1

Introduction to Plastic Wastes: Processing Methods, Environmental and Health Implications

Ali Mahmoudnia[1], Behnam Nejati[2], Mahsa Kianmehr[3], Masood R. Deiranloei[1], and Farshad G. Kootenaei[1]

[1]Faculty of Environment, University of Tehran, 16th Azar St., Enghelab Sq, 1417466191, Tehran, Iran
[2]Department of Renewable Energies Engineering, Science and Research Branch, Islamic Azad University, Hesarak blvd, Daneshgah Square, Sattari Highway, 1477893855, Tehran, Iran
[3]Faculty of Medicine, Mashhad University of Medical Sciences, Knowledge and Health Town, Shahid Fakouri Blvd, 9919191778, Mashhad, Iran

1.1 Introduction

The term "pliable," which means "easily formed," has been the origin of the word plastic [1]. The word "plastic" was first used in the 1630s to refer to a material that could be shaped or molded. This word is obtained from the Latin word "plasticus," meaning to mold or shape, and the Ancient Greek word plastikos, which describes something that may be molded. Leo Hendrick Baekeland initially used the term "plastic" in the current sense in 1909, and it is now a general term that is used to describe a wide range of materials [2]. Moreover, plastics are referred to as long chains of monomers called monomers, joined to different indistinguishable subunits to create a polymer. Depending on the type of plastic, commercial plastics typically include between 10,000 and 100,000,000 monomers per chain. Polymers in which each monomer is the same as the following monomer in the sequence are called "homopolymer." Nevertheless, polymers may be made up of various alternating monomers, named "copolymers." Polymers can also be made from branched chains in different architectures, different from a simple and basic linear polymer chain. Two polymers may also be blended to create a plastic mix that concurrently demonstrates the features of each polymer, subsequently giving both advantages. Moreover, combining two polymers can comprise a blend with improved features compared to either polymer alone. Polymers can have originated by nature, namely cellulose, which serves as the primary the components of plant cell walls and aids in the adaptation of cellular activities [3, 4]. Cellulose is known to be one of the most prevalent bio-based polymers on the globe. However, synthetic plastics created by

Plastic Waste Management: Methods and Applications, First Edition. Edited by Kalim Deshmukh and Jyotishkumar Parameswaranpillai.

humans are the vast majority of polymers of the modern age. John Wesley Hyatt was the inventor of the process for making celluloid, the first artificial plastic. John Wesley created a synthetic plastic that could be molded into many shapes and made to replicate natural materials namely horn, tortoiseshell, and linen that could be used in the manufacture of plastic by correctly processing cellulose polymers formed from cotton fibers with camphor [5].

The invention of synthetic polymers utilized to produce plastic materials has extended their application in varieties of products from packaging to cosmetics. Nevertheless, the majority of these polymers are not biodegradable, and after they are utilized and destroyed, they pose significant problems for waste management. Nevertheless, the usage of plastics can also have unfavorable externalities, including increasing atmospheric greenhouse gases (GHGs) or harm to the environment. It often is not biodegradable, which means that it might stay around as garbage for a very long period and possibly endanger both the environment and public health.

In the current chapter, we draw on existing knowledge about plastic to be an introduction to plastic waste management. We discuss plastics' environmental and health effects and show how plastic materials contribute to climate warming from cradle to the grave. We also present that the widespread use of plastic materials is a fix that backfires archetype. Then appropriate strategies to deal with plastic waste are discussed.

1.2 Plastic materials: Composition and Classification

The bulk of plastics consist of fillers, binders, plasticizers, pigments, and additional ingredients. Plastic's main characteristics are determined by the binder, and frequently, the plastic's name is derived from binder molecules. Binders might be synthetic or natural, including milk protein, casein, or a derivative of cellulose. It is also noted that most binders are made of synthetic resins [6]. For the most part, plastics are made from polyethylene. In accordance with the required properties of the finished product, it can alternatively be described as an ethylene polymer with the molecular and empirical formulae CH2–CH2 and $(–CH2–CH2–)_n$, respectively. The majority of organic solvents, acids, alkalis, and water have no effect on polyethylene [7]. Thermoplastics and thermosets are two categories of plastic that may be distinguished depending on their chemistry and physical features. Thermoplastics are a form of plastic that can be heated up, melted, and molded, then cooled down to become rigid. Additionally, these three steps are repeatable for thermoplastics. This feature of the plastic also makes them suitable for mechanical recycling, which is an effective means of waste management. The internal structure of thermoplastics, which including chemical bonding, as well as other structural characteristics and properties, can be used to categorize them.

1.2.1 Thermoplastics

Since 1940, the thermoplastic polyethylene terephthalate (PET) has been made based on fossil feedstock. Currently, it is utilized in the packaging of bottles and the textile industry. PET still enters the environment in substantial amounts even though it was developed for industrial purposes. A type of thermoplastic polymer known as high-density polyethylene (HDPE) is created from ethylene monomers. Similar ethylene molecules undergo a polymerization event to create polyethylene. According to this empirical formula $(C2H4)_n$, polyethylene is an unsaturated organic alkene formed of structurally organized hydrogen and carbon. HDPE is an inexpensive thermoplastic having a linear structure with minimal branching in comparison with other thermoplastics. It is made at a low pressures of 10 to 80 bar and low temperatures of 70–300°C environment. HDPE is frequently used to make soap containers and liquid cleaning product packaging, freezer and shopping bags, food and drinks storage, faux wood planks, bottle caps, pipelines, protective helmets, insulation, and vehicle fuel tanks [8].

The production of polyvinyl chloride (PVC) is the world's biggest use of chlorine gas. In total, human activities consume 16 million tons of chlorine or 40% of global production annually. Organochlorine, which can be referred to as a massive class of compounds that have recently come under regulatory and scientific investigation due to their widespread use and negative impact on public health and also the environment, is most commonly produced in PVC. The majority of plastic wastes with chemical compositions devoid of chlorine are more harmful to the community than plastic trash produced by plastics [9]. Vinyl manufacture, the creation of hazardous compounds, and excessive energy and resource consumption during various production stages all have negative consequences on the environment.

Ethylene is made from natural gas, oil, or chlorine gas, which is mostly made from sea salt through high-energy electrolysis. These are the two essential ingredients used to create vinyl [10]. Chlorine gas and the organic molecule ethylene are joined in chemical reactions to produce ethylene dichloride (EDC), also known as 1,2-dichloroethane in science. The term "chlorination" refers to this manufacturing procedure. A by-product of this process is organic HCl, which is mixed with more ethylene to make additional EDC via the chemical manufacturing technique known as oxychlorination. By a process known as pyrolysis, the generated EDC is simultaneously further transformed into chloroethylene (VCM – vinyl chloride monomer). A lengthy chain of PVC known as white powder is created by joining the VCM monomers created during the pyrolysis process. Stabilizers, plasticizers, colorants, and different essential additives, which can provide any particular attribute for the desired plastic working, are added with pure PVC. Because of its stiffness, brittleness, and ability to progressively accelerate its disintegration with intensity from UV radiation, PVC in its pure state is not terribly beneficial. PVC is made usable by adding additives to the polymer to boost its moldability and flexibility. [11]. PVC is frequently utilized in vinyl records, sewage and water pipes, garments, water bottles, and medical containers. It is also utilized in furniture, flooring, electric conductors, and other utilitarian wires [12].

In contrast to HDPE that has an extensive branching structure and contains both short-chain and long-chain monomers, LDPE is a long chain of identical subunits that is transparent and semirigid. Free radical polymerization is used to produce LDPE, which requires very particular circumstances including high pressure and temperatures ranging from 80 to 300 degrees Celsius. A total of 4000–40,000 carbon atoms with numerous short branches and subbranches are used in the LDPE's synthesis. Two alternative processes, stirred autoclaving and tubular methods, can be used to create LDPE. Presently, tubular reactors are utilized more frequently compared to autoclaving because of the benefits that tubular reactors provide, including a greater ethylene transformation rate. Laundry bags, bin bags, drink cartons, work tables, drink ring holders, machine components, lids, trays, protective shells, computer hardwires, playground fixtures, and containers are just a few typical uses for LDPE.

Thermoplastic polymers utilized in different usage is polypropylene (PP), and $(C3H6)_n$ is the empirical formula for it. PP, a semi-nonpolar chemical molecule that is partially crystalline, is produced through a polymerization reaction that converts propylene into a continuous chain of the polymer. The advantages of PP as a polyolefin, which is less dense than other commodities, led to its invention in 1954. Chemical resistance is just one of several advantages that make PP well suited for use in a diverse range of applications and conversion procedures, including extrusion molding and injection. High-temperature resistance and chemical branching are related to its physical and chemical features. The fabrication of various household objects, like as bottles, instrument jars (which may be often cleaned for use in a clinical setting), funnels, pails, and trays is both possible and given top attention by PP. PP's superior mechanical qualities and colorlessness make it a better choice than polyethylene in many applications. Due to colorless nature of PP and having superior mechanical qualities, polyethylene is a preferable choice than polyethylene in many applications. PP is widely utilized in a variety of industries, including packing tape, food containers, crisp bag, straws, hobby model supplies, lunch boxes, bottle caps, apparel, and surgical instruments and tools [13].

1.2.2 Thermosets

Thermosets are polymers that undergo a number of physicochemical conversion processes under various heat treatments, in which a cross-linking reaction materializes the chemical linkage between macromolecular chains and facilitates the creation of a three-dimensional network. After being subjected to the heating treatment, these thermoset molecules are unable to be reconstructed or remolten, and the process of transformation itself is irreversible. The fact that thermosets may change their physical state from a liquid with a relatively low viscosity to a solid with a high melting point illustrates that a wide variety of materials with different physical and chemical characteristics can be generated using thermosets. The viscosity of thermosetting monomers or subunits is typically low, making it possible to modify them and make them simple for consumers. The performance of thermosets may be maximized and optimized through the application of a number of additives, which in turn makes it possible for these materials to be put to a broad variety of specialized uses [14].

The polymerization of organic monomers known as urethane leading the polymer formation known as polyurethane, which also known as a carbonate in the commercial is setting. Many thermoset polyurethanes are also known as thermoplastic polyurethanes [15]. Polyurethane is widely used in a number of goods, including paints, coatings, foams, furniture, adhesives, and insulators because of its versatility and physical and chemical properties. Polyurethanes, much like many other types of polymers, are mostly composed of petrochemicals, either as the primary component of their main structural components or as a basic ingredient or subunit [16].

1.3 Techniques of Plastic Processing

Processing of plastic is the set of operations that turns raw plastic or polymer ingredients into refined products that can alter the standard of living in a variety of aspects, including financial, health, and developmental ones. Plastics see heavy application in the food and drink processing industries. Plastics can have their durability, applications, and modifiability enhanced by the use of certain synthetic substances that are referred to as additives. Examples of additives that can help with the altering processes include plasticizers made of phthalates and bisphenols. Several techniques can be used to transform polymer into high-quality plastics. There are several ways to turn polymer into high-quality plastics, and these ways can be classified into three different categories. For instance, there are primary processing techniques like transfer molding, compression, extrusion, and injection, secondary processing techniques such as thermoforming, coating, calendaring and fabrication, roto-coating, as well as casting, and tertiary processing techniques includes drilling, welding, and briquetting.

1.3.1 Primary Techniques

Thermosets, also known as thermoplastics, can be manufactured at a temperature that is kept under control by employing an injection process that involves the use of a plunger or screw pump to lower the viscosity of the polymer that is stored in a heated barrel and inject it under regulated pressure by compression into runners through a nozzle, molds cavities, and gates [17]. The mold injection method is used for creating a wide variety of goods, including those used in the automobile industry, as well as bottle caps, spools, gem clips, crates, bobbins, and buckets. Another common processing technique is blow molding, which requires the use of electricity and band heaters to heat the area to the point where plastic melts and may be deformed from the raw material of plastic pellets [18]. The blow molding technique is used to make a wide variety of goods, including portable toilets, air ducts, drinking bottles, armrests, and gas tanks. During the extrusion processing, raw thermoplastic materials or resins are loaded into the mounted hopper at the top, where they are allowed to fall into the extruder's barrel as a result of the gravitational attraction force. Chemical additives, such as UV inhibitors and colorants, can be inserted and incorporated into the resin before it reaches the hopper in order to finish the processing of extruding plastics. These chemical additives can come in the form of pellets or liquids [19, 20]. A number of the products which can be manufactured using extrusion are plastic films and sheeting, strapping, thermoplastic coatings, multilayer films, and pipe or tubing [19]. Another technique for processing plastics that involves heating is compression molding. A heated polymer is introduced into a hot mold cavity during the plastic material processing. The mold is completely sealed with the plug or closed, and then the material is compressed to fill the whole inside surface of the mold cavities [21]. This compression molding method simplifies the production of a material with intricate patterns in terms of thickness and length. The high strengths, hardness, and durability of the items produced using this technology make them appealing to users from a wide variety of industries and individuals [22]. A vast range of useful things are produced using compression and molding operations, including engine handles, cisterns, plugs, electrical sockets, and switches for engine casings. Another common plastic processing method employed by many specialists to produce different kinds of rubber components is transfer molding. Throughout the course of processing, the quantities of molding must be calculated, positioned, and introduced into the pot; afterward, the material is heated and put under pressure, which causes it to enter into the mold cavity [23].

1.3.2 Secondary Techniques

The plastic molding process known as rotational molding is well suited for creating hollow objects. In contrast to previous techniques, no pressure is used throughout this procedure. As casting techniques are used, the production process is shortened, and production costs are reduced, so having a short production process is advantageous from an economic standpoint [24]. Thermoforming is a type of plastic molding that can be used to make many different kinds of practical plastic instruments. In the manufacturing process, small plastic sheets are heated to facilitate an easy manipulation process. The sheets are heated to a malleable temperature to create the required products, and the final product is then cooled down to finalize the production process [25]. Calendaring is a type of secondary processing techniques utilized to produce a variety of high-quality plastic sheet and film products as well as high-volume plastics. It is frequently used to produce PVA and other polymers with different properties. The molten polymer is sent through the extruder, where it is treated to heat and pressure, and the calendaring rolls are used to shape the resulting sheets [26]. Another fascinating and practical way to process plastic is by casting method, which involves pouring a liquid state into a mold with cavities that resembles the shape of the finished product. Once the liquid has solidified, it takes on the shape of the plastic needed to create the desired product. In order to complete the process of the solidified component, the mold must be extracted or cast out from the product.

1.4 Global Plastic Production

Due to their outstanding physicochemical characteristics (e.g. durability, availability, hygienic, lightweight, and flexibility) and being cost-effective, plastic has become a primary product around the world and has diverse applications in industrial and commercial commodities. The amount of plastic produced worldwide has increased significantly to satisfy the growing market for these products [27, 28]. Annual global plastic production has accelerated throughout the last decade from 2 million tons in the 1950s to 359 million tons in 2018 [29] and reached 368 million tons in 2020 [30]. Historically, global plastic production has incremented by approximately 9% per year [31]. According to scientific reports by 2014, the rate of the world's plastic production had achieved 311 million tons each year [32]. This indicates that global plastic production has increased by around 25% annually in just 5 years; meanwhile, global annual plastic production has grown dramatically to 20,000% in 65 years. China is known as the world's largest plastic producer, followed by European countries and North America which, respectively, produce 26%, 20%, and 19% of global plastic production (Figure 1.1) [33]. Moreover, recent long-term projections indicate that the manufacture of plastic products displays no signs of slowing down and is anticipated to increase further [34]. Scientific research has projected that about an additional 33 billion tons of plastic materials will have been produced by 2050 [35], and the global annual plastic production will be between 850 million tons [36] and 1124 million tons [34]. However, these projections can be more aggravated due to the unprecedented consumption of plastic-containing materials, including plastic-based PPE and packaging.

The foremost commonly used and plenteous polymers (namely polystyrene (PS), PET, PVC, PP, HDPE, and low-density polyethylene (LDPE)) are presented in Table 1.1. They together comprise nearly 90 percent of the whole plastic production of the world [37]. To determine specific sorts of plastics materials from other

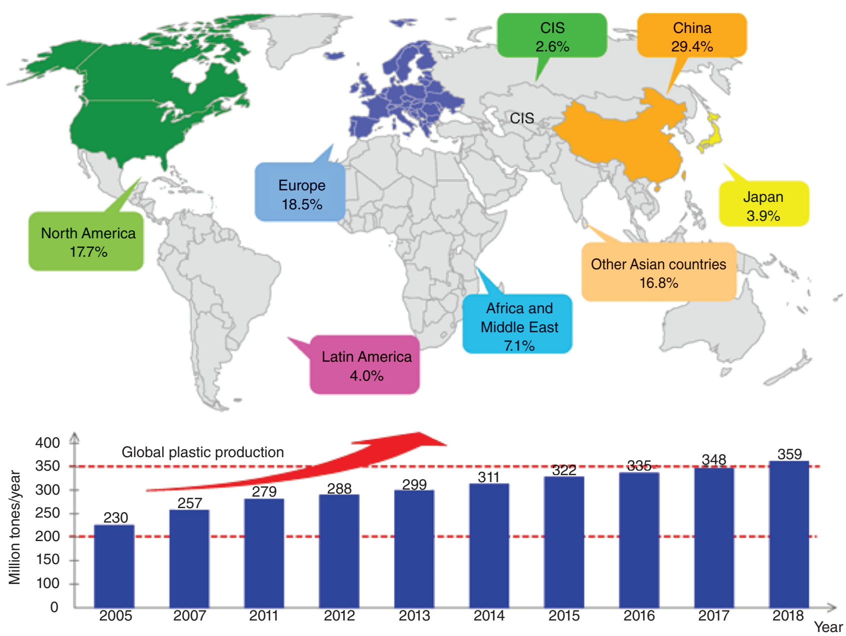

Figure 1.1 Global plastics production. Source: Shen et al. [33] /Elsevier/CCBY 4.0/ Public domain.

Table 1.1. Different kinds of plastic products.

ASTM designator code	Polymer type	Specific gravity	Applications
06 PS	Polystyrene (PS)	1.05	Foam packaging, plastic tableware, food containers, single-use cups, cassette boxes, CDs, jugs, tanks, and building materials (insulation)
02 PE-HD	High-density polyethylene (HDPE)	0.94	Detergent bottles, pipes, tubes, milk jugs, and insulation molding
04 PE-LD	Low-density polyethylene (LDPE)	0.91–0.93	Shower curtains, outdoor furniture, films, siding, clamshell packaging, and floor tiles
01 PET	Polyethylene terephthalate (PET)	1.37	Bottles of carbonated beverages, pipes, tubes, plastic film
07 O	Polyester (PES)	1.40	Textiles and fibers
03 PVC	Polyvinyl chloride (PVC)	1.38	Plumbing pipes and guttering, window frames, shower curtains, films, and flooring
07 O	Polyamides (PA) (nylons)	1.13–1.35	Fibers, toothbrush bristles, fishing line, and food packaging
07 O	Polycarbonate (PC)	1.20–1.22	Compact disks, lenses, security windows, riot shields, construction materials, and eyeglasses
07 O	High-impact polystyrene(HIPS)	1.08	Refrigerator liners, vending cups, food packaging, and electronics
07 O	Acrylonitrile butadiene styrene (ABS)	1.06–1.08	Electronic equipment (such as keyboards and printers), automotive bumper bars, and drainage pipe
05 PP	Polypropylene (PP)	0.83–0.85	Drinking straws, appliances, bottle caps, car fenders, tanks, and jugs

Source: Crawford and Quinn [2]. Copyright 2017. Reproduced with permission from Elsevier.

types, most plastic products, particularly those utilized in packaging, food, and drink, have an internationally recognized codes that determine the kind of polymer from which the commodities are made. The American Society for Testing and Materials (ASTM) has issued the present coding system. The Society of Plastics Industry (SPI) administered the most common commodity plastics in 1998, with a designator code to help reprocessing measures, allowing plastics materials to be recognized easily [38]. Nevertheless, ASTM International took charge of the oversight of the codes in 2008. ASTM International, in 2013, took the decision to alter the familiar three mutually chasing arrows, revise the symbols, and replace them with solid equilateral triangles as a part of the recent modified ASTM D7611 system. The reason of this action was that the initial symbols were very similar to the global recycling symbol. It can be inferred that was a source of confusing because, despite the mutually chasing arrows, at that time, many recycling facilities would only accept plastics with specific codes and would not accept any other plastic sorts (Figure 1.2) [2]. Therefore, consumers were bewildered why the plastics were refused even with a recycling emblem. Hence, ASTM International desired to guarantee that the introduced symbols and abbreviations just determined the kind of plastics, regardless of their capacity to be recycled [39]. Therefore, the solid equilateral triangle system was presented to provide efficacious and trustworthy usage of the resin recognition coding system for the stakeholder society.

Despite their outstanding features, plastic waste has become a severe concern globally. Among all the plastics that have been made, yearly, around 33% are expected to be disposable and are normally discarded within 12 months of production [2]. Moreover, among all plastics manufactured, it is assessed that around 10 percent has been discharged into the global ocean [39]. The assessment of United Nations Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) suggested that about 80% of waste in the marine environment originates from land, while only 20% results from sea activities (Figure 1.3). It has been assessed that between 4.8 and 12.7 million tons of plastic litter ended up in the global ocean in 2010 alone [40], while according to scientific estimates, in 2015, approximately 8 million tons of plastic waste

Figure 1.2 Comparison of the familiar SPI system and the new ASTM system for plastic identification. Source: Crawford and Quinn [2]. Copyright 2017. Reproduced with permission from Elsevier.

Figure 1.3 Plastic litter can substantially end up in the global ocean.

were reached by the ocean [34]. This amount is anticipated to rise to about 32 million tons annually by 2050 [34]. Thus, the increasing amount of marine plastic litter poses various challenges from environmental and health aspects.

1.5 The Health and Environmental Effects of Plastic Debris

The increasing population, rapid industrialization, and growing urbanization have all contributed to various environmental problems caused by human activity. Solid waste management has emerged as one of the most pressing problems facing our planet, particularly in metropolitan regions and megacities and is considered to be one of the most significant environmental issues. Currently, the generation of municipal solid waste (MSW) is approximately 2 billion tons annually, and by 2025, it is anticipated to reach 3 billion tons [41]. MSW has comprised a wide range of wastes, include organic residues like vegetables, fruits, and food scraps as well as inorganic wastes, like plastic, glass, and metal (Figure 1.4) [42]. A large segment of the MSW's inorganic components is made up of plastic litter fractions. Plastic garbage in MSW principally incorporates bottles, bags, packaging material, lids, containers, and cups. Because of their durability and stability, originating from their polymeric nature [43], plastic wastes have drawn tremendous attention compared with any other type of MSW. Due to the growing pace of plastic production materials and the lack of availability of appropriate means of management, treatment, and disposal, plastic trash has emerged as a serious problem in the modern world. Around 16% of plastic garbage produced annually in India, over 10% annually in China, and 2.5% annually in the UK [43]. Due to their recalcitrant and nonbiodegradable nature,

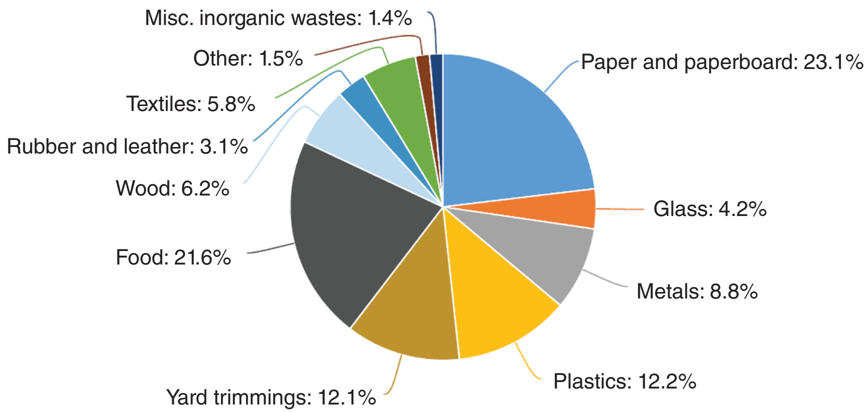

Figure 1.4 MSW components [42]. *Source:* https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/guide-facts-and-figures-report-about.

it takes centuries for complete degradation. Hence, plastic wastes tend to accumulate instead of decomposing in natural environments or landfills. The accumulation of this growing amount of plastic debris in the environment can cause various health and environmental effects. The fate and detrimental effects of plastic particles are depicted in Figure 1.5 [44] and will be discussed in the following sections.

1.5.1 Plastic Debris and Microplastics

While scientific communities are dealing with that tremendous amount of mismanaged plastic waste, the microplastics' arrival has posed a severe new concern for the world. Microplastics are characterized as 1-m to 5-mm polymer particles [45, 46]. Microplastics are categorized into secondary and primary microplastics considering their sources [47, 48]. "Primary microplastic" refers to plastic particles made in micro-size primarily. They exist in personal care and cosmetic products, toothpaste, facial cleansers, body washes, and lipstick. In contrast, "secondary microplastic" refers to micro-size plastic particles formed by the breakdown of broader plastic products, such as face masks and clothes' synthetic fibers, due to exposure to severe environmental conditions such as UV radiation and mechanical forces [49–53]. Therefore, washing clothes, road marking and tiers, landfilling, littering, construction, sports arenas, plastic production industries, mulching in agriculture fields, cosmetics, and healthcare products are the potential sources of microplastics [54–59]. Microplastics are subdivided based on their size and appearance into 10 types as part of standardized size and color sorting system (SCS), including pellets (plastic spheres with diameters ranging from 1 to 5 mm), microbeads (small spherical pieces of plastic less than 1 mm to 1 μm in diameter), fragments (irregularly shaped pieces of plastic less than 5–1 mm in size along its longest dimension), microfragments (irregularly shaped pieces of plastic less than 1 mm–1 μm in size along its longest dimension), fiber (plastic filament or strand that is less than 5–1 mm in length along its longest dimension), microfiber (plastic filament or strand

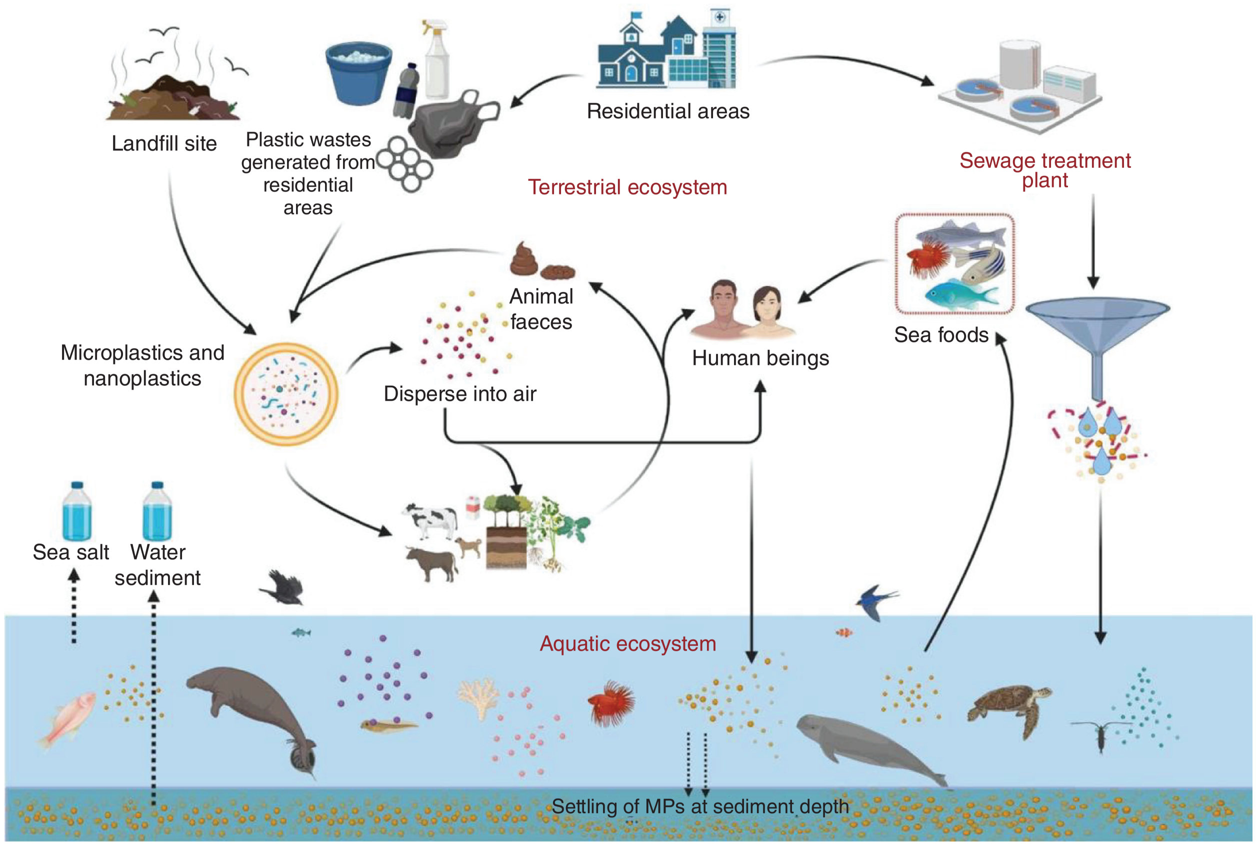

Figure 1.5 Fate and detrimental effects of plastic products on the ecosystem. Source: Lamichhane et al. [44]. Copyright 2023. Adapter from Springer Nature.

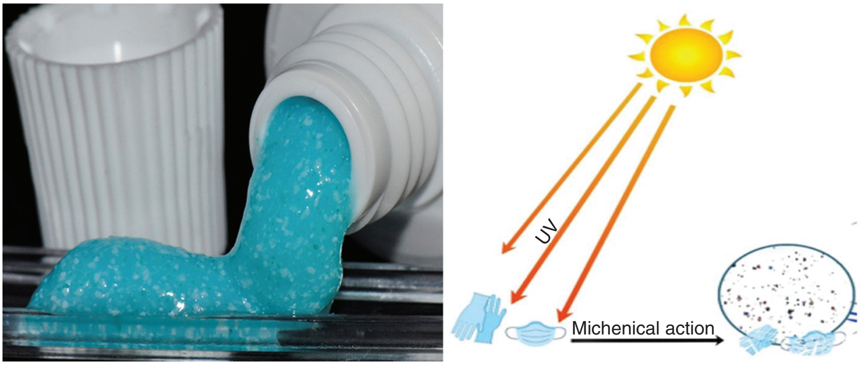

Figure 1.6 Primary microplastics (left side) and secondary microplastics (right side).

less than 1 mm–1 μm in size along its longest dimension), film (thin sheets of plastic less than 5–1 mm in size along their longest dimension), microfilm (thin sheets of plastic less than 1 mm–1 μm in size along their longest dimension), foam (foam-like plastics less than 5 mm to 1 mm in size along their longest dimension), and micro-foam (foam-like plastics less than 1–1 μm in size along their longest dimension) [60]. These plastic particles may distribute vertically or horizontally. Almost the primary cause of the vertical transportation of (micro) plastics in the water column is polymers' density [61, 62]. While they can distribute horizontally because of hydrodynamic processes including river flow, wind, as well as ocean current, or they may be transferred by fauna after ingestion [58]. This distribution process may be allowed microplastics to end up in acceptor ecosystems, including freshwater [63], oceans [46], soil [64], groundwater [65], Arctic snow [66], the atmosphere [67], human foods like fishes [68], and eventually human body [69]. Figure 1.6 shows examples of primary and secondary microplastics.

Thus, the extensive persistence and buildup of (micro)plastics in ecosystems across the world clearly pose a threat to public health. Our knowledge of the potential dangers of microplastics on public health is, however, fairly limited because of ethical limitations, a lack of effective detection techniques, and stringent biosecurity regulations for handling human samples. Therefore, it is still debatable how (micro)plastic environmental impacts and the increased incidence of associated human disorders interact. The various entry points for (micro)plastics into the human body as well as any potential negative consequences on health are discussed in the section that follows. Then, the environmental effects of plastic waste will be discussed. The chapter intends to identify future avenues for (micro)plastics research by helping readers better understand the intricate environmental health issues around (micro)plastic contamination.

1.5.2 Plastic Effects on Human Health

Microplastics may reach the human body via three critical pathways: by ingestion of microplastic-contaminated water and food, inhalation of microplastics from the

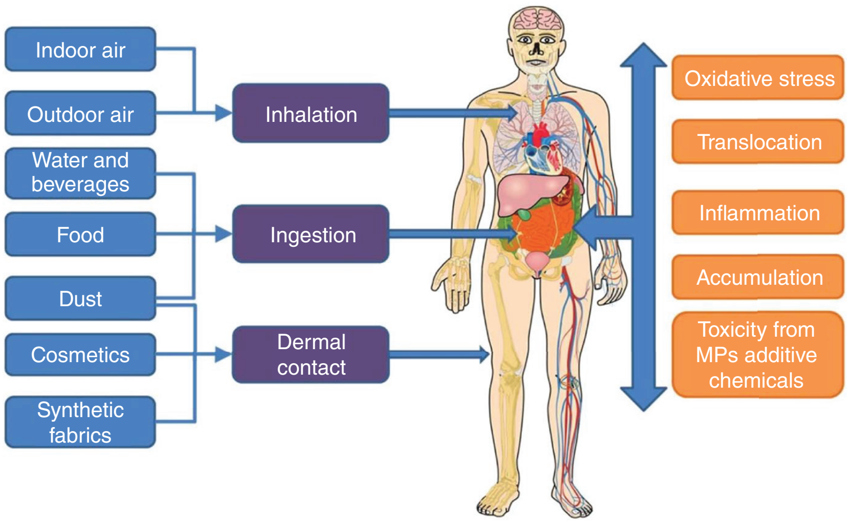

Figure 1.7 Potential pathways of microplastic exposure in the human body and their toxicity routes. Source: Ageel et al. [71]/© Royal Society of Chemistry.

environment, and skin contact with microplastics found in dust, goods, or textiles [69, 70]. Figure 1.7 shows potential pathways of microplastic exposure in the human body and their toxicity routes [71]. Microplastics have been shown to contain in human foods, such as commercial fish [72], mussels [73], sugar [74], table salt [75], and drinking water [76]. Therefore, ingestion is considered the primary pathway of individual's exposure to microplastics [77]. Based on food consumption, it is predicted that each individual consumes between 39,000 and 52,000 particles of microplastic annually [78]. Microplastics may end up in the gastrointestinal system through foodstuff, possibly leading to increased permeability, an inflammatory response, and changes in metabolism and gut microbe composition [79].

Microplastics may remain suspended in the atmosphere, settle in aquatic or terrestrial, and then resuspend in the atmosphere. These airborne microplastics resulting from mismanaged plastic waste can be considered particulate matter (PM) constituents in air pollution. Microplastics may be present in an unidentified part of the PM because the minimum size of microplastics detected by usual methods is 5 μm. Nevertheless, recent research quantified and characterized a considerable amount of airborne microplastics in urban, suburban, remote mountains, and indoor environments [80–82]. The result of a scientific research note that indoor microplastic concentrations ranged from 3 to 15 MP particles/m^3 in private apartments or offices [83]. Moreover, the concentration of microplastics in the outdoor environment in Spain reported by González-Pleiter et al. [84] are 1.5 particles/m^3 in a rural area and 13.9 particles/m^3 in Madrid. It is estimated that adults' average air volume is approximately 15 m^3/day [85]. Thus, every human is exposed to a considerable amount of airborne microplastics each day, which depends on individuals' situation, such as their job, population density in the city of residence, and the amount of time spent indoors. It is estimated that airborne microplastics via inhalation by adults would be 26–130 microplastic per day [86]. Moreover, dermal contact (from dust, microbeads in cosmetics, and synthetic fibers) is another plastic particle exposure pathway in the human body and mainly is related to nanoplastics (<100 nm) [69].

After exposure, microplastics cause toxicity in different ways. Due to their vast area of surface, the release of oxidizing pollutants such as metals adsorbed to their surface, or reactive oxygen species (ROS) unleashed during the inflammatory response, microplastics can be the origin of oxidative stress in the human body [87]. For example, oxidative stress in mice [88] and zebrafish (Danio rerio) [89] has been noted after exposure to microplastics. Oxidative stress, particle toxicity, and inflammation caused by plastic particles can also lead to cytotoxicity. Schirinzi et al. [90] has reported that in epithelial and cerebral human cells, exposure to PS and polyethylene at concentrations between 0.05 and 10 mg/l increased ROS to high quantities, which contributed to cytotoxicity. The equilibrium between intake, expenditure, and the amount of energy available from reserves is known as energy homeostasis. Recent research has demonstrated that microplastics may affect human energy homeostasis by reducing nutrient (energy) intake, increasing energy consumption, and adjustment of metabolism [69]. Nevertheless, because humans require more energy than the examined species and are exposed to lower exposure concentrations, it may be difficult to observe these effects.

After exposure, plastic particles may accumulate locally or translocate in the body, leading to exposure of other tissues. For instance, ingested microplastics may end up in the ileum and penetrate mucus in the intestinal lumen. Although T-cells, B-cells, and macrophages internalize plastic particles, M-cells transmit microplastics to the lymph and blood vessels. In this way, microplastics re-release and translocate to other textiles before going to urine and feces [77]. The accumulation or translocation of microplastics depends on their size, charges, surface area, and hydrophobicity [91, 92]. In contrast, the tissues' inflammation has been shown to increase the permeability of epithelial boundaries and their translocation. It is also noted that unhealthy diets with a high level of saturated fats and fructose sugars also increase the permeability of the gastrointestinal mucosa [93], leading to an increased MPs concentration in the lymphatic system or blood vessels.

After exposure, particles, dependent on their dissemination, may induce systemic or local immune responses. Environmental exposure can, in some circumstances, such as those involving genetic predisposition, be sufficient to impair immune function and promote autoimmune or immunosuppressive disorders. As PM in the air, microplastics may disrupt immune function. After exposure to microplastics, immunosuppression and tissue-dependent immune response modulation have been reported in Mytilus spp. However, this has not yet been observed in humans. Hence, further research on microplastic impacts on the immune system is warranted.

Regardless of the inherent toxicity of microplastics, many researchers indicate microplastics can colonize and carry a broad range of chemical pollutants, including heavy metals [94], toxic chemicals [95], antibiotics [96], persistent organic pollutants (POPs) [97], as well as pathogens [98]. Microplastics may expose organisms to larger quantities of the aforementioned potentially dangerous pollutants after exposure, or they may even increase the toxicity of those pollutants. However, adverse effects of the translocation of vector microplastics, the kinds of ingested particles, the release rate, the clearance time, the quantity of the contamination, its noxious effects, and its translocation in body cells all play a significant role in the chemical release or pathogens adsorption to microplastics [69].

Micropollutant exposure can cause neurotoxicity, which is linked to neurological illnesses. Microplastics can really influence neuronal function and behavior, as shown by in vivo toxicity testing. A decrease in acetylcholinesterase (AChE), oxidative stress with an increment in the quantity of lipid peroxidation and a rise in the anaerobic energy generation are all reportedly caused by microplastics in the brain of Dicentrarchus labrax (European seabass) [99]. Moreover, it has been observed that exposure to PS impairs mouse neurotransmission, altering blood levels of neurotransmitters and increasing AChE activity. About the evidence of neurotoxicity when evaluating microplastics in cells or creatures, it is necessary to appreciate how microplastics might be related with neurotoxicity in people, adding to an increased risk of the development of neurological diseases.

1.5.3 Plastic and Climate Change

Earlier environmental effects research predominantly concentrated on plastic waste's sources, distribution, fate, toxicity, and behavior; narrow attention has been paid to the unignorable contribution of plastic materials to increasing atmospheric GHGs. With the increment in plastic debris, their adverse effects to the planet's climate have increased remarkably. According to scientific studies, each stage of the plastic' life cycle such as extraction and transport of plastics' raw materials, manufacturing, management of plastic debris, and even entering the natural environment contribute to GHG emissions. Hence, despite narrow information on the role of plastics in incrementing atmosphericGHG, the available data imply the fact that GHS emissions from the cradle to the grave of plastic are inevitable and considerable. Plastic's direct and indirect contributions to climate change are demonstrated in Figure 1.8. Common methods to address plastic litter include, landfill, sanitary, recycling, incineration, and so forth. These approaches to plastic waste management directly contribute to GHG emissions.

Recycling plastic debris imply the physical procedure of retrieving material without changing the polymer's molecular structure. Recycling plastic reduces GHG emissions significantly when compared to alternative plastic waste management strategies currently in use. Theoretically, increased recycling might reduce the need for raw materials and prevent emissions from generating the same quantity of raw materials. The US Environmental Protection Agency indicates that recycling 3.17 million tons of plastic debris in 2014 could prevent 3.2 million tons of carbon dioxide emissions, which is the same as removing 670,000 cars from the road for a year. Additionally, recycling plastic packaging could prevent 1.4 million tons of carbon dioxide emissions [33]. Producing new plastic from recycled plastic materials is more than three times more efficient when it comes to GHG emissions than producing the same product from raw materials, which is predominant because original

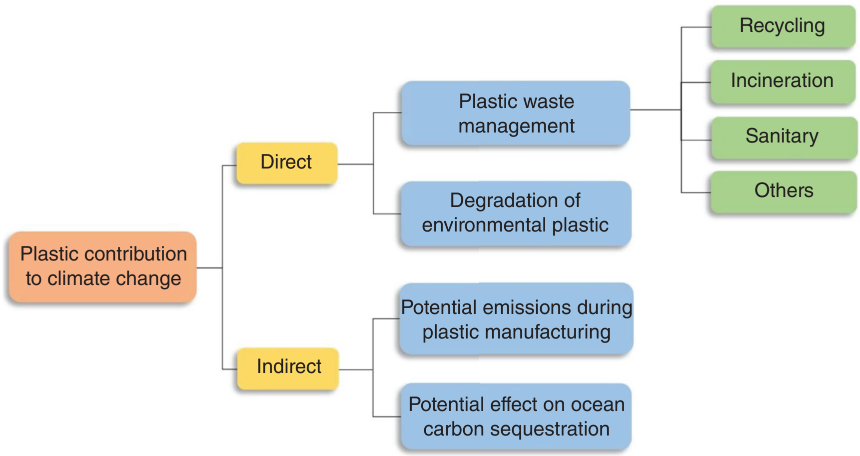

Figure 1.8 GHG emissions in the life cycle of plastic.

products are being replaced and renewable energy is being conserved. However, due to many limitations and challenges, very little proportion of "recyclable" plastic debris is transmuted to the primary goods. Thus, recycling mainly is considered as the primary approach to address the plastic problem has a long-length route.

Recent times have seen incineration viewed as a quick fix for the widespread pollution of land-based plastics. In addition to efficiently reducing plastic pollution, it may also provide heat and energy for human consumption. Plastic debris are converted into combustion gas, fly ash, and bottom ash, during incineration, which also produces heat through burning. In metropolitan regions, collected plastic garbage is burned alongside biomass or fossil fuels in facilities for power generation, waste incineration and other industrial applications, primarily cement kilns, utility boilers, and paper mills. However, burning plastic trash can result in the production of GHGs, often CO_2. Scientific evidence indicates that every ton of plastic packing debris typically contains about 79% flammable carbon, unleashing 790 kg of carbon into the atmosphere, or approximately 2.9 tons of carbon dioxide [100]. More than half of the US's 11 million tons of CO_2e emissions from waste incineration in 2015 (5.9 million tons) originated from plastic waste. The environmental effect of burning plastic garbage in the United States is similar to driving 1.26 million automobiles for each year [33].

Sanitary landfill usually implies the usage of clay or some liners to separate debris from groundwater and put a soil layer to diminish debris exposure to the atmosphere. Emissions of GHG from sanitary landfills are primarily associated with organic waste, including wood, food waste, and paper decomposition. So far, there is no narrative of GHG emissions from plastic landfills. The emission associated with landfill plastic packing litter comes from the treatment and classification of pre-landfill debris and the usage of fossil fuels for the transportation of debris from collection points to landfills. Yet, this does not eliminate the potential of GHG emissions from landfills.

An additional 32% of plastic packing debris is not treated, in addition to the management techniques stated above. Different approaches for unmanaged plastic debris include dumping, littering, and burning that are frequent in regions with underdeveloped facilities for the management of wastes. Nevertheless, the effect of unmanaged plastic debris on global warming is not yet understood completely. Open burning, defined as a technique of burning flammable debris in the environment, severely affects human health and climate due to it occurring at lower temperatures and is conducted with no measures to reduce air pollution compared with a debris incinerator. According to scientific data, each ton of plastic debris emits 2.9 million tons of GHG during open burning [33]. Generally, in general, it is unclear how the open disposal of plastic debris contributes to climate change. Recent scientific studies have revealed that plastic degradation under sunlight in the nonaquatic environment can unleash GHG more quickly than in the oceanic environment [101]. Nonetheless, these emissions' magnitude and annual rate are still yet to be determined. Investigating the amount of GHG emitted from unmanaged plastic waste can show the full harm posed by plastic packing debris to climate warming, despite significantly insufficient data on waste management methods. The effect of unmanaged or mismanaged plastic debris on climate warming is mainly related to the percentage of open burning and, similarly, leads to varieties of worldwide concerns.

Disposing of microplastics will not stop the emission of GHG and the impacts of microplastics on the environment. After exposure to radiation, it was discovered that several of the most popular types of plastic release detectable levels of two GHGs (ethylene and methane). Emission rates for CH_4 are between 10 and 4100 pmol/day/g, and those of C_2H_6 is between 20 and 5100 pmol/day/g [101]. In addition, the emissions of GHG from virgin plastics were much higher than those from old ones. Besides, whereas the emissions of GHG from aged plastic stay constant over time, they rise with time from virgin ones. Anti-ultraviolet plasticizers, which limit the impacts of ultraviolet radiation and delay the degradation process, are likely to be responsible for this. [101]. Compared to other sources of GHG emissions, including industrial processes, vehicle transport, and agricultural operations, the rate of GHG generation from plastic materials may be considered insignificant. However, as plastic manufacturing rises and more improperly disposed of waste plastics, emissions of GHG associated with plastic degradation will probably rise as well, which may be a greater concern [40].

GHGs are inevitably emitted throughout the mining, transportation, refining, and manufacturing processes of plastics. Global GHG emissions from well to refineries in 2015 are approximated to be 1.7 gigatons CO2e [102]. Considering the distribution of around 4% of crude oil as plastics' raw material, it is projected that the world's oil sector contributed around 68s million tons of CO_2e to the emission of plastic manufacture in 2015. New facilities for the production of natural gas has been completed or strongly suggested thus far, and there will be additional developments in the following decades. These facilities are driven not just by the need for natural gas but also by the fast expansion of the plastics industry. Thus, the influence of oil, coal, and gas extraction on GHG emissions is concerning, and this is doubtful that GHG emissions would be diminished without a considerable reduction in these large industries, which are only the first stage in plastic manufacture. Moreover, the plastics manufacturing process contributes to global warming by releasing GHGs. These emissions result from the conversion of petrochemical raw materials into usable commodities including propylene and ethylene [103]. Based on the effectiveness, control system, and service life of the product, manufacturing plants often manage GHG emissions during production. In the America, 72 plastic manufacturing units produced roughly 17 million tons of CO_2e in 2014, or 46,324 tons per day [104]. Many industrial procedures for the purpose of converting fossil fuels to plastic materials, in addition to a large number of manufacturing steps, make it significantly challenging to ascribe GHG emissions from industry to plastic manufacture. Considering the shortage of information on GHG emissions from the entire procedure of plastic production, the growing evidence indicated that plastic manufacturing is associated with GHG emissions. Plastic manufacturing is worldwide, as are GHG emissions and their effects.

Except for the direct emission of GHG, plastic debris, especially maritime plastic, may contribute to global warming in a less direct but eventually more substantial way by impacting organisms that serve as the basis of the ocean food web [105]. Ocean is considered the most significant natural pool of carbon dioxide that has a crucial function in adsorbing carbon from the atmosphere. As the capability of the ocean for carbon adsorbing is unsettled, the earth's carbon cycle will change dramatically, therefore endangering the primary necessities for the survival of humans. The particular question is whether oceanic (micro)plastic can interrupt ocean carbon sequestration. Evidence has indicated that (micro)plastics negatively impact growth and photosynthesis of phytoplankton [106]. Phytoplanktons play a tremendous role in the oceanic ecosystem. Phytoplankton is considered the basic producer of marine ecosystems, and it can use sequestrated atmospheric carbon for producing organic matter and oxygen through photosynthesis (Figure 1.9). However, reflecting and shielding sunlight by microplastics at the surface of the ocean can diminish phytoplankton's sunlight absorption and decrease the capability for photosynthesis of these creatures. Laboratory investigations indicated that microplastic exposure has detrimental impacts on phytoplankton, and the smaller the microplastics, the higher their negative impact [107].

Moreover, microplastics may damage zooplankton by having toxicity on them and affecting reproduction and development of these creatures. Zooplanktons are the primary and most significant consumers of phytoplankton. Zooplanktons have a vital role in the flow of mass, the regeneration of oceanic nutrients, and energy, the cycling of biogenic elements, genetic information through the food chain, and the decomposition of oceanic pollutants. Zooplanktons are able to degrade particulate organic carbon (POC) in the ocean via respiration; hence, they can affect the profundities of remineralization of oceanic POC and the ability of marine in adsorbing atmospheric carbon. If zooplanktons are not entangled in the processes of OCS, the sequestered carbon will return to the atmosphere and water right away. However, the prevalence of microplastics in the oceans could have a harmful impact on ocean's ability for sequestrating CO_2. Because ingesting microplastics causes satiety, scientific studies acknowledged that they may have negative impacts

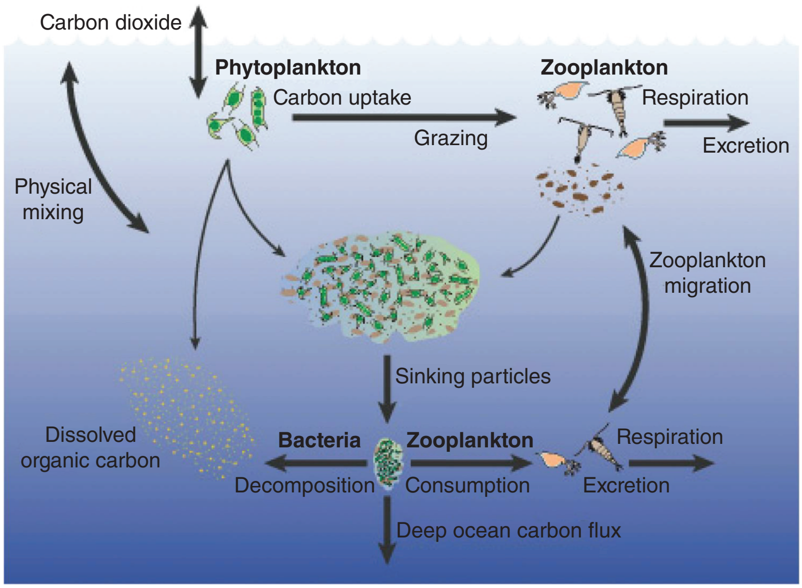

Figure 1.9 Microplastics harmful effects on the ocean carbon sequestration. Source: Gander [106]/© Taylor & Francis.

on zooplankton (copepods) and diminish their carbon consumption. After ingesting (micro)plastic, copepods consumed 40 percent less food, and over time, their eggs grew smaller and were less likely to hatch, increasing their overall death rate. Moreover, increasing zooplankton exposure to (micro)plastics over time may significantly reduce their consumption of carbon-containing material [108]. Moreover, as zooplankton antecedes phytoplankton, fecal particles transport the carbon they consume to the ocean floor. Then these particles descend gradually into the ocean's depth and deposit within the mud of the ocean floor. Cole et al. noted that fecal pellets could transport microplastics to the seabed [108]. Scientific studies have revealed that fecal particles with microplastics had much smaller comparable spherical diameters and a 1.35-fold lower descending rate [109]. Further, compared to unpolluted pellets, microplastic-polluted pellets descend more slowly and degrade more quickly, reducing the amount of carbon that settles on the ocean floor. However, the knowledge of (micro) plastics' behavior and impacts in deep ocean is still in its embryonic stages. As such, further investigations are required to comprehend the probable dimensions, scope, and main factors of the issue.

1.6 Management Strategies for Plastic Debris

Given the aforementioned, plastic pollution is a global issue. Plastic waste causes harm that is not localized to any one area; rather, it has global effects and poses global concerns. Therefore, international cooperation is necessary for countermeasures to control plastic debris. Furthermore, it is critical to recognize that the suggested strategies to deal with plastic litter must be sustainable. These ought to make a significant difference in reducing the amount of plastic in the environment, but they should not be considered exhaustive. Source reduction, remediation, and cleanup should all be priorities in any countermeasures used to manage and reduce plastic pollution. This section after that lists these measures. It should be remembered; nevertheless, that each of these strategies has its pros and cons.

1.6.1 Improving 4R Concept

Assume that public attention to the environmental and public health hazards of plastic waste is widely expanded through Big Tech companies and the mainstream media. It is to be hoped that this will result in a major decrease in the consumption of various plastic goods, such as disposable plastic. The quantity of plastic waste that enters the environment can be drastically reduced by developing recycling technique, boosting recycling-related infrastructure investment in solid waste, and creating a circular economy. Moreover, repeated use of plastic products can greatly lower the quantity of debris that is generated and that enters the ecosystem (while taking into account health considerations). Plastic debris also can be used as a source of energy (incineration, pyrolysis, and gasification), and their ingredients can be recovered to create useful products and synthetic crude. A circular economic model could address plastic leaks at all life cycle steps. The environmental leakage minimization needs consensus and adaptation of all stakeholders, for instance, discouraging littering, and designing for reuse (Figure 1.10) [110]. Most probably one key to the performance of this model for circular economics is to enhance the value

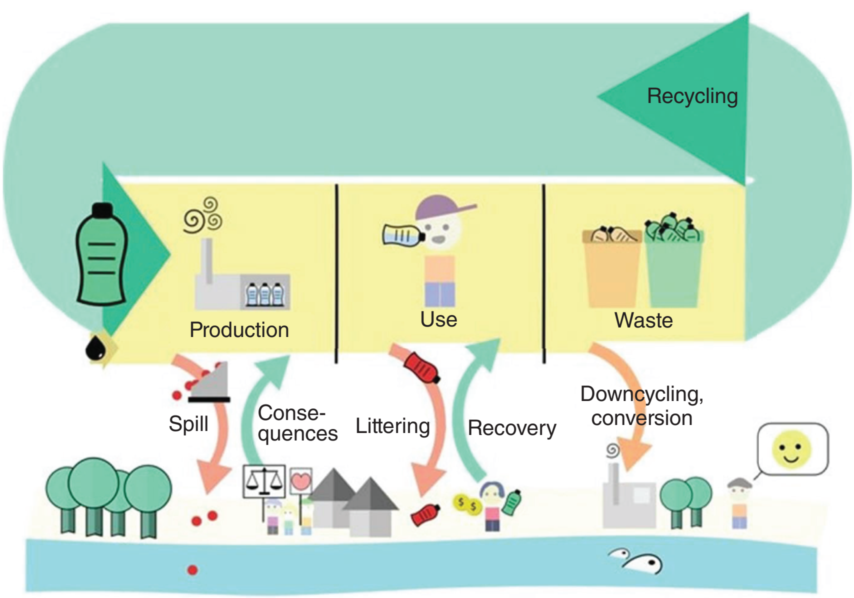

Figure 1.10 Circular economy model for plastic materials. Source: Eriksen et al. [110]/ Springer Nature.

chain of plastic materials at all stages of their functional life. The model also highlights preventive efforts when environmental concerns are taken into account. In addition, prevention is far better for the environment and more economical than some postconsumer cleanup schemes.

1.6.2 Landfills

Plastic debris dumping in landfills, therefore, seems as one of the ultimate approaches for removing almost all plastic waste from the environment, effectively establishing a linear economic model. Landfills are any sites where we discard all used plastic waste prior to burying it under the earth's surface. Many safety precautions should be taken throughout this manual disposal process to prevent further adverse effects, including groundwater pollution and soil deterioration, which can arise from substandard treatment [111]. In order to meet the aforementioned goals, landfill arrangements are designed to give a safer site for the discharge of plastic debris while also protecting aquatic life and airspace. It requires a lot of effort on the part of the community, such as excavating a deep pit or dumping at great depths and then filling this with waste and leaving it to decompose. This procedure is carried out very slowly and may take over a year [112]. Evey inorganic compound is subject to microbial degradation and breakdown in the landfill's processes. When disposed of in landfills, due to their unique biochemical characteristics, different plastic debris may require a long period of time to degrade [113]. As a result, reuse or recycling must be the first option to dispose of all plastic products properly. Landfills are a great source of energy because of the carbon dioxide and methane gas generated by microbial degradation. It helps to maintain sanitary conditions in urban areas and separates wastes into usable and potentially hazardous categories. Furthermore, managing plastic waste in this way is economical. Despite the fact that this approach can be utilized for managing plastic debris, it has significant drawbacks, such as contributing to global warming. It is ecologically damaging and contaminating the water and the soil [114].

1.6.3 Development of Cleanup Technologies

Discharging into the ocean, incineration, and burying in landfills are among the traditional practices for the disposal of plastic garbage, all of which may result in secondary pollution [115]. Therefore, a smart method for dealing with plastic debris is to create and develop the appropriate cleanup approach for plastic-contaminated places. The breakdown of organic polymers into smaller chemicals such as H_2O and CO_2 is a process known as biodegradation [116]. Microorganisms have an intrinsic capability to adapt to many environments and have the ability to degrade different chemical compounds, such as microplastics [117]. Microbes' employment for microplastic degradation will improve biodegradation [115], making it an advantageous and environmentally secure approach to promote natural biodegradability and to

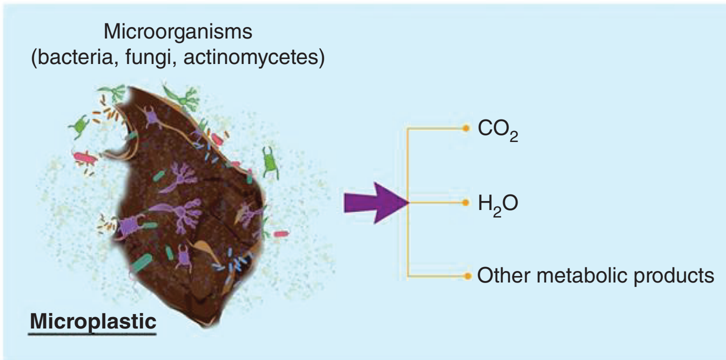

Figure 1.11 Microorganism potential for (micro)plastic degradation.

improve cleanup of the environment without generating unfavorable effects [118]. Scientific studies have noted that different kinds and mixtures of microorganisms, including bacteria, bacterial consortia, fungi, bacterial, and biofilms, can degrade various microplastics (Figure 1.11). However, few applicable microorganisms have been isolated at present, microorganisms' and microplastics' interactions have yet to be clarified, and there stays a lack of knowledge regarding microplastic biodegradation. Hence, it seems crucial to extend acquaintance by specifying how to develop further functional microorganisms and enhance their microplastic-degrading performance, as well as to elevate knowledge of how microbes metabolize and use microplastics [119].

1.7 Conclusion

Plastic products are very useful in today's world due to their unique features. Plastic production has expanded significantly. Therefore, the production of plastic waste has become a serious concern due to insufficient waste management infrastructure in most parts of the world. The chapter demonstrates the adverse consequences of plastics debris on the environment and public health as a result of exposure to harmful ingredients utilized in the production of plastic materials. People utilize plastics without completely realizing how hazardous they are. However, the majority of the literature clearly has demonstrated how hazardous plastics are to both public health and the environment. The nation's government, law-enforcing bodies, and health authorities should do more attempt to promote the manufacturing, usage, and disposal of plastics in a sustainable manner. Moreover, the chapter provided some sustainable and appropriate strategies to ameliorate the adverse impacts of plastic debris. These techniques for addressing plastic debris are not only practical economically, but they can also aid in the eradication of infectious diseases that are spread by contaminated plastic particles.

References

1 Evode, N., Qamar, S.A., Bilal, M. et al. (2021). Plastic waste and its management strategies for environmental sustainability. *Case Stud. Chem. Environ. Eng* 4: 100142.

2 Crawford, C. and Quinn, B. (2017). Plastic production, waste and legislation. In: *Microplastic pollutants*, 39–56. Elsevier Science.

3 Qamar, S.A., Ashiq, M., Jahangeer, M. et al. (2020). Chitosan-based hybrid materials as adsorbents for textile dyes–A review. *Case Stud. Chem. Environ. Eng.* 2: 100021.

4 Asgher, M., Afzal, M., Qamar, S.A., and Khalid, N. (2020). Optimization of biosurfactant production from chemically mutated strain of Bacillus subtilis using waste automobile oil as low-cost substrate. *J. Environ. Sustain.* 3: 405–413.

5 Gilbert, M. (2017). Plastics Materials: Introduction and Historical Development. In: *Brydson's Plastics Materials*, 1–18. Elsevier.

6 White, G. and Reid, G. (2018). Recycled waste plastic for extending and modifying asphalt binders. In: *8th Symposium on Pavement Surface Characteristics*, 2–4.

7 Ronca, S. (2017). Polyethylene. In: *Brydson's Plastics Materials*, 247–278. Elsevier.

8 Bassiouny, R., Ali, M., and Hassan, M. (2016). An idea to enhance the thermal performance of HDPE pipes used for ground-source applications. *Appl. Therm. Eng.* 109: 15–21.

9 J. Thornton, "Environmental impacts of polyvinyl chloride (PVC) building materials," A Healthy Building Network Report, Washington D.C; 2002.

10 Liu, Y., Zhou, C., Li, F. et al. (2020). Stocks and flows of polyvinyl chloride (PVC) in China: 1980-2050. *Resour. Conserv. Recycl.* 154: 104584.

11 Mukhamediev, M.G. and Bekchanov, D.Z. (2019). New anion exchanger based on polyvinyl chloride and its application in industrial water treatment. *Russ. J. Appl. Chem.* 92: 1499–1505.

12 Wang, F., Pan, S., Zhang, P. et al. (2018). Synthesis and application of phosphorus-containing flame retardant pasticizer for polyvinyl chloride. *Fibers Polym.* 19: 1057–1063.

13 Karger-Kocsis, J. (ed.) (2012). *Polypropylene: an AZ Reference, 2*. Springer Science & Business Media.

14 Mullins, M.J., Liu, D., and Sue, H.J. (2018). Mechanical properties of thermosets. In: *Thermosets*, 35–68. Elsevier.

15 Vinayagamoorthy, R. and Rajmohan, T. (2018). Machining and its challenges on bio-fibre reinforced plastics: A critical review. *J. Reinf. Plast. Compos.* 37: 1037–1050.

16 Das, A. and Mahanwar, P. (2020). A brief discussion on advances in polyurethane applications. *Adv. Ind. Eng. Polym. Res* 3: 93–101.

17 Rosato, D.V. and Rosato, M.G. (2012). *Injection Molding Handbook*. Springer Science & Business Media.

18 Romo-Uribe, A. and Lichtenhan, J.D. (2021). Melt extrusion and blow molding parts-per-million POSS interspersed the macromolecular network and simultaneously enhanced thermomechanical and barrier properties of polyolefin films. *Polym. Eng. Sci.* 61: 245–257.

19 Alam, M., Kaur, J., Khaira, H., and Gupta, K. (2015). Extrusion and extruded products: Changes in quality attributes as affected by extrusion process parameters: A review. *Crit. Rev. Food Sci. Nutr.* 56: 445–473.
20 Szostak, E., Duda, P., Duda, A. et al. (2020). Characteristics of plastic waste processing in the modern recycling plant operating in poland. *Energies* 14: 35.
21 Asgher, M., Muzammil, M., Qamar, S.A. et al. (2020). Environmentally friendly color stripping of solar golden yellow R dyed cotton fabric by ligninolytic consortia from Ganoderma lucidum IBL-05. *Case Stud. Chem. Environ. Eng* 2: 100031.
22 Mendible, G., Rulander, J., and Johnston, S. (2017). Comparative study of rapid and conventional tooling for plastics injection molding. *Rapid Prototyp. J.* 23: 344–352.
23 Ageyeva, T., Sibikin, I., and Kovacs, J. (2019). A review of thermoplastic resin transfer molding: Process modeling and simulation. *Polym. J.* 11: 1555.
24 Ogila, K., Shao, M., Yang, W., and Tan, J. (2017). Rotational molding: A review of the models and materials. *EXPRESS Polym. Lett.* 11: 778–798.
25 Landsecker, K. and Bonten, C. (2019). Thermoforming simulation of heat conductive plastic materials using the K-BKZ model. *AIP Conf. Proceed.* 030049.
26 Mitsoulis, E. (2008). Numerical simulation of calendering viscoplastic fluids. *J. Non-Newton. Fluid Mech.* 154: 77–88.
27 Frienkel, S. (2020). Plastics: A Toxic Love Story, Henry Holt, 2011, New York. 6: 22.
28 Rhein, S. and Schmid, M. (2020). Consumers' awareness of plastic packaging: More than just environmental concerns. *Resour. Conserv. Recycl.* 162: 105063.
29 Plastic Europe (2019). *An Analysis of European Plastics Production, Demand and Waste Data*. Brussels, Belgium: Plastics Europe.
30 Plastic Europe (2021). *An analysis of European plastics production, demand and waste data*. Brussels, Belgium: Plastics Europe.
31 Hirai, H., Takada, H., Ogata, Y. et al. (2011). Organic micropollutants in marine plastics debris from the open ocean and remote and urban beaches. *Mar. Pollut. Bull.* 62: 1683–1692.
32 Plastics Europe (2018). *An Analysis of European Plastics Production, Demand and Waste Data*. Brussels, Belgium: Plastics Europe.
33 Shen, M., Huang, W., Chen, M. et al. (2020). (Micro)plastic crisis: Un-ignorable contribution to global greenhouse gas emissions and climate change. *J. Clean. Prod.* 254: 120138.
34 Neufeld, L., Stassen, F., Sheppard, R., and Gilman, T. (2016). The new plastics economy: rethinking the future of plastics. In: *World Economic Forum*.
35 Rochman, C.M., Browne, M.A., Halpern, B.S. et al. (2013). Policy: Classify plastic waste as hazardous. *Nature* 494: 169–171.
36 Shen, L., Haufe, J.I., and Patel, M. (2009). Product overview and market projection of emerging bio-based plastics-PRO-BIP 2009. In: *Report for European Polysaccharide Network of Excellence (EPNOE) and European Bioplastics*, vol. Vol. 243, 1–245.
37 Andrady, A.L. and Neal, M.A. (2009). Applications and Societal Benefits of Plastics. *Philos. Trans. R. Soc. B: Biol. Sci.* 364: 1977–1984.

38 Harris, M.E. and Walker, B. (2010). A novel, simplified scheme for plastics identification: JCE classroom activity 104. *J. Chem. Educ.* 87: 147–149.

39 Laglbauer, B.J.L., Franco-Santos, R.M., Andreu-Cazenave, M. et al. (2014). Macrodebris and microplastics from beaches in Slovenia. *Mar. Pollut. Bull.* 89: 356–366.

40 Jambeck, J.R., Geyer, R., Wilcox, C. et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347: 768–771.

41 Charles, W., Walker, L., and Cord-Ruwisch, R. (2009). Effect of pre-aeration and inoculum on the start-up of batch thermophilic anaerobic digestion of municipal solid waste. *Bioresour. Technol.* 100: 2329–2335.

42 US EPA. (2023). Guide to the facts and figures report about materials, waste and recycling. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/guide-facts-and-figures-report-about.

43 Rivard, C., Moens, L., Roberts, K. et al. (1995). Starch esters as biodegradable plastics: Effects of ester group chain length and degree of substitution on anaerobic biodegradation. *Enzyme Microb. Technol.* 17: 848–852.

44 Lamichhane, G., Acharya, A., Marahatha, R. et al. (2023). Microplastics in environment: global concern, challenges, and controlling measures. *IJEST* 20: 4673–4694.

45 Rochman, C.M., Brookson, C., Bikker, J. et al. (2019). Rethinking microplastics as a diverse contaminant suite. *Environ. Toxicol. Chem.* 38: 703–711.

46 Isobe, A., Uchiyama-Matsumoto, K., Uchida, K., and Tokai, T. (2017). Microplastics in the southern ocean. *Mar. Pollut. Bull.* 114: 623–626.

47 Lehtiniemi, M., Hartikainen, S., Näkki, P. et al. (2018). Size matters more than shape: Ingestion of primary and secondary microplastics by small predators. *Food Webs* 17: e00097.

48 Van Cauwenberghe, L., Devriese, L., Galgani, F. et al. (2015). Microplastics in sediments: A review of techniques, occurrence and effects. *Mar. Environ. Res.* 111: 5–17.

49 Simon, M., Vianello, A., and Vollertsen, J. (2019). Removal of >10 μm microplastic particles from treated wastewater by a disc filter. *Water* 11: 1935.

50 Sun, J., Dai, X., Wang, Q. et al. (2019). Microplastics in wastewater treatment plants: Detection, occurrence and removal. *Water Res.* 152: 21–37.

51 Herbort, A.F., Sturm, M.T., Fiedler, S. et al. (2018). Alkoxy-silyl induced agglomeration: A new approach for the sustainable removal of microplastic from aquatic systems. *J. Polym. Environ.* 26: 4258–4270.

52 Ngo, P.L., Pramanik, B.K., Shah, K., and Roychand, R. (2019). Pathway, classification and removal efficiency of microplastics in wastewater treatment plants. *Environ. Pollut.* 255: 113326.

53 Prata, J.C., da Costa, J.P., Duarte, A.C., and Rocha-Santos, T. (2019). Methods for sampling and detection of microplastics in water and sediment: a critical review. *TrAC - Trends Anal. Chem.* 110: 150–159.

54 Fahrenfeld, N.L., Arbuckle-Keil, G., Naderi Beni, N., and Bartelt-Hunt, S.L. (2019). Source tracking microplastics in the freshwater environment. *TrAC - Trends Anal. Chem.* 112: 248–254.

55 Hüffer, T., Wagner, S., Reemtsma, T., and Hofmann, T. (2019). Sorption of organic substances to tire wear materials: Similarities and differences with other types of microplastic. *TrAC - Trends Anal. Chem.* 113: 392–401.

56 Järlskog, I., Strömvall, A.-M., Magnusson, K. et al. (2020). Occurrence of tire and bitumen wear microplastics on urban streets and in sweepsand and washwater. *Sci. Total Environ.* 729: 138950.

57 Garcés-Ordóñez, O., Castillo-Olaya, V.A., Granados-Briceño, A.F. et al. (2019). Marine litter and microplastic pollution on mangrove soils of the Ciénaga Grande de Santa Marta, Colombian Caribbean. *Mar. Pollut. Bull.* 145: 455–462.

58 Coyle, R., Hardiman, G., and Driscoll, K.O. (2020). Microplastics in the marine environment: A review of their sources, distribution processes, uptake and exchange in ecosystems. *Case Stud. Chem. Environ. Eng* 2: 100010.

59 Cai, Y., Mitrano, D.M., Heuberger, M. et al. (2020). The origin of microplastic fiber in polyester textiles: The textile production process matters. *J. Clean. Prod.* 267: 121970.

60 Crawford, C.B. and Quinn, B. (2017). Microplastics, standardisation and spatial distribution. In: *Microplastic Pollutants*, 101–130. Elsevier.

61 Lefebvre, C., Saraux, C., Heitz, O. et al. (2019). Microplastics FTIR characterisation and distribution in the water column and digestive tracts of small pelagic fish in the Gulf of Lions. *Mar. Pollut. Bull.* 142: 510–519.

62 Zobkov, M., Esiukova, E., Zyubin, A., and Samusev, I. (2019). Microplastic content variation in water column: The observations employing a novel sampling tool in stratified Baltic Sea. *Mar. Pollut. Bull.* 138: 193–205.

63 Yang, L., Zhang, Y., Kang, S. et al. (2021). Microplastics in freshwater sediment: A review on methods, occurrence, and sources. *Sci. Total Environ.* 754: 141948.

64 Chai, B., Wei, Q., She, Y. et al. (2020). Soil microplastic pollution in an e-waste dismantling zone of China. *Waste Manag.* 118: 291–301.

65 Kumar, R. and Sharma, P. (2021). Microplastics pollution pathways to groundwater in India. *Curr. Sci.* 120: 249.

66 Evangeliou, N., Grythe, H., Klimont, Z. et al. (2020). Atmospheric transport is a major pathway of microplastics to remote regions. *Nat. Commun.* 11: 1–11.

67 Chen, G., Fu, Z., Yang, H., and Wang, J. (2020). An overview of analytical methods for detecting microplastics in the atmosphere. *TrAC Trends Anal. Chem.* 130: 115981.

68 Thiele, J., Hudson, M.D., Russell, A.E. et al. (2021). Microplastics in fish and fishmeal: an emerging environmental challenge? *Sci. Rep.* 11: 1–12.

69 Prata, J.C., da Costa, J.P., Lopes, I. et al. (2020). Environmental exposure to microplastics: An overview on possible human health effects. *Sci. Total Environ.* 702: 134455.

70 Rahman, A., Sarkar, A., Yadav, O.P. et al. (2021). Potential human health risks due to environmental exposure to nano-and microplastics and knowledge gaps: a scoping review. *Sci. Total Environ.* 757: 143872.

71 Ageel, H.K., Harrad, S., and Abdallah, M.A.-E. (2022). Occurrence, human exposure, and risk of microplastics in the indoor environment. *Environ Sci Process Impacts* 24: 17–31.

72 Neves, D., Sobral, P., Ferreira, J.L., and Pereira, T. (2015). Ingestion of microplastics by commercial fish off the Portuguese coast. *Mar. Pollut. Bull.* 101: 119–126.
73 Li, J., Green, C., Reynolds, A. et al. (2018). Microplastics in mussels sampled from coastal waters and supermarkets in the United Kingdom. *Environ. Pollut.* 241: 35–44.
74 Afrin, S., Rahman, M.M., Hossain, M.N. et al. (2022). Are there plastic particles in my sugar? A pioneering study on the characterization of microplastics in commercial sugars and risk assessment. *Sci. Total Environ.* 837: 155849.
75 Lee, H.-J., Song, N.-S., Kim, J.-S., and Kim, S.-K. (2021). Variation and uncertainty of microplastics in commercial table salts: critical review and validation. *J. Hazard. Mater.* 402: 123743.
76 Pivokonsky, M., Cermakova, L., Novotna, K. et al. (2018). Occurrence of microplastics in raw and treated drinking water. *Sci. Total Environ.* 643: 1644–1651.
77 Galloway, T.S. (2015). Micro-and nano-plastics and human health. In: *Marine anthropogenic litter*, 343–366. Cham: Springer.
78 Cox, K.D., Covernton, G.A., Davies, H.L. et al. (2019). Human consumption of microplastics. *Environ. Sci. Technol.* 53: 7068–7074.
79 Salim, S.Y., Kaplan, G.G., and Madsen, K.L. (2014). Air pollution effects on the gut microbiota: a link between exposure and inflammatory disease. *Gut Microbes* 5: 215–219.
80 Abbasi, S., Keshavarzi, B., Moore, F. et al. (2019). Distribution and potential health impacts of microplastics and microrubbers in air and street dusts from Asaluyeh County, Iran. *Environ. Pollut.* 244: 153–164.
81 Allen, S., Allen, D., Phoenix, V.R. et al. (2019). Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nat. Geosci.* 12: 339–344.
82 Catarino, A.I., Macchia, V., Sanderson, W.G. et al. (2018). Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal. *Environ. Pollut.* 237: 675–684.
83 Gasperi, J., Wright, S.L., Dris, R. et al. (2018). Microplastics in air: are we breathing it in? *Curr. Opin. Environ. Sci. Health* 1: 1–5.
84 González-Pleiter, M., Edo, C., Aguilera, Á. et al. (2021). Occurrence and transport of microplastics sampled within and above the planetary boundary layer. *Sci. Total Environ.* 761: 143213.
85 Huang, Y., Qing, X., Wang, W. et al. (2020). Mini-review on current studies of airborne microplastics: Analytical methods, occurrence, sources, fate and potential risk to human beings. *TrAC Trends Anal. Chem.* 125: 115821.
86 Prata, J.C. (2018). Airborne microplastics: consequences to human health? *Environ. Pollut.* 234: 115–126.
87 Kelly, F.J. and Fussell, J.C. (2012). Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. *Atmos. Environ.* 60: 504–526.

88 Braeuning, A. (2017). Uptake of microplastics and related health effects: a critical discussion of Deng et al., Scientific Reports 7: 46687. *Arch. Toxicol.* 93 (2019): 219–220.
89 Lu, Y., Zhang, Y., Deng, Y. et al. (2016). Uptake and accumulation of polystyrene microplastics in zebrafish (Danio rerio) and toxic effects in liver. *Environ. Sci. Technol.* 50: 4054–4060.
90 Schirinzi, F., Pérez-Pomeda, I., Sanchís, J. et al. (2017). Cytotoxic effects of commonly used nanomaterials and microplastics on cerebral and epithelial human cells. *Environ. Res.* 159: 579–587.
91 Norris, D.A. and Sinko, P.J. (1997). Effect of size, surface charge, and hydrophobicity on the translocation of polystyrene microspheres through gastrointestinal mucin. *J. Appl. Polym.* 63: 1481–1492.
92 Florence, A., Hillery, A., Hussain, N., and Jani, P. (1995). Factors affecting the oral uptake and translocation of polystyrene nanoparticles: histological and analytical evidence. *J. Drug Target.* 3: 65–70.
93 West-Eberhard, M.J. (2019). Nutrition, the visceral immune system, and the evolutionary origins of pathogenic obesity. *PNAS* 116: 723–731.
94 Brennecke, D., Duarte, B., Paiva, F. et al. (2016). Microplastics as vector for heavy metal contamination from the marine environment. *Estuar. Coast. Shelf Sci.* 178: 189–195.
95 Wang, F., Wong, C.S., Chen, D. et al. (2018). Interaction of toxic chemicals with microplastics: a critical review. *Water Res.* 139: 208–219.
96 Li, J., Zhang, K., and Zhang, H. (2018). Adsorption of antibiotics on microplastics. *Environ. Pollut.* 237: 460–467.
97 Bakir, A., Rowland, S.J., and Thompson, R.C. (2014). Transport of persistent organic pollutants by microplastics in estuarine conditions. *Estuar. Coast. Shelf Sci.* 140: 14–21.
98 Galafassi, S., Sabatino, R., Sathicq, M.B. et al. (2021). Contribution of microplastic particles to the spread of resistances and pathogenic bacteria in treated wastewaters. *Water Res.* 201: 117368.
99 Barboza, L.G.A., Vieira, L.R., Branco, V. et al. (2018). Microplastics cause neurotoxicity, oxidative damage and energy-related changes and interact with the bioaccumulation of mercury in the European seabass, Dicentrarchus labrax (Linnaeus, 1758). *Aquat. Toxicol.* 195: 49–57.
100 Hamilton, L.A., Feit, S., Kelso, M. et al. (2019). Plastic & Climate. The Hidden Costs of a Plastic Planet. In: *Center for International Environmental Law (CIEL)* (ed. A.K.a.C. Muffett), 1–108.
101 Royer, S.-J., Ferrón, S., Wilson, S.T., and Karl, D.M. (2018). Production of methane and ethylene from plastic in the environment. *PloS One* 13: e0200574.
102 Masnadi, M.S., El-Houjeiri, H.M., Schunack, D. et al. (2018). Global carbon intensity of crude oil production. *Science* 361: 851–853.
103 Posen, D., Jaramillo, P., Landis, A.E., and Griffin, W.M. (2017). Greenhouse gas mitigation for US plastics production: energy first, feedstocks later. *Environ. Res. Lett.* 12: 034024.

104 Geyer, R., Jambeck, J.R., and Law, K.L. (2017). Production, use, and fate of all plastics ever made. *Sci. Adv.* 3: e1700782.
105 Brierley, S. (2017). Plankton. *Curr. Biol.* 27: R478–R483.
106 Gander, M.J. (2022). Climate change and the water quality threats posed by the emerging contaminants perand polyfluoroalkyl substances (PFAS) and microplastics. *Water Int.* 1–23.
107 Anbumani, S. and Kakkar, P. (2018). Ecotoxicological effects of microplastics on biota: a review. *ESPR* 25: 14373–14396.
108 Cole, M., Lindeque, P.K., Fileman, E. et al. (2016). Microplastics alter the properties and sinking rates of zooplankton faecal pellets. *Environ. Sci. Technol.* 50: 3239–3246.
109 Wieczorek, M., Croot, P.L., Lombard, F. et al. (2019). Microplastic ingestion by gelatinous zooplankton may lower efficiency of the biological pump. *Environ. Sci. Technol.* 53: 5387–5395.
110 Eriksen, M., Thiel, M., Prindiville, M., and Kiessling, T. (2018). Microplastics: What are the Solutions? In: *Freshwater microplastics: emerging environmental contaminants?* 283. Springer Nature.
111 Zheng, Y., Yanful, E.K., and Bassi, A.S. (2005). A review of plastic waste biodegradation. *Crit. Rev. Biotechnol.* 25: 243–250.
112 Liang, Y., Tan, Q., Song, Q., and Li, J. (2021). An analysis of the plastic waste trade and management in Asia. *Waste Manag.* 119: 242–253.
113 Zhou, C., Fang, W., Xu, W. et al. (2014). Characteristics and the recovery potential of plastic wastes obtained from landfill mining. *J. Clean. Prod.* 80: 80–86.
114 Kedzierski, M., Frère, D., Le Maguer, G., and Bruzaud, S. (2020). Why is there plastic packaging in the natural environment? Understanding the roots of our individual plastic waste management behaviours. *Sci. Total Environ.* 740: 139985.
115 Restrepo-Flórez, J.-M., Bassi, A., and Thompson, M.R. (2014). Microbial degradation and deterioration of polyethylene–A review. *Int. Biodeter. Biodegr.* 88: 83–90.
116 Lucas, N., Bienaime, C., Belloy, C. et al. (2008). Polymer biodegradation: Mechanisms and estimation techniques–A review. *Chemosphere* 73: 429–442.
117 Brooks, A.N., Turkarslan, S., Beer, K.D. et al. (2011). Adaptation of cells to new environments. *WIREs Systems Biol. Med.* 3: 544–561.
118 Shah, F., Hasan, A.H., and Ahmed, S. (2008). Biological degradation of plastics: a comprehensive review. *Biotechnol. Adv.* 26: 246–265.
119 Alshehrei, F. (2017). Biodegradation of synthetic and natural plastic by microorganisms. *Appl. Environ. Microbiol.* 5: 8–19.