# Plastics

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A. Reichelt-Brushett (ed.), *Marine Pollution—Monitoring, Management and Mitigation*,
Springer Textbooks in Earth Sciences, Geography and Environment,
https://doi.org/10.1007/978-3-031-10127-4_9

## Acronyms and Abbreviations

| | |
|---|---|
| BPA | Bisphenol A |
| EDCs | endocrine-disrupting chemicals |
| EU | European Union |
| FTIR | Fourier-transform infrared spectroscopy |
| GPGP | Great Pacific Garbage Patch |
| MARPOL | International Convention for the Prevention of Pollution from Ships |
| MOOC | Massive Open Online Course |
| POP | Persistent Organic Pollutant |
| PVC | polyvinyl chloride |
| SPI | Society of the Plastics Industry |
| UV | ultraviolet |
| USA | United States of America |



## 9.1 Introduction

Plastic production has grown exponentially, from 1.5 million tonnes in the 1950s (Plastics Europe 2012) to 359 million tonnes in 2018 (Plastics Europe 2019). Valued for being versatile, durable, lightweight and inexpensive to produce, plastic is used in all aspects of our daily life. Plastic has shaped the development of modern society and has benefited many sectors, including healthcare, science and technology, agriculture, packaging, transportation, and construction (Napper and Thompson 2020; Plastics Europe 2017). The largest market demand of plastic is for single-use disposable packaging materials, with approximately 50% of all plastic production going towards single-use purposes (Hopewell et al. 2009; Xanthos and Walker 2017).

**Plastic is extremely durable and non-biodegradable**. Although plastic can break into pieces that are invisible to the naked eye, plastic longevity is estimated to range from hundreds to thousands of years (Barnes et al. 2009), making plastic waste management a global challenge. Plastic waste management is considered inadequate or non-existent in many parts of the world, despite high levels of plastic production and consumption (Bucci et al. 2020). Although most developed countries have invested in recycling technologies, there are many factors that impact recycling success, including the lack of technology to recycle all plastic types, lack of collection points, recycling feedstock contamination (which occurs when plastic food containers are not properly cleaned) and consumer apathy (Law 2017). Many developing countries lack the waste management practices, services, systems or infrastructure for garbage, let alone recycling. From 1950 to 2015, the cumulative waste generation of primary and recycled plastic amounted to 6300 million tonnes (6300 Mt), with only 9% recycled and 12% incinerated, while at least 60% persists in landfills or in the natural environment (Geyer et al. 2017).

In 2010, an estimated 4.8–12.7 million tonnes of plastic entered the world's oceans from land (Jambeck et al. 2015; Vince and Stoett 2018). Not surprisingly, plastics make up about 80% of all marine debris (defined as any persistent manufactured or processed solid material discarded, disposed of or abandoned in the marine environment and coastal environment) (UNEP 2016). Abundance estimates have predicted that tens of millions of metric tonnes of plastic debris is floating on global ocean surfaces (Lebreton et al. 2018), with microplastic estimates ranging between 15 and 51 trillion items (van Sebille et al. 2015), making plastic pollution internationally recognised (Rochman et al. 2013).

The longevity of plastic, large inputs into the ocean, and natural movement of the material via winds and currents have made plastic a persistent and ubiquitous pollutant throughout global coastal and marine environments, including in remote areas, such as the Arctic Ocean (Eriksen et al. 2020). Decades worth of evidence shows plastic pollution harms marine wildlife and habitats (Laist 1987; Gregory 2009; Baulch and Perry 2014; Beaumont et al. 2019) and human health (Thompson et al. 2009; Waring et al. 2018), with an associated economic loss and decline in ecosystem services (benefits people obtain from nature). This chapter explores the global issue of marine plastic pollution. In it we discuss topics such as plastic types and characteristics, sources of marine plastic pollution, transport and accumulation, impacts, challenges in governance, and initiatives aimed at reducing the use of plastics.

## 9.2 Plastic Types and Characteristics

The term **plastic** covers a wide range of synthetic or semi-synthetic materials that we use to help make life cleaner, easier, and safer (Andrady and Neal 2009; Plastics Europe 2020). They are produced from synthetic polymers, which are long, chain-like molecules of repeating chemical units (Napper and Thompson 2020). These units consist of hydrocarbons, usually sourced from fossil fuels such as coal, natural gas, and crude oil, but also from materials such as cellulose or salt (ACC 2020; Höfer and Selig 2012). Different plastic polymers are used for various product types (▶ Box 9.1), including polyethylene (clear food wrap, plastic bags, detergent bottles), polystyrene (Styrofoam packaging), polypropylene (packaging, industrial parts, textiles), and polyvinyl chloride (PVC, used for pipes and in the medical industry). To create durable plastic products, plastic polymers are combined with chemical additives such as fillers, plasticisers, flame retardants, and stabilisers (ultraviolet (UV) and thermal) (Andrady and Neal 2009). The coding of different types of plastics was developed by the Society of the Plastics Industry (SPI) and is used as the global standard (Wong 2010). Plastic polymers can be identified using laboratory techniques such as Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy.

**Box 9.1: Plastic Polymers: Recycling Numbers and Examples of Common Uses**

| Polymer name | Polyethylene terephthalate (PET or PETE) | High-density polyethylene (HDPE) | Polyvinyl chloride (PVC) | Low-density polyethylene (LDPE) | Polypropylene (PP) | Polystyrene (PS) | Other |
|---|---|---|---|---|---|---|---|
| Recycling Symbol | ♳ 1 | ♴ 2 | ♵ 3 | ♶ 4 | ♷ 5 | ♸ 6 | ♹ 7 |
| Common Uses | Soda bottles, water bottles, rope | Milk jugs, toys, snack food boxes | Plumbing pipes, credit cards, floor covering | Plastic wrap, bubble wrap, plastic grocery bags | Prescription bottles, most bottle tops, potato chip bags | Disposable foam cups, take-out food containers, plastic cutlery | Baby bottles, medical storage containers, eyeglasses |

Adapted from Wong (2010)

In addition to polymer type, plastic debris is described using numerous characteristics including size, shape (e.g. beads, pellets, foams, fibres, fragments), colour, and original usage (e.g. fishing gear, food packaging) (Andrady 1994, 2017; Napper et al. 2015). The two most common size categories are macroplastic (>20 mm diameter) and microplastic (<5 mm), with further categorisations such as megaplastic (>1000 mm), mesoplastic (5–20 mm), and nanoplastic (<1000 nm) (▶ Box 9.2) (Barnes et al. 2009; Ivar do Sul and Costa 2014; Thompson et al. 2009). Plastic debris from all size categories are found throughout the marine environment, at beaches, on the water surface, in the water column, and on the seafloor (◘ Figure 9.1).

**Box 9.2: Marine Plastic Debris: Examples of Debris in Different Size Categories**

| Nano (<1 µm) | Micro (<5 mm) | Meso (5–20 mm) | Macro (>20 mm) | Mega (>1000 mm) |
|---|---|---|---|---|
| • Fibres from clothing<br>• Nano items in personal care products and pharmaceuticals | • Microbeads from personal care products<br>• Fragments from larger existing plastic debris<br>• Polystyrene balls from packaging | • Bottle caps<br>• Cigarette filters and butts<br>• Lighters<br>• Candy wrappers | • Beverage bottles<br>• Plastic bags<br>• Cutlery<br>• Beer-ties<br>• Balloons<br>• Fishing lines, floats, and buoys | • Abandoned fishing nets<br>• Rope and rope conglomerates |

Adapted from UNEP (2017)


◘ **Figure 9.1** Plastic debris is ubiquitous in the marine environment, some examples include **a** plastic found washed up on beaches **b** floating on the water's surface **c** floating within the water column **d** and deposited on the seafloor. *Photos*: A. Malmgren (a), K. Berry (b–d)

### 9.2.1 Macroplastics

Macroplastic (>20 mm) debris commonly observed in the marine environment can include floating plastic bags and bottles and plastic beach debris (◘ Figure 9.2a). Significant levels of macroplastic debris can become a navigational hazard for both marine wildlife and vessels. Further significant impacts to the marine environment and organisms are numerous, for example, the smothering of coral reefs (Personal observation, K. Berry), seagrass beds (Kiessling et al. 2015) or mangroves (Martin et al. 2019), and the entanglement or ingestion of plastic debris by marine fauna (Gregory 2009; Wesch et al. 2016).

### 9.2.2 Microplastics

Microplastics (<5 mm) are sub-categorised into primary and secondary microplastics. Primary microplastics are intentionally manufactured to be small for various uses and include virgin plastic resin pellets, small items or spheres used in personal care products known as microbeads (e.g. for face washes, toothpaste, or cosmetics, ◘ Figure 9.2b, as well as abrasives in cleaning products (Cole et al. 2011; Derraik 2002). Secondary microplastics are created during the breakdown of larger plastic items. They commonly take the form of weathered and degraded plastic pieces (see ▸ Section 9.5) and microfibres that are shed from synthetic and semi-synthetic fabrics during washing (◘ Figure 9.2c, d).

## 9.3 Sources

Plastic enters the marine environment from land and maritime sources, with a larger proportion (70–80%) entering from land (◘ Figure 9.3) (UNEP 2005, 2009). **Land-based sources** consist of mismanaged waste (e.g. uncovered garbage dumps or littered plastic, ◘ Figure 9.4), spillage of virgin plastic pellets, litter flowing into storm drains and rivers, treated and untreated sewage effluent, as well as aerial deposition (items or fibres that are emitted into the air from industrial facilities that are then deposited on the ocean) (Critchell et al. 2019). **Maritime sources** include shipping vessels, fishing and recreational boats, aquaculture facilities, offshore oil industry and tourism (Boucher and Friot 2017). Despite international regulations (see also ▸ Chapter 16) forbidding the discharge of waste at sea (International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78), cargo loss during storms and intentional disposal of waste from ships does occur. Lost and abandoned fishing gear is also a major contributor to marine plastic pollution worldwide (Richardson et al. 2017). For example, fishing gear used for catching octopus accounts for 94% of larger plastic debris found in the Moroccan Southern Atlantic Ocean (Loulad et al. 2017).

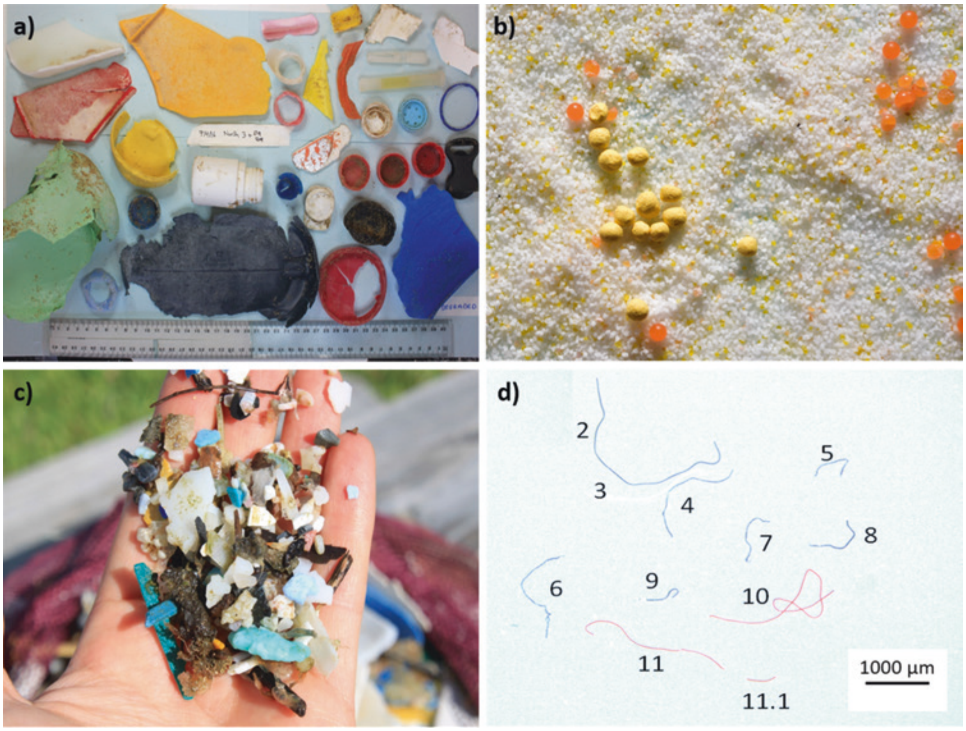


**Figure 9.2** Marine plastic pollution comes in all shapes and sizes and is categorised by size, shape, and colour. **a** Larger plastic debris is referred to as macroplastic (>20 mm) and is often observed floating **c** on the ocean surface or washed up on beaches. Smaller plastic debris, known as mesoplastic (5–20 mm) and **b** and **d** and microplastic (<5 mm) are harder or impossible to detect with the naked eye. Microplastics are sub-categorised into "primary", which are purposely manufactured to be small, such as microbeads used in exfoliating face cleansers (b), and "secondary" microplastics, formed from the breakdown of larger plastic items (c and d). *Photos*: K. Berry

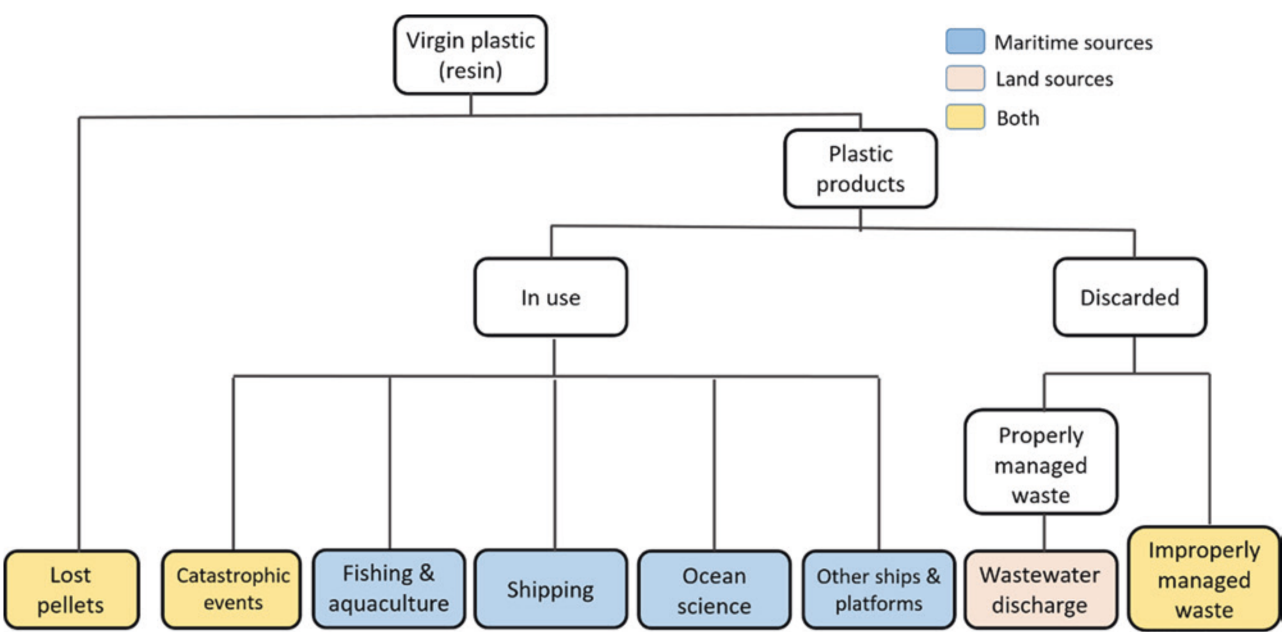


**Figure 9.3** Plastic enters the marine environment from land and maritime sources. Virgin plastic pellets may spill during manufacturing and transport, entering waterways. Manufactured plastic products may enter the marine environment due to degradation, accidental loss, or intentional disposal. Discarded waste, whether properly or improperly managed, may still enter the environment via numerous pathways such as wastewater effluent discharge, storm drains, and rivers. Adapted from Law (2017) by K. Berry

Many microplastic items, such as microbeads and microfibres, are washed down drains, entering waterways either directly or via wastewater management systems. More than 700,000 microplastic fibres can be released from a typical six kilogram wash of synthetic clothing, such as polyester and nylon (Napper and Thompson 2016). Large quantities of microplastic items (up to 90%) can be removed from sewage during various


**Figure 9.4** Mismanaged waste is a major source of plastic debris to the marine environment. **a** and **b** Waste may be considered mismanaged due to lack of full containment, **c** and **d** that may result in accidental loss, or due to a lack of waste management infrastructure, which results in plastic items being discarded directly into the environment. These photos, depicting mismanaged waste, were taken in Indonesia (a, b, c) and Myanmar (d). *Photos*: A. Reichelt-Brushett (a, b, c), K. Berry (d)

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wastewater treatment stages (Carr et al. 2016), however, the capture of microplastic items is dependent on types of treatment processes. Due to their small size (microbeads are <50 µm) they are not always captured by filtration devices. The quantity of microplastic items released in effluent can equate to 300 million plastic pieces per day, making wastewater discharge a major source of microplastic debris into the aquatic environment (Edo et al. 2019). The most commonly reported types of marine microplastic debris worldwide are pellets, fragments, and fibres (GESAMP 2015), however, ropes, sponges, foams, rubber, and microbeads are also important contributors to plastic pollution (Auta et al. 2017).

Although most plastic enters the marine environment because of human activity, natural events such as floods, earthquakes, and tsunamis can result in large quantities of plastic debris unintentionally entering the ocean (Murray et al. 2018; Veerasingam et al. 2016).

## 9.4 Plastic Transport in the Marine Environment

Plastics move through the marine environment via winds and ocean processes such as currents and eddies (Eriksen et al. 2014). Exactly how items move and how far is governed by the physical properties of the plastic object. The size, shape, and polymer density all influence where the item will sit in the water column, and how easily it will move into another part of the water column (Chubarenko et al. 2016; Erni-Cassola et al. 2019; Lenaker et al. 2019). Ocean water has a density in the range of 1.02–1.03 g/cm$^3$ and therefore plastic polymers range from buoyant to negatively buoyant (e.g. PVC is denser than seawater [1.38 g/cm$^3$] and therefore tends to sink) (Andrady 2011; Plastics Europe 2014; Wang et al. 2016). Yet, where the plastic item sits in the water column depends also on the physical size and shape of the object. Despite PVC having a higher density than seawater (Syakti 2017), if a PVC object is large and hollow (e.g. a chemical drum), it may remain buoyant due to displacement. If it was a microplastic item (<5 mm), then the polymer type would have a much stronger influence on where it is found in the water column, and it will most likely sink. Very small plastic items such as microplastics can easily be mixed through the water column and can sink to different depths in the ocean (Reisser et al. 2015).

Plastic debris in the marine environment will often become substrate for sessile (immobile) marine organisms (this process is called bio-fouling), which can increase an item's density (e.g. Fazey and Ryan 2016; Kaiser et al. 2017). Smaller plastic debris and those with a density closer to that of sea water, which experience bio-fouling, can have their density changed enough that the item will eventually sink to the seafloor (Kane and Clare 2019). Size is an important factor. Even microscopic sized pieces of plastic (known as nanoplastics, <1 µm), with a low polymer density making them very buoyant, can become tangled in marine snow (organic detritus in the water column) and sink (Porter et al. 2018). A similar process is thought to occur in the faeces of marine organisms that ingest and then excrete nanoplastics (Kvale et al. 2020). Larger plastic debris, instead, continues to drift in the ocean until it accumulates, either on beaches or in large ocean circulations, like the Great Pacific Garbage Patch (GPGP).

### 9.4.1 Modelling the Movements of Plastic

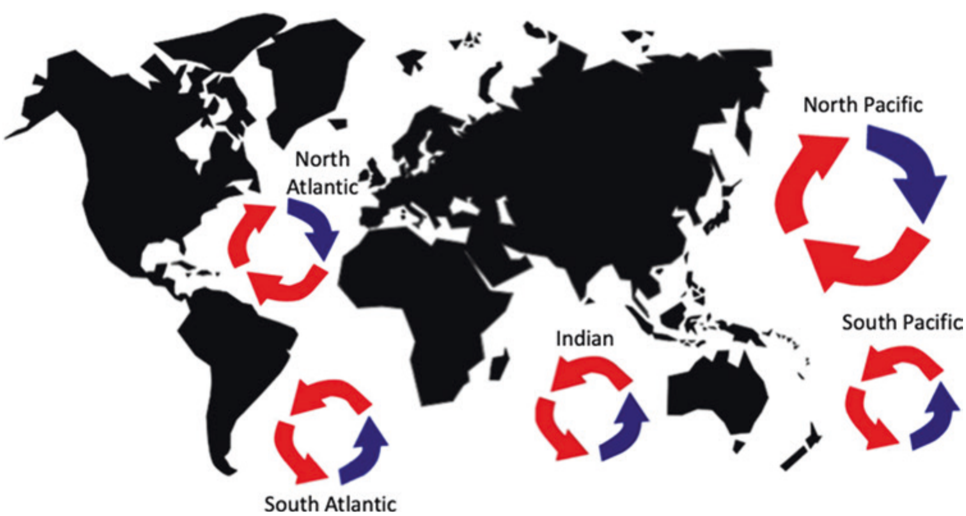
As with many ocean processes, it is not possible to study real-time **plastic** debris **dispersal and movement at ocean scales** in the field. The area is too large, the time scales are too long, and working on, or in, the ocean is expensive. Therefore, scientists use models to understand and predict plastic movement. Early studies modelled the movement of plastic debris at the scale of whole oceans (e.g. Law et al. 2010; Maximenko et al. 2012; van Sebille et al. 2012), while more recent studies focussed on the scales of seas and individual beaches (e.g. Cozar et al. 2014; Turrell 2018; Yabanlı et al. 2019). These models allow us to learn about the processes that transport and accumulate plastic debris in the environment.

### 9.4.2 Accumulation

Oceanic gyres are now infamous as large-scale debris accumulation areas for plastic pollution (Cozar et al. 2014; Eriksen et al. 2013). Gyres are large-scale eddies in the ocean, generated by oceanic currents and global wind patterns. The world's five major gyres (◘ Figure 9.5) are found in the middle of the oceanic basins of the North and South Atlantic Ocean, the Indian Ocean, and the North and South Pacific Oceans. The largest gyre-associated "*floating garbage patch*" is the GPGP in the North Pacific Gyre (Lebreton et al. 2018), situated in the subtropical waters of the Pacific between California and Hawaii. In the GPGP, microplastic debris accounts for 94% of the plastic pieces floating in the area (Law et al. 2014). The micro- and meso-plastic debris concentrations in the GPGP are reported to be between 22,000 and 678,000 pieces/km$^2$, respectively (Lebreton et al. 2018).

Oceanic gyres are not a static accumulation of plastic debris, however, the time in which a plastic item remains within a gyre is very high (Howell et al. 2012). Accumulation can be defined as occurring when the supply (or input) to an area is larger than loss (or output). Each piece of plastic is perpetually moving, being mixed, and eventually leaving the gyre. Yet, this loss of plastic is very small when compared with the supply. Floating plastic debris has also accumulated in semi-enclosed regional seas globally, for example, the Caspian Sea (Nematollahi et al. 2020), the Mediterranean Sea (Suaria et al. 2016; Vianello et al. 2018), and Laizhou Bay in China (Teng et al. 2020).

The seabed is an accumulation zone that is only beginning to be understood (Woodall et al., 2014). Because degradation processes and bio-fouling can cause most categories of plastics to sink to the seafloor (Kowalski et al. 2016), microplastic debris has been found in sediments collected from the deepest parts of the ocean (Peng et al. 2020). This includes in deep sea sediments from the Great Australian Bight, the Southern Ocean, the North Atlantic Ocean, and the Mediterranean Sea (Van Cauwenberghe et al. 2013; Barrett et al. 2020;). A plastic bag was recently found in the world's deepest ocean trench, the 10,898 m deep Mariana Trench (Chiba et al. 2018).




◘ **Figure 9.5** The world's five major oceanic gyres. Adapted from what are the 7 continents (2020) by P. Lewis

### 9.4.3 Plastics in Remote Environments

Plastics have polluted remote terrestrial and marine environments, from the highest mountains to the depths of the ocean. These include the Arctic, Antarctic, and Southern Ocean, the Tibetan Plateau at 3000 m altitude, and the deep sea, at greater than 1000 m in depth (Wang et al. 2019a). Baseline pollution in remote polar regions, such as the Arctic and Antarctic, are considered indicators of global environmental health. The Arctic in particular is now being recognised as a global sink for anthropogenically derived particulates (Eriksen et al. 2020), with microplastics and microfibres being dispersed into the region from population centres by subsurface currents (Wichmann et al. 2019). Recent studies have also identified the atmosphere and snowfall as significant transport routes (Bergmann et al. 2019). Another significant source and transport vector within the region is the Arctic sea ice, which can trap between 38 to 234 plastic items per $m^3$ of ice (Obbard 2018), items that can then be re-released after the seasonal migration and melting of the ice in the North Atlantic (Peeken et al. 2018) (► Box 9.3).

At the other end of the world, the Antarctic Convergence current that surrounds Antarctica was thought to act as a potential barrier to flowing debris and pollutants from the north (Ainley et al. 1990). However, studies now show the presence of microplastics in sea ice, sediments, and surface waters of the Antarctic and Southern Ocean, as well as in the scat of seabirds from sub-Antarctic Islands and the Antarctic Peninsula (e.g. Isobe et al. 2014; Bessa et al. 2019; Kelly et al. 2020; Sfriso et al. 2020; Waluda et al. 2020).



#### Box 9.3: What is the Significance of Microplastic Items in Sea Ice?

Microplastic concentrations within Arctic sea ice can impact the absorption of incident solar radiation, which affects the light reflectance (albedo) of sea ice. Light reflectance is how the ice reflects solar energy and is one of its key properties, regulating heat exchange between the ocean and the atmosphere. High salinity sea ice has been associated with large concentrations of microplastic items, which could adversely affect albedo and how the ice melts, but also the brine volume content, which controls the permeability of sea ice. Microplastic impurities can be light-absorbing, affecting light penetration depth, potentially impacting algae that lives underneath, algae that forms the basis of the Arctic foodweb.[1] A total of 96 microplastic items from 14 types of polymers were discovered in sea ice samples collected near Casey Station in East Antarctica.[2] Local sources include clothing and equipment used by tourists and researchers, as well as varnishes and plastics commonly used by the fishing industry (◘ Figure 9.6).

For further reading:

The Guardian Australia ► https://mville.libguides.com/c.php?g=370027&p=5932225#:~:text=Structure%20of%20a%20citation%20for,Publisher%2C%20Publication%20date%2C%20URL.

◘ **Figure 9.6** ► Box 9.3: AWI scientists sample a melt pond on Arctic sea ice, discovering record levels of microplastics. *Photo*: Mar Fernandez/Alfred Wegener-Institute

1 The Conversation 2019
► https://theconversation.com/microplastics-may-affect-how-arctic-sea-ice-forms-and-melts-120721.

2 Ecowatch 2020
► https://www.ecowatch.com/antarctica-microplastics-sea-ice-2645809545.html?rebelltitem=2#rebelltitem2.

## 9.5 Degrading Processes

Durability is a valued property of plastic. Nonetheless, plastic items do not remain in their original form forever, and eventually degrade over time. Plastics can undergo different weathering and aging processes in the marine environment, due to a wide variety of environmental factors (► Box 9.4). These include photo-degradation from the sun, thermal aging, bio-film growth, and oxidation that results in the degradation of the plastic polymers (Andrady 1994; Min et al. 2020). The physical damage that results from this degradation can include cracking, surface erosion, and abrasion, all of which depends on the structure and chemical properties of the plastic polymer (Andrady 2011; Min et al. 2020). Photo-degradation, or the physical and chemical weathering by UV light, breaks polymer bonds, weakening the plastic structure and allowing the item to fragment, forming secondary microplastics (Efimova et al. 2018). Plastic that has sunk to ocean depths, or that is buried in sediment, does not experience exposure to UV light, therefore it will not undergo fragmentation processes, unless exposed to another mechanism of degradation (Andrady 2011). Mechanical forms of degradation are possible, particularly in the swash zone of high-energy beaches (Corcoran et al. 2009). The relentless battering of the plastic against sand grains, pebbles, and stones will cause it to break up, with previous UV light exposure exacerbating the process (◘ Fig. 9.7). These processes are believed to be the most common ways in which plastics become microplastics (described in ► Sect. 9.2.2).

Weathering processes can also release harmful additives from the plastic polymer matrix (Teuten et al. 2009). These can include plasticisers such as phthalates (Schrank et al. 2019), flame retardants (Fauser et al. 2020), and other endocrine-disrupting chemicals (EDCs) (Gallo et al. 2018). Biological degradation of plastic is also possible, through the bio-fouling of plastic surfaces (Fazey and Ryan 2016). Emerging research suggests that the cells of some microbes conform to the pits and grooves found on the surfaces of microplastics and may be degrading polymers in situ (Zettler et al. 2013; Reisser et al. 2014). Laboratory studies by McGivney et al. (2020) found physiochemical changes in microplastics exposed to bacterioplankton biofilms extracted from coastal waters in Sweden. Biofilm effects were dependent upon polymer type. Increases in crystallinity and maximum compression were observed in polyethylene and polystyrene items respectively, while polypropylene items decreased in stiffness when exposed to the biofilm (McGivney et al. 2020). Gene sequencing analyses found significantly higher abundances of *Sphingobium* spp., *Novosphingobium* ssp., and uncultured Planctomycetaceae on polyethylene, while polypropylene and polystyrene both had greater abundances of Sphingobacteriales and Alphaproteobacteria. These results provide evidence to support the hypothesis that bacteria are degrading microplastics and that different members of the bacterial community are responsible for this degradation, depending upon polymer type. More work is needed in order to determine how these biological modifications, in concert with the physical and chemical changes from abiotic factors, impact the fate of the various microplastic polymers in the marine environment.

**Box 9.4: The Physical and Chemical Degradation Processes of Plastic**

**Type** – **Details**

**Biological** – Microorganism actions cause degradation

**Photo** – UV light or photons, usually sunlight, cause degradation

**Thermo-oxidative** – Slow oxidative, molecular degradation at moderate temperatures

**Hydrolysis** – Chemical reaction with water causes degradation

**Mechanical** – Physical breakdown of plastics on high energy beaches

Adapted from Rochman et al. (2015).

**Weathering Agents in Different Marine Zones**

| Weathering agent | Beach | Surface water | Deep water or sediment |
|---|---|---|---|
| Sunlight | Yes | Yes | No |
| Temperature | High | Moderate | Low |
| Oxygen levels | High | High/moderate | Low |
| Fouling (screens solar radiation) | No | Yes | Yes |

Adapted from Andrady (2015)

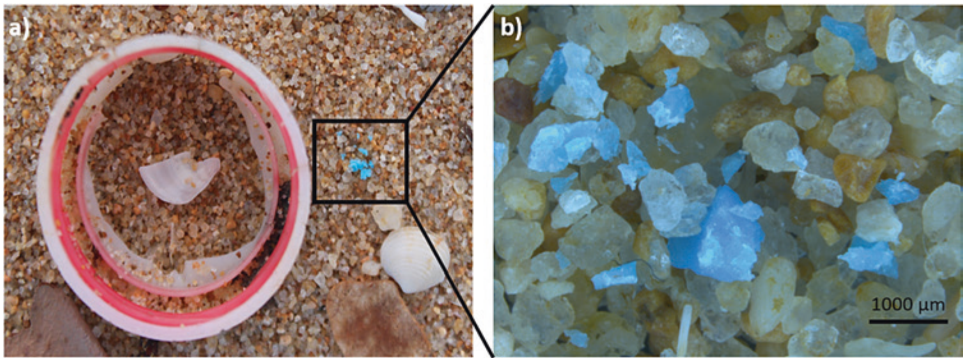



**Figure 9.7** Weathering (physical and chemical) contributes to the degradation of plastic items on beaches, **a** This blue plastic item was observed during the fragmentation process on a beach in Queensland, Australia, and **b** a sample was collected and taken back to the lab for imaging under a stereomicroscope, which revealed that the plastic pieces were fragmenting into more than 20 microplastic pieces, many of which were smaller than a grain of sand. If left on the beach, these new smaller fragments would continue to break into smaller and smaller pieces *Photos*: K. Berry



### 9.5.1 Complications of Measuring and Comparing Plastic Pollution

Scientific research on the **quantification** and environmental impacts of macro- and microplastic have increased drastically over recent years, providing critical information to scientists and policy makers (Forrest 2019). However, **discrepancies** in terminology, reporting units, and **inconsistencies** in methodologies make accurate geographical comparisons and summaries of this issue difficult (Provencher et al. 2020; Pittura et al. 2023).

Plastic quantification is presented by either (1) the number of plastic pieces per $m^2$, (2) the number of plastic items per litre of seawater, or (3) weight (Miller et al. 2017). The range of units makes it difficult to make accurate comparisons between study sites or obtain true estimates of total plastic contamination at the local, regional, or global level. Laboratory studies have quantified plastic ingestion by extracting plastics from animal tissue, yet all extraction methodologies have limitations (Miller et al. 2017). For example, digestion techniques using acid solutions can digest certain plastic polymers, resulting in the underestimation of plastics (Claessens et al. 2013; Li et al. 2015; Vandermeersch et al. 2015), while, methods using physical extractions may fragment plastic pieces, resulting in over-estimations (Kathryn Berry personal observation). These over- and underestimations can also occur when microplastic polymer types are not identified correctly, for example, many naturally derived materials can also resemble plastic, requiring these pieces to be validated as synthetic polymers (Lusher et al. 2020; Zhao et al. 2018). FTIR and Raman spectroscopy are the most commonly used methods for plastic polymer identification, however this equipment is expensive and the process is time consuming (Cozar et al. 2014; Lv et al. 2019). Consequently, any study that has not correctly validated microplastic polymers using one of these techniques is likely overestimating microplastic contamination (Song et al. 2015; Provencher et al. 2020).

Lastly, procedural contamination by microfibres is a serious concern (Woodall et al. 2015; Torre et al. 2016), as is the ecological relevance of studies. Many studies investigating the potential effects of microplastics utilise concentrations and sizes of microplastics not commonly reported in the natural environment, meaning that the true implications of the results may be misinterpreted (Phuong et al. 2016). Increased baseline studies, standardised collection and quantification methods, and consistent reporting units will help provide accurate and comparable environmental data to inform management and policy decisions (Cowger et al. 2020; Pittura et al. 2023).

## 9.6 Impacts of Plastic Debris

### 9.6.1 Impacts Overview

The ubiquity of plastic debris and diversity of plastic debris characteristics (e.g. shape, size, density, chemical composition) results in many interaction pathways with marine wildlife (◘ Table 9.1) and humans. Plastic pollution is known to impact many trophic levels and can have physical and chemical effects. It is aesthetically unpleasing, creates human health concerns, and is an economic burden. In this section, we will discuss the impacts of plastic pollution on the environment, human health, and the economy.

### 9.6.2 Physical Interactions with Wildlife

Entanglement and ingestion are the most commonly reported interactions between marine plastic debris and wildlife (◘ Table 9.1) (Kühn and van Franeker 2020).

**Table 9.1** Summary of plastic debris impacts on marine wildlife related to encounter types (field and laboratory measurements)

| Animal | Encounter type | Predominate debris type | Impact (response) | Study |
|---|---|---|---|---|
| Grey seals | ENT | Fishing line, net, rope | Constriction | Allen et al. (2012) |
| Manatees | ENT | Fishing line, bags, debris | Death | Beck and Barros (1991) |
| Elephant seals | ENT | Fishing line, fishing jibs | Dermal wound | Campagna et al. (2007) |
| Fur seals | ENT | Trawl net, packing bands | Death | Fowler (1987) |
| Invertebrates, fish, seabirds, marine mammals | ENT | Derelict gillnets | Death | Good et al. (2010) |
| Gorgonians | ENT | Fishing line | Damage/breakage | Pham et al. (2013) |
| Sea turtles | ENT | Fishing gear | Death | Vélez-Rubio et al. (2013) |
| Whales | ENT | Fishing line | Dermal wound | Winn et al. (2008) |
| Manatees | ING | Fishing line, bags, debris | Death | Beck and Barros (1991) |
| Penguins | ING | Plastic, fishing, debris | Perforated gut, death | Brandão et al. (2011) |
| Sea turtles | ING | Plastic bags, ropes | Gut obstruction, death | Bugoni et al. (2001) |
| Seabirds | ING | Plastic items, pellets | Perforated gut | Carey (2011) |
| Fish (L) | ING | Nano items | Biochemical/cellular | Cedervall et al. (2012) |
| Seabirds | ING | Plastic debris | Gut lesions | Fry et al. (1987) |
| Sperm whales | ING | Fishing gear, debris | Gastric tear, death | Jacobsen et al. (2010) |
| Copepods (L) | ING | Micro- and nanoplastics | Death | Lee et al. (2013) |
| Sea turtles | ING | Marine debris | Gut obstruction | Vélez-Rubio et al. (2013) |
| Seabirds | ING | Microplastics | Gut obstruction | Gilbert et al. (2015) |
| Mussels (L) | ING | Microplastics | Biochemical/cellular | von Moos et al. (2012) |
| Bivalves (L) | ING | Microplastics | Limited response | Bour et al. 2018 |
| Marine larvae (L) | ING | Microplastics | Limited response | Kaposi et al. (2014) |
| Brine shrimp (L) | ING | Microplastics | Limited response | Wang et al. (2019b) |
| Marine fish (L) | ING | Microplastics | Limited response | Critchell and Hoogen-boom (2018) |
| Copepods Zebrafish (L) | ING/CON | Microplastics | Trophic transfer, POP uptake | Batel et al. (2016) |
| Fish | ING | Microfibres | Limited response | Kroon et al. (2012) |
| Zebra Fish (L) | ING/CON | Microplastics | Pb (lead) bioavailable | Boyle et al. (2020) |
| Pearl oyster | ING/CON | Aquaculture gear | Leachate absorption, reproduction | Gardon et al. (2020) |
| Seabirds | ING/CON | Microplastics | PBDE body burden | Tanaka et al. (2013) |
| Coral reef | INT | Fishing gear | Tissue abrasion | Chiappone et al. (2005) |
| Seagrass | INT | Fishing gear, debris | Breakage, death | Uhrin and Schellinger (2011) |
| Coral (L) | INT | Microplastics | Limited response | Berry et al. (2019) |

Abbreviations: *ENT* entanglement, *ING* ingestion, *INT* interaction, *(L)* laboratory experiment, *CON* contaminant

Wildlife is more likely to become entangled in certain shapes/types of plastic debris, such as ropes (Figure 9.8a, b), bags, or circular plastic items, such as aluminium can six-pack rings. Entanglement can cause tissue abrasion, strangulation, reduced feeding efficiency, reduced growth and development, and death due to drowning (e.g. Allen et al. 2012). Plastic debris may cause additional **physical harm to marine habitats and** sessile benthic **organisms** (e.g. corals, seagrass, mangroves) via smothering (Figure 9.8c), and when dragged along the seafloor. Fishing nets (referred to as ghost nets) that are lost, abandoned, or discarded at sea

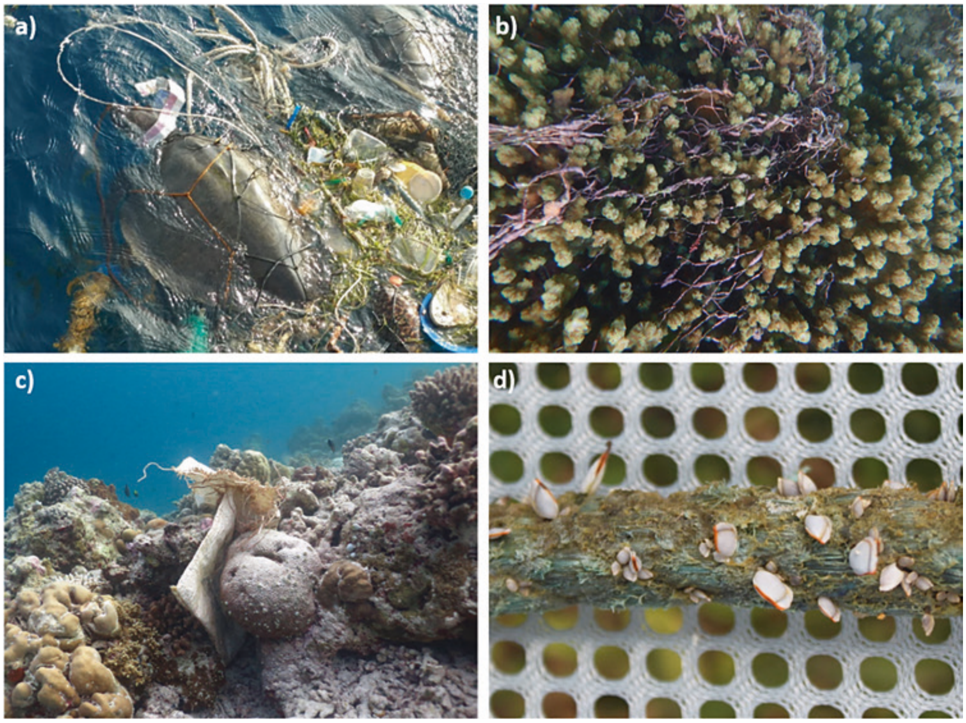





**Figure 9.8** Plastic debris interacts with the marine environment and wildlife in numerous ways: **a** and **b** Organisms, such as turtles and corals may become entangled in fishing nets/rope, **c** sunken plastic debris may smother sessile organisms such as corals, causing physical harm and blocking out essential light and **d** plastic can act as a platform to transport fouling organisms and microbes. *Photos*: A. Hassan (a), A. Reichelt-Brushett (b), K. Berry (c, d)

can continue to catch fish and other marine organisms such as rays and turtles for many years (Gunn et al. 2010). These environmental impacts may create economic loss associated with losses to fisheries due to depletion of fish stocks and gear replacement costs.

Many marine species are reported to ingest plastic debris, including the smallest marine animals at the bottom of the food chain, zooplankton (Cole et al. 2013), fish (Kroon et al. 2018), turtles (Caron et al. 2018), seabirds (Gilbert et al. 2015), whales and other large marine animals (Besseling et al. 2014; Germanov et al. 2019; Moore et al. 2020). Ingestion of plastic debris occurs due to an organism mistaking plastic debris for prey either by sight, for example, turtles mistaking plastic bags for jellyfish (Schuyler et al. 2014), or by smell, for example, some species of seabirds ingest microplastics after targeting zooplankton swarms (Gilbert et al. 2015; Savoca et al. 2016). Ingestion is influenced by the size and shape of the plastics, an organism's feeding behaviour, and feeding range (depth) within the water column (Fossi et al. 2012; Cole and Galloway 2015; Lusher et al. 2017). Impacts associated with ingestion are often related to size of the plastic debris, ranging from minimal effects (likely due to the animal simply passing the plastic debris through its digestive system) to obstruction of the intestinal tract and reduced stomach capacity (which can lead to malnutrition and reduced growth rates), internal injury, changes in behaviour, reduced swimming performance, impaired reproduction, and oxidative stress (Sigler 2014; Cole et al. 2015; Gray and Weinstein 2017; Foley et al. 2018).

### 9.6.3 Plastic as an Unnatural Substrate

Micro- and macroplastics act as a platform for colonisation (Figure 9.8d) by sessile organisms and microbes, including pathogens. Movement of colonised plastic debris may increase an organism's dispersal and transport of invasive species (Barnes et al. 2009; Gregory 2009). Colonisation of sunken plastic debris may alter habitat structure by providing sessile benthic organisms with alternative substrate to settle and grow upon. The long-term implications of plastic debris as a 3D habitat structure are unknown.

Plastic debris provides a novel habitat upon which microbes can flourish (Zettler et al. 2013). The **plastisphere** refers to the unique structure and taxonomy of the microbial community that forms on the surface of marine plastic debris, which differs significantly from the overall microbial community of the surrounding substrates (Bryant et al. 2016; Feng et al. 2020; Zettler et al. 2013). It has yet to be determined if the taxonomy of the plastisphere varies between polymer types, as other factors such as the age of the debris (i.e. virgin or weathered), season, and geographic location appear to also play a role (Erni-Cassola et al. 2019; Oberbeckmann et al. 2016; Zettler et al. 2013). The plastisphere has been shown to include pathogenic *Vibrio* and *Escherichia coli* species, antibiotic-resistant bacteria, harmful algal bloom species, and the fish disease causing bacteria *Aeromonas salmonicida* (Kirstein et al. 2016; Casabianca et al. 2019; Rodrigues et al. 2019; Silva et al. 2019; Laverty et al. 2020; Moore et al. 2020). Although this field of research is still novel, the likelihood of coral disease increased from 4 to 89% when corals (from 159 reefs in the Asia-Pacific region) were in contact with macroplastic debris. This suggests microbial colonisation of plastic by pathogens may contribute to disease outbreaks in the ocean (Lamb et al. 2018). Further research is required into the mechanisms of plastic as a vector for pathogens, trophic transfer of pathogens via plastic ingestion, and the potential for plastics to act as a vector for the long-distance dispersal of harmful microorganisms.

### 9.6.4 Chemical Effects of Microplastics

While ingestion of microplastics may cause physical harm to marine biota, there is also the potential for chemical impacts. The physical processes that weather plastic objects to microplastics can create a large specific surface area on the particles, causing the items to act as a **sponge** by taking up contaminants from sediments or the water column via adsorption (Fred-Ahmadu et al. 2020). Adsorbed contaminants can include Persistent Organic Pollutants (POPs) (Mato et al. 2001; Endo et al. 2005; Teuten et al. 2009), metals (Ashton et al. 2010), and EDCs (Hermabessiere et al. 2017).

The addition of chemical additives during the plastic manufacturing process can also pose a chemical threat (Rios et al. 2007; Oehlmann et al. 2009; Guo and Wang 2019). Additives include plasticisers such as phthalates or bisphenol A, flame retardants, and stabilisers such as lead (Pb) and other metals. These can leach into the marine environment as plastic weathers (Gardon et al. 2020; Lomonaco et al. 2020), or if ingested, into the tissues and guts of organisms (Teuten et al. 2007; Engler 2012; Tanaka et al. 2013). The harmful substances sorbed and leached are often persistent, enabling plastic objects to become vectors for contaminants or **biovectors** (Figure 9.9) (Wang et al. 2020), resulting in bioaccumulation (Paul-Pont et al. 2016; Gallo et al. 2018).

The cumulative effects of microplastics and associated pollutants remain a developing field. Theoretical modelling has shown that the effect of adsorbed pollutants in organisms ingesting microplastics should be minor (Koelmans et al. 2016). However, laboratory-based studies have shown that once microplastics are ingested, the associated contaminants can be readily released into the bloodstream of marine organisms (Tanaka et al. 2013; Besseling et al. 2014). Further impacts may occur through biomagnification (e.g. Rochman et al. 2013; Batel et al. 2016). As these impacts can increase through the marine food chain, there are also implications for human health (Wang et al. 2019b; Enyoh et al. 2020).

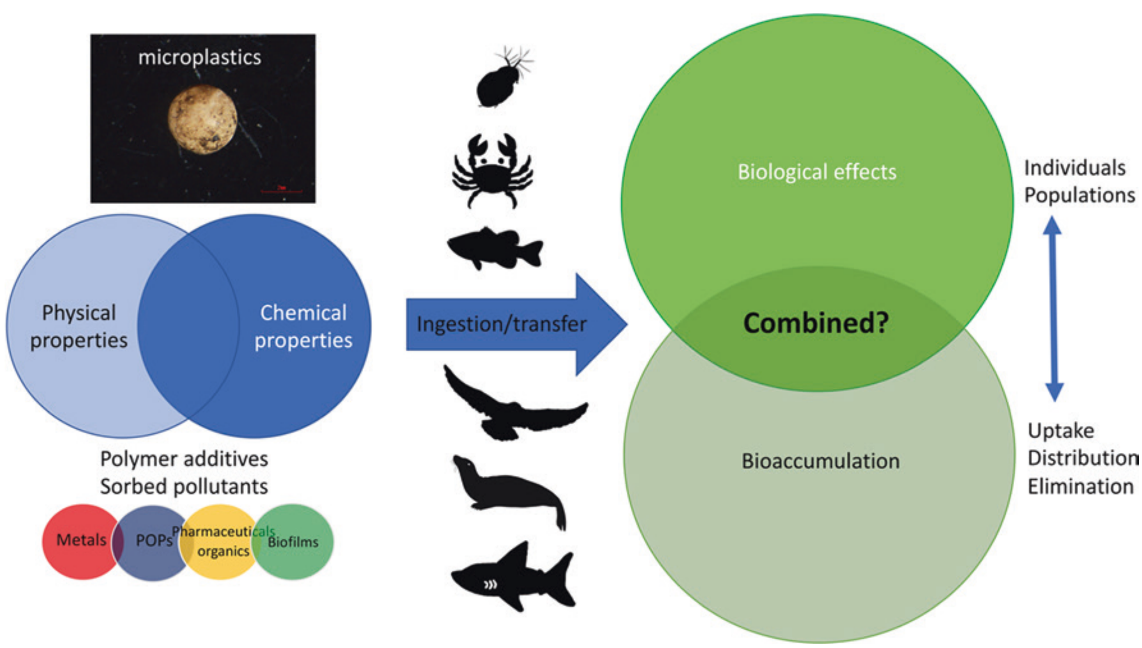



**Figure 9.9** Through their physical and chemical properties, microplastics can act as biovectors of contaminants through marine food chains, with increasing biological effects and bioaccumulation through trophic levels. Yet the combined impacts of microplastic ingestion and transfer of chemicals on individuals or populations require further research. *Image*: P. Lewis

### 9.6.5 Human Health Impacts

Similar to marine wildlife, marine plastic pollution interacts with humans via numerous pathways. Humans may be exposed to plastic debris through seafood, as microplastic debris has been found in invertebrates, crustaceans, and fish harvested for human consumption (Van Cauwenberghe and Janssen 2014; Rochman et al. 2015; Carbery et al. 2018; Smith et al. 2018; Cox et al. 2019; Walkinshaw et al. 2020). Since most plastic remains in the digestive tract of an animal, the risk of ingestion by humans is higher when organisms are consumed whole, such as with small fish or bivalves (Rochman et al. 2015). There is concern that the chemical impacts associated with micro- and nanoplastic ingestion documented in marine wildlife are also a concern for human health, including adsorption across the gastrointestinal tract (Waring et al. 2018), chemical toxicity associated with leaching of plastic additives (e.g. BPA, heavy metals, EDCs) (Campanale et al. 2020), or sorbed contaminants (Smith et al. 2018), as well as hazards associated with microbial colonisation (Wright and Kelly 2017; Wang et al. 2019a, b). **Knowledge on the implications of microplastic consumption by humans is currently limited**, however the severity of impacts will be dependent on seafood contamination levels, exposure frequency, and effects of exposure. Similar to other organisms, it is possible humans simply ingest and then egest plastic pieces. While evidence is growing about the interactions between micro- and nanoplastic exposure, toxicology, and human health (Wright and Kelly 2017; Smith et al. 2018; De-la-Torre 2020), further research is required on this topic.

Marine plastic debris on beaches can directly impact an individual's physical and mental health (Beaumont et al. 2019). Sharp plastics or plastic containers that contains chemical waste can result in cuts or exposure to dangerous liquids and unsanitary items (Santos et al. 2005). Littered coastlines can negatively impact mood and mental wellbeing, resulting in a reduction in recreational use of littered areas (Wyles et al. 2016). Additionally, since some people experience wellbeing in the knowledge that culturally significant animals will be experienced and enjoyed by future generations, a loss of wellbeing can be associated with the adverse impacts of plastic debris on culturally significant marine megafauna such as turtles and whales (Beaumont et al. 2019).

### 9.6.6 Economic Impacts

Economic costs associated with marine plastic pollution can be either direct or indirect (McIlgorm et al. 2011). Marine plastic pollution negatively impacts tourism, fishing (subsistence, recreational, commercial), shipping, aquaculture, recreation, and other ecosystem services. Ecosystem service are the benefits people obtain from nature, including food, carbon storage and cultural benefits (Worm et al. 2006; Liquete et al. 2013) and evidence suggests that plastic pollution causes significant impacts to almost all global ecosystem service (Beaumont et al. 2019). In 2011, based on ecosystem service values and marine plastic abundance estimates, marine plastic's economic costs were conservatively estimated at between US$ 3300 and US$ 33,000 per tonne of marine plastic per year (Beaumont et al. 2019).

Renowned or frequently visited beaches that are littered may incur a range of economic costs including clean-up expenses and lost tourism revenue (Beaumont et al. 2019). Shipping, navy, coast guard, and fishing industries are impacted by direct damage and entanglement of fishing gear in propellers (Chen 2015). Fishing industries also suffer economic loss due to plastic debris negatively impacting fish habitats (e.g. sunken derelict fishing gear) and stocks (e.g. ghost fishing) (Kaiser et al. 2003; NOAA 2015). In Indonesia, local fisherfolk described the direct and indirect negative impacts of marine debris, including propeller entanglements, fouling of gill nets and hooks, damage to fishing gear, and injuries (Nash 1992). Such impacts can result in additional fishing time and modified fishing behaviour to attain the same yield compared to as if there were no waste associated losses. Some modified fishing behaviour includes the adoption of harmful fishing methods (Nash 1992).

## 9.7 Actions to Drive Change

Our current knowledge and understanding of the marine plastic pollution issue, including key sources, waste management inefficiencies, and gaps in legislation, provide a solid foundation for developing actions to combat this global issue (Rochman et al. 2016). Despite knowing where actions are required, finding effective solutions is a complex task for many reasons:

- there are economic incentives for continued and increased use of plastic;
- production continues to rise;
- waste management is inadequate and inconsistent within and amongst countries;
- plastic inputs are difficult to predict and hard to control;
- plastic knows no boundaries and will move to new jurisdictions;
- there are areas with no jurisdiction; and
- plastic debris accumulates in remote areas, or may sink out of sight.

As such, solutions require coordinated approaches by a range of stakeholders, including producers, consumers, scientists, and policy makers (local, regional, national, and international levels) (Löhr et al. 2017).

Global partnerships and commitments are being made to address marine plastic pollution (and other types of marine litter) at many major global fora (e.g. G7, G20, and the 2017 World Oceans Summit) (Vince and Hardesty 2018). International partnerships have led to instruments that regulate marine plastic pollution through conventions, strategies, action plans, agreements, and regulations (Chen 2015). For example, the EU Action Plan for a Circular Economy (a Europe-wide strategy committed to reducing plastic pollution impacts and increasing material value in the EU economy), MARPOL Convention (prevention of pollution from ships), the Honolulu Strategy (improving co-operation to prevent land-based plastic entering the oceans), and The Clean Seas Global Campaign on Marine Litter (worldwide elimination of single-use plastics and microplastics in cosmetics by 2022) (Ferraro and Failler 2020). In March 2022 Heads of State, Ministers of environment and other representatives from UN Member States endorsed a historic resolution at the UN Environment Assembly (UNEA-5) to

> "*End Plastic Pollution and forge an international legally binding agreement by 2024. The resolution addresses the full lifecycle of plastic, including its production, design and disposal*".

Although international instruments are a step in the right direction, international policy framework can be fragmented, its focus can be limited, and laws are often soft (i.e. non-binding) (Vince and Hardesty 2018; Ferraro and Failler 2020). It is therefore imperative that these efforts coincide with actions taking place at local and national, levels, such as legislation and regulation creation.

A critical short-term action to reduce plastic inputs into the marine environment includes improvements to waste management regulations and infrastructure (Löhr et al. 2017). Around 4.8–12.7 million tonnes of marine plastic pollution enter the ocean from land-based sources annually, originating from 20 of 192 coastal countries (Jambeck et al. 2015). Highly polluting counties include China, Indonesia, Philippines, Vietnam, Sri Lanka, Thailand, Egypt, Malaysia, Nigeria, and Bangladesh (Jambeck et al. 2015). Many of the listed countries lack adequate waste management, making improvements to waste management (e.g. providing and improving collection infrastructure and technologies) critical for reducing plastic inputs into the ocean. Many new instruments are taking a hierarchical approach to waste management (Figure 9.10), which prioritises inhibiting waste generation and movement of litter into the marine environment, rather than cleaning up what is already in the ocean (Watkins et al. 2012). This is not to say that ocean and beach cleanups are not important, but rather highlights how approaches that prioritise prevention rather than mitigation and curative measures are very important (Critchell et al. 2019; Watkins et al. 2012).

Large system changes such as behavioural changes and transitioning to a circular economy are suggested as longer-term solutions (Löhr et al. 2017). A circular economy focuses on purposeful design to incorporate end-use and reuse from the start of a product's life cycle (reduce, reuse, recycle, redesign, recover), encouraging supply chain investments that will ultimately reduce waste entering the ocean (Ellen MacArthur Foundation 2017). A circular economy approach is designed to not only benefit the environment, but also the economy, as it recaptures costs currently being lost (WEF 2016).


**Figure 9.10** Hierarchical approaches to waste management guide and rank waste management decisions. The preferred option is the prevention of waste generation, through limiting raw materials or acquiring used/recycled materials or materials that can be recycled. Waste disposal is unsustainable and can have long-term environmental impacts. Disposal is the least preferred option and should be carried out responsibly. *Image*: Wikibooks: CC-BY-SA-3.0

All pro-environmental movements require behavioural changes, which can be facilitated at numerous stakeholder levels using many strategies. For example, governments (regional and national) can create new policy and legislation aimed at reducing plastic product use or specific activities (e.g. bans on plastic grocery bags or microbead use in cosmetics, ten Brink et al. 2016). In 2015, the Canadian province of Ontario banned the production of microbeads (Legislative Assembly of Ontario 2015), and the United States of America (USA) passed a federal law banning microbead use in rinse off products by 2018 (Rochman et al. 2015; United States Congress 2015). Many other countries (e.g. Netherlands, United Kingdom) have expressed interest in creating similar laws (reviewed in Xanthos and Walker 2017). Economic incentives can target consumption, including the application of deposit refunds for plastic bottles, and charges/taxes to plastic bags and other one-use items (ten Brink et al. 2016).



Education and change-oriented public awareness is critical if we are to increase proper waste disposal rates and to promote consumers' refusal of products containing plastic and sustainable substitutes (ten Brink et al. 2016). Notable recent actions include the "*Beat The Microbead*" campaign (Plastic Soup Foundation 2020) and the Massive Open Online Course (MOOC) on Marine Litter, which is part of the "*Clean Seas*" campaign (Brown 2013). MOOC targets a range of sectors and stakeholders and aims to provide actionable and change-oriented open access learning on a global scale (Brown 2013; Leire et al. 2016).

## 9.8 Summary

Thirty-three billion tonnes of plastic will be created globally by 2050, if plastic production continues to increase at its current rate of 5% per year (Rochman et al. 2013). For context, compact cars weigh slightly over 1 tonne, while large cars weigh closer to 2 tonnes. It is imperative that strong efforts are made to reduce plastic production, use, and disposal as soon as possible. The natural environment is already inundated with plastic debris, and the ocean acts as a main sink for discarded and mismanaged plastic waste. This chapter highlighted some of the interactions and negative implications of plastic pollution in the marine environment, however, estimates of total plastic debris in the ocean are conservative, suggesting that the interactions with wildlife and potential adverse effects are much worse than what has been documented. As with any environmental stressor, it is also important to consider that the impacts of plastic may act in combination with other environmental stressors, such as over-exploitation, other types of pollution, and climate change, and that the cumulative effects of these stressors may be causing more damage than plastic pollution alone.

While there are many governance challenges and complexities influencing the success of plastic waste reduction and management, significant steps have been made. These include strategies to change consumer behaviour, transitioning to a circular economy, and the implementation and enforcement of policies and law (Löhr et al. 2017). The further success of initiatives will require actions from a range of stakeholders (e.g. producers, consumers, industry, and policy makers). Nonetheless, as is the case for most environmental issues, individuals can create positive change by staying informed, educating others, and changing their behaviour. Some easy actions to start with include: (1) read personal care product labels for plastic ingredients and don't purchase products that use microplastics; (2) carry reusable bottles/thermal cups and refuse single-use plastic items; (3) pick up and properly discard plastic litter; (4) educate yourself on local recycling policies and ensure you're recycling plastics properly; (5) read clothing labels and only purchase clothes that made from natural fibres, such as cotton, wool, hemp, and bamboo. These seemingly minor actions will contribute greatly to the positive changes occurring worldwide.

## 9.9 Questions and Activities

1. Take the time to monitor how much plastic waste you create each week. What activities result in the most plastic consumption?
2. What are three actions you can take regularly to reduce your plastic use?
3. What types of marine wildlife are most at risk from plastic floating in the ocean?
4. What characteristics make an animal more vulnerable to the impacts of plastic pollution in the ocean?
5. Provide examples of how a circular economy could reduce plastic waste from entering the ocean.

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