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# Chapter 1

# Introduction

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## 1.1 INTRODUCTION

Owing to their properties, plastics are one of the most-used polymers worldwide. As a consequence of its widespread usage from home to industrial levels, billions of tons of plastic debris accumulate in environmental systems, including water, air, and soil. As the degradation processes of plastics are prolonged and take a long time for them to degrade in the natural environment, plastic wastes pose a serious threat to both terrestrial and marine biota.

According to a recent marine environment study, several marine species have died as a result of plastic trash ingestion or entanglement in plastic debris. Nevertheless, among the various methods to tackle plastic waste, plastic reduction at the source and the improvement of plastic waste management techniques such as plastic recycling and recovery, including bioremediation among others are considered eco-friendly alternatives and cost-effective methods (Ru *et al*., 2020).

This chapter introduces a comprehensive and up-to-date review of the issues and solution ideas on *plastic productions and trends, plastic processing technology and its additives, mismanaged plastic litters in waste management practices, macro-, micro- and nano plastics, bioaccumulation and biomagnification of plastic litter, toxicology and toxicity of micro-contaminants in plastics, implications on public and human health, and impacts of microplastics on human health*.

## 1.2 PLASTIC PRODUCTION AND TRENDS

### 1.2.1 Synthesis uses and properties of plastics

The diversity and various qualities of polymer, the main component in plastics, render plastics tremendously useful materials in a wide range of products that enable medical and technological advancements, and common societal facilities (Gilbert, 2017). Some examples of the diverse plastic properties are light weight, high strength, high durability, high corrosion resistance, high thermal and electrical insulation properties (EPA, 2021). Moreover, the considerable potential for new plastic applications has brought benefits to mankind in various forms including novel medical applications, the generation of renewable energy, and energy consumption reduction in transportation (Hammer *et al*., 2012; Thompson *et al*., 2009).

Currently, almost all aspects of daily life involve plastics, for instance, in infrastructure, transport, telecommunications, clothing, footwear, and packaging materials that facilitate the transport of a wide range of food, drinks, and other goods (Plastics Europe, 2018). The term plastics, as commonly used, refers to a group of synthetic *polymers (defined as large organic molecules composed of repeating carbon-based units or chains that occur naturally and can be synthesized)*. The polymers that make up plastics are long molecular chains made from joined short repeating sub-units in a chemical process known as polymerization. On the contrary, monomers are molecules capable of combining, by a process called polymerization, to form a polymer (Edmondson & Gilbert, 2017; SAPEA, 2019). For example, monomer ethylene is polymerized, using a catalyst to form polyethylene (PE) (Kershaw, 2016).

The production of numerous monomers used to synthesize plastics, such as ethylene and propylene are derived from fossil hydrocarbons, while polymers can also be natural or synthetic (Gilbert, 2017). Common natural polymers include chiton (insect and crustacean exoskeleton), lignin and cellulose (cell walls of plants), polyester (cutin), and protein fiber (wool, silk), including protein fiber and starch. These are also generated from agricultural or specifically grown crops such as sugarcane, corn, and trees (Bowers *et al*., 2014; Brodin *et al*., 2017; UNEP, 2018a, 2018b).

Plastics have been found in all major basins and oceans, with an estimated 4–12 million metric tons of plastic waste generated on land entering the marine environment in 2010 alone. On the contrary, almost all the generally used plastics are difficult to biodegrade, or some types are non-degradable, resulting in accumulation rather than decomposition of plastics in the natural environment (water, air, and soil, including landfills) (Horton *et al.*, 2017). Contamination of freshwater systems and terrestrial habitats is also increasingly reported, as is environmental contamination with synthetic fibers (Jambeck *et al.*, 2015). Furthermore, plastic debris easily gets transported into aquatic and terrestrial domains through the atmosphere. Recently, disposable face masks (produced from polymers) contaminated with the Coronavirus have also added to the environmental pollution as these are likely sources of plastic debris.

### 1.2.2 Production of plastic products

Among consumption patterns of widely used types of plastics in different applications, well over a third of consumption is in packaging applications such as containers and plastic bags (Hammer *et al.*, 2012), and building products including common products such as plastic pipes and vinyl cladding (Gilbert, 2017; Plastics Europe, 2018).

Plastics are a mixture of macromolecules and chemicals, ranging from several nanometers to meters. The commercial production of plastics started around 1950s and has seen an exceptional growth to the present global annual production of 330 million metric tons in 2016 including the resin used in spinning textile fibers (Plastics Europe, 2018). Plastic use has increased, especially in developing countries (Geyer *et al.*, 2017; Kershaw, 2016; Kole *et al.*, 2017). The global production of plastics has been following a clear exponential rising trend since the beginning of mass plastic consumption and production in the 1950s, and from a global production of 311 million tons in 2014; it is projected that plastic production to reach approximately 1800 million tons in 2050 (UNEP, 2018a, 2018b).

### 1.2.3 Advantages of plastic products

Almost all aspects of daily life involve plastics such as clothing, footwear, and products used in food and public health industries. Over 40 million tons of plastics are processed as textile fibers such as nylon, polyester, and acrylics, which are used in the clothing industry. Moreover, polycotton clothing contains high polyethylene terephthalate (PET) plastics; high-performance clothing is almost exclusively made from plastic-polyesters, fluoropolymers, and nylons (Gilbert, 2017). Furthermore, fleece clothing is 100% plastic and can be made from recycled PET. Most footwear also relies heavily on plastics; the footbeds and outsoles are made from polyurethane or other elastomeric material, while the uppers might be vinyl or other synthetic polymers (Geyer *et al.*, 2017; Shah *et al.*, 2008).

Plastics in various types such as PE, polystyrene (PS), polyurethane, polyvinyl chloride (PVC), polypropylene (PP), PET, nylon, polycarbonate, and polytetrafluoroethylene are used in daily life. Plastic polymers show the highest usage in different parts of the world. Various plastic-based products such as plastic wares, plastic packaging material (for food and beverages), plastic bottles, and other miscellaneous articles have widely dominated the various markets (Arutchelvi *et al.*, 2008; Sangale *et al.*, 2012; Varda *et al.*, 2014). The overview of plastic usage at the global level are: 35% of packaging, 23% of building and construction, 8% of electric and electronics, 8% of furniture/ housewares, 8% of transport, 7% of agriculture, 3% of sports, 2% of mechanical engineering, 2% of medical, toys, and 1% of footwear (Varda *et al*., 2014).

Due to their light weight, plastics reduce transportation costs, thus reducing atmospheric carbon dioxide emissions. Plastics can also improve performance and reduce the costs of building materials. In addition, plastic material benefits may facilitate clean drinking water supplies and enable medical devices ranging from surgical equipment to advanced packaging materials (Geyer *et al*., 2017).

## 1.3 PLASTIC PROCESSING TECHNOLOGY AND ITS ADDITIVES

### 1.3.1 Production process of plastics

Plastics are a wide range of synthetic or semi-synthetic organic compounds that are malleable and so can be molded into solid objects (Hammer *et al*., 2012; Niaounakis, 2017; UNEP, 2016). Plastics are organic materials, just like wood, paper, or wool. Numerous organic, synthetic or processed materials are mostly thermoplastics or thermosetting polymers of high molecular weight that can be made into objects, films, or filaments (US EPA, 2016). As the petrochemical industry is the greatest contributing factor in the growth of the plastic industry, the plastic industry is integrated with the oil industry. Currently, the two industries have a remarkable degree of interdependence. Thus, if the current production and use trends continue unabated, then plastic production is estimated to increase, approaching 2000 million tons by 2050 (as described in Section 1.2).

### 1.3.2 Types of plastics

With respect to characteristics, plastics are lightweight, tough, and resistant to chemical materials that can be molded in various ways and utilized in a wide range of applications. Although it is also difficult to corrode and biodegrade, photodegradation can slowly break down plastics into tiny fragments known as microplastics (Niaounakis, 2017; UNEP, 2018a, 2018b). Polymers can be natural or synthetic. Natural polymers include materials such as cellulose, protein fiber, and starch. The polymers that make up plastics are long molecular chains made from joined short repeating subunits in a chemical process known as polymerization (see Section 1.1). Raw materials for plastics are mostly obtained from non-renewable resources, including products from the fossil fuel industry such as styrene and ethylene (Andrady & Neal, 2009; Gilbert, 2017). Plastic manufacturing requires an estimated 4–8% of global oil production, for raw materials and energy for processing (World Economic Forum, 2016; Zhu *et al*., 2016).

Bio-based polymers which are becoming increasingly popular (Hansen *et al*., 2014; Zhu *et al*., 2016) are generated from agricultural or forestry waste or specifically grown crops such as sugarcane, corn, and trees (Bowers *et al*., 2014; Brodin *et al*., 2017; Zhu *et al*., 2016). Bioplastics usually refer to plastics sourced from renewable resources, but, sometimes, they are used to refer to biodegradable plastics (Kershaw, 2016). Nevertheless, during the production of both conventional plastics and bioplastics, various additives may be added to the polymer to change its character (Edmondson & Gilbert, 2017; Kershaw &

Rochman, 2015). Generally, additives allow plastics to take on many forms with varying appearances, durability, and performance. Common additives include plasticizers (used to enhance flexibility and durability), ultraviolet blockers, thermal stabilizers, dyes and pigments, flame retardants among others (Hansen *et al.*, 2014). However, some of the chemicals are harmful in low quantities and can leach out of plastics, posing health and environmental risks (de Souza Machado *et al.*, 2018; Oehlmann *et al.*, 2009; Talsness *et al.*, 2009; Thompson *et al.*, 2009).

For plastics derived from organic products, the raw materials used to produce these plastics are natural products such as cellulose, coal, natural gas, salt, and crude oil. Due to a complex mixture of compounds in crude oil, plastic production starts with a distillation process in an oil refinery involving the separation of heavy crude oil into lighter groups called fractions (Gilbert, 2017; Zhu *et al.*, 2016). Each fraction is a mixture of hydrocarbon chains (chemical compounds made up of carbon and hydrogen), which differ in terms of size and structure of the molecules (Boucher & Friot, 2017; Niaounakis, 2017). During plastic production, several factors of polymer such as the solubility characteristics, the effect of specific chemicals and environments on polymer at elevated temperatures, the effect of high-energy irradiation, the aging and weathering should be considered. Moreover, plastic polymers are mixed with various additives to improve performance, such as carbon and silica to reinforce the material, plasticizers to render the material pliable, thermal, and ultraviolet (UV) stabilizers, flame retardants, and coloring. Some additive chemicals are potentially toxic, and there is a particular concern about the extent to which additives released in the environment from plastic products of high production volume and wide usage (e.g. phthalates, bisphenol A (BPA), bromine flame retardants, UV screens, and anti-microbial agents) have adverse effects on animal or human populations (Thompson *et al.*, 2009), while a recent study estimated that the direct ingestion of microplastics by some aquatic species is a negligible pathway for exposure to nonylphenol and BPA (Koelmans *et al.*, 2014).

### *1.3.2.1 Petroleum-based plastics*

In engineering, soil mechanics, materials science and geology, plasticity refers to the property of a material able to deform without fracturing. According to the US EPA (2016), plastic material can be categorized into two types based on the properties: (a) *Thermoplastic*s which are polymers that soften when heated and solidify upon cooling, allowing them to be remolded and recycled without negatively affecting the material physical properties (common examples include PE, PP, PS, and PVC); and (b) *Thermosets* which are plastics that are set into a mold once and cannot be re-softened or molded again. Due to their properties, thermosets are appropriate for high-heat applications such as electronics and appliances such as phenolic resins, amino resins, polyester resins, and polyurethanes.

#### 1.3.2.1.1 Thermoplastics

The most commonly used plastics around the globe accounting for 69% of the global plastics used are PE, PP, PVC, PET, and PS (Emily Petsko, 2020). The symbols and properties of these plastics are illustrated in Table 1.1.

**Table 1.1** Symbol types and properties of plastics.

| Symbol | Properties of Plastics |
|---|---|
| 1 PETE | Clear, strong, and lightweight with high ductility and impact strength as well as low friction |
| 2 HDPE | Stiff and hardwearing; hard to the breakdown in sunlight |
| 4 LDPE | Lightweight, low-cost, versatile; fails under mechanical and thermal stress |
| 3 V | Can be rigid or soft via plasticizers; used in construction, healthcare, electronics |
| 5 PP | Tough and resistant with effective barrier against water and chemicals |
| 6 PS | Lightweight, structurally weak and easily dispersed |
| 7 OTHER | Diverse in nature with various properties |

(1) PE is a thermoplastic and elastic polymer which is popularly used in plastic containers, bottles, bags, and plastic toys. In addition, it can be used to produce plastic cement. The types of PE, depending on its density and branching, are low-density polyethylene (LDPE) and linear LDPE, linear versions or high-density polyethylene (HDPE) and ultra-high molecular weight PE and cross-linked PE.

(2) PP is a thermoplastic polymer used in food containers, packaging, toys, furniture, and textiles. It is characterized by its high durability, transparency, and resistance to chemical stress, and it can sometimes contain dyes, antioxidants and, in some cases, flame retardants.

(3) PVC is one of the most used thermoplastic polymers in the world. It is used in construction, packaging for food, textiles, and medical materials.

Other specific applications include cosmetic containers, electrical conduits, plumbing pipes and fittings, blister packs, wall cladding, roof sheeting, bottles, garden hoses, shoe soles, cable sheathing, blood bags, tubing, watch straps, and commercial cling wraps.

(4) PET is a clear, strong, and lightweight plastic, commonly found in beverage bottles, perishable food containers, mouthwash, jars, and plastic bottles. Being impact resistant, PET is used in textiles and packaging, and its materials may contain dyes and color pigments.

(5) PS is used for lining refrigerators, packaging, construction, and trays in the medical industry.

#### *1.3.2.2 Bio-based plastics*

Bioplastics refer to either bio-based or biodegradable sources which are made from renewable resources instead of fossil fuels (European Bioplastics, 2020; Napper *et al.*, 2015; UNEP, 2015). Generally, renewable carbon resources include corn, potatoes, rice, soy, sugarcane, wheat, and vegetable oil. Sugar cane is also processed to produce ethylene, which can then be used to manufacture PE among others, while starch can be processed to produce lactic acid and subsequently polylactic acid (PLA).

**Biodegradable plastics** are plastics that can be decomposed by living organisms, usually microbes. Biodegradable plastics are commonly produced with renewable raw materials, micro-organisms, petrochemicals, or combinations of all three.

**Non-biodegradable plastics** are generally comprised of carbon, hydrogen and oxygen. Because the source of carbon is entirely and partly from petrochemicals, these plastics are referred to as non-biodegradable. Non-biodegradable describes polymers that do not break down into a natural, environmentally safe condition over time through biological processes (Rahman & Syamsu, 2018).

Most plastics are non-biodegradable, which are widely used due to their low cost, versatility, and durability. The durability is due in part to the fact that plastics are an uncommon target for microorganisms, making it non-biodegradable. Furthermore, the durability is partly due to the inability of microbes to digest plastics, rendering them non-biodegradable. On the contrary, most plastics can be made biodegradable by adding chemicals that break down the structure of polymer. Bioplastics and bio-based plastics are plastics made from renewable biological resources. Bioplastics encompass many materials that are either bio-sourced or biodegradable or both. A biodegradable material can be decomposed under the actions of microorganisms (bacteria, fungi, algae, earthworms) with end products such as water, carbon dioxide, and methane. Oxo-degradable or oxo-biodegradable plastics are conventional plastics such as PE with an additive that helps break down fragments. Bio-based, and biodegradable plastics can be divided into three categories: (1) biodegradable (bio-based plastics): polylactic acid, polyhydroxyalkanoates, bio polymers-polybutylene succinate; (2) biodegradable (petroleum-based plastics): polybutylene adipate terephthalate, polybutylene succinate, polycaprolactone, polyvinyl alcohol; and (3) non-biodegradable (bio-based plastics): bio-PET, bio-PE, polyethylene furanoate (PEF), bio-PP, bio-PAs, polytrimethylene terephthalate.

### 1.3.3 Use of plastic products

#### *1.3.3.1 Global plastic market*

According to European Bioplastics, the global market for plastics is forecasted to be USD 115.10 billion by 2023 from USD 80.7 billion in 2018, at a compound annual growth rate of 7.2% during the forecast period (European Bioplastics, Nova-Institute, 2018). The latest market data show that the global bioplastics production capacity is set to increase from around 2.11 million tons in 2019 to approximately 2.43 million tons in 2024. An innovative biopolymer, such as bio-based PP and polyhydroxy-alkenoates shows the highest relative growth rates. In 2019, due to the widespread application of PP in a wide range of sectors, bio-based PP entered the market on a commercial scale with a strong growth potential. Polyhydroxyalkanoates are an important polymer in which production capacities are estimated to more than triple in the next five years. These polyesters are 100% bio-based and biodegradable and feature various physical and mechanical properties depending on their chemical composition. Bio-based, non-biodegradable plastics altogether, including the drop-in solutions bio-based PE and bio-based PET, as well as bio-based PA, currently accounts for over 44% (almost 1 million tons) of the global bioplastics production capacities. For instance, increasing trend for lightweight vehicles, increasing demand for connected vehicles, and growing awareness about reducing vehicular emissions are driving the engineering plastics market in the automotive and transportation end-use industry.

#### *1.3.3.2 Bioplastics major end-use market*

Rigid bioplastic applications are available for cosmetics packaging of creams and lipsticks as well as beverage bottles and many more. Materials such as PLA, bio-PE, or bio-PET are used in aforementioned businesses. Some use bio-PE as materials for different packaging kinds of cosmetic products. Polylactic acid is also gaining pace in the rigid packaging market as a potentially mechanically recyclable material. Biodegradability is a feature often used for food packaging for perishables.

Bioplastics can be found in the following market segments: packaging, food service, agriculture/horticulture, consumer electronics, automotive, consumer goods, and household appliances. In 2019, global production capacities of bioplastics amounted to about 2.11 million tons with almost 53% (1.14 million tons) of the volume destined for the packaging market – the biggest market segment within the bioplastics industry (European Bioplastics, Nova-Institute, 2018). There is a high demand for packaging made from bioplastics used as food wrapping such as films and trays are particularly suitable for fresh produce such as fruit and vegetables, enabling longer shelf life.

#### *1.3.3.3 Plastic consumption*

##### 1.3.3.3.1 Plastic consumption by country

Based on the amount of plastic consumption, China is among the largest consumer of plastic products, accounting for 20% of global plastic consumption, while Western Europe accounts for 18%. However, based on plastic consumption per capita, China is ranked much lower than other countries. Israel is one of the largest per capita consumers of plastics; however, it has significantly lower plastic production rates compared to other countries. The developing countries have become the world's production hub of plastic products that are consumed overseas. For instance, India saw a steady increase in PET production in 2015–2016 (1458 kilotons of PET) compared to the previous year (982 kilotons). PET plastic production (650 kilotons) was exported in 2015–2016 from India to Bangladesh, USA, Italy, Israel, Romania, Ukraine and UAE among others. Export volumes have grown in recent years, closely tracking overall production levels in India. PET is imported to India (107 kilotons) to a smaller extent, mainly from Taiwan, China, Iran, and Malaysia.

#### 1.3.3.3.2 Agricultural applications of plastics

The global usage of plastics in agriculture is 6.5 million tons per year. The use of plastic materials in agriculture started with the use of cellophane to cover small greenhouses, which was then replaced by PVC. Moreover, there is widespread and continuously increasing usage of plastic films in agriculture, particularly in protected horticulture. Increased yields, earlier harvests, reduced herbicide and pesticide use, frost protection, and water conservation as well as preserving, transporting, packaging, and commercializing agro-food products are some of the reported benefits of using plastics in agricultural fields. Greenhouses, tunnels, mulching, plastic reservoirs and irrigation systems, silage, crates for crop collecting, handling and transport, components for irrigation systems like fittings and spray cones, and tapes that help hold the aerial parts of the plants in the greenhouses among others are the most important applications identified by Plastics Europe in agriculture. A comprehensive overview of applications of plastics in agriculture is indicated in Table 1.2.

The use of plastics in agriculture is evident in the form of the lining of farm ponds, greenhouse cultivation, micro-irrigation (drips and sprinklers), and plastic mulching. The problems resulting from plastic use are decreased soil porosity and air circulation, changed microbial communities, and lower farmland fertility. Plastic mulch should be of concern as it is a potential source of entry into the food chain system.

**Table 1.2** Comprehensive overview of applications of plastics in agriculture.

| **Applications of Plastics in Agriculture** | |
|---|---|
| Protected cultivation films | Greenhouses and tunnels, low tunnels, mulching, nursery films, direct coverings, covering vineyards and orchards |
| Nets | Anti-hail, anti-bird, wind-breaking, shading, nets for olives and nut picking |
| Piping, irrigation; drainage | Water reservoirs, channel linings, irrigation tapes and pipes, drainage pipes, micro-irrigation, drippers |
| Packaging | Fertilizer sacks, agrochemical cans, containers, tanks for liquid storage, crates |
| Other | Silage films, fumigation films, bale twines, bale wraps, nursery pots, strings, and ropes |

1.3.3.3.3 Industrial applications of plastics

The changing lifestyle and increasing penetration of organized retail is principally expanding the plastic product application scope. Because plastics are transparent, tough, flexible, and rigid, lightweight, and versatile forms of packaging, various industries such as food and beverage, personal care need plastic packages. The primary functions of packaging are to offer protection to the products and to ensure efficient transportation over long distances and storage. The growing use of rigid HDPE and polycarbonate plastic canisters, bottles and tanks for industrial packaging applications, as opposed to wraps, films and bags, is likely to promote better market growth for rigid plastics as compared to flexible plastics. Because of its increasing use in industrial applications, the rigid sector is forecast to rise steadily.

The global production of petroleum plastics (fossil fuel-based plastics) saw a dramatic increase, from 2 million tons in 1950 to more than 454 million tons in 2018. Between 1950 and 1980, 9.7 billion tons of plastics were produced, 50% of which was after 2005. Projections based on present growth rates indicate that plastics production should double by 2025 and more than triple by 2050. Among all types of plastics introduced in the market since 1950, PP and LDPE account for 17 and 16%, respectively, of the global plastic production followed by HDPE (13%) and poly-phthalimide (13%). Additives used in plastic products manufacturing also have a significant share in global plastic production (6%).

#### *1.3.3.4 Plastic waste generation*

1.3.3.4.1 Sources and types of plastic waste

In general, plastic waste generation rates are influenced by economic development, the degree of industrialization and public habits. These parameters are used to estimate plastic waste generation in different countries worldwide. The generation of plastic waste can be classified into pre-consumer or industrial plastics waste, and post-consumer plastics waste. In terms of pre-consumer plastic waste, the amount of waste comes from production of plastic resins and plastic products. Plastic resin is generated in synthetic resin, by-product, and residual resin production processes when sieving. Moreover, these kinds of plastic resin products could be directly recycled in the plastic factories. Some edge, gate, and defective products are inevitably generated in the plastic production and re-processing process. These types of plastic products could be directly disposed of in plastic factories. Meanwhile, the post-consumer waste comes in the form of municipal solid waste, which comes from the post-consumer market, such as industrial and agricultural plastic waste, commercial plastic waste, and residential plastic waste, as well as in the following economic sectors: distribution and large industry, agriculture, construction, and demolition, automotive, electronics, and electric. Plastic packaging has the largest share (35.8%) in the market. It is also the biggest plastic waste generator accounting for 46% of plastic waste generation, as illustrated in Figures 1.1 and 1.2 (Geyer *et al.*, 2017).

1.3.3.4.2 Plastic waste management

Of the 8.3 billion tons of plastics that have been introduced in the market between 1950 and 2015, a total of 5.8 billion tons of plastic waste have been

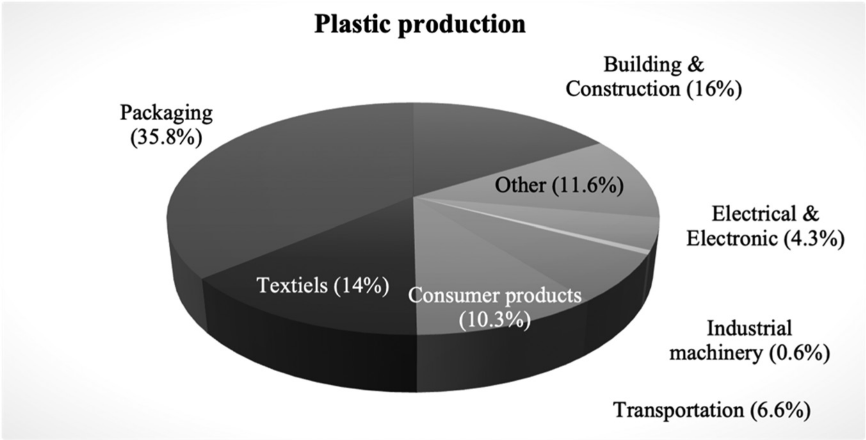


**Figure 1.1** Plastic production (percentages) (454 300 000 tons) (*Source*: adapted from Geyer *et al.*, 2017).

generated. Of that, 12% has been incinerated, 9% recycled, and around 60% discharged in landfills or the environment. Plastic waste is disposed of in landfills and dumpsites in large amounts (56%) or escapes into the environment as shown in Figure 1.3. According to a UNEP (2020) report, plastic waste recycling and incineration have increased over the years, reaching 19% and 25, respectively.

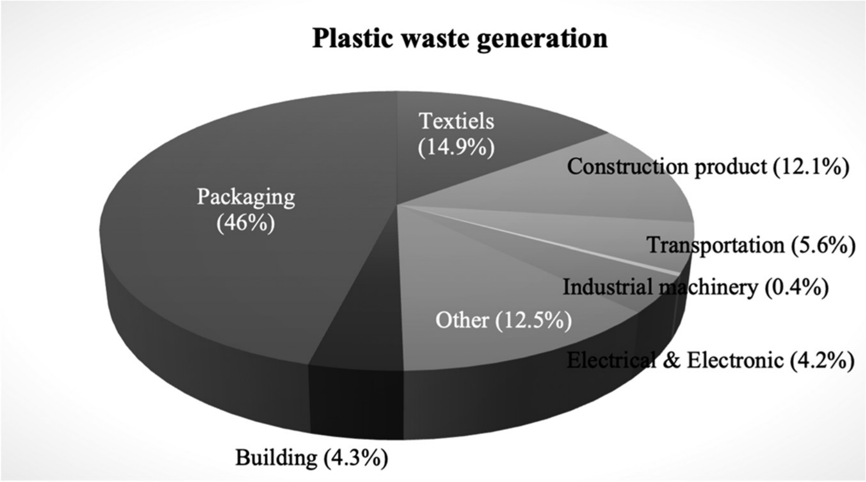


**Figure 1.2** Plastic waste generation (percentages) (342 600 000 tons) (*Source*: adapted from Geyer *et al.*, 2017).

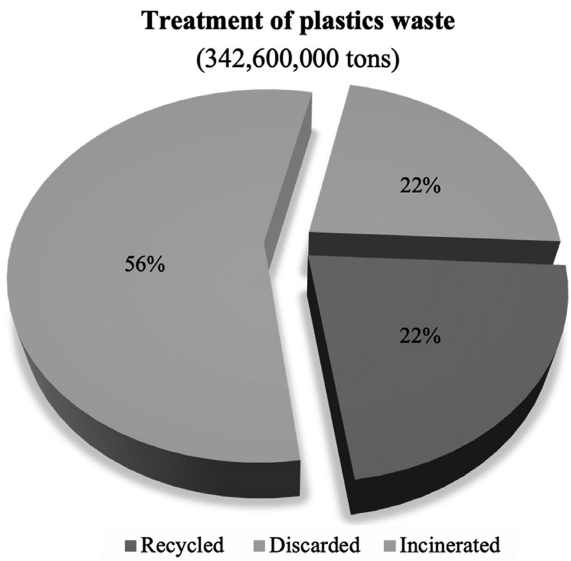


**Figure 1.3** Treatment of plastic waste (percentages) (*Source*: adapted from Geyer *et al.*, 2017).

#### *1.3.3.5 Single-use plastic and its distribution production by region*

Single-use plastics, referred to as disposable plastics, are designed to be discarded after a single use. They are commonly used as plastic packaging and are intended to be used only once before being discarded or recycled. Some examples are plastic bags, straws, coffee stirrers, water bottles and most food packaging (UNEP, 2018a, 2018b). Plastic packaging is mostly single-use, especially in business-to-consumer applications, and most of it is discarded the same year it is produced (shown in Figure 1.4). Global consumption of plastics can be estimated by observing the amount of plastic waste produced.

Plastic products have long life spans (or product lifetimes): building and construction materials (35 years), industrial machinery (20 years), plastic products in the transportation sector (13 years), electrical/electronic plastic products (8 years), and textiles (5 years). However, the majority have a short life cycle lasting between one day (e.g., disposable plastic cups, plates, takeaway containers or plastics bags) to three years (e.g., food and drink containers, cosmetics, or agricultural film). Currently, a global analysis of all mass-produced plastic is conducted by developing and inputting, into a comprehensive material flow model, global data on the production, use, and end-of-life fate of polymer resins, synthetic fibers, and additives (UNEP, 2020). Estimated decomposition times for plastics and other common marine debris items are shown in Figure 1.5.

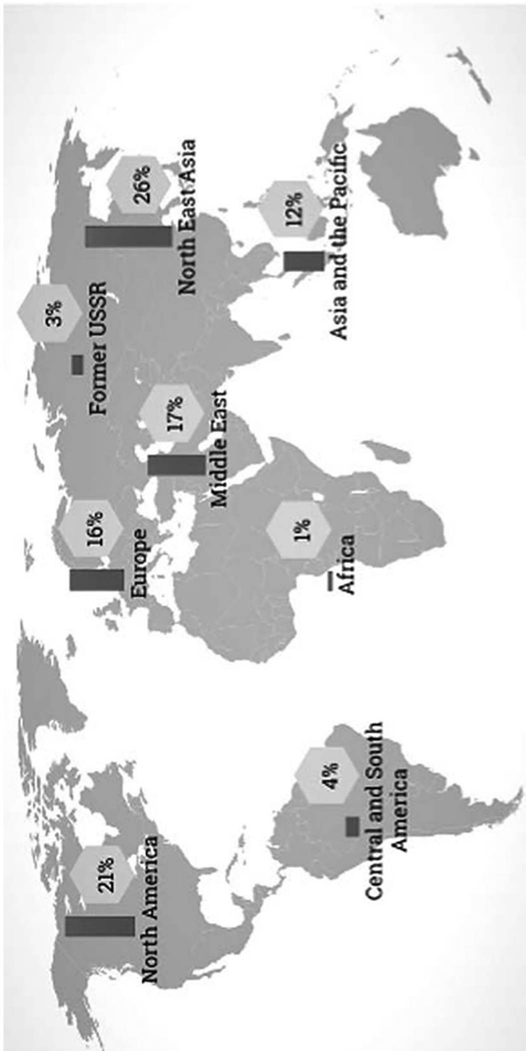


**Figure 1.4** Distribution of single-use plastics production by region (UNEP, 2018a, 2018b).

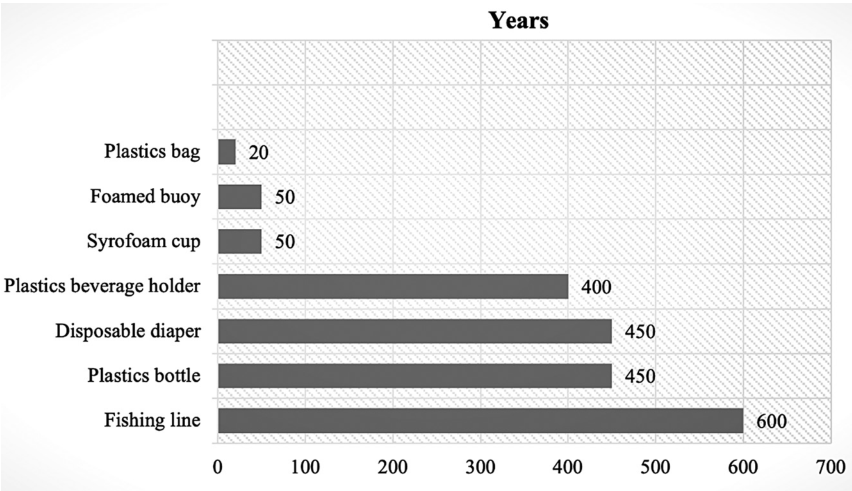


**Figure 1.5** Average decomposition times of typical marine debris items (*Source*: adapted from UNEP, 2020).

## 1.4 MISMANAGED PLASTIC LITTER IN WASTE MANAGEMENT PRACTICES

### 1.4.1 Disposed of plastic waste in municipal solid waste

Plastic waste in municipal solid waste is distributed between three categories: plastics in use, post-consumer managed plastic waste, and mismanaged plastic waste, the last of which includes urban litter. Managed waste is accounted for and is typically disposed of by incineration or landfilling. Packaging-related plastics have a particularly short in-use phase and become, subsequently, mismanaged waste. Mismanaged waste also includes inadequately contained waste such as in open dumps and is therefore transportable via runoff and wind. Street sweepers and concerned citizen groups may have collected some mismanaged waste. Both per capita use of plastics and the population density at a given location determine consumers' local plastics demand, representing the in-use category. The former generally scales with the local gross domestic product, with the more affluent countries using as much as over 100 kg per population per year. However, in populous countries such as India or China, a relatively low per capita use of plastics coupled with a high population density can still yield a large amount of plastic waste (Lebreton & Andrady, 2019).

Plastic waste in developed countries can go through a well-established material recycling process, resulting in recycled plastic materials with some added value and energy recovery at the transfer station and final disposal site. Nevertheless, this behavior is not commonly adopted in several developing countries. Figure 1.6 indicates municipal plastic waste has a considerable share in the composition of municipal solid waste in both developed and developing countries.

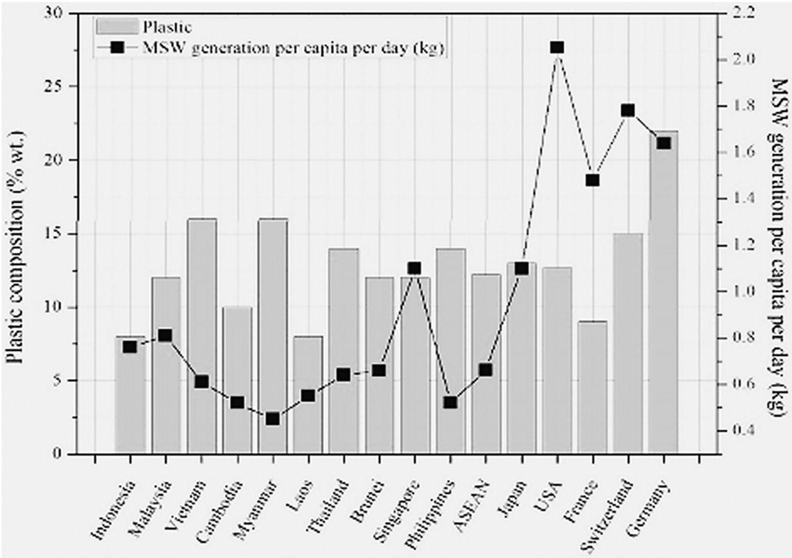


**Figure 1.6** Plastic waste in MSW (per capita per day) (*Source*: Areeprasert *et al.*, 2017).

Mismanaged waste is the sum of either littered or inadequately disposed of waste, including disposal in dumps or open, uncontrolled landfills. The figure of mismanaged plastics is therefore linked to the effectiveness of waste management worldwide. Jambeck *et al.* (2015) estimated that the total mismanaged plastic waste from the coastal population accounted for 31.9 million tons in 2010. Later Lebreton *et al.* (2019) estimated that for the 2015 calendar year, between 60 and 99 million metric tons out of 181 million tons of global municipal plastic waste were improperly disposed of and released into the environment. Countries in Southeast Asia and the Pacific have the highest share of plastic waste deemed inadequately mismanaged and led to the escape of plastics in the terrestrial and marine environment. In Asia and sub-Saharan Africa, between 80 and 90% of plastic waste is inadequately disposed of, with China, Indonesia, the Philippines, Thailand, and Vietnam producing half of all plastic waste in the world's oceans. On the contrary, high-income countries such as European countries, North America, Australia, and Japan have effective waste management systems, and almost no plastics waste is considered inadequately managed. Scientists estimate that 8.3 billion tons of plastic had been produced globally by 2015, over a ton of plastics for every person on the planet. Of this, 6.3 billion tons (76%) had been discarded as waste. Between 1950 and 2015, 9% of plastic waste was recycled, 12% was incinerated, and the remaining 79% has accumulated in landfills and the environment. The total amount of waste generated per person varies significantly between countries in Table 1.3.

**Table 1.3** Total solid municipal waste and plastic waste estimates.

| Countries | Waste Generation Rate (g: Person: Day) | Plastics in Waste Stream (%) | Plastic Waste Per Capita (g: Person: Day) |
|---|---|---|---|
| Denmark | 1160 | 2.25 | 26 |
| Canada | 2160 | 1.6 | 35 |
| Japan | 1940 | 3 | 58 |
| Spain | 950 | 11 | 104 |
| Australia | 1190 | 9 | 107 |
| France | 1540 | 7.6 | 117 |
| New Zealand | 1370 | 9 | 124 |
| Ireland | 1990 | 8 | 159 |
| Germany | 1610 | 12.4 | 199 |
| United Kingdom | 1720 | 13 | 224 |
| United States | 1330 | 20 | 266 |

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

### 1.4.2 Present pollution trends

Over the past decade, efforts have been made to define and quantify different sources of plastic leakage, either at the country level or globally, into the terrestrial environment and waterways in Table 1.4. Plastics which may escape and are found in the environment are defined as macroplastics or microplastics. Macroplastics are large plastic waste that usually enters the marine environment in their manufactured sizes, while small plastic particulates below 5 mm in size are called microplastic. Microplastics may be plastics that directly escape into the environment through small particles (e.g., microplastics in cosmetics, textiles, etc.) or maybe the result of plastic fragmentation once exposed in the environment due to photodegradation/or weathering.

Plastics that escapes to the environment can have various land-based and ocean-based sources. The main on-land-based sources is the uncontrolled dumping of waste, which is usually the result of littering by public members from day-to-day and recreational activities, and of the absence of waste management systems. Additionally, plastics can end up in the environment in two ways; (1) through direct dumping of plastics into the terrestrial and/or surface aquafers including high amounts of plastics dumped directly into the rivers, and (2) through non-engineered landfills or dumpsites after collection.

**Table 1.4** Plastic and microplastic losses to the environment.

| Study | Million Tons of Plastic Losses to the Environment | Million Tons of Microplastic Losses to the Environment |
|---|---|---|
| Ryberg *et al.* (2019) | 9.2 | 3.0 |
| UN Environment (2018c) | 8.28 | 3.01 |
| Boucher and Friot (2017) | – | 3.5 |

**Table 1.5** Collected items from the top 10 most found items made of plastic.

| Items | Quantities (tons) |
|---|---|
| Cigarette butts | 5 716 331 |
| Food wrappers | 3 728 712 |
| Straw stirrers | 3 668 871 |
| Forks, knives, spoons | 1 968 065 |
| Plastic beverage bottles | 1 754 908 |
| Plastic bottle cups | 1 390 232 |
| Plastic grocery bags | 964 541 |
| Other plastic bags | 938 929 |
| Plastic lids | 728 892 |
| Plastic cups and plates | 656 276 |

*Source:* Ocean Conservancy (2019)

Suffice to say that plastic waste is now accumulated in landfills and in the natural environment. However, the number of landfills in some locations is exponentially increasing, which means less space is available. Also, in the future, because of the longevity of plastics, disposal to landfills may become problematic resulting in a significant source of contaminants to aquatic environments. **Coastline (Beach)**, an ocean conservancy, holds a long record of items collected during annual Beach Cleanup activities around the globe since the 1980s. The International Coastal Cleanup was organized in 2018 with 1 080 358 volunteers who removed 10 584 tons of litter, totaling 35.9 km of coastline around the world. Of the collected items, the top 10 most found items were made of plastic (including cigarette butts, which contain plastics filters) as shown in Table 1.5.

Along the Algerian coast, the National Waste Agency reported that nearly 81% of the collected waste is plastics, mainly single-use plastics. Due to the circular ocean currents, plastics can be moved and transported worldwide. Floating plastic waste has been shown to accumulate in five subtropical gyres that cover 40% of the world's oceans. Several researchers have made attempts to provide the number of plastics entering the environment and the sea each year. It is reported that more than 10 million tons of plastics enter the ocean per year, with an estimated 40% of that falling into the single-use category, while hundreds of thousands of tons of lost, abandoned and discarded fishing gear litter the world's oceans. Microplastics account for around 1.5 million tons of plastics entering the ocean in Table 1.6.

**Table 1.6** Plastics and microplastics entering the marine environment.

| Study | Plastics (million tons) | Microplastics (million tons) |
|---|---|---|
| Jambeck *et al.* (2015) | 4.8–12.7 | N/a |
| EUNOMIA (2016) | 12.0 | 0.95 |
| Boucher and Friot (2017) | 10 | 1.5 |

According to Boucher and Friot (2017), most of the global plastics leakage into the ocean comes from China (2.21 million tons per year), followed by India and South Asia (1.99 million tons per year). Macroplastics in the marine environment are expected to have the same composition as the macroplastics found on the coastline, including abandoned and discarded fishing gear. Microplastics in the marine environment mainly come from washing synthetic textiles followed by tiny bits of tire rubber material due to wearing down of car tires.

### 1.4.3 Degradation of plastics in the environment

Degradation is the partial or complete breakdown of a polymer under the influence of environmental factors such as water, heat, light, microbes, and mechanical actions. Most polymeric materials that enter the environment are subjected to degradation caused by a combination of factors, including thermal oxidation, photo-oxidative degradation, biodegradation, and hydrolysis. Plastics are man-made long-chain polymeric molecules. Over time, the stability and durability of plastics change continuously. Any physical or chemical change in the polymer is caused by environmental factors, such as light, heat, moisture, chemical conditions, or biological activity. Degradation of plastic polymers can generally be classified as biotic or abiotic, following different mechanisms, depending on a variety of physical, chemical, or biological factors. Polymers are converted into smaller molecular units (e.g., oligomers, monomers, or chemically modified versions) and possibly are completely mineralized. The important processes for the degradation of polymers include physical degradation (abrasive forces, heating/cooling, freezing/thawing, wetting/drying), photodegradation (usually by ultraviolet radiation (UV) light), chemical degradation (oxidation or hydrolysis) and biodegradation by organisms (bacteria, fungi, algae).

#### *1.4.3.1 Hydrolytic degradation*

Most polymers such as polyolefins, including PE, PP and copolymers, are hydrophobic. Other vinyl polymers, such as PS and halogenated vinyl polymers, and for most rubbers are also hydrophobic. In general, polymers with pure carbon backbones are particularly resistant to most types of degradation. Hydrolysis is the cleavage of bonds in functional groups by reaction with water. This reaction occurs mainly in polymers that take up a lot of moisture and that have water-sensitive groups in the polymer backbone. The rate of hydrolytic degradation can vary from days to years depending on the type of functional group, structure, morphology, and pH. Some synthetic polymers that degrade when exposed to moisture include polyesters, polyanhydrides, polyamides, polyethers and polycarbonates (Gewert *et al*., 2015).

#### *1.4.3.2 Thermo-oxidative degradation*

Temperatures and oxygen levels affect plastics. Certain plastics will fragment more rapidly in regions with higher temperatures. High temperatures increase the rate of chemical reaction, generating greater degradation. There are reports that PS or polycarbonate has the possibility of thermal degradation under the subtropical condition (30–50°C). The light-initiated oxidative degradation is accelerated at higher temperatures depending on the process's activation energy

($E_a$); for example, for an $E_a$ of about 50 kJ/mol, the rate of degradation doubles when the temperature rises by only 10°C. Activation energy is the minimum amount of energy required to initiate a reaction in which it is the height of the potential energy barrier between the potential energy minima of the reactants and products. Activation energy is denoted by $E_a$ and typically has units of kilojoules per mole (kJ/mol) or kilocalories per mole (kcal/mol).

#### 1.4.3.3 Photo-degradation

Most plastics degrade primarily through photo-degradation in the environment. UV radiation in sunlight (100–400 nm) plays a key role in photo-oxidation, which induces plastic degradation. The photo-oxidative degradation of common polymers such as LDPE, HDPE, PP, and aliphatic polyamides (nylons) exposed to the environment is predominantly caused by UV-B radiation (280–315 nm) from sunlight. Once started, the breakdown can accelerate thermo-oxidatively for a while without the need for more UV exposure. If oxygen is accessible in the solution, the autocatalytic degradation reaction sequence can continue. The molecular weight of the polymer is reduced during photo-degradation, and oxygen-rich functional groups are formed in the polymer.

#### 1.4.3.4 Biodegradation

The conventional polymers such as PE, PP, PS, PET, nylons, PVC, and the composites and/or blends of these polymers prolong biodegradation rates and thus remain semi-permanently disposed of in the sea. The microbial species that can metabolize these polymers are rare in nature. Several features of PE make it resistant to biodegradation. Among these features are (1) highly stable C–C and C–H covalent bonds; (2) high molecular weight, which makes it too large to penetrate the cell walls of microbes; (3) lack of readily oxidizable and/or hydrolyzable groups; and (4) highly hydrophobic nature.

Bacteria and fungi are involved in the degradation of both natural and synthetic plastics. The biodegradation of plastics proceeds actively under different soil conditions according to the properties because the microorganisms responsible for the degradation and optimal growth conditions in the soil differ from each other, including polymer characteristics, type of organism, and nature of pretreatment. In the degradation process, the polymer is first converted to its monomers, and then these monomers are mineralized. The initial breakdown of a polymer can result from a variety of physical and biological forces. Physical forces, such as heating/cooling, freezing/thawing, or wetting/drying, can cause mechanical damage such as cracking of polymeric materials.

During degradation, exo-enzymes from microorganisms break down complex polymers yielding smaller molecules of short chains, for example, oligomers, dimers, and monomers, that are small enough to pass the semi-permeable outer bacterial membranes, and then to be utilized as carbon and energy sources. Environmental conditions often determine dominant groups of microorganisms and the degradative pathways associated with polymer degradation. When $O_2$ is available, aerobic microorganisms are mostly responsible for the destruction of complex materials, with microbial biomass, $CO_2$, and $H_2O$ as the final products. In contrast, under anoxic conditions, anaerobic consortia

**Table 1.7** Various polymer degradation routes.

| Factors (Requirement/ Activity) | Photo-Degradation | Thermo-Oxidative Degradation | Biodegradation |
|---|---|---|---|
| Active agent | UV-light or high-energy radiation | Heat and oxygen | Microbial agents |
| Requirement of heat | Not required | Higher than the ambient temperature required | Not required |
| Rate of degradation other consideration | Initiation is slow. But propagation is fast | Fast | Moderate |
| Other considerations | Environment friendly if high-energy radiation is not used | Environmentally not acceptable | Environment friendly |
| Overall acceptance | Acceptable but costly | Not acceptable | Cheap and very much acceptable |

of microorganisms are responsible for polymer deterioration. The primary products will be microbial biomass, $CO_2$, $CH_4$, and $H_2O$ under methanogenic (anaerobic) conditions (Dussud *et al*., 2018).

### *1.4.3.5 Mechanical degradation*

Mechanical degradation can happen through the combined efforts of wave and tide action, and abrasion of sediment particles, which can scratch the surface of the plastics and increase its rate of fragmentation. In most cases, the aging of the polymer by environmental influences, such as photo-degradation or chemical degradation of additives, changes the polymer properties and leads to the embrittlement of the polymer. This degradation generally leads to smaller plastic particles, with sizes between 1 and 5000 $\mu$m. Such particles are classified as microplastics. However, mechanical degradation can lead to nano-plastics when the plastic particles are reduced to the size range smaller than that of microplastics.

### *1.4.3.6 Combined degradation processes*

The degradation of the most common plastics encountered in the environment is attributed to the combined actions of sunlight, atmospheric oxygen, and seawater. Among the degradation processes involved, the most important is photo-oxidation, followed by mechanical action and thermal oxidation, and to a lesser degree, biodegradation and hydrolysis in Table 1.7.

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