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Kalim Deshmukh and Jyotishkumar Parameswaranpillai

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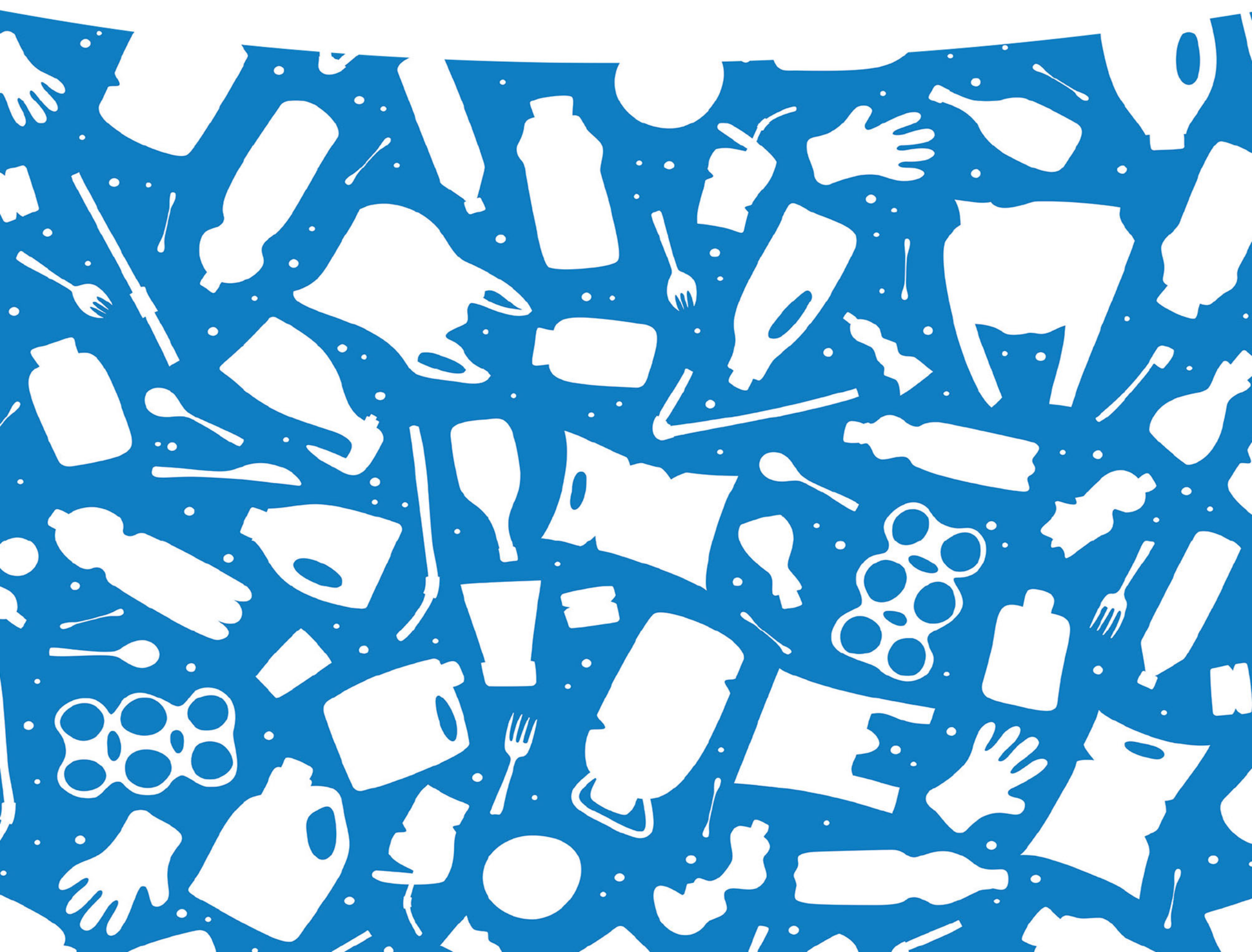
Methods and Applications



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Preface

Nowadays, plastics have become an important product worldwide because of their manifold applications in commercial and industrial sectors comprising electronics, construction, automotive, healthcare, agriculture, and packaging owing to their remarkable physical and chemical properties. In recent years, the demand for plastics has grown significantly owing to their number of advantages, which include resistance to corrosion, sustainability, ease of use, production simplicity, and low cost. Based on their functionality, plastics can be easily modified to desired shape and color, and the large-scale production of plastics has increased drastically because of high community demand and worldwide industrial revolution. However, the excessive utilization of plastics and their nondegradable nature accompanies several environmental and health problems caused by poor waste management after utilization and negligence during the production of plastics. Municipal solid waste contains about 10% to 12% of residual plastic, which post-combustion releases the gases into the environment, thereby increasing air pollution and causing greenhouse effects. In general, the poor disposal and ill-treatment of plastic waste affect animals, public health, and environmental pollution. The implications of plastic waste management on health and the environment are increasing day by day, particularly in developing countries, and therefore regulatory affairs dealing with environmental clearance and safety are employed. Thus, governments, municipal corporations, civil society, and territorial governance constitute various measures and legislative norms concerning environmental protection that can guide citizens to dispose of waste plastic after its use. Some examples of waste management strategies are recycling, incineration, bioremediation, and landfilling. These strategies are developed to ensure environmental safety, cleanliness, and efficient disposal of plastic waste. Thus, constituting accessible and efficient waste management policies is a cornerstone of sustainable development and environmental sustainability.

This edited book provides a comprehensive discussion on cutting-edge research and breakthrough advancements in plastic waste management. The book offers a complete guide to the best plastic waste management practices through recycling, incineration, landfilling, and other processes. The book provides an in-depth understanding of plastic waste management techniques and approaches that are useful in maintaining environmental sustainability. In particular, the book emphasizes different recycling techniques (chemical, mechanical, and biological) for plastic waste with an emphasis on life cycle analysis and different processes being implemented for developing efficient waste collection systems. The environmental and health implications of plastic waste and the applications of plastic waste management including energy generation, biochemical production, construction, and food packaging industry are also discussed in this book. The book comprises 15 chapters covering various topics. Chapter 1 introduces plastic waste management and discusses processing methods and environmental and health implications. Chapter 2 discusses different management strategies for plastic waste that can serve as a roadmap toward a circular economy and environmental sustainability. Chapter 3 provides a discussion on the implementation of the analytical hierarchy process for developing a better waste collection system. Chapter 4 discusses the processing and recycling strategies of plastic waste used in sustainable material management. Chapter 5 provides a critical review of the chemical recycling methods of plastic waste for sustainable development. Chapter 6 discusses the challenges and future perspectives of plastic waste management and disposal in developing countries. Chapter 7 discusses the challenges and strategies of plastic waste management during and after the COVID-19 pandemic. Chapter 8 describes the mechanisms, perspectives, and challenges of biodegradation of plastic waste. Chapter 9 provides a discussion of the global perspectives on the conversion of plastic waste into value-added materials. Chapter 10 gives a comprehensive review of the opportunities and technological challenges of plastic waste management in the construction industry. Chapter 11 discusses perspectives on material flow analysis in plastic waste management. Chapter 12 gives information about the life cycle assessment used in mitigating plastic waste management. Chapter 13 provides a critical discussion on the global perspective of the technologies and recycling strategies of municipal solid waste. Chapter 14 discusses the ecotoxicity, ecological implications, and management of marine plastic debris. Chapter 15 provides a discussion on societal awareness, regulatory framework, and technical guidelines for the management of plastic waste.

Overall, this book will be a valuable source for all working in the fields of environmental science, environmental engineering, plastic engineering, and waste management. We highly appreciate the excellent cooperation and valuable chapter contributions from various authors. Our sincere appreciation also goes to the staff at Wiley-VCH, especially Felix Bloeck and Dorairaj Vijayan, Aswini Murugadass, Chandra Mohan Vishali and Anjana Sridhar for their dedicated support during the publication of this book. Finally, we would like to thank Wiley-VCH for publishing this book on time.

Dr. Kalim Deshmukh
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1

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

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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

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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

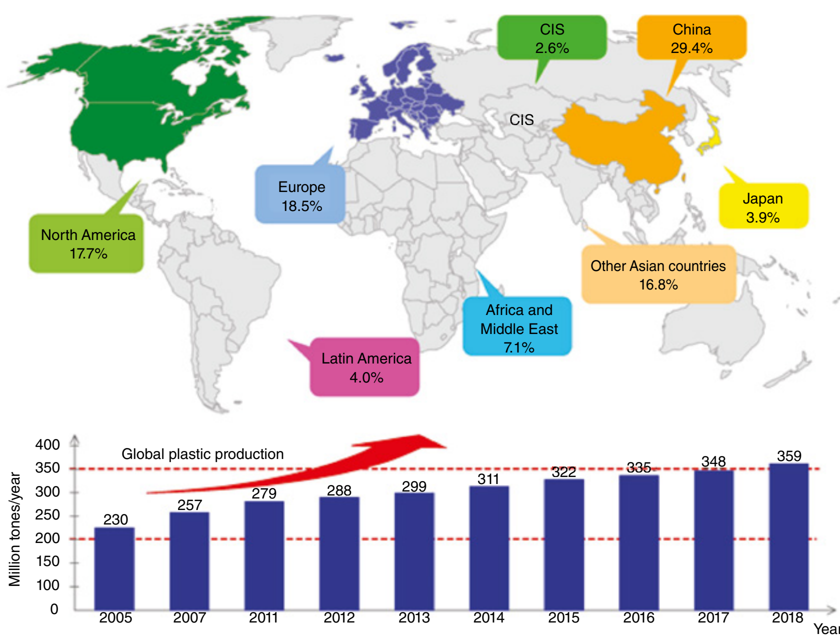

Figure 1.1 Global plastics production. Source: Shen et al. [33] /Elsevier/CCBY 4.0/ Public domain.

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

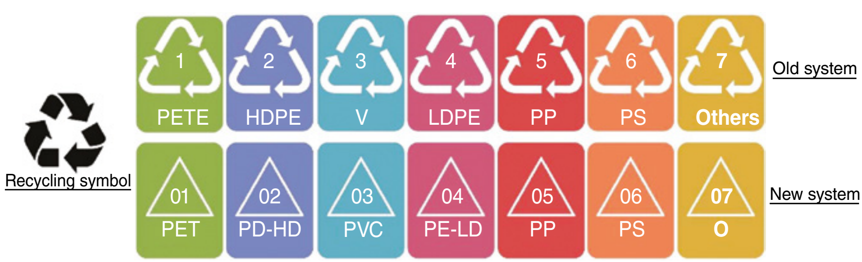

Figure 1.2 Comparison of the familiar SPI system and the new ASTM system for plastic identification. Source: Crawford and Quinn [2]. Copyright 2017. Reproduced with permission from Elsevier.

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,

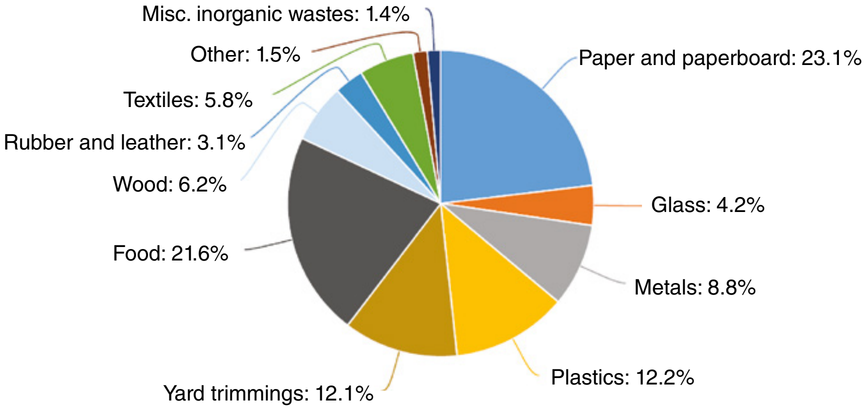

Figure 1.4 MSW components [42]. *Source:* https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/guide-facts-and-figures-report-about.

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

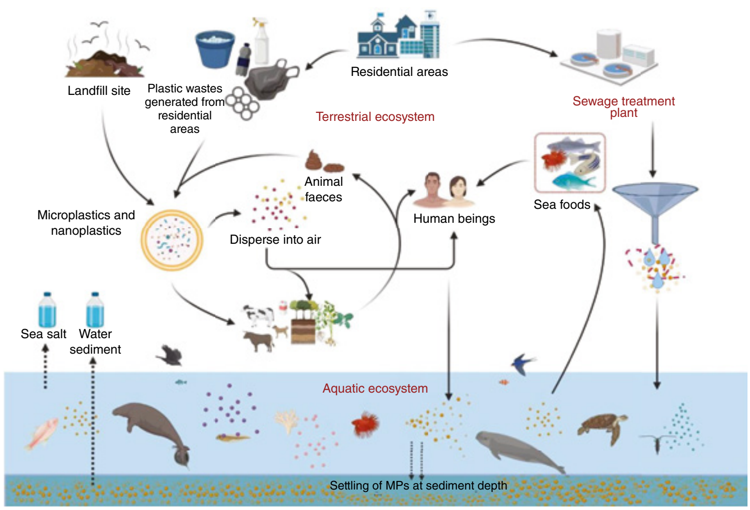

Figure 1.5 Fate and detrimental effects of plastic products on the ecosystem. Source: Lamichhane et al. [44]. Copyright 2023. Adapter from Springer Nature.