible for the suspected health risks. Most of the additives present in plastics are potential carcinogens and endocrine disruptors. Ingestion, skin contact and inhalation are the main routes of exposure of humans to these additives. Dermatitis has been reported from skin contact with some of the additives present in plastics. MPs are major contaminants that can bioaccumulate in the food chain after ingestion by a wide range of freshwater and marine life, leading to public health risks. Human consumption of animals exposed to MPs and plastic additives can be detrimental. Biomonitoring studies on human tissues have shown that plastic constituents persist in the human population by measuring environmental contaminants.

2.5.1 Plastic litter exposure pathways

Human exposure to specific plastic precursors or additives has potential impacts on health along the plastic life cycle, especially plastic waste management processes and plastics in the environment. Once plastics reach the environment in the form of macro- or MPs, they slowly fragment into smaller particles and contaminate all areas of the environment (air, water, and soil), accumulate in food chains, and release toxic additives or concentrate additional toxic chemicals in the environment, making them bioavailable again for direct or indirect human exposure. To fully assess the health impacts of our global dependence on plastic, one must therefore consider each stage of this life cycle and all possible exposure pathways of the variety of substances used and released throughout the life cycle (Figure 2.25). Impacts of any substance on human health will vary depending on the specific route of exposure to the substance: **inhalation** – what we breathe, **ingestion** – what we eat and drink, and **skin contact** – what we touch or encounter topically.

2.5.2 Public health effects of plastic additives

Different additives are used in the production of plastics and have been reported to have various detrimental effects on humans. Table 2.10 shows the different

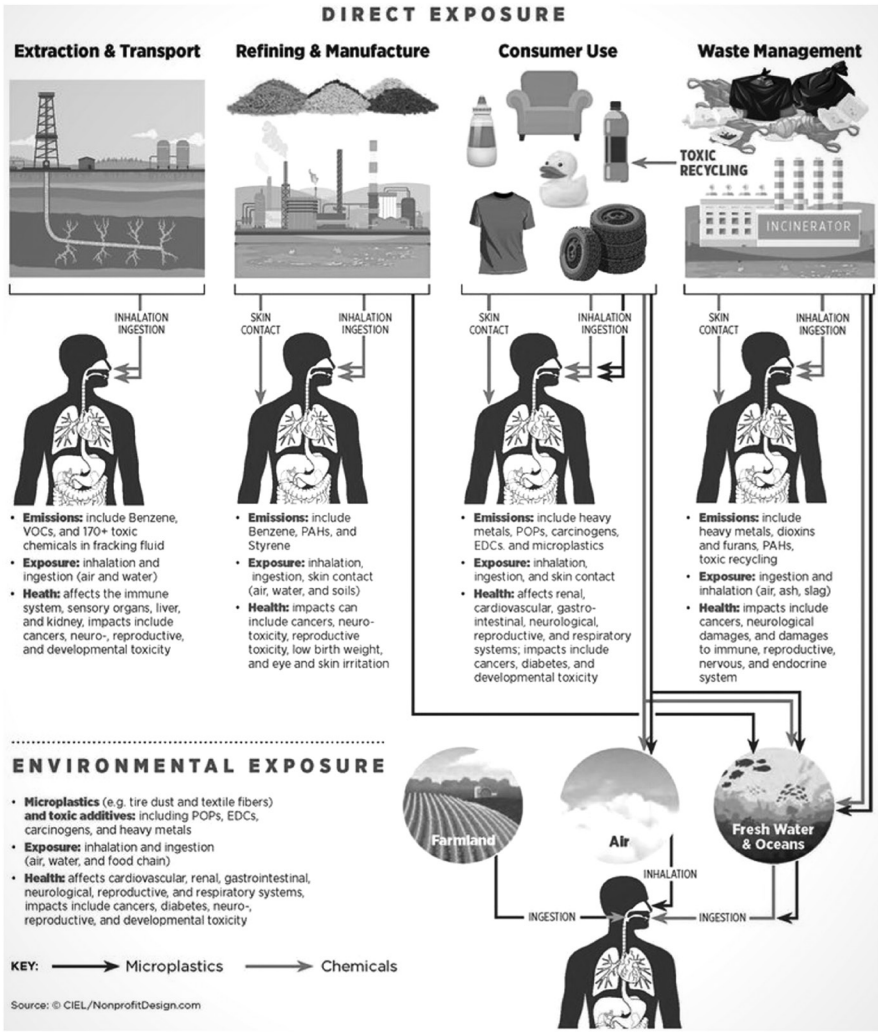


Figure 2.25 Human exposure to a large variety of toxic chemicals and MPs through inhalation, ingestion, and direct skin contact, all along the plastic lifecycle (*Source*: Azoulay *et al.*, 2019).

types of additives used in plastic production, their effects and the types of plastics.

2.5.3 Toxicity of MPs

Fiber and human health studies among nylon flock workers suggested there was no evidence of increased cancer risk, although workers had a higher

Table 2.10 Different additives used in plastic production, their effects and the plastic types.

Toxic Additives	Uses	Public Health Effect	Plastic Types
Bisphenol A	Plasticizers, can liner	Mimics estrogen, ovarian disorder	Polyvinyl chloride (PVC), polycarbonate (PC)
Phthalates	Plasticizers, artificial fragrances	Interference with testosterone, sperm motility	Polystyrene (PS), polyvinyl chloride (PVC)
Persistent organic pollutants (POPs)	Pesticides, flame retardants, and so on	Possible neurological and reproductive damage	All plastics
Dioxins	Formed during low temperature combustion of PVC	Carcinogen, interferes with testosterone	All plastics
PAHs	Used in making pesticides	Developmental and reproductive toxicity	All plastics
PCBs	Dielectrics in electrical equipment	Interferes with thyroid hormone	All plastics
Styrene monomer	Breakdown product	Carcinogen, can form DNA adducts	Polystyrene
Nonylphenol	Anti-static, anti-fog, surfactant (in detergents)	Mimics estrogen	PVC

Source: Alabi *et al.* (2019).

prevalence of respiratory irritation. Interstitial lung disease, a work-related condition that induces coughing, dyspnea (breathlessness), and reduced lung capacity, has been identified in 4% of workers from nylon flock plants in the US and Canada. Workers processing para-aramid, polyester, and PA fibers in the Netherlands presented similar symptoms, including coughing, dyspnea, wheezing, and increased phlegm production. Prick tests and nasal and inhalation provocation tests in nylon workers also found synthetic fibers, such as nylon, may act as haptens, causing an allergic reaction leading to occupational asthma. Histopathological analysis of lung biopsies from workers in the textile (nylon, polyester, polyolefin, and acrylic) industry showed interstitial fibrosis and foreign-body-containing granulomatous lesions postulated to be acrylic, polyester, and/or nylon dust. The clinical symptoms presented were similar to allergic alveolitis (a form of inflammation in the lung). Although occupational exposure likely occurs at levels higher than those in the environment, health outcomes are evidence of the potential for MPs to trigger localized biological responses, given their uptake and persistence.

Both cellulosic and plastic microfibers have been observed in non-neoplastic and malignant lung tissues taken from patients with different types of lung cancer. The fibers exhibited little deterioration, supporting the notion that they are persistent.

Additionally, these observations suggest that the human airway is of a sufficient size for plastic fibers to penetrate the deep lung; one fiber found was 135 μm in length, approximately one-quarter of the diameter of a respiratory bronchiole of generation 17 (540 μm diameter, 1410 μm length). These observations confirm that some fibers avoid clearance mechanisms and, as they persist, these foreign bodies may induce acute or chronic inflammation. In addition to persistence, fiber dimensions play a role in toxicity. Thinner fibers are respirable, whereas longer fibers are more persistent and toxic to pulmonary cells; fibers of 15–20 μm cannot be efficiently cleared from the lung by alveolar macrophages and the mucociliary escalator fibers of 10 μm in length are mostly carcinogenic.

2.5.4 Potential for and factors that may affect bioaccumulation

An essential factor determining whether MPs present a physical threat or act as a vector for chemical transfer is the ability of these particles to accumulate. Throughout evolution, both the lungs and GIT have likely been exposed to non-degradable, exogenous nano and microparticles, and endogenous nanoparticles. Recently, there has been an increased dietary influx of non-degradable microparticles, approximately 40 mg/person/day, primarily due to their inclusion as additives in processed foods. The contribution of MPs to exogenous microparticle exposure is unknown, however, the biological response to MPs in comparison to other non-degradable microparticles could differ due to their unique chemical composition and properties. MPs are resistant to chemical degradation in vivo. If inhaled or ingested, they may also resist mechanical clearance, becoming lodged or embedded. Their bio-persistence is an essential factor contributing to their risk, along with their use. The findings suggested nano- and microparticles could translocate across living cells to the lymphatic and/or circulatory system, potentially accumulating in secondary organs, or impacting the immune system and health of cells. Retention time, and therefore the likelihood of uptake and clearance, is influenced by particle characteristics such as size, shape, solubility, and surface chemistry; by biological factors such as the anatomical site of deposition and structure; and by the nature of particle interaction with different biological structures, including the air–liquid interface, aqueous phase, and free cells (e.g., macrophages, dendritic cells, epithelial cells). Uptake of inhaled MPs will depend on their wettability; it is possible that inhaled MPs deposited in the airway will not be immersed in the lung-lining fluid due to their hydrophobicity and may therefore be subjected to mucociliary clearance leading to exposure via the gut (Figure 2.26a). The shape also affects displacement at the air–liquid interface; shapes with sharper edges are less likely to be displaced in liquid. However, the histological prevalence of plastic microfibers in flock workers and lung cancer tissue biopsies implies that uptake and embedment of at least plastic microfibers are possible. As with lining fluid of lungs, mucus is the first layer in the GIT that foreign particles interact with. Here, mucus can cause particles to aggregate; surfactants reduce mucus viscosity, increasing the uptake of particles.

Size and surface charge also influence the ability of MPs to cross the GIT mucus gel layer and contact the underlying epithelial cells; smaller sizes and negative surface charge are most likely to lead to increased uptake. If a MP

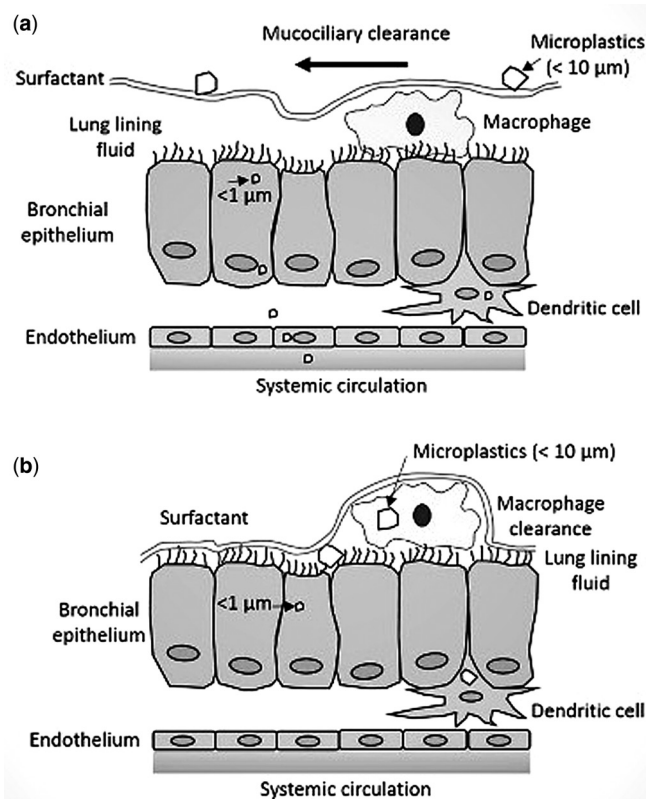


Figure 2.26 Potential MP (0.1 $>$ 10 μm) uptake and clearance mechanisms in the lung. (a) The chance of MP displacement by the lung-lining fluid (surfactant and mucus) is reduced in the upper airway, where the lining is thick (central lung). Here, mucociliary clearance is likely for particles $>$1 μm. For particles $<$1 μm, uptake across the epithelium is possible. (b) If the aerodynamic diameter of a MP permits deposition deeper in the lung, it may penetrate the thinner lung-lining fluid and contact the epithelium, translocating via diffusion or active cellular uptake (*Source*: Wright & Kelly, 2017).

contacts the airway or gastrointestinal epithelium, there are several routes of uptake and translocation that may occur. This is primarily via endocytic pathways in the lung and GIT, and also via perception in the GIT. Paracellular transfer of nanoparticles through the tight junctions of the epithelium has been postulated for the GIT. Although tight junctions are extremely efficient at preventing such permeation, their integrity can be affected, potentially allowing for particles to pass-through (Figure 2.27).

2.5.5 Toxicity of MP particles to cells and tissues

Compared to chemicals used in plastic, less is known about the toxic effects of plastic particles in the human body. A recent review of potential health

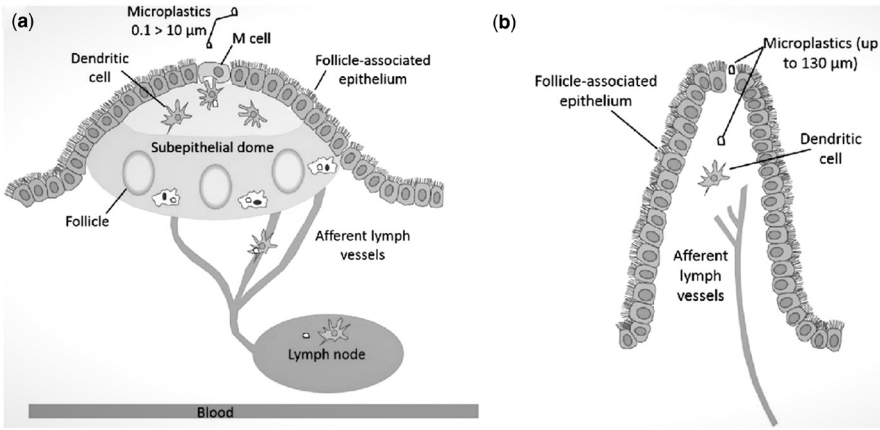


Figure 2.27 Predicted pathways of MP uptake from the GIT. (a) MP ($0.1 > 10\,\mu m$) uptake from the GIT lumen via endocytosis by the M cells of the Peyer's patches. M cells sample and transport particles from the intestinal lumen to the mucosal lymphoid tissues. (b) MP uptake from the GIT lumen via paracellular perception. Nondegradable particles, such as MPs, may be mechanically kneaded through loose junctions in the single-cell epithelial layer into the tissue below. Dendritic cells can phagocytose such particles, transporting them to the underlying lymphatic vessels and veins. Distribution of secondary tissues, including the liver, muscles and brain, could occur (*Source*: Wright & Kelly, 2017).

risks of MP particles listed concerns that MP entering the human body could lead to inflammation (linked to cancer, heart disease, inflammatory bowel disease and rheumatoid arthritis among others), genotoxicity (damage to the genetic information within a cell causing mutations, which may lead to cancer), oxidative stress (leading to many chronic diseases such as atherosclerosis, cancer, diabetes, rheumatoid arthritis, post-ischemic perfusion injury, myocardial infarction, cardiovascular diseases, chronic inflammation and stroke), apoptosis (cell death associated with a wide variety of diseases including cancer), and necrosis (cell death associated with cancer, autoimmune conditions, and neurodegeneration). Over time, these effects could also lead to tissue damage, fibrosis and cancer.

All plastic contains reactive oxygen species (ROS), or free radicals, which are unstable molecules that contain oxygen and easily react with other molecules in a cell. A build-up of free radicals in cells may cause damage to DNA, RNA and proteins, and can lead to cell death. Inflammation appears to be the main response to micro- and nanoplastics entering the GIT or the pulmonary system. The effects of plastic particles released into the body from degraded plastic prosthetic implants indicate that inflammation is a notable outcome of plastic particles crossing the respiratory or GIT epithelium. PE and PET particles move around the body, travelling through the lymph system and to the liver and spleen. PE wear particles accumulate in the lymph nodes, surrounding joint replacements that completely replace the lymph nodes, resulting in severe

inflammation. Similar reactions can occur by ingesting or inhaling MPs if they can cross the epithelia.

2.5.6 Human health effects of plastic additives (consumer use)

Whether plastic is only used once (such as a polystyrene coffee cup) or is used for years (such as casing around a television), plastic use in consumer goods can negatively impact human health. Mass-produced plastics entered the global market after World War II. A recent analysis of all plastics ever made estimates that 8300 million metric tons of virgin plastics have been produced through the end of 2015. That analysis breaks plastics into three categories: polymer resins, synthetic fibers, and plastic additives. The most prevalent plastic resins are manufactured from polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), polyethylene terephthalate (PET) and polyurethane (PUR) resins. The most common plastic fibers come in the form of polyester, polyamide and acrylic (PP&A). As a result of the global shift from reusable to single-use packaging (including containers), the most significant market for plastics today is packaging and accounts for 42% of all plastics ever produced. Packaging is also the product with the shortest lifespan. Because most of it is designed for single-use, most plastic packaging leaves the economy the same year it is produced.

2.5.6.1 Plastic particles, plasticizers, and other chemical additives

When considering the human health impacts of plastics, one must distinguish between the impacts of plastic particles (micro- and nanoplastic particles) entering the human body and the impacts of the chemical additives, plasticizers, and contaminants associated with plastic particles. To date, most of the research on the impacts of micro- and nanoplastic particles has focused on impacts on marine life, while their impacts on human health have received less attention. There is emerging data demonstrating the presence of micro- and nanoparticles in plastics (including toxic chemical additives) in the food we eat, the air we breathe, and the water we drink, raising concerns among scientists about their potential impacts on human health.

Though our understanding of the impact of micro- and nanoparticles on plastics on human health is limited, the emerging body of research is raising fundamental questions about the historic belief that plastics are inert and safe. Increasingly, the research demonstrates that the same characteristics that make plastic material with diverse and desirable applications for bettering human life, that is, lightweight and incredibly durable molecular bonds, also make them widely dispersed, ubiquitous and a potential threat to human life and the ecosystems upon which humans rely.

More research has been conducted on plasticizers and other chemical additives in plastics and their health risks. However, there is still a significant dearth of information on the health impacts of toxic additives, and food packaging chemicals in particular, since only a handful of chemicals in use have gone through a health risk evaluation. A well-developed understanding of the impacts of plastics on human health is further hampered by limited information that quantifies the cumulative risks of chronic exposure.

2.5.6.2 Plasticizers used in plastics and other consumer products

The term plastics is used to refer to various types of polymers, which are synthesized from monomers that are polymerized to form macromolecular chains. Plastics can leach unreacted chemical monomers, some of which are hazardous. The plastics that are most hazardous based on carcinogenic monomer release include polyurethanes (flexible foam in furniture, bedding and carpet backing), polyvinyl chloride (pipes, packaging, wire and cable coatings, the monomer being vinyl chloride), epoxy resins (coatings, adhesives, and composites, such as carbon fiber and fiberglass) and polystyrene (food packaging, CD cases, hard plastics in consumer products and the monomer being styrene). In addition, the hormone-disrupting plasticizer BPA leaches as an unreacted monomer from polycarbonate plastic and epoxy can liners.

A wide array of chemicals and additives may be used in the manufacturing process to create a polymer, including initiators, catalysts and solvents. Additional chemical additives are used to provide various characteristics including stabilizers, plasticizers, flame retardants, pigments and fillers. They can also be used to inhibit photodegradation, to increase strength, rigidity, and flexibility, or to prevent microbial growth. Most of these additives are not bound to the polymer matrix, and due to their low molecular weight, they easily leach out of the polymer into the surrounding environment, including air, water, food or body tissues. As plastic particles continue to degrade, a new surface area is exposed, allowing continued leaching of additives from the core to the surface of the particle. A global analysis of all mass-produced non-fiber plastics showed that on average they contain 93% polymer resin and 7% additives by mass. Some polymers contain higher concentrations of toxic additives than others. Plasticizers are used to make plastic flexible, often comprising a significant portion of the final product, as much as 80% of all products. PVC is the monomer filled with the greatest diversity of additives, including heat stabilizers to keep the polymer stable, and plasticizers, such as phthalates, to make the polymer flexible. PP is highly sensitive to oxidation and therefore contains antioxidants and ultraviolet (UV) stabilizers.

MPs that accumulate in the body are a source of chemical contamination to tissues and fluids. A variety of chemical additives in plastics, plastic monomers, and plastic processing agents have known human health effects. For example, several plasticizers, such as bis (2-ethylhexyl) phthalate (DEHP) and BPA, can cause reproductive toxicity. Yet other harmful chemicals known to leach from plastic polymers include antioxidants, UV stabilizers, and nonylphenol (Table 2.11).

2.5.7 Potential threats associated with accumulated pollutants in plastic particles

Plastic is hydrophobic, meaning it tends to absorb hydrophobic POPs, such as PCBs and PAHs, while circulating in marine waters. The accumulated pollutants can concentrate to as much as 100 times background levels in seawater. Some of these chemicals have been found to desorb into tissues of marine species when ingested. While some recent studies have concluded that MP ingestion is unlikely to be a significant source of exposure for marine organisms to organic

Table 2.11 Plastics identified in MP debris and their relative hazard ranking.

Polymer Type	Density, g/cm^3	Relative Hazard Score[a]
Polyethylene (low, high density)	0.917–0.965	11
Polypropylene	0.9–0.91	1
Polystyrene	1.04–1.1	1628–30
Polyamide		63–50
polyethylene teraphthalate	1.37–1.45	4
Polyvinylchloride	1.16–1.58	10 551–5001

[a]Relative hazard score derived from different constituent monomers.
Higher ranking = greater hazard.
Adapted from Galloway (2015).

pollutants, a recent study in conditions simulating the digestive environment of warm-blooded organisms (38°C, pH 4) showed up to have 30 times faster desorption rates than in seawater. Therefore, it is likely that in mammals, including humans, the transfer of pollutants from inhaled or ingested plastic debris is more important than originally thought. The overall contribution of plastic debris contaminated with accumulated pollutants to the body burden (the total amount of toxic chemicals in the body) remains unanswered. In light of the projected increase of plastic accumulation in terrestrial and marine environments, a precautionary approach should be adopted while investigating this answer.

2.5.8 Food packaging chemicals

Because chemicals can migrate from packaging into food, the US Federal Food Drug and Cosmetics Act defines food packaging chemicals as indirect food additives. Migration of chemicals from food packaging into food and beverages is considered the main source of human exposure to contaminants associated with plastics. Some plastic polymers used for food contact degrade when they come into contact with acidic or alkaline foods, UV light, and heat. Toxic monomers like styrene are released in these conditions. Plastic additives are a diverse group of substances fulfilling various functions. Since they are often not tightly bound to the material, they are another common source of chemicals leaching into food. Non-intentionally added substances (NIAS) such as impurities, side products and contaminants additionally contribute to the migration or leaching of chemicals. In contrast, a few food packaging chemicals are designed to intentionally migrate out of the package to perform various functions, such as preventing foods from spoilage.

2.5.9 Human health effects related to plastic waste management

2.5.9.1 Environmental health impact of waste incineration

The waste incineration industry claims that incineration using highly advanced emission control technologies provides clean energy that reduces climate impacts and toxicity. However, extensive evidence demonstrates the harmful short- and long-term effects of emissions and by-products from waste incineration.

2.5.9.2 Air emissions associated with waste incineration

Metals (mercury, lead, and cadmium), organics (dioxins and furans), acid gases (sulfur dioxide and hydrogen chloride), particulates (dust and grit), nitrogen oxides and carbon monoxide can be emitted from incineration of plastics. Workers and nearby communities can be directly and indirectly exposed to these toxic emissions through inhaling contaminated air, touching contaminated soil or water, and ingesting foods that were grown in an environment polluted with these substances. These toxic substances pose a threat to vegetation, human and animal health, and the environment, and they persist and bio-accumulate through the food chain. Burning plastics also increases the fossil content of the energy mix and adds greenhouse gas emissions to the atmosphere. In some countries, newer incinerators apply air pollution control technologies, including fabric filters, electrostatic precipitators, and scrubbers. The filters do not prevent hazardous emissions, such as ultra-fine particles that are unregulated and particularly harmful to health, from escaping into the air. Malfunctions also tend to occur when the facility starts up and shuts down, or when the composition or volume of the waste changes, and these system failures result in greater emissions compared to normal operating conditions. It is estimated that in 2015, these kinds of airborne particulates caused the premature deaths of over four million people worldwide. Incinerators are also disproportionately built in low-income and socio-politically marginalized communities, burdening them with toxic ash and air pollution, noise pollution and accidents.

2.5.9.3 Toxic by-products of incineration on land and water

In addition to toxic air emissions, incineration technologies produce highly toxic by-products at various stages of thermal processing. Pollutants captured by air filtering devices are transferred to the byproducts of incineration, such as fly ash, bottom ash, boiler ash (also known as slag) and wastewater treatment sludge. Bottom ash comes from the furnace and is mixed with slag.

Fly ash is particulate matter in flue gases containing hazardous components, such as dioxin and furans, and are emitted from the stack. The toxicity in fly ash is greater than that in the bottom ash because they are small particles that are readily windborne and more likely to leach. At municipal waste incinerators, the more efficient the air pollution control system, the more toxic the ash is (Table 2.12 and Figure 2.28).

2.6 IMPACT OF MP ON HUMAN HEALTH

2.6.1 Ingestion

MP can enter the human body via two main pathways: airborne through nasal passages into the lungs and ingestion through the mouth into the stomach. Ingestion of MPs via food consumption raises health concerns because of the potential translocation of particles from the digestive tract to other tissues and as a delivery mechanism for toxic chemicals. MPs contain an average of 4% of additives, but this can vary depending on the plastic type. Plastic additives such as phthalates, BPA and some flame retardants, are endocrine disruptors and carcinogens. It also shows that plastics can accumulate heavy metals and

Table 2.12 Compounds generated during the incineration of polyvinylchloride and their harmful effects.

Compound	Health Effect(s)
Acetaldehyde	Damages the nervous system, causing lesions.
Acetone	Irritates the eyes and the respiratory tract.
Benzaldehyde	Irritates the eyes, skin, respiratory system, and limits brain function.
Benzole	Carcinogenic, adversely affects the bone marrow, liver, and immune system.
Formaldehyde	Serious eye damage, carcinogenic, may cause pulmonary edema.
Phosgene	Gas used in WWI. Corrosive to the eyes, skin, and respiratory organs.
Polychlorinated dibenzo-dioxin	Carcinogenic, irritates the skin, eyes, and respiratory system. It damages the circulatory, digestive and nervous system, liver, and bone marrow.
Polychlorinated dibenzofuran	Irritates the eyes and the respiratory system, causes asthma.
Hydrochloric acid	Corrosive to the eyes, skin, and the respiratory tract.
Salicyl-aldehyde	Irritates the eyes, the skin, and the respiratory tract. It can also affect the central nervous system.
Toluene	Irritates the eyes and the respiratory tract can cause depression.
Xylene	Irritates the eyes. It can also affect the central nervous system, reduces the level of consciousness and impairs learning ability.
Propylene	Damages the central nervous system by lowering consciousness.
Vinyl chloride	Carcinogenic, irritating to the eyes, skin and respiratory system. Effect on the central nervous system, liver, spleen, and blood-forming organs.

Source: Alabi *et al.* (2019).

absorb toxic contaminants, such as PAHs and organochlorine pesticides from the surrounding water.

2.6.2 Ingesting MP particles

The potential impacts of ingesting microparticles have been studied for decades but are not yet fully understood because the particles are associated with such a diverse range of additives and contaminants. For example, the polyvinyl chloride particles have been transported from the digestive tract to the lymph and the circulatory systems, bile, cerebrospinal fluid, urine, lungs, and the milk of lactating animals. The interaction between MPs and other gut contents, including proteins, lipids, and carbohydrates, is highly complex. The accumulation of MP can lead to inflammation, tissue damage, cell death, and

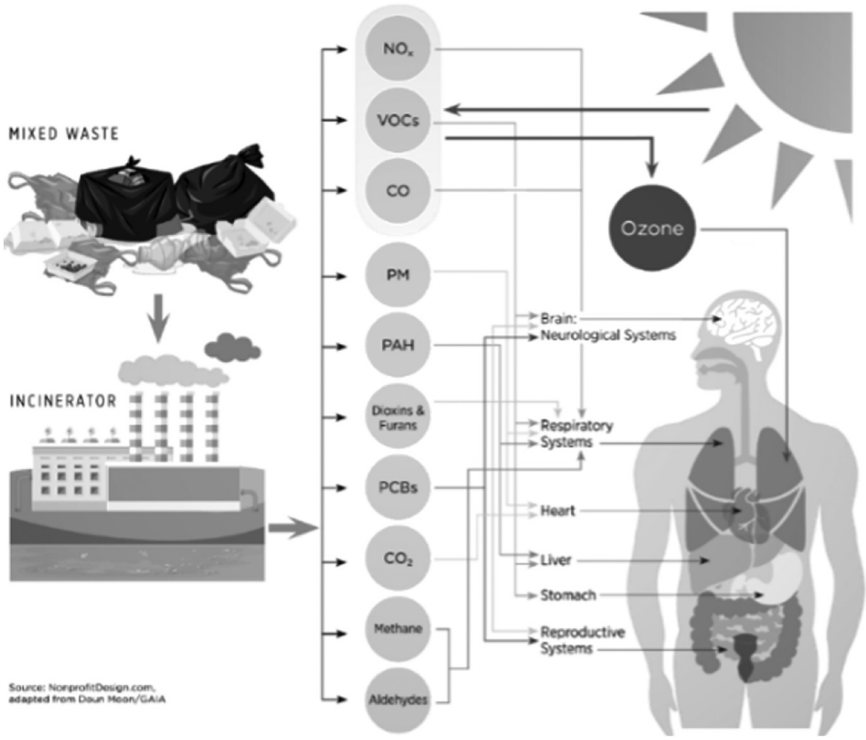


Figure 2.28 Toxic exposure from incineration (*Source*: Azoulay *et al.*, 2019).

carcinogenesis. In addition, there is the potential for toxicological effects from harmful chemicals that leach or desorb from MP.

2.6.3 MPs and toxic chemicals

The possibility of chemical contaminants from MPs transferring to humans through food is not fully understood and warrants additional research. Uncertainties surround the health impacts of MPs ingestion, and scientists have suggested urgent research be undertaken, particularly on the potential effects on the endocrine system. Humans are exposed to MPs and associated chemicals that can be toxic even in low doses. Although plastics are only one source of chemical exposure, they could be a significant source of some toxic chemicals.

2.6.4 MP and the potential for disease

Another health concern relates to bacteria that grow in MPs. One study investigated a bacterium living on the surface of MPs collected from the North and Baltic seas. The bacterium can cause gastrointestinal illness in humans, and more research is needed to understand whether pathogens on the surface of MPs consumed by humans may present a serious disease risk.

2.6.5 Inhaling MPs

The fallout of airborne plastic particles may result in accumulation on the skin and on food, resulting in dermal and gastrointestinal exposure. Based on the reported indoor air concentrations and the average volume from air inhaled, researchers postulate that a person's lungs could be exposed to 26–130 airborne MPs/day. Other sources of airborne plastics include plastics and films used in agricultural processes that have degraded, fibers released from clothing dryers and sea-salt aerosol (i.e. caused by wave action). More recently, dust from vehicle tire wear has been acknowledged as one of the main sources of MP in the air. Airborne plastics can also be dispersed in global air currents.

2.6.6 Skin contacts of plastics in agricultural soil

One health concern regarding plastics in soils is the potential transfer of toxic chemicals to crops and animals. The plastic industry is a major source of chemical additives reaching the environment. Some of these additives, including endocrine-disrupting chemicals such as phthalates, polybrominated diphenyl ether (PBDEs) and bisphenol A have been found in fresh vegetables and fruit. Although pinpointing the precise source of a given contaminant is almost impossible, reports of plastic additives and toxic contaminants in vegetables and fruit serve as an early warning that should trigger the urgent implementation of the precautionary principle to reduce exposure.

Evidence of the indirect effects of plastic-associated chemicals is emerging in scientific literature. Earthworms that encounter polyurethane particles in soils can accumulate PBDEs. Earthworms are important to maintain healthy ecosystems and soils, particularly in agricultural regions. Worms aerate in the soil through burrowing, process detritus, move the soil, and are a key food source for other animals. It is possible that PBDEs could be transferred in worms to other areas of soil and through the food web (Figure 2.29).

2.6.7 Human illnesses and disabilities caused by MPs and carried chemicals

There is medical evidence linking the following human illnesses and disabilities to one or more POPs: Cancers and tumours, including soft-tissue sarcoma, non-Hodgkin's lymphoma, breast cancer, pancreatic cancer, and adult-onset leukemia; neurological disorders, including attention deficit disorder, behavior problems such as aggression and delinquency, learning disabilities, and impaired memory; and reproductive disorders, including abnormal sperm, miscarriages, pre-term delivery, low birth weight, altered sex ratios in offspring, shortened period of lactation in nursing mothers, and menstrual disorders.

2.6.8 Standards and guidelines for preventing the effects of plastics and MPs

The accumulation of plastics in the environment will ultimately have an impact on water and soil quality, and so a sustainable relationship with plastics is a necessity for the Anthropocene. Many years of research have gone into the plastic materials currently used, and thus their physical/chemical properties and costs are optimized from the point of view of manufacturers. Plastic

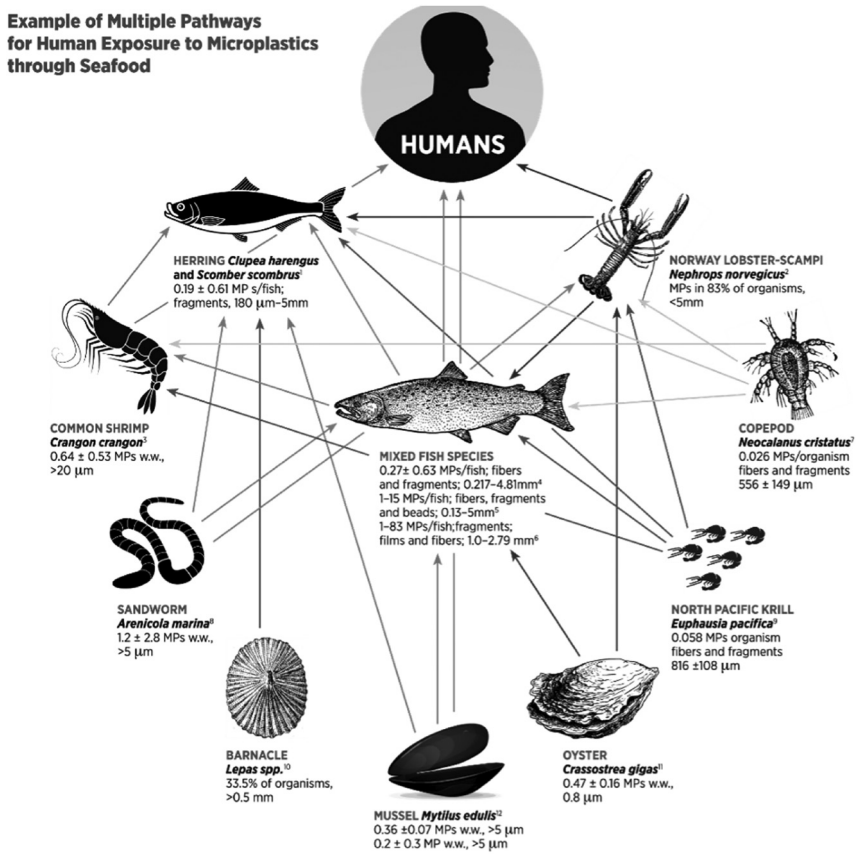


Figure 2.29 Multiple pathways for human exposure to MP through seafood (*Source*: Azoulay *et al.*, 2019).

opponents criticize plastic production and use because of all the externalities and impacts that cannot be fully characterized and controlled. With additional research and development, alternative materials may catch up in terms of both price and performance, but limited global resources should be targeted to scientifically defendable cases of increased sustainability, not too regrettable replacements or marketing stories. There is a need for an unbiased assessment of the hazard, fate and societal benefits of primary MPs throughout the regulatory process. Regulation should be enforceable and focused, and most importantly linked to hazards. The standards and guidelines for preventing the effects of plastics and MPs should be more rigorous. Then, the replacement of critical MPs can become an example of sustainable development and strict environmental regulations can stimulate innovation of new, more competitive, and environmentally conscious materials.

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