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Plastic Pollution. The Role of (Bio)Degradable Plastics and Other Solutions

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3.1 Introduction and Problem Definition

The issue of plastic waste in the environment has been obvious and problematic for some time, and the extent of health effects as a result of prolonged human exposure to micro- (0.1 μm to 5 mm) and nano-plastics (<0.1 μm) via the air we breathe, the food and drinks we consume, and via contact with our skin is still uncertain today.

When mass production of plastics began after the 1950s, it quickly found application into all facets of modern daily life. However, there was never a serious consideration about the fate of plastics in the environment, the resulting almost endless accumulation (due to very slow degradation), and of the short- and long-term effects that plastics will exert on living organisms when produced at today's enormous and still-expanding scale.

Despite all societal benefits, "plastics" are rightfully challenged by society because of their carbon footprint and because of the plastic litter that is accumulating on land, in rivers, and in oceans. It is however important to note that plastic littering is not an inherent plastic property. It is the society itself that did not design proper use and after-use protocols for safely handling plastic materials. This includes both careless consumers littering the environment and the release of plastic particles upon normal use of products such as textiles and tires. Plastics in the environment are of increasing concern because of their persistence and universal occurrence.

Plastics have been found in large amounts everywhere on land, on the highest mountain tops, and the most remote locations such as the poles, in the air, in rivers and on coast lines, in arctic sea ice, and at the sea surface and on the sea floor. Seven hundred marine species are known to have ingested or become entangled in macroplastics [1, 2], and evidence also shows that plastics are ingested by many terrestrial organisms [3]. Weathering and biodegradation of plastic debris cause

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fragmentation into particles that even small marine invertebrates may ingest. Its small size also renders this debris untraceable to its source and impossible to remove from marine environments. This suggests that the most effective mitigation strategies must involve redesigning plastics and reducing outputs to the environment. Even with the implementation of the best strategies to mitigate plastic waste leaking into the environment it will be impossible to prevent contamination altogether. It is therefore important to evaluate if we can also do something about the plastic waste lifetime in the environment (see Figure 3.1).

Many of the current large-volume plastics degrade extremely slowly in the environment or virtually not at all. The environmental conditions also play a role here. Polyolefins (polyethylene [PE], polypropylene [PP], polystyrene [PS]) have a low density (0.8–0.9 g/cm^3) and, as a consequence, they will float on seawater (density 1.03 g/cm^3). Floating plastics are exposed to oxygen, heat, and UV radiation from the sun, three factors that have been shown to accelerate non-biological plastic degradation. Other plastics such as polyvinyl chloride (PVC), polyesters such as polyethylene terephthalate (PET), and polyamides such as nylon-6 and -66 have densities higher than 1 g/cm^3, and as a consequence, they will migrate to the sea floor where it is dark, and typically in a lower temperature, but as our own research has shown, there can be typically more microbial activity in the sediment than in the seawater itself.

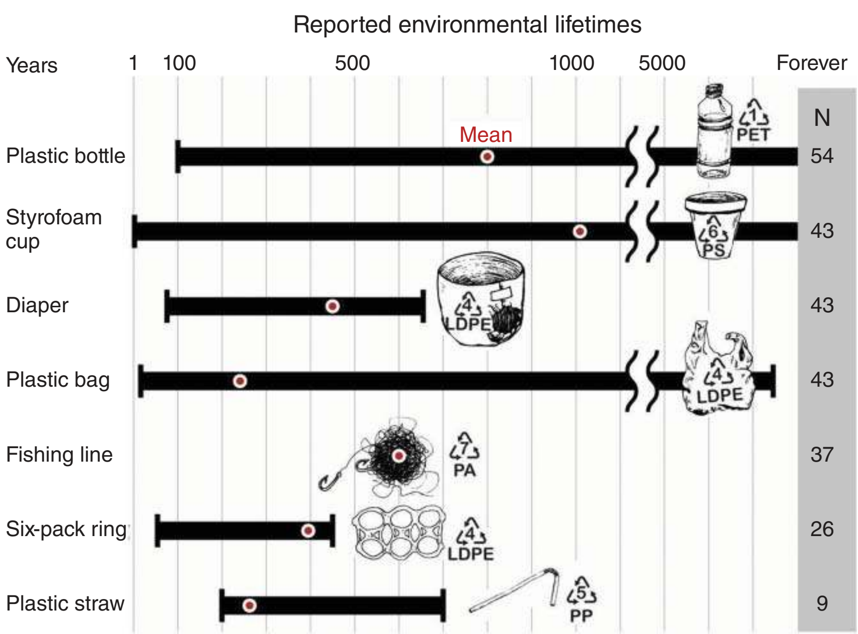
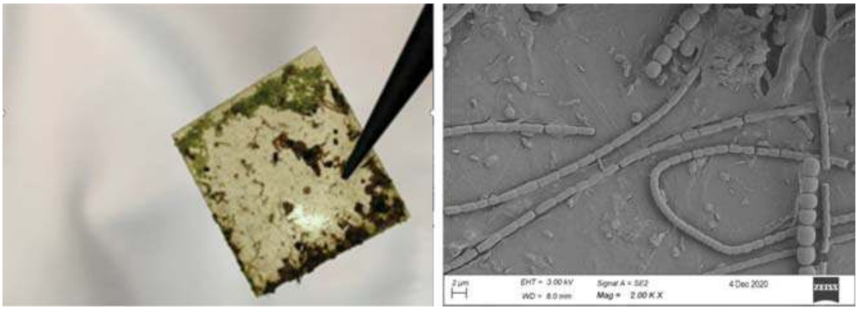


Figure 3.1 Review of 57 information graphics and documents that report environmental lifetimes of common plastic consumer goods. The bars represent the range of estimates, the red circles represent the mean of estimates, and the number of estimates for each plastic good (*N*) is provided on the right (*N* = 255 in total). PET = polyethylene terephthalate, PS = polystyrene, LDPE = low-density polyethylene, PA = polyamide, and PP = polypropylene. Source: From ref. [4]. Image credit: Natalie Reiner.



(a) (b)

Figure 3.2 Example of a biofilm formed on a 2 × 2 cm plastic PEF film (a) and an electron microscopic image showing fungi and bacteria (b). Source: Pictures Yue Wang; Industrial Sustainable Chemistry, HIMS, University of Amsterdam.

Plastic densities are not always stable. Plastic species in a marine environment will be covered by a community of microorganisms, invertebrates, and algae, together called a biofilm (see Figure 3.2). As a consequence, the particle density can increase and polyolefin debris may at some point in time sink.

Growing alongside the volume of global production and consumption of plastics are the diverse concerns about their impacts on the ecosystem and on human health, particularly as micro- and nanoplastics (MNPs) [5]. The concerns about MNPs are diverse [6, 7]. The first concern is about the MNPs irritation of body cells and tissues potentially leading to infections. Secondly, MNPs may contain residual monomers and additives (e.g. plasticizers, anti-oxidants, UV stabilizers) that can slowly diffuse into the body and eventually intervene in the metabolism. Finally, MNPs tend to accumulate toxic hydrophobic contaminants present in the air or in the water, such as polychlorinated biphenyls (PCBs). These contaminants can be released in the organism and affect its metabolism.

3.2 Sources of Macroplastics and MNPs

3.2.1 Mismanagement of Waste

Since mass production of plastics started in the 1950s, production has grown exponentially to over 370 million tons in 2019 (Figure 3.3), and this does not even include the production of fibers, thermosets, and rubber [8]. Contrary to the trend, this remained at a comparable number in 2020, which is explained by the crisis caused by the COVID-19 outbreak (https://phys.org/news/2021-06-global-plastics-production-falls.html). Only a very small group of polymers makes up the vast majority of these plastics: PE (low-density polyethylene [LDPE], linear low-density polyethylene [LLDPE], high-density polyethylene [HDPE]), PP, PET, PS, and PVC. In practical terms these materials should be considered non-biodegradable. They are, however, susceptible to wear, leading to the formation of small particulates of these plastics. When we relate this to the amounts of mismanaged plastic waste

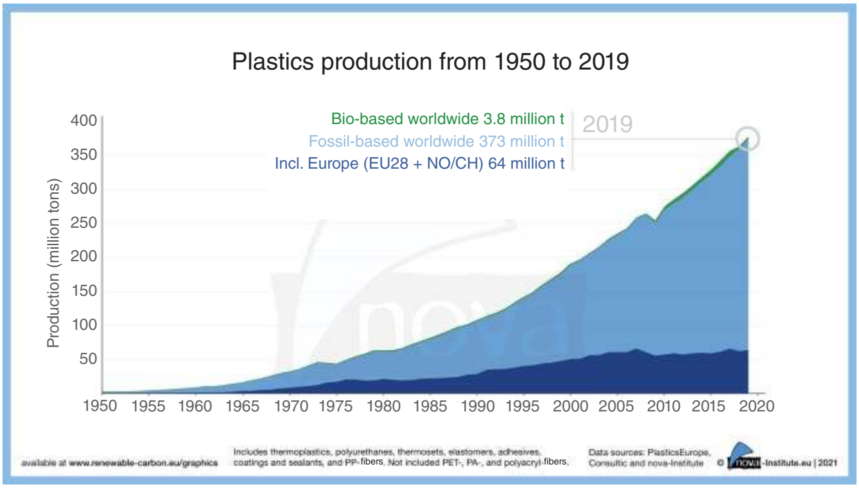


Figure 3.3 Worldwide plastics production since 1950 [8]. Source: nova-Institute GmbH, press release, 2021-01-28.

generated annually (>30 Mt), it becomes clear that millions of tons of macroplastics and MNPs enter the environment from simply mismanaging waste. Given the steep growth of plastics consumption this amount is only increasing.

In 2010, an estimated 2.5 billion tons of municipal solid waste was generated by 6.4 billion people living in 192 coastal countries (93% of the global population). Approximately 11% (275 million tons) of this waste was plastic, which roughly followed 2010 plastic resin production (270 million tons), with differences resulting from the time lag in disposal of durable goods (lifetime of years to decades). It was estimated that about 100 Mt of plastic waste was generated in coastal regions (population living within 50 km of the coast). Of this, about 32 million tons was classified as mismanaged and an estimated 4.8–12.7 million tons entered the ocean in 2010, i.e. 1.7–4.6% of the total plastic waste generated in those countries [9]. Next to this macroplastics pollution, 1.5 Mt of primary microplastics [10] enter the ocean annually after normal wear of consumer products such as fibers in clothing and tires, or because these microplastic were intentionally added to consumer product, e.g. as abrasives in cosmetics. The macroplastics in the environment can also break down into microplastics; these are referred to as secondary microplastics. If plastic production and waste generation continue to grow as we have seen in the last decades, the annual amount of plastic pollution may more than double by 2050 [11, 12] resulting in a 10-fold increase in the cumulative amount of ocean plastic in the period 2010–2025 relative to the cumulative plastic pollution in the 60 years of plastic production and use prior to 2010 (Figure 3.4) [9]. To visualize these amounts: 9.5 million tons of plastics entering our oceans every year is 300 kg/s. As a garbage truck fits 20 m^3 waste plastic with an average bulk density of 50 kg/m^3, this amount is the same as 18 full garbage trucks spilling their contents into the oceans every minute (Figure 3.5).

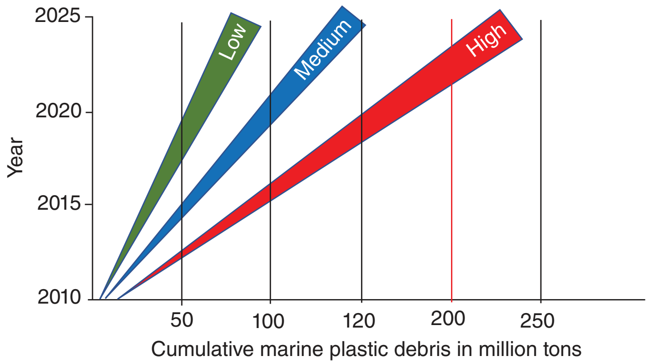


Figure 3.4 Estimated mass of mismanaged plastic waste input to the ocean (in millions of metric tons) by populations living within 50 km of a coast in 192 countries, plotted as a cumulative sum from 2010 to 2025. Estimates reflect assumed conversion rates of mismanaged plastic waste to marine debris (high, 40%; mid, 25%; low, 15%) [9].

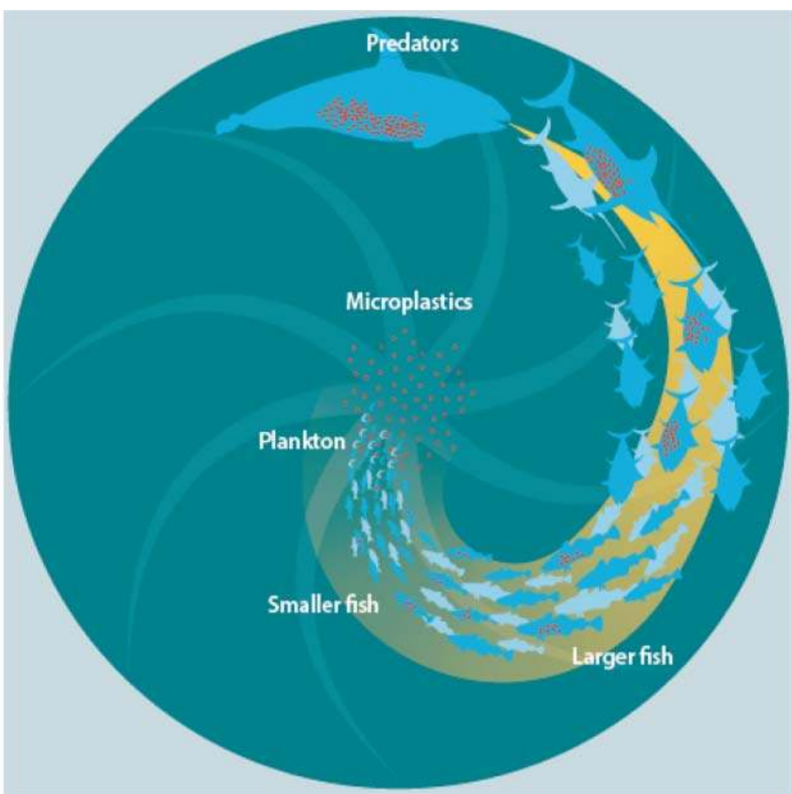


Figure 3.5 MNPs bio-accumulation in the food web. Source: Picture from Ref UNEP and GRID-Arendal [13].

3.2.2 Accidental Release

The primary production of plastics to be used downstream to make products is typically in the form of granules and small resin pellets. Through accidental spillage during land or sea transport, inappropriate use, and by direct outflow from processing plants (spillage and clean-up by hosing down floors), these raw material pellets enter the environment. In an assessment of Swedish waters, KIMO Sweden found plastic particle amounts in the typical range of 150–2400 per m^3. However, in a harbor adjacent to a plastic production plant, the amount of particles was more than 100 000 per m^3 [14, 15].

Many industrial sites that use raw plastics materials in the form of pellets are frequently located near bodies of water. If spilled during transport and processing, these materials may enter the surrounding environment, polluting waterways [16].

3.2.3 MNPs in Products

Microplastics that are intentionally added to certain personal care products fulfill the functions of scrubbing, cleansing, and exfoliating. Leslie [17] indicates that polymers more widely fulfill a wide range of functions depending on the polymer type, size and shape of the ingredient, and nature of the product it is used in. The following functions were listed: viscosity regulators, emulsifiers, film formers, opacifying agents, liquid absorbents binders, bulking agents, for an “optical blurring” effect (e.g. of wrinkles), glitters, skin conditioning, exfoliants, abrasives, oral care such as tooth polishing, gellants in denture adhesives, for controlled time release of various active ingredients, sorptive phase for delivery of fragrances, vitamins, oils, moisturizers, insect repellents, sun filters, and a variety of other active ingredients, prolonging shelf life by trapping degradable active ingredients in the porous particle matrix (effectively shielding the active ingredient from bacteria, which are too big to enter particle pores). By design these types of products result in littering of microplastics, as these polymer particles are essentially intended to be flushed out with the wastewater. This can be seen as significantly different from most of the plastic-littering issues, which are caused by unintended littering, sloppiness, or the absence of a proper waste-management infrastructure.

3.2.4 Degradation of Outdoor Objects

Paints and surface coatings also contain polymers, and painted surfaces, roadway markings, and vessels are subject to weathering. In addition to polymers, paints often contain metal-based pigments such as Cu and Zn. In one study, up to 0.2% of the mass of sediments that were analyzed were shown to consist of paint particles [18]. When investigating microplastics in waters of Jinhae Bay, Korea, the abundance of paint particles exceeded those of other microplastic types and that size frequencies peaked in the 50–100 μm range [19]. Alkyd ship paint resins and poly(acrylate/styrene) from fiberglass resins were dominant polymers. Similar findings were reported for the Incheon/Kyeonggi coastal region (Korea) [20].

In 2019, surface slicks (meandering lines of smooth water on the ocean surface that accumulates floating objects and organisms) were shown to contain a plastics-to-larval fish ratio that was 60-fold higher than that of adjacent waters [21]. Microplastics and paint particle loads were reported in beach sediments from an Italian subalpine lake in 2016 [22]. The paint particles typically were smaller than other types of microplastics, mostly 1–50 μm, likely due to their brittleness.

While terrestrial sources are the most important, large amounts of plastics enter the oceans from wear of sea-based sources every year. The fishery sector uses large amounts of plastics. Losses in the fisheries sector include loss of fishing gear (nets, ropes, floats, lines, gloves, fish boxes, strapping bands), and release of fibers and other fragments due to normal wear and tear (e.g. use of ground ropes). Fishing gear may be lost at sea by accident, abandonment, or deliberate disposal (together termed "abandoned, lost, or otherwise discarded fishing gear" or ALDFG), and likely is the largest category in terms of volume and potential impact of all the ocean sources. ALDFG can have a significant impact on depleting fish and shellfish and can cause unnecessary impacts on non-target species and habitats.

Expanded polystyrene (EPS) buoys are used extensively in Asia for the hanging culture of mussels and oysters. It is estimated that approximately 1.8 million are discarded into the marine environment annually [23]. Each EPS buoy (~60 l) can generate 7.6 million micro-size EPS fragments of <2.5 mm diameter, or 7.6×10^{21} nanoparticles of <250 nm diameter [24]. Consequently, EPS buoys and fragments accounted for >10% of marine debris on 94 Korean beaches in 2008 [23]. In 2012, the Korean Ministry of Ocean and Fisheries provided financial support to fishermen to replace old buoys with high-density, less easily degraded buoys.

3.2.5 Wear (Tires, Clothing)

Apart from littering and other unintended spillage of plastics into the environment, the wear of many products during normal use also causes the release of synthetic material into the environment. These are materials that are used in daily life, often for durable applications, and just wear down over time: carpets, clothing, tires, shoes, artificial turf. In most cases these contain polymers of some kind (rubbers, thermosets, and thermoplastics) that will therefore be released into the environment in the form of small particles. The total amount of these primary microplastics entering the environment is estimated to be well over three million tons per year [10]. For such applications, alternatives should be sought further upstream, in the design phase.

The most common and closest-to-home example of microplastic release into the environment comes from textile. Currently the majority of textiles used are synthetic, most commonly nylon (polyamide) and (PET) polyester. During each wash a single garment could lose close to 2000 fibers [25]. Other studies indicate losses as high as 700 000 fibers for every 6 kg of laundry [26]. These fibers end up in the wash water and are thus flushed into the sewage systems. Filtering is often absent at any point of the water-management chain or it is not very efficient. This means that polyamide and polyester microplastics are constantly being released into the environment, and this type of waste is building up over time. Laundry of synthetic fabric is the largest source of all primary microplastic pollution, amounting to 30–35% of microplastic pollution. The severity of this problem, e.g. the impacts on aqueous water ecosystems, is still largely unknown and may thus be underestimated.

It is estimated that annually approximately 1.3 Mt of tire wear is generated on European roads [27, 28]. That is equal to over 2 kg per person per year. Tire wear is estimated to contribute to >50% of microplastic emissions in Denmark and Norway and approximately 30% in Germany [28]. There is no reason to assume that these values would differ much in other areas of the world, and tire wear is therefore estimated to be responsible for almost 30% of all primary MNP pollution. To make matters worse, tire wear plays an important role in the particulate matter burden (as a large contributor to air pollution) in urban areas.

Tire tread typically consists of natural or synthetic rubber (40–50 wt%), filler (soot, carbon black, silica, chalk; 30–35 wt%), softener (oil and resin; 15 wt%), vulcanization agents (sulfur and ZnO; 2–5 wt%) and additives (plasticizers, antioxidants, preservatives, etc.; 5–10 wt%) [28, 29].

Rubbers have been the focus of biodegradability research for over a century. This is especially the case for natural rubbers, which are based on *cis*-1,4-isoprene. Initially this was an undesired property regarding durability of the material. A century later this is now desirable for the opposite reasons of trying to understand the fate of these materials in nature. A lot of the research focuses on the isolation of certain organisms, both bacteria and fungi, and researching their effect on the breakdown of these rubbers [28, 30, 31]. Often significant mass losses and decrease in molecular weight are observed in a matter of weeks or months. It appears that also vulcanized natural rubbers, as well as synthetic *cis*-1,4-isoprene-based rubbers are susceptible to biodegradation [31]. A lot is known about the organisms and enzymes responsible for the biodegradation, as well as the mechanisms, yet given that a lot of research focuses on isolating and applying certain organisms, rather than random degradation in soil or aquatic environments, it is difficult to make statements regarding the timeframe of these materials breaking down in various natural environments.

Today plastic pollution is ubiquitous: macroplastic can be seen everywhere, but especially in less prosperous parts of the globe and there is an exponential growth. There is, however, also the invisible pollution of microplastics, which are found in every corner of the world. Microplastics, especially from fibers and tire and road particles, typically have densities higher than 1 g/cm^3, which means they sink to the bottom of rivers, lakes, and oceans. They are ingested by living organisms and thus find their way up the food chain.

3.2.6 Waste and Wastewater Management (Water/Wind)

Rivers represent a key entry point of macro- and MNPs to the ocean. From the limited data available, it would appear that river catchments, especially those draining areas with high population densities and industrial development, can carry a significant plastic load to the ocean. However, there is a great lack of information on the quantities entering the ocean globally via this entry point, which sources are most important, what measures may be effective at controlling these sources, and how all these aspects differ regionally. The effectiveness of wastewater and solid waste management will be an important factor in modifying the input to waterways, whatever the nature of the land-based sources concerned. For these reasons, significant regional differences may be expected. Extreme flooding events have the potential to mobilize plastic that would not be transported to the ocean otherwise. The effects of heavy rainfall are exacerbated by unsustainable land-use practices (e.g. deforestation, compacted soils). There is evidence that extreme events are becoming more common as a consequence of global warming.

3.3 Impacts of Macroplastics and MNPs

This section is focused on the impact of MNPs on ecosystems and economics. Emphasis has been given to MNPs as the ultimate ecological impact of MNPs is not well understood thus far. Furthermore, most of the published studies have focused on the marine surface and the actual amount of MNPs in different environmental compartments (terrestrial, marine, freshwater, and atmospheric), and their impacts have not been widely discussed. This is due to the difficulties in assessing the quantity of MNPs (because of the small size of MNPs and the lack of adequate analytical approaches) and the fact that little is known about the (bio)chemical mechanisms in organisms regarding MNPs (due to the immensity and diversity of ecological species).

3.3.1 Ecological Impact of Macroplastics (Entanglement and Ingestion)

Entanglement has been recognized as the most visible ecological impact of macroplastics, especially on marine organisms (e.g. mammals, fish, and birds). Entanglements are often related to fishing gear, and they can lead to acute and chronic injury or death. It is estimated that between 57 000 and 135 000 pinnipeds and baleen whales globally are entangled each year, and up to 50% of humpback whales in US waters show scars from entanglement [26].

Ingestion of macroplastics is another important ecological problem and has been reported for a wide range of marine organisms. Large quantities of plastic sheeting and plastic bags are frequently found in gut compartments of turtles and toothed whales. Ingestion of plastic debris has been reported in seabirds such as albatrosses and in 46 cetacean (whale) species: for some species in as much as 31% of the cases. The different feeding habits of closely related species can influence their susceptibility. Chemicals leached from the plastic debris can cause additional adverse health effects on marine organisms.

3.3.2 Economic Impact of Macroplastics

It is estimated that the impact of plastic pollution in the oceans alone is at least US$8 billion per year [32]. The economic impact of macroplastics can be direct and indirect. For example, macroplastics can lead to economic costs in the commercial shipping sector due to damage caused by entanglement or collision. Indirect impacts include loss of target species due to ghost fishing and the loss of attractiveness of beaches and shorelines for recreational purposes. Decrease of tourism leads to a loss of revenue and jobs in the local and regional economy. Also, clean-up costs can be significant and pose an undue burden on local authorities. Given the difficulty of cleaning and the low production cost of plastics, removing plastics is likely significantly more expensive than producing them.

3.3.3 Ecological Impacts of MNPs

The biological effects of MNPs involve physical interactions (e.g. ingestion of MNPs), chemical exposure to plastic-related compounds (e.g. additives), to sorbed toxins (synthetic or natural), and to surface-associated organisms (e.g. pathogens). The impacts of MNPs on biota in the aquatic environment, especially the marine environment, have been widely investigated since the 1970s. However, investigations on the ecological impacts of MNPs on soil and atmosphere only started in the last 20 years.

3.3.3.1 Aquatic Environment

The MNPs, from different sources (direct release, washed by surface run-off, blown by wind, etc.), eventually end up in the aquatic environment. MNPs were detected in rivers, estuaries, and oceans. Numerous studies have proven the ingestion of MNPs by various aquatic organisms [33] and is considered the most common cause for MNP uptake by marine species. It often starts with small aquatic biota, like plankton, and subsequently moves up the food chain to filter organisms, small fish and whale sharks, affecting the entire food chain [13]. It has been reported that 36% of pelagic (bottom feeding) and demersal (open water) fish collected from the English Channel had MNPs in their digestive systems [34]. MNPs have been found in the digestive tract of all the specimens sampled along the British coast [35]. Aquatic biota may take MNPs in as their food due to misidentification or indiscriminate consumption, and/or ingest indirectly as a result of trophic transfer along the food web [33]. In addition, the adherence of MNPs to soft tissues of mussels has been reported as a novel way for MNPs uptake beyond ingestion, which contributes about 50% of the MNPs uptake in mussels [36]. The shore crab (*Carcinus maenas*) can even take up MNPs through inspiration across the gills [37].

MNPs can accumulate in the tissues of blue mussel (*Mytilus edulis*) and translocate from the gut to the circulatory system within three days [38]. Ingestion or tissue translocation of MNPs can induce several adverse effects in aquatic biota, including digestive system blockage, tissue damage, behavioral changes, growth delay, decrease in reproductivity, immune response, and even death [39]. For example, the feeding capacity of the copepod *Calanus helgolandicus* was significantly altered after the prolonged exposure to PS [40]. For limnic zooplankton (*Daphnia magna*) ingestion of MNPs led to immobilization under laboratory conditions [41]. Exposure to MNPs led to histopathological changes and changes in blood biochemical parameters in juvenile African catfish (*Clarias gariepinus*) [42]. To make matters worse there is increasing evidence that MNPs can sorb pathogens and pollutants, and these pathogens and pollutants can also lead to growth delay, decrease in reproductivity, and increase in mortality of aquatic organisms [43]. In addition, plastic-related chemicals (PRCs) are present. These are substances related to plastics, including residual monomers, antioxidants, additives, or the degradation products of plastics. PRCs such as bisphenol analogues (e.g. bisphenol A [BPA], bisphenol F [BPF], bisphenol S [BPS], and bisphenol AF [BPAF]), 4-nonylphenol, and some phthalates have been detected in bottled water, water, seafood, vegetables, and many different types of packaged food. Many of these chemicals can cause adverse health effects in humans, including endocrine disruption, changes in neurobehavioral development, and metabolic diseases such as diabetes and obesity, raising concerns of consumer safety.

PRCs can enter the environment and food through pathways such as the discharge of industrial wastes to the environment, irrigation with reclaimed water, or through the application of polymers in agriculture and food or as food contact material [43].

3.3.3.2 Terrestrial Environment

Soil appears to be a sink of MNPs [33]. These MNPs may impact the geochemistry of soil and interact with soil biota [44]. The adverse effects of MNPs on terrestrial environment have, however, not been investigated as much as the impact on the aquatic environment. Most of the research was done through laboratory experiments, and earthworms and soil collembolans (springtails: wingless primitive insects) are generally used to investigate the ingestion of MNPs.

It is understood that earthworms and soil collembolans can ingest MNPs as well as transport them in the soil [33]. Earthworms are ingested by other animals, chickens among others, which in turn also ingest these MNPs. This has been shown in research on MNPs in soil, earthworm casts, and the feces, crops, and gizzards of chickens [45]. Polymer additives can accumulate in house crickets (*Acheta domesticus*) exposed to polyurethane MNPs [46]. This shows the risk of MNPs carrying these adsorbed chemicals into the food chain. In addition to the impacts on terrestrial organisms, MNPs may also facilitate the accumulation of high-molecular-weight humin-like material and stimulate enzymatic activity [47].

3.3.3.3 Atmosphere

MNPs in the form of fibers (mostly resulting from washing of textiles) can be airborne, as has been measured in many places and will be inhaled by humans and animals. So far, the ecological impact of airborne MNPs on atmosphere (climate and global warming, atmospheric chemistry, etc.) and wildlife has not been well understood. The inhaled or ingested MNPs may accumulate and exert localized particle toxicity by inducing or enhancing an immune response [6]. It is important to realize that airborne MNPs can be transported everywhere, and it is therefore understandable that microfibers are found in the most unexpected places, far from the sea and far from humanity, but can also be transported to aquatic and terrestrial environments, and thus, induce adverse impacts on aquatic organisms as well.

3.3.4 Threat to Human Health

3.3.4.1 MNPs in the Human Food Chain

As mentioned in Section 3.1, MNPs have been detected in hundreds of species of marine organisms, and it is safe to assume that they are present in the seafood sold for human consumption. It is estimated that humans ingest up to several thousand MNP particles per year through seafood consumption, with numbers varying depending on eating habits and living locations [13]. The most likely route for MNPs ingestion by human is the consumption of filter-feeding invertebrates like mussels and oysters because people eat the whole organism of shellfish (and sometimes the small fish), and many studies have reported the presence of MNPs in their tissues and gut (Section 3.3.3.1).

Furthermore, MNPs have been found in beer, sugar, honey, and table salt [48]. Food should therefore be considered an important source of MNPs exposure for humans. As MNPs may contain or absorb contaminants, ingestion of MNPs could be a health threat to humans. Furthermore, MNPs in nano-size (less than 100 nm) have the potential to be absorbed by the body through the digestive system as evidenced by medical studies where nanospheres are used for drug delivery [13].

3.3.4.2 Plastic-Related Contaminants

In addition to the physical effects of MNP ingestion, the chemical additives and monomers that may be released from MNPs can have adverse health effects on human. Some of the plastic additives, like flame retardants, antioxidants, UV-stabilizers, and plasticizers, are toxic to humans. For example, phthalates and BPA show endocrine disruption potential in humans, and animal studies have also suggested their carcinogenicity and the negative impact on reproductive functions even at very low doses [13]. More importantly, some of the additives, such as phthalates and parabens, do not degrade quickly and may thus be biomagnified in the food web. These can, in the end, be ingested by humans.

3.3.4.3 Other Contaminants

MNPs may function as a vector for carrying contaminants and pathogens. For example, MNPs can absorb environmental pollutants, including PCBs, dichlorodiphenyldichloroethylene, nonylphenols, polycyclic aromatic hydrocarbons (PAHs), and metals. Besides, MNPs can also absorb pathogens and transport them inside organisms via MNPs ingestion [49]. In addition, MNPs can concentrate these contaminants to orders of magnitude higher than in the surrounding environment due to their high surface-area to volume ratio [13]. These contaminants have the potential to enter the food web and accumulate through the ingestion of MNPs carrying them. Consequently, they can end up in the human diet. Although human exposure to PCBs and PAHs via MNPs ingestion is much lower than from other pathways (e.g. ingestion of crops treated with herbicide, burning of waste, and industrial exposure) [13], concerning the increasing occurrence of MNPs in food as well as the toxicity of the mentioned contaminants, ingestion of MNPs still poses a risk to human health.

3.3.5 Socio-Economic Impacts of MNPs

MNPs can impact social and economic activities. To date, there is no evaluation of the exact bill for MNPs removal or the income loss due to MNPs in the form of marine and land litter. This is mainly because the economic and social costs are difficult to fully assess as the full extent of the impact of MNPs on ecosystems and human health is still unknown. It is typically more costly to clean up pollution than to prevent it, and in this case that should also be expected due to the small size and high level of dilution. It makes much more sense to deal with this at the source. In addition, the cost for MNPs analysis and monitoring should also be considered.

Apart from the economic costs, there are social costs which include reduced opportunities for recreational activities, health risks to visitors, and psychological benefits of access to nature (e.g. concerns and stress about the presence of [large] amounts of visible plastic or about the ingestion/inhalation of MNPs). However, the social cost cannot be estimated due to the lack of credible research evidence.

3.4 Plastic Biodegradability

The mechanism of biodegradation and the impact of polymer type and environment on biodegradability is discussed in detail in Chapter 4 of this book. Biodegradable plastics are polymers that (simply said) degrade to CO_2, water, and biomass (in aerobic conditions) by means of microorganisms. There are huge differences in biodegradation rates for different biodegradable polymers and of the biodegradation rate of a single polymer in various environments. It is therefore important to report the environmental conditions in which degradability occurs (e.g. home or industrially compostable). Home-compostable plastics are polymers that biodegrade at a similar rate or faster than cellulose (wood) at ambient temperature in 12 months in soil (e.g. polyhydroxyalkanoates [PHA's]). At the time of writing, there is no European standard for home compostability, and the French standard AFNOR NF T 51-800 should be considered for home-compostability requirements. Industrially compostable plastics are polymers that biodegrade at >50 °C in six months in soil (e.g. polylactic acid [PLA]). EN 13432 or equivalent standards (e.g. ISO 18606) should be considered for industrial compostability requirements.

It is important to realize that there are also plastics that are not biodegradable according to home- or industrial compostability standards, but that degrade (much) faster than conventional polymers in nature. For example, our own (yet unpublished) research shows that PLA and polyethylene furanoate (PEF) degrade under ambient conditions within years, while PET shows no degradation in these timeframes in centuries. With novel bio-based plastics we now have an option to avoid these mistakes by designing/selecting our future plastics for better closed-loop recycling and a better fate-in-nature [50].

Polymers which will biodegrade in the terrestrial environment, under favorable conditions (e.g. cellulose acetate, polybutylene succinate [PBS], polycaprolactone

[PCL], polyethersulfone [PES], polyvinyl alcohol [PVA]), also biodegrade in the marine environment, but much more slowly and their widespread use is likely to lead to continuing littering problems and undesirable impacts.

Some of the claims and counterclaims about particular types of polymer, and their propensity to biodegrade in the environment, appear to be influenced by commercial interests. Some evidence, albeit limited, suggests that public perceptions about whether an item is biodegradable can influence littering behavior; i.e. if a bag is marked as biodegradable it is more likely to be discarded inappropriately. On the balance of the available evidence, biodegradable plastics will not play a significant role in reducing marine litter [51].

Oxo-degradable materials contain a pro-oxidant that induces chemical degradation (degeneration) under favorable conditions. In this process CO_2 is not formed, so this polymer property should not be considered to be similar to biodegradation. Complete breakdown of the polymers and biodegradation still have to be proven.

3.5 Solutions

It is evident that solutions must be found for the large-scale pollution of the earth with plastic waste. Given the exponential growth of plastic consumption, with in its wake the littering, the problem is increasing and already getting out of hand. As is the case for many problems: if it could be solved easily, the problem would not be there, or it would at least be relatively under control. Banning synthetic polymers and moving away from plastics is an undesirable scenario, for many alternatives for these materials would lead to other major environmental issues. Replacing synthetic garments with cotton, for example, appears to be a relatively straightforward solution; the cultivation of cotton, however, is often environmentally and socially taxing.

3.5.1 Cleaning Up

The Ocean Cleanup project (www.oceancleanup.com), initiated by Dutchman Bojan Slat, uses collection systems to filter floating plastic waste out of the Oceans. As of May 2021, the total amount of plastic waste collected by Ocean Cleanup is 464 920 kg. This project has garnered a lot of attention and really put a spotlight on marine-littering issues. The amount of waste they are able to process, however, is very small compared to the immense size of the problem, as millions of tons of plastic enter the oceans every year. Such clean-up projects could play an important role in dealing with already-existing litter and preventing that from persisting in nature for centuries, but it will be futile unless we stop adding to the problem at this alarming rate and also when one looks at the size of the operation run by Ocean Cleanup and the costs that come with it. When plastic has to be collected from the ocean by these systems and then transported, potentially sorted and recycled, or dealt with otherwise, it is highly likely that this will be much more expensive than producing and using that same amount of plastic sustainably. This in turn means that the unsustainable production and use of plastics are much more expensive than we are led to believe.

3.5.2 Waste Mitigation

To tackle the plastic waste problem, a combination of measures is required. The best solutions to mitigate plastic pollution often start with managing plastic waste, which varies significantly depending on geographical and social circumstances [52]. Many different solutions have been suggested, often at regional or national level [53, 54]. Suggested options include post-consumption waste management [55, 56], reducing plastic, reuse, and the implementation of new delivery models [57], bans on single-use non-recyclable plastics (e.g. EU directive 2019/904) and microbeads in cosmetic products [58, 59]. The Basel convention was amended to regulate international plastic waste trading [60].

Littering is generally caused by the fact that plastics are considered cheap and often used only for single-use application. Treating plastic as a valuable material would put an incentive on collection for reuse or recycle. In general, it would make sense to reuse materials more and to design materials to be fit for reuse. To facilitate the reuse of plastics in the economy all products should be designed with an after-use pathway in mind and without planned obsolescence.

3.5.3 Material Design

Next to the earlier-mentioned design of products for reuse (thermal and caustic resistance) and design for recycling (from multilayer to monolayer, avoiding pigments, fillers, and additives that hamper recycling), from polyolefins to closed-loop recyclable polyesters, special attention needs to be given to designing plastics that do not contain toxic chemical additives such as plasticizers, flame retardants, and pigments, as this undermines their potential for secondary use and creates health and ecological risks. Chemicals regulations need implementation and reform to phase out toxic chemicals through substitution and circular economy solutions. For some applications, non-plastic materials may provide innovative, cost-effective, and competitive alternatives with beneficial outcomes (e.g. paper straws). Such substitutions and alternatives should be explored, researched, and developed, alongside the re-design of old-generation plastic products to improve their reparability and recyclability.

3.5.4 Bringing It All Together

In the last decade, many studies and reports have advanced the understanding of the (ocean) plastic pollution challenges. At the same time, an evidence-based roadmap that describes available mitigation pathways as well as an actionable plan was still missing. In 2020, the PEW Charitable Trusts with SYSTEMIQ published a report called "Breaking the Plastic Wave," one of the first comprehensive assessments of pathways toward stopping plastic pollution [14]. The findings of their analysis were also published in *Science* [61]. The report evaluated very different responses to the plastic pollution crisis, from laminating plastics to turning it into fuels, from developing biodegradable substitutes to closed- and open-loop recycling. From this, **10 critical findings** were proposed to reduce the future plastic pollution by 80% without compromising social and economic benefits:

1. Without action, the annual flow of plastic into the ocean will triple by 2040 to 29 Mt/yr.
2. New policies and voluntary commitments can reduce annual plastic leakage with 7% (narrow focus and typically implemented in low-leakage countries).
3. There is no single solution. Upstream and downstream solutions must be deployed together.
4. Solutions to reduce ocean pollution by 80% by 2040 exist today: reduce growth; substitute; design for recycling; expand waste collection in middle/low-income countries; develop plastic to plastic; build facilities to convert non-recyclable plastic; reduce plastic waste exports; implement known solutions for microplastics (MPs) from tires, textiles, and cosmetics.
5. Additional innovation across value chain. Upstream: replacing multilayer and other multi-material plastics requiring new materials and new delivery models. Biodegradable materials can play a role here. Expected investments: $100 billion per year by 2040.
6. Major reduction (from $2500 billion in 2021 to $1200 billion in 2040) and redirection of capital investments in the plastic industry.
7. 80% Reduction of plastic leakage will be an opportunity for a new circular plastics economy.
8. Differentiate implementation priorities regionally. High-income countries focus on microplastic leakage, while middle/low-income countries target reduce, collection, sorting, and recycling.
9. Plastic leakage reduction also benefits climate, economy (jobs), health, and environment.
10. The time is now! An implementation delay of five years results in an additional 80 million tons plastic leaking into the ocean by 2040.

Point 5 of the 10 critical findings mentions the development of new materials, which we addressed above (Section 3.5.3). At first glance an obvious solution for plastic in the environment, and one that is often embraced by consumers, is to make all packaging material biodegradable. If we were to continue the current way of consuming plastic, this would appear to make sense, since a lot of applications are single use and if these plastics would be biodegradable, littered material would degrade faster. This, however, ignores many key issues regarding the pollution: the amount of plastics used is increasing, so even if these plastics are biodegradable, if littering is not stopped, the waste will still be there. Then there is the issue of the rate of biodegradation: how fast should something degrade? Your material cannot degrade faster than the time needed for the application. Furthermore, the integrity of the material will already be negatively affected long before it has been completely degraded. Realistically one must think of degradation times of two to five years. This timeframe is still not enough when considering the life cycle of many animals and the issue of animals ingesting these plastics. Furthermore, if littering increases, even though materials degrade, the pollution still increases. Then there is the question of how well these materials would degrade under less favorable conditions: cold temperatures, anaerobic conditions, marine environment.

The next issue is related to CO_2 emissions: if all 350–400 Mt of plastics produced every year, using 8% of fossil resources production, are biodegradable and degrade in a timeframe of five years, it would essentially increase CO_2 output by 8%. This would mean that these materials should be made from either biomass or CO_2-sourced building blocks. This biomass needs to regrow to recapture this CO_2. Bio-based and CO_2-based monomers typically have a higher fraction of heteroatoms in their molecular structure, unless one seeks to make drop-in chemicals from biomass (bioPE, bioPET). Given how inexpensive oil-based monomers are, this does not make sense from an economic point of view. The most common source of fixed carbon is biomass, and carbohydrates form the majority of this biomass. About half the mass of carbohydrates consists of oxygen atoms, and it is difficult and therefore expensive to remove this to make for instance BioPE. PE is mostly used for single-use applications and does not have the mechanical properties to make it suitable for reuse. It therefore makes very little sense to produce bioPE, except for specialized applications.

As has been mentioned the current polymer market is dominated by only five different materials. Since these are very inexpensive, typically between 0.8 and 2.5$/kg, they are often used because they are good enough for the application and cheap. Assuming an average cost of $1.50/kg for the almost 400 million tons produced per year comes down to a total market size of around $800 billion. With a world population of around seven billion people, this means the average person spends around $100 per year on plastic. This makes the "it is too expensive to change to sustainable" argument a weak one, especially considering the price societies are paying for the consequences of this pollution, both in economic and social costs.

Looking at the future and the pollution issues regarding plastics, both from greenhouse emissions and littering, it would make more sense to look at designing materials with sustainability and durability in mind. Enormous strides can be made by simply reusing materials more often: reusing a bottle 10 times would by definition reduce the waste to 10% compared to single-use. This means this bottle needs to be designed to be fit for reuse, and materials such as PE, PP, and PET are not necessarily suitable for this, given their intrinsic chemical and mechanical properties. After an application is not anymore suitable for reuse, it should be recycled as much as possible (see Chapter 11). Applying deposit systems to add economic incentive would stimulate collection and reduce littering.

The intrinsic chemical structure of biomass and the monomers that can be produced from this offer opportunities that fossil-based monomers and thus polymers do not provide (Figure 3.6). Since novel materials are required to be designed to fit future needs in terms of reuse, recycle, and designed degradability of plastics, it

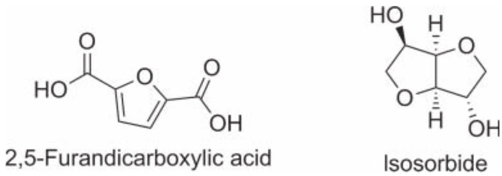


Figure 3.6 2,5-Furandicarboxylic acid and isosorbide: rigid monomers that in principle can be made only from biomass.

would make sense to produce them from sustainable sources: biomass, CO_2, and other carbon already "above ground" (i.e. waste PET).

Currently recycling is a complicated process for most plastic applications, due to multilayers, colorants, and blends. In Japan, for instance, it is prohibited to add colorants to plastics to facilitate recycling. The suggestion to add even more (novel) plastic materials into the mix may seem to steer away from facilitating our current recycling. However, we should realize that the transition to sustainable circular materials has hardly started! Only two million tons of our current plastics (0.5%) is (partly) bio-based, and we must evaluate novel materials that can better fulfill the requirements for reuse, closed-loop recycling, and fate-in-nature than the materials that we use today. Unfortunately it is not possible today to predict the winning (sustainability, performance, and cost) plastic materials of the future.

The microplastic issue is a different issue to deal with. Primary microplastic pollution is mainly caused by wear of durable materials (tires, clothing), which means these materials should last, something that conflicts with a high level of biodegradability. With regard to microfibers from clothing, it would make most sense to fit washing machines with appropriate filters.

Data must be generated and used to inform citizens. Smartphone applications have facilitated local authorities and non-government organizations (NGOs) in collecting local data on marine litter (e.g. the European economic area [EEA] Marine Litter Watch app, Trashhunters app). Citizens and public procurement officers can also be empowered with better data on the products they buy (e.g. the Beat the Microbead app, the Good Scrub Guide), finding opportunities to reduce their contribution to marine litter. The United Nations Environment Program massive open online course (MOOC) in 2015–2016 on marine litter provided free public access to the latest research. A second edition of the MOOC in 2017 will continue this (https://www.marinelittermooc.org).

3.5.5 Policies and Legislation

Structural waste should be avoided in all economic sectors. Producers should consider shifting from selling goods to providing services or access to (rather than ownership of) goods where this can increase product durability and reduce material demand and waste from the manufacturing stage through to product end of life. Business models based on reusable packaging exist in the context of B2B (e.g. Svenska Retursystem, operating a pool of reusable packaging for the whole retail sector) and B2C (e.g. Splosh and Replenish, shipping active-cleaning ingredients to be used in refillable bottles; and Repack, developing reusable transport packaging for e-commerce). Other innovative delivery models such as The Disappearing Package avoid packaging altogether, rethinking the entire packaging concept.

3.6 Conclusions

Plastic debris in the form of macroplastics or MNPs are everywhere, especially in the marine environment. These plastics originate from a multitude of sources and are composed of a great variety of polymers and copolymers as well as additives and, optionally, adsorbed pollutants. We can conclude that more information is required about the sources, distribution, fate, and potential impact of plastics on both human and animal health, on land, in the air, and in the marine environment. This is particularly true in the case of MNPs, as we lack adequate knowledge of their potential physical and chemical effects. Information is needed at all scales, as sources, circumstances, and mitigation strategies at each scale will vary.

If plastic is treated as a valuable resource, rather than just as a cheap waste product, opportunities to create a secondary value for the material after its first intended use will provide economic incentives for collection and reprocessing. All efforts to design future products for reuse or better recycling will add to the waste value of plastics. Non-recyclable plastics will have lower value and will end up in the environment more frequently. In addition, solutions need to be part of comprehensive programs to improve waste management generally: that is, waste collection and disposal infrastructure, waste-management practices, and enforcement. Such programs could include improved design and application of single-use plastics, increased consumer awareness and behavioral changes, improved recycling and re-use, and the introduction of economic instruments to reduce littering and promote secondary uses of plastic debris [61].

Innovative technologies in recycling can lead to recycling of a greater proportion of waste. The concept of extended producer responsibility, according to which a producer's responsibility for a product is extended to the postconsumer stage of the product's life cycle [62], could lead to more responsible packaging design.

Successful global management of the marine litter problem will require the development and implementation of effective policies and measures, supported by international and regional treaties and conventions. Decision makers must give marine litter a higher profile in national environmental protection regulations and development plans. It will be especially important to use education and outreach programs to encourage key user groups, industry sectors, and the general public to modify behavior and assume greater personal responsibility for their actions. Tackling the plastic waste issue will move us toward a cleaner ocean, will reduce the many pressures and impacts on biodiversity and, at the same time, will greatly reduce related social and economic costs [63].

Finally, the economic and social costs of plastic litter are difficult to fully assess as the full extent of the impact of MNPs on ecosystems and human health is still unknown. It is typically more costly to clean up pollution than to prevent it. It thus makes much more sense to deal with this at the source.

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3.A Definitions

Degradation

The partial or complete breakdown of a polymer as a result of, e.g. UV radiation, oxygen attack, biological attack. This implies alteration of the properties, such as discoloration, surface cracking, and fragmentation.

Biodegradation

Biological process of organic matter, which is completely or partially converted to water, CO_2/methane, energy and new biomass by microorganisms (bacteria and fungi).

Mineralization

Definition in the context of polymer degradation, as the complete breakdown of a polymer as a result of the combined abiotic and microbial activity, into CO_2, water, methane, hydrogen, ammonia, and other simple inorganic compounds.

Biodegradable

Capable of being biodegraded.

Compostable

Capable of being biodegraded at elevated temperatures in soil under specified conditions and time scales, usually only encountered in an industrial composter (standards apply).

Oxo-degradable

Containing a pro-oxidant that induces degradation under favorable conditions. Complete breakdown of the polymers and biodegradation still have to be proven.