Post-Consumer Plastic Waste Management

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Challenges associated with plastic waste management range from littering to high collection costs to low recycling rates. Effective collection of plastics is obviously an important step in the management of plastic waste and has an impact on recycling rates.

types of polymers plastic packaging plastic waste management recyclables

1. Introduction

Polyolefins (POs), also known as olefins or alkenes, are polymers made from compounds with at least one carbon–carbon double bond. Polymers produced from materials such as ethylene, 1-butene, propylene, and other α-olefins monomers are usually the main components of POs. The most commonly used POs are polyethylene (PE) and polypropylene (PP). The PO family of polymers includes high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), ultra-high molecular weight polyethylene (UHMWPEPP), and other α-olefins and combinations of these polymers. Not only are consumer products generated from plastic polymers, but they are also used in numerous applications to produce synthetic fibers, foams, coatings, adhesives, and sealants. The term post-consumer plastic waste is related to various products (e.g., plastic packaging, used electronic equipment, old window frames, etc.), which are discarded by the end user after they have served their intended purpose and can no longer be used. Because of the short lifespan of many plastic materials and products, plastic waste is produced in huge quantities. Approximately 40% of plastic products are estimated to have a lifespan of less than one month. The active lifespan of some polymers is only 1 to 2 years (e.g., filters), while in the case of other products, a lifespan can be 10 or more years (e.g., automotive parts). Different types of plastics tend to have different life expectancies, uses, and environments. There are two distinct approaches when considering plastic components: the first is that some products consist of only one component (e.g., a bottle cap) and the second is that they consist of a system of more than one component (e.g., a sealed bottle (cap + bottle) or an assembled vehicle). In the latter case, plastic materials are more difficult to recycle [1]. Of the post-consumer plastic waste collected in the EU27 + 3 in 2020, the largest share came from packaging applications (61%), followed by building and construction applications (6%) and electrical and electronic applications (6%). Optimization of waste management processes is crucial to increase resource efficiency and thus the recycling fraction. The 2020 data from the EU27 + 3 shows that the recycling rate has increased to nearly 35%, and 65% of post-consumer plastic waste is still sent to energy recovery or landfill. In Europe, plastics are mainly used for packaging (33.5%), followed by applications in construction (23.9%), the automotive industry (9.7%), electrical uses and electronics (7.5%), and other sectors (16.1%) [2]. Plastic packaging protects food and goods from spoilage and/or contamination, thus conserving resources. Plastic packaging has a lighter weight, which in comparison to other materials, for example, saves fuel and reduces emissions during transport.

China, which is considered the world's largest plastic producer and consumer, generated about 26.74 million tons of plastic waste in 2019. This country has taken ambitious challenges to address the plastic waste problem. Sun et al. [3] projected the development of plastic waste generation and the cost of its management in China (2020–2035) and proposed three different scenarios (business as usual—BAU, current policy scenario—CPS, and target policy scenario—TPS). Tahy found that in 2035, the production of plastic waste will be 34.82 million tons according to BAU, 13.49 million tons according to the CPS, and 2.63 million tons according to the TPS. Environmental and economic benefits increase with the rigor of the plastic waste management policy, as a net income of USD 3.01 billion will be generated under the TPS scenario, in contrast to net costs of USD 2.61 billion under the BAU scenario and USD 120 million under the CPS scenario. Other large producers of plastic waste in the world are countries in Southeast Asia (e.g., Indonesia, the Philippines, Vietnam, Thailand, and Malaysia). The annual generation by these countries together is 8.9 million tons of plastic waste. At the per capita level, Japan ranks second globally [4]. South Korea's plastic waste generation in 2017 was compared with three developed countries (the U.S., Japan, and Germany). In the U.S., plastic waste generation in 2017 was 35.4 MT, whereas Japan and Germany produced around 9.03 MT and 6.2 MT, respectively [5]. Among others, the main problems of post-consumer plastic waste management in South Korea are (i) the design and production of hard-to-recycle plastics, (ii) over-packaging, and (iii) the use of disposable products. Moreover, the system is highly dependent on private companies which serve collection, transportation, recycling, and final disposal. In addition, there is a huge difficulty to maintain the profitability of the recycling industry. This is because multilayer plastic packaging has a short life span, a large production volume, and different compositions, which poses a challenge for waste management. More than one layer of different materials constitutes the structure of multi-material (multilayer structures). Depending on the requirements, they can be in the form of (i) flexible packaging (e.g., most popular bags, shrink films, pouches, and other flexible issues) or (ii) rigid packaging (e.g., trays, containers, cups). This type of packaging, characterized by a relatively low price and a relatively short life, is widely used in the FMCG (fast-moving consumer goods) industry in items such as beverages, food, and toiletries. One of the categories of multi-layer post-consumer plastic waste includes materials used for express deliveries. Joerss et al. [6] forecasted that delivery volumes in Germany and the U.S. could double in the next decade (until 2025), reaching roughly 5 billion and 25 billion packages per year, respectively. Duan et al. [7] showed that corrugated boxes were used in 46.5% of these shipments, followed by plastic bags (30.4%), mixed packages (corrugated boxes wrapped with plastic bags, 10.1%), envelopes (5.0%), polystyrene foam boxes (4.2%), and fabric bags (2.8%). The authors estimated that in 2017, because of the 40 billion parcels or packages that were delivered in China, 7.8 million metric tons of packaging waste were generated. This is equivalent to about 4.1% of the total municipal waste generated in China in 2017, or the total municipal waste generated in the Netherlands, Malaysia, and Algeria in 2016. The wide variability of plastic polymers and post-use impurities hinder or complicate closed-loop recycling. Mixed plastics from municipal solid waste, particularly household waste, are a highly heterogeneous waste stream because they contain a variety of different immiscible polymers, product types, and designs.

The implementation of waste collection systems (WCS) around the world is particularly important for public health reasons and ultimately to recover materials for reuse, recycling, or recovery. In order to drive the demand side for recycled plastic polymers, three factors should be considered: price, quality, and quantity. Eriksen et al. [8] concluded that the most efficient plastic recovery system (the separation of rigid and soft plastics at the source, high efficiency in source separation) could potentially allow the closing of 42% of the material loop. It is essential to reduce the presence of impurities in the recovered fractions. Moreover, closing the loops for high-quality plastic should be more important than plastic in general. Resource recovery alternatives to landfilling plastic waste are (i) mechanical recycling (also known as primary recycling substituting for virgin materials and secondary recycling), (ii) chemical recovery (with the second term of tertiary recycling), and (iii) energy recovery (being quaternary recycling). Only for some plastic types and fractions (e.g., for car bumpers or PET (polyethylene terephthalate) bottles) is it possible to substitute virgin polymers with those from primary recycling [9].

2. Characteristics of Post-Consumer Plastic Waste

The plastic types that can be found in post-consumer waste (PPW) include PET, e.g., soda or water bottles; PP, e.g., meal trays for microwaves, those for ice-cream, and bottles for kitchen and bathroom cleaning agents; PE, e.g., bottles for milk or most shampoo; film, e.g., carrier bags and packaging foils; a mix of hard plastics, e.g., PS (polystyrene) and PVC (polyvinyl chloride); and non-bottle PET and falsely sorted PE, PP, and PET. With the exception of polyvinyl chloride (PVC), the largest share of the other five polymers (HDPE, LDPE, PP, and PET) is used in packaging applications; thus, these will also dominate the composition of PPW. For example, Roosen et al. [10] indicated that it is possible to analyze the type of polymer, its elemental composition (i.e., most common in C, H, N, S, O, but also metals and halogens) of the separable components of different plastic packaging (e.g., for a PET bottle, a PE cap, a PP label). On the contrary, the PET bottle itself can be identified. Because PPW consists of numerous immiscible types of polymers, with the addition of product designs (e.g., color, polymer separability), considerable physical losses can be found during the sorting process. Moreover, low-quality recycled plastic can be produced. Danish source-separated rigid plastic waste was described in detail by Eriksen and Astrup [11]. They presented not only the type of product but also the details regarding the type of polymer (also design and separability) in the main product component and its color. PET, PE, and PP materials, used for the production of food and non-food packaging, made up >90% of the source-separated plastic. It was found in 10–11% of black plastic, and about 44% consisted of multiple polymers, one-third of which were inseparable. Bonifazi et al. [12] pointed out that a separate collection system (often based on a deposit system) in Denmark exists for PET bottles. Thus, it is considered that PET bottles belong exclusively to this waste stream. The predominant polymers in PPW, in order of dominance, are PET (from thermoformed food trays), PP (trays), LDPE (foils), PVC (flexible packaging), acrylonitrile butadiene styrene (ABS), and PS (yogurt cups, food trays). An example of the typical composition of this waste was the following: 26.80% PET, 24.90% PVC, 3.10% rubber, 9.60% PS/ABS, 5.40% PA/PBT (polyamide/polybutylene terephthalate) and other polymers, 11.90% PE/PP, 5.50% PE/PP, 4.20% paper/fiber, and 8.60% metal/inserts. Multilayer products are an important part of PPW materials. These include PET/PE, PET/PE/EVOH (ethylene vinyl alcohol (EVOH)), and PA/PE. Typically, the initial sorting of PPW packaging waste (PCPPW) is performed by the flotation of polyolefins (PP and phenol formaldehyde (PF)) in water.

3. Plastic Functional Additives

Materials such as flame retardants, plasticizers, acid scavengers, antioxidants, thermal, light and heat stabilizers, antistatic agents, pigments, lubricants, and slip compounds are the most commonly used additives in different types of polymeric packaging. Additives play important roles because they not only deliver but also enhance the final functional properties of a plastic product [13]. The following categories of additives can be distinguished: (i) functional additives (e.g., stabilizers, antistatic agents, flame retardants, plasticizers, lubricants, slip agents, curing agents, foaming agents, biocides, etc.), (ii) colorants (e.g., pigments, soluble azo-colorants, etc.), (iii) fillers (e.g., mica, talc, kaolin, clay, calcium carbonate, barium sulfate), and (iv) reinforcements (e.g., glass fibers, carbon fibers). In almost all cases, plastic polymers and additives are not chemically bound to each other. Only reactive organic additives, e.g., some flame retardants, are polymerized with the plastic molecules and become part of the polymer chain. In plastic manufacturing, the substances used as monomers, intermixed polyolefin diates, or catalysts, are not considered to be additives. Duan et al. [7] highlighted a problem arising from the use of packaging in the express delivery industry. This packaging is mainly made of recycled plastic films from agriculture and contains harmful chemical residues from the use of pesticides. Exposure to harmful chemical residues in plastic packaging materials can lead to serious health and environmental problems in the future.

4. Collection System for Post-Consumer Plastic Waste

Two ways of post-consumer plastic collection can be distinguished: source separation or post-separation. In source separation, households should separate plastics from other waste before their collection, while in post-separation, waste should be separated after collection, mostly at treatment and recovery centers. Luijsterburg and Goossens [14] indicated that post-consumer plastic waste can be collected via different schemes. In the Netherlands, this waste is collected in practice either through the so-called separate collection or the mixed collection with municipal solid refuse waste (MSRW). Subsequently, mechanical recycling is usually carried out. In source separation, consumers separate plastic packaging waste, which is then collected via curbside services or drop-off containers. Pires et al. [15] analyzed curbside collection performed simultaneously with a bring collection, and they termed this system a mixed collection system. This system displays better economic indicators than other collection systems. However, the authors identified a lack of optimization of curbside collection in the system. Martinho et al. [16] found that this mixed collection system resulted in higher material separation and recycling rates and lower contamination rates than an exclusively drop-off-only system due to the curbside component in the former system. In the mixed system, the operational efficiency of the curbside collection is lower than that of the drop-off collection and in the exclusive drop-off system. Cimpan et al. [17] have shown that post-separation is technically simple, requires less infrastructure for collection, and is more convenient for citizens (fewer containers). Comparisons between waste collection systems are not easy, partly because of the diversity of indicators used in the literature to measure performance. To determine the degree of efficiency of four MSW collection systems, Gallardo et al. [18] used the following indicators: the fractioning rate, the separation rate, and the quality in container rate. In a five-fraction collection system (the mixed and organic waste in curbside bins, and paper/cardboard, glass, and light packaging, which are picked up from drop-off points), the selected waste was kept as clean as possible from the time it was separated in households until it arrived at recycling facilities. Three main collection schemes implemented in England were investigated by Hahladakis et al. [19]. The authors examined (i) curbside collection, (ii) household waste recycling centers (HWRCs) (also known as “civic amenity sites”), and (iii) bring sites/banks (BSs). In curbside collection, packaging plastics recovery was higher than that in the HWRCs and BSs, with respective percentages by weight (wt%) of 90%, 9%, and 1%. An alternate weekly collection of mixed plastic recyclables in wheeled garbage cans resulted in a higher yield in curbside collection. Only a small percentage (16%) of the mixed plastic bottles and mixed plastics were sent to reprocessors. Chruszcz and Reeve [20] estimated that in 2015/16, half of curbside collected plastics (50.8%) were bottles, followed by rigid plastic packaging pots, tubs and trays (27.2%), and film (15.7%). For example, toys or pipes, which are considered non-packaging plastics, account for 4.4% of total plastics. The identification of about 1.9% of the collected materials was not possible. Three types of rigid plastic polymers were collected for recycling: PET, HDPE, and PP. Among them, PET was the most prominent, comprising 40.3% of the total composition, followed by HDPE (21.6%) and PP (10.2%). Only small amounts of plastics were made up of other types of polymers, such as PVC (0.1%), expanded polystyrene (EPS) (0.4%), and PS (1.5%), and black plastics comprised 3.7%. Overall, the polymers that are most commonly recycled (HDPE, PET, and PP) and for which there is, therefore, more of an end market, accounted for 72.0% of the plastics collected for recycling, while the remaining material consisted mainly of plastic films (15.7%), which in some cases can be recycled. Dijkgraaf and Gradus [21] reported that national municipalities (in the Netherlands) may choose how potentially recyclable materials, such as paper, glass, textiles, and plastics, are collected. If there is a problem with their collection at the curbside, citizens can deliver them to collection points. These points can be located at central locations nearby, for example in shopping centers and schools. In all Dutch municipalities, unsorted waste was collected at the curbside. According to Brouwer et al. [22], the Netherlands originally had not only a collection system for various plastic packaging, which mainly included the materials from PE and PP (i.e., bottles and trays, as well as plastic films), but also a deposit–refund system for large PET bottles for water and soda drinks. In 2015, beverage cartons and metal packaging started being collected in a separate collection system. Later, in July 2021, small PET bottles were enclosed in a deposit–refund system. Brouwer et al. [23] indicated that to increase the recycling rate, household plastic packaging should be expanded in the curbside collection system. Combined co-collection systems for packaging materials are commonly used; however, many variations exist. Civancik-Uslu et al. [24] outlined the Belgian PPW collection system. Belgium has a curbside collection system for some waste fractions with the so-called PMD (plastic packaging, metal packaging, drink cartons) system, which handles plastic bottles and flasks that are collected together with metal packaging and drink cartons. Currently, in Belgium, a transition phase is observed, in which an enhanced P + MD collection system is being introduced. Plastic packaging fractions, such as films, trays, tubes, etc., in a single bag were included, and from 2021 onwards, fourteen fractions, including eleven plastic fractions (containing a residual fraction, and, e.g., PP rigid, PS rigid, mixed polyolefins rigid, PE films, and other films), two metal fractions, and drink cartons, should be sorted. A significant reduction in plastic waste that is incinerated as a part of the residual household waste was identified to be a huge problem in neighboring countries where similar collection systems existed. For instance, a deposit–refund system for single-use beverage packaging was implemented in 2003 in Germany. In this country, two collection systems were applied: one for mixed residual waste and the other for a separately collected waste (the so-called dual system), where packaging and non-packaging consisting of plastic, paper, metals, and composite materials are disposed of for commingled collection. Picuno et al. [25] estimated that the separate collection efficiency is 74.8% ± 2.9%, which considers all separate collection systems (i.e., the deposit system for PET bottles and the dual system). The authors indicated that, sometimes, refill/deposit systems have been considered barriers to cross-border trade. Specifically, for the separative collection of PPW, three collection systems are operating: (i) PET bottles (deposit system), (ii) mixed residual waste, and (iii) a separate collection system (through the dual system). In the latter, system packaging and non-packaging wastes (plastic, paper, metals, and composite materials) are disposed of for commingled collection and transported to the sorting installations. The recovery of mono-materials from refill/deposit systems commonly used for the collection of beverage bottles can be applied. PET bottles can be recycled into their previous original application (closed-loop recycling) or recycled for other uses (e.g., polyester fibers for textiles). Very high return rates (90%) may be achieved with the use of PET deposit programs. This activity also ensures very low levels of contamination of post-consumer PET and higher market values. Mian et al. [26] compared the Chinese municipal solid waste management system with that of other developed and developing countries. The authors found that there are some limiting factors in China's MSW management system, the most important of which is the weak waste collection system. Source separation is one of the key steps in MSWM, with an important effect on overall waste management. Chinese municipal waste management authorities should establish and implement a separate waste collection system, separate bins for disposing of waste, and encourage people to put their waste in the proper, separate bin, as is practiced in other developed countries. Door-to-door waste collection from large buildings requires the provision of various free bags for recyclable, non-recyclable, and organic food waste, and it needs to collect these wastes separately. To improve MSW management by developing a comprehensive waste separation, collection, transportation, and recycling system, Ningbo Municipality (China) was financially supported by the World Bank (2013–2020). Moreover, it was emphasized that raising public awareness and participation in household waste separation at the source can be key factors for this improvement. The project helped raise the rate of waste recycling (from 0 to 17.54%) and increase the number of materials recycled to 71,600 tons a year by 2020 in eight urban districts. In total, 905,000 households and all institutional waste generators started to participate in waste separation. An incentive program based on a QR code-enabled waste tracking system that rewards communities that perform well in waste separation was one of the successful innovations. The other was a 'Give a Hand' recycling system comprising reverse vending machine units for dry recyclables. When residents put their presorted dry waste into the vending machines, they received a set-price payment in return.

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