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Review

Post-Consumer Plastic Waste Management: From Collection and Sortation to Mechanical Recycling

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Abstract: 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. For this reason, several countries have transformed their collection systems in recent decades. Collecting more plastic packaging comes at a cost, as the feedstock for the sorting process becomes more complex and leads to cross-contamination within the sorted fractions. Therefore, a balance must be obtained between some elements, such as the design of packaging, collection and recycling rates, and finally, the quality of fractions that have been sorted. Further investment to improve pretreatment, sorting, and recycling technologies and simpler recyclable packaging designs are, therefore, key to further increasing plastic recycling rates. It is essential to possess more data, especially on the type of containers and plastics, and examine how often unsorted waste is collected. The automated waste collection monitoring system is a step forward in automating manual waste collection and sorting. Multi-sensory artificial intelligence (AI) for sorting plastic waste and the blockchain sorting platform for the circular economy of plastic waste are forward-looking activities that will increase the efficiency of recycling plastic waste. This review focuses on the development of collection systems and sorting processes for post-consumer plastic recycling. The focus is on best practices and the best available technology. Separate collection systems for recyclable plastics are presented and discussed along with their respective technical collection and sorting solutions, taking into consideration that progress in separation and sorting systems are implicitly linked to approaches to waste collection.

Keywords: types of polymers; plastic packaging; plastic waste management; recyclables; automatization; collection systems; sorting solutions; advanced processes

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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]. This review discusses, in detail, the problems of plastic waste management outlined above. It presents the functioning of collection systems, the sorting of plastic waste, and the principles of mechanical recycling as one of the parts of the life cycle of plastic products in a closed cycle. The key factors determining the achievement of the goals of a circular economy are the development of technology and the use of technologies supporting the efficiency of collecting and sorting plastic waste.

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.

5. Advanced Technology for Automatic Quality Monitoring of the Selective Collection of Plastic Waste

Automatic waste collection monitoring systems can facilitate the automation of manual collection and source-sorting of wastes. For example, radio-frequency identification (RFID) technology has shown considerable promise to help decrease packaging waste and improve recycling. Abdoli [27] pointed out that some European households use RFID-enabled garbage collection services that enable monitoring of the weight of on-site storage bins during curbside collection. Waste collection vehicles are equipped with a scale to weigh the waste bin, and the household is identified by an RFID tag on the bin. An RFID antenna and reader on the vehicle read the tag on the waste container when it is placed on the vehicle's scale. Hannan et al. [28] presented an advanced image processing approach integrated with communication technologies and a camera for monitoring the level of waste in bins. Every trash bin in the bin-level monitoring system has an RFID tag mounted on it. The truck that collects waste from the trash bins is equipped with a black box consisting of an RFID reader, a camera, and a GSM module. RFID can also be used to create incentives for customers. For example, a smart recycling bin could count the number of items put in it and reward the consumer depending on the amount of collected waste. The weakness of RFID-based systems is that they do not provide real-time monitoring of the fill level of containers. Litter bins are only monitored when the truck is within range of the RFID tags. RFID tags are used to uniquely identify containers but do not provide any data on filled container levels, and additional infrastructure is required to monitor container fill levels. The Internet of Things (IoT) and wireless sensor networks (WSNs) are being used to overcome the problems of

RFID technology. Survey et al. [29] have been testing a WSN, which is a network of a large number of wireless sensors. They are installed "ad hoc" to monitor the physical or environmental parameters of a system. The architecture consists mainly of a central monitoring station, a base station, and clusters that include several trash bins equipped with sensor nodes. All these sensor nodes are connected to the coordination nodes of the different clusters, which in turn are connected to the base station. It acts as the processing unit of the WSN. In addition, the base station exchanges data with the Internet to enable remote monitoring. To accelerate the practical adoption of IoT systems, low-power sensors, cloud computing, long-range connectivity, and machine learning are used. A network of web-centric smart devices using embedded electronic devices, such as communication hardware and sensors, to collect, send, and process data from their environment is the main part of the IoT environment. Ramson et al. [30] presented the development and validation of a low-cost, energy-autonomous, intelligently networked IoT-based waste management system (IoT-SWM). The architecture comprises four sections, namely the IoT end devices, gateways or base stations, cloud servers, and end users. The other features of the proposed system are protection against battery overcharging and overdischarging, battery condition indicators, and smart graphical user interfaces to monitor bin levels and locate trash bins. To reduce infrastructure requirements, the smart connect Wi-Fi modules enable trash bins to connect with the existing Wi-Fi networks.

6. Technical Approaches in Sorting for Recycling Material

There are two very different approaches to the recovery of recyclables: separation at the source (in individual households) and separate collection systems, and recovery in centralized facilities that receive a larger waste stream by mechanical processing and sorting of mixed residual waste. There are three collection/sorting configurations for recycling material. The first is mixed municipal waste sorting, which primarily involves recycling metals, plastics, and glass, along with the production of a large amount of refuse-derived fuel. The second configuration is termed mixed dry recyclables, i.e., the sorting of metal, plastic, glass, and paper for use or further sorting. The third is referred to as source-separated recyclables and entails fine sorting of individual material fractions and different sorting technologies, producing different quantities and qualities of source material for recycling. Centralized sorting and separation systems in the form of material recovery facilities (MRFs), packaging sorting facilities, and mechanical–biological treatment (MBT) plants play essential roles in waste management and recycling systems. Cimpan et al. [16,17] evaluated the centralized sorting of recyclables commonly found in household wastes. The technologies developed for sorting mixed recyclables from separate collections have also been used to successfully upgrade residual waste recycling facilities. Recyclable materials, plastics, and metals are recovered from residual waste, complementary to source separation. The centralized sorting of residual waste is proving particularly relevant in areas where source separation is difficult and could be used either to complement source separation or as a substitute for separate collection of certain materials, such as plastics and metals. Given the increasing complexity of materials, rapidly growing urbanization, which complicates conventional collection systems, and the growing global demand for secondary raw materials, centralized sorting will certainly play an even greater role in the future. Dijkgraaf and Gradus [31] show that there is evidence that the cost-effectiveness of recycling plastic waste increases when post-separation is chosen. The recycling rate for these collected mixed plastics is 75%, which means that 25% of the collected household plastics continue to be used for energy recovery (since unsorted waste is incinerated in the Netherlands). The advantage of post-separation is that these "contaminated" and ultimately incinerated plastics do not need to be separated, but a large investment is required to build an appropriate plant. Post-separation should be combined with a reduction in the number of mixed plastics. Fee differentiation and a ban on inappropriate plastics are also important to attain a more closed-loop recycling system [31]. Several large-scale trials in Germany have tested the technical feasibility of packaging waste fractions directly from mixed municipal waste. Current food packaging sorting systems are mostly based on NIR technology and have so far focused on the recovery of PET bottles (three colors), HDPE, and sometimes PP [32]. For the current implementation of the extended (so-called P + MD) street collection in Belgium, to obtain as many mono-materials as possible, the sorters receiving the mixed plastics waste have to sort them into 11 different fractions. Chruszcz and Reeve [20] analyzed plastic output material produced by MRFs and PRFs. It was estimated that the total composition of the output produced by the MRFs and PRFs consisted of 72.2% bottles (MRF only), 13.2% rigid packaging (MRF only), and 7.4% plastic films (MRF only). In addition, 3.7% non-plastic materials and 1.0% fines were found in the output. The percentage of non-plastics ranged from zero for PET bottle jazz to 9.6% for mixed plastics. There were material fractions that were potentially more difficult to process, such as 1.5% non-packaging plastics (ranging from 0% for the PET bottle jazz outputs to 9.8% for pot, tub, and tray outputs). Both manual sorting and automatic/mechanical sorting are two technical approaches used to separate waste into individual materials. Sorting facilities mostly use a combination of manual and automatic sorting, as some steps in the process are best handled manually. Other steps, however, benefit from targeted, safer, and less expensive automation. For example, different techniques, such as waste screening (disc, trommel, or oscillating screen), air separation (rotary, zigzag, and crossflow classifiers, or suction hood), ballistic separation, magnetic sorting eddy current separation, film grippers, sensor technology (NIR (near infrared), VIS (visual spectrophotometry), XRF (X-ray fluorescence), XRT (X-ray transmission), EMS (electromagnetic sensor), FIR (far-infrared)), and manual sorting depend on the type of waste stream. These technologies are often used in combination [33]. MBT design covers highly automated sorting systems as a solution for residual waste treatment to recover as much recyclable material as possible from the separate collection.

The separation of packaging and composite films are the most pressing topics in polymer sorting and recycling, in addition to dealing with metal impurities in sorting. Moreover, there is a lack of capability of recycling PET trays and beverage cartons. Thus, the sorting and separation processes of these fractions have to be improved, along with their recycling routes [34]. Digitization and artificial intelligence (AI) methods can make an important contribution to improving the sorting of plastic waste. Chidepatil et al. [35] pointed out that multisensor-based artificial intelligence for plastic waste segregation and a blockchain platform for a circular economy involving plastic waste are currently under investigation. Three types of sensors are used in the multisensor-based separation process. They are classified as VIS, NIR, and FIR based on their operating frequencies. These sensors capture different types of information (attributes) about plastic waste, such as color, physical and chemical composition, shape, etc. These attributes are used to separate the plastics into different types. Combined with blockchain technology, which serves as a trust-based platform between plastic waste separators, recyclers, and buyers of recycled raw materials (manufacturers), it is possible to close the loop in the life cycle of plastic products. Manual sorting can be replaced by sorting with a robot using AI. Usually, a conveyor belt feeds the waste past a package of sensors, such as visible spectrum and NIR spectroscopy cameras, 3D laser scanners, and metal sensors. At the same time, robotic arms, operating above the belt, remove materials as waste passes below. To minimize uncertainty and enable efficient and intelligent separation in this multi-sensor platform, AI is commonly used. For example, the AI can train the separation system to recognize two bottles of the same type, even if one of them looks quite different from the other (deformed or discolored). In these cases, the AI can train the system to correctly recognize and correctly separate the bottles. Wilts et al. [36] presented the use of an AI-based sorting system for mixed MSW. Based on the empirical data, they showed that up to 100% purity of the sorted fractions and separated materials can be achieved, which significantly exceeded initial expectations. However, waste recovery was not successful. There is strong evidence that significant benefits could be realized with further adaptation and optimization of the operating conditions of a real waste treatment plant, integrating the increasing digitization of waste management in its various forms and not considering digitization solely from the perspective of material recovery rates [33]. A key role in increasing recycling rates can be played by improving recyclability by facilitating the separation and sorting of materials and the sharing of recycling-related data. To provide more information about ingredients, a digital product passport can be used. This can lead to higher-value new products from municipal waste. As the accuracy and sensitivity of these technologies become more refined, new technologies are being developed to identify different materials in waste streams. For example, to facilitate the identification and classification of individual packages, the use of RFID tags in packaging has been proposed. In this concept, RFID tags are embedded in the individual packages, which can then be read either at collection or at the sorting facility to enable accurate sorting of different types of plastics. However, the price may be the main barrier to wider use of this technology, but potential contamination by the tags themselves may also be considered.

Emerging infrastructure and the opportunities offered by cyber-physical systems (CPS), blockchain technology (BCT), and the Internet of Things (IoT) are enabling coordination between physical and computational infrastructures. Blockchain applications in waste management are mainly focused on facilitating payments or rewards and monitoring and tracking waste. Steenmans et al. [37] identified four areas of blockchain use that are beginning to transform waste management practices (payments, rewards for recycling and reuse, waste monitoring and tracking, and smart contracts). According to Gong et al. [38], one particular function of BCT is tokenization, which serves as the main approach for motivating participation. Users must deliver the collected waste to designated recycling sites and separate the waste into smart bins according to the type of waste. This process is usually supported by sensors and smartphones. By scanning codes, waste information (e.g., waste type and weight) is uploaded to users' digital accounts. Users then receive corresponding rewards in digital currency at set reward prices. Digital currencies can be exchanged for physical goods. In another solution, individuals can bring waste to specific collection points. There, it is weighed, and then payment is made to the individual via a blockchain-based banking system. In the second type of application, data on the waste collected and dropped off is recorded.

One of the promising approaches to achieving high sorting purity is to mark resins made of polymers with unique fluorescent markers (tracers). During the manufacturing process, the markers are incorporated into new resins at concentrations of ppm (or sub-ppm). The levels are just high enough for sensitive instruments to detect them based on fluorescence emissions. However, the optical appearance and mechanical properties of the polymers are not affected. A prototype measurement system was invented by Brunner et al. [39]. This development allows for the identification of fluorescently labeled polymers and provides the necessary information for sorting devices. Currently, this prototype system can process approximately 1800 small plastic flakes (mill material) per second. A similar solution to today's multilayers and other sorting challenges is tracer-based sorting (TBS), which uses fluorescent tracers to provide sorting information about packaging [34]. Industrial print tests with tracer materials showed good print quality. An extensive analysis of packaging sorter input was conducted for a study of the feasibility of TBS waste management, focusing on the type of materials, label, color, and label fate. The implementation of a TBS-modified NIR sorter in sorting tests guaranteed excellent detection rates. However, the effectiveness of recycling plastic waste from separate collections should be compared to the technical sorting of municipal waste. Similarly, the manner in which separate waste collection can be managed when new and multi-material plastic waste is generated should be discussed. Finally, the recycling results with mixed municipal waste and mixed collected PPW should be analyzed. Dahlbo et al. [40] addressed the debate regarding the effectiveness of collecting plastic packaging from mixed municipal waste versus that of a separate collection of plastic packaging by analyzing these two types of waste streams. Their mechanical and rheological test results showed that plastic waste, even when it is obtained from mixed municipal waste, can be a useful raw material. The origin of the plastic waste and the method of processing it seemed to have less influence on its mechanical quality than the type of plastic that it comprised. Feil et al. [41] presented the efficiency of plastic recycling from municipal waste. The amount of municipal waste was 337 kg/person, and it had a plastic content of 13.7 wt%, resulting in an average amount of plastic waste of 46 kg/person, which is significantly higher than the amount of separate waste collected. Strikingly, the plastic waste contained a high proportion of films of about 31 wt%, which are difficult to sort, and a high proportion of non-packaging plastics of 28 wt%. After 35 mm screening and wind sifting, the plastic content increased to 16.8 wt% (10.1 wt% 3D plastics, i.e., rigids; and 6.7 wt% 2D materials, e.g., films) because organic material, inert material, and plastics <35 mm (1.3 wt%) were removed from the material stream. Nevertheless, the materials had high percentages of impurities. The rigid plastic blend contained up to 28 wt% non-polymers (paper, residuals), and the film fraction contained up to 49 wt% of these impurities. In addition, the 3D-shaped fraction contained about 42 wt% films. Luijsterburg and Goossens [13] reported that comprehensive sorting results in purer waste fractions with better mechanical properties. No quality differences were found between the separately collected and the mixed collected PPW. The quality of these materials can be similar. However, the share of contaminants (so-called cross-contamination by other solid waste materials) reduces the quality of separately collected fractions. Common differences include higher moisture content and surface contamination. Nonetheless, these materials are traded and recycled in secondary materials markets.

7. Indicators to Evaluate Sorting Performance

Several indicators are typically used to evaluate sorting performance and the composition of sorted fractions. Ip et al. [42] proposed using grade and recovery to evaluate the performance of MRFs. Recovery generally reflects the proportion of target packaging captured in the correctly sorted fraction relative to the total amount of packaging collected. It can be considered a performance indicator for the sorting of a particular type of packaging. In order to describe the yield of the sorting process, the indicator has been defined as reflecting how much of the plastic packaging that enters the market also ends up in the correctly sorted fraction. Thus, this indicator, which takes into account both collection efficiency and sorting efficiency, is termed net recovery. If only sorting efficiency is considered, the indicator is termed sorting recovery. For plastic waste evaluation, Roosen et al. [10] used the following indicators: product quality, which is the purity of the desired product in a sorted fraction; polymer quality, which is the purity of the desired polymer in the sorted fraction; and Simpson's diversity index (SDI), which is a measure of the diversity of the composition of the sorted waste fraction. The SDI value should be in the range of 0 to 100%. As expected, the diversity of polymers in a sorted fraction is greater when it is closer to 100%. In general, a higher SDI, reflecting greater variability in polymer composition, makes plastics more difficult to recycle. Even if certain sorted fractions have the same degree of purity, a higher number of polymer components leads to complications in mechanical recycling [43], as the processing of multiple polymers affects the homogeneity of the particular fractions [44].

8. Mechanical Recycling (MR)

Four categories of recycling can be distinguished: (i) primary recycling (mechanical reprocessing into a product which possesses equivalent properties), (ii) secondary recycling (mechanical reprocessing into products with lesser properties), (iii) tertiary recycling (recovery of chemical components), and (iv) quaternary recycling (recovery of energy). Primary recycling is often related to closed-loop recycling (the circular economy) and secondary recycling is related to downgrading. Technologically, there are two options for recycling plastics: mechanical recycling and feedstock recycling. Mechanical recycling (MR) involves pretreatment steps such as sorting or washing, which remove most extraneous materials (e.g., other polymers) and contaminants (e.g., food residues). Ragaert et al. [44] summarized the techniques and potential limitations of MR. The techniques used for MR include flotation (sink-float), which is a well-known technique. Efficiency is determined by density differences of plastics, such as the low-cost technique (mainly in relation to binary mixtures). Melt filtration is useful in the removal of non-melting impurities, and possible pressure variations in production may require additional melt pressure. For FT-NIR (Fourier Transform Near Infrared), the plastic waste should be dry, and the limitation is no detection of black plastics. Triboelectric (electrostatic) separation is efficient for various plastics. The density-based technique can be improved by magnetic separation and density overlap remains, but it allows the sorting of multiple polymer fractions in a single step. X-ray detection accuracy and cost-efficient techniques can be used for sorting plastic waste.

In reprocessing, the sorted fractions are then ground and remelted in an extruder with the addition of auxiliary materials (stabilizers, antioxidants, etc.). In the mechanical recycling technique, the material remains unaffected and thus the polymerization energy is preserved. The recycling is of high quality despite progressive thermal–mechanical degradation. Arends et al. [45] pointed out that the lower recycling quality achieved by remelting, semi-volatile hazardous additives such as flame retardants, plasticizers, and stabilizers can only be removed by precise presorting, presorting by density separation, X-ray fluorescence (XRF), or spectroscopic near-infrared (NIR) sorting technologies, resulting in a high rejection rate for plastics with a high content of legacy additives. Schyns and Shaver [46] studied the mechanical recycling of five major packaging materials: PET, PE, PP, PS, and PVC, and indicated that reprocessing leads to polymer degradation that requires mechanisms and strategies to improve recycling. Degradation processes vary from polymer to polymer, and changing chain length and mechanical properties remains a technological challenge. Degradation by the use of antioxidants, chain extenders, blends, plasticizers, and fillers can be limited but is complicated by the fact that there are no standards for polymer types. Moreover, these additives further compromise recyclate quality. Civancik-Uslu et al. [24] found that MR is an environmentally friendly option compared to thermochemical recycling (TCR) for the impact categories studied if the products could replace virgin materials at a 1:1 ratio. The main reason for the better results is the higher number of avoided impacts due to a shorter cycle in the production of MR regranulates or flakes. Problems such as contamination or mixing of different plastics associated with effective mechanical recycling affect product quality, can limit economies of scale, and cause fluctuating prices for recycled materials. Mechanical recycling processes are associated with limited costs, the degradation of mechanical properties, and inconsistent product quality.

Milios et al. [47] categorized the barriers to the adoption of recycled plastic into four broad themes: (i) low plastic recyclables demand, which is related to low demand from manufacturers due to price and quality, and low demand from consumers for recycled plastic products, (ii) limited market communication and lack of value chain coordination, which ultimately leads to a lack of traceability of plastics along the value chain, (iii) technological barriers to better recycling, and (iv) regulatory barriers affecting the recycled plastic market. New technological innovations are expected to improve recycling efficiency. However, Ueda et al. [48] showed that the decision of who collects and processes used products is equally important and affects the costs and benefits of recycling, even without technological changes. Hestin et al. [49] pointed out that another important barrier to increasing plastic recycling may be inadequate sorting capacity combined with inefficient separation technologies. Recycling mixed plastic waste from the MSW stream presents many challenges, but this fraction may also represent a major opportunity for increased plastic recycling in the future. Recycling typically involves higher costs than incineration due to higher labor requirements, the need to transport light and bulky waste over long distances, and the need for significant investment in technologies to automatically monitor the collection system and sorting.

9. Conclusions

Moving to a circular economy where plastics are maintained in their highest value state is critical to reducing environmental impacts and promoting reduction, reuse, and recycling. Mechanical recycling is an important tool for environmentally and economically sustainable plastics management, but current recycling practices are limited by cost, the reduction in mechanical properties of plastic materials, and their inconsistent quality. Some significant challenges remain, both for technological reasons and because of economic or social behaviors related to recycled waste collection and virgin substitution. Unfortunately, the quality of recycled plastic is most often lower than virgin plastic. This lower quality results from the fact that the recycled materials are commingled and thus, many different types of polymers are mixed. Moreover, they may also contain various additives, labels, and other non-plastic elements that hinder the process. Sorting technologies currently in use are not technologically advanced enough to effectively separate such mixtures. From a plastic waste management perspective, any advances in collection, sorting, and recycling processes would be of little benefit if there is no demand for recycled plastics to absorb the volume of recycled plastics. It should emphasize that a key aspect of the development and sustainability of recycling plastic materials is the ability of recyclers, which want to meet demand and sell at high prices, to produce high-quality products.

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