Plastic Waste Management: Current Status and Weaknesses

Oksana Horodytska, Andrea Cabanes, and Andrés Fullana

Contents

Abstract The weaknesses of existing plastic waste management strategies lead to the pollution of the natural environment. Although around 75% of plastic litter come from developing countries, an important 25% is originated in western countries mainly due to the limited efficiency of the collection systems and low recycling rates. Global plastic production has almost doubled over the last decade, and it is predicted that it will continue to grow. This chapter provides an extensive review of current waste management routes and existing recycling and recovery options. Two types of plastic products have been considered: rigid and flexible materials. These materials show different behaviour and usually are treated separately. Plastic waste sources can also be diverse, but they are commonly grouped into post-industrial and post-consumer. In this chapter, the focus has been placed on post-consumer plastics since a higher amount of this type of waste is being generated and its treatment is more challenging.

Keywords Circular economy, Plastics, Recycling, Upcycling, Waste management

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1 Introduction

Plastics can now be found in every aspect of our lives. There are several good reasons for such success. Excellent mechanical and thermal properties, low manufacturing costs, versatility, and lightness are just some of the advantages that are worth mentioning. Usually plastic materials are divided into thermosets and thermoplastics. Thermosetting polymers present highly crosslinked structures which provide the materials with high mechanical and physical strength and heat stability. Well known thermosets are epoxy and phenolic resins, polyurethanes (PUR), and acrylonitrile butadiene styrene (ABS). These materials are mainly used when heat and chemical resistance is required (e.g. automotive manufacture, construction equipment, electrical components). Thermoplastic materials consist of linear or branched chains linked by intermolecular interactions. This is a flexible structure which allows thermoplastics to flow when the temperature is high and to solidify when the temperature decreases. Some of the polymers belonging to this group are polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), and polyethylene terephthalate (PET).

More than 8.3 billion tons of plastic have been produced worldwide since the 1950s [1]. The global plastic production rose sharply from 0.35 million tons in 1950 to 348 million tons in 2017. China is the world's largest plastics producer (Fig. 1), accounting for 29.4% of global production in 2017, followed by Europe (18.5%) and North America (17.7%). European plastic demand reached 51.2 million tons in

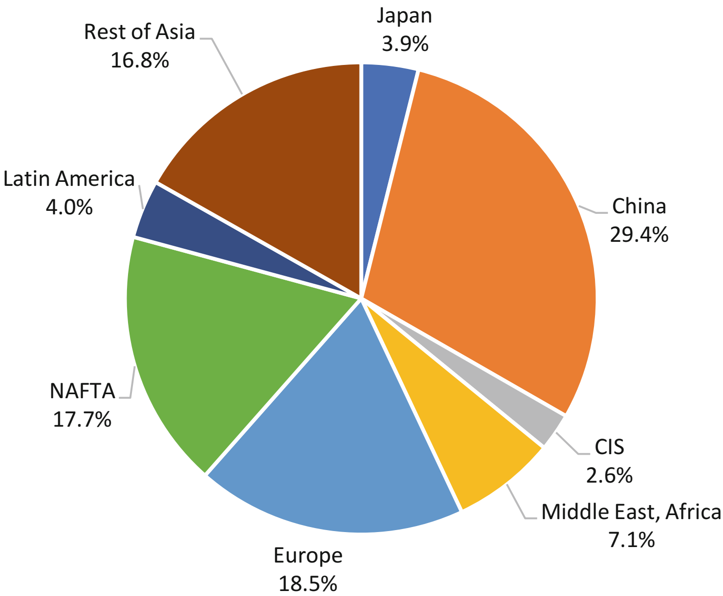

Fig. 1 Distribution of global plastic production in 2017 [2]

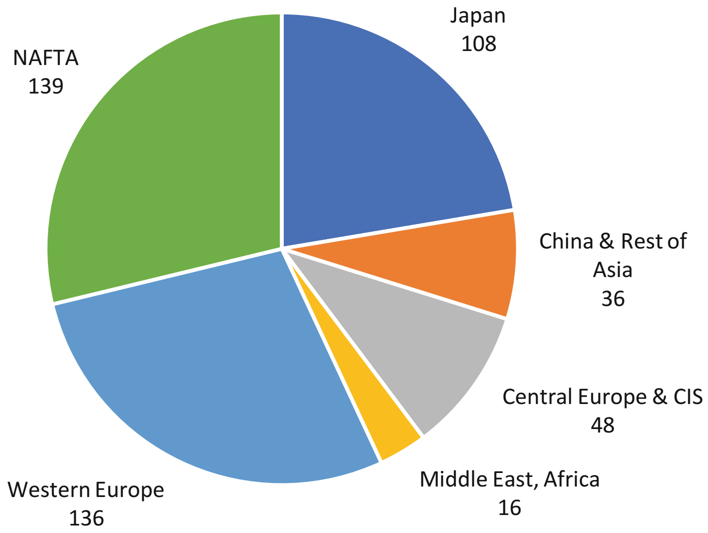

Fig. 2 Plastic consumption rates per region in 2015 (kg/person) [3]

2017, with Germany in the lead, followed by Italy, France, Spain, and the UK [2]. Globally, North America, Western Europe, and Japan show the highest consumption rates (Fig. 2). The regions which produce the most plastic are not necessarily the largest consumers. For instance, Japan is a region with one of the lowest plastic production rates; however, it is one of the biggest consumers. On the other hand, China is the largest producer, but the consumption rate is lower compared with other regions (almost four times smaller than North America or Europe) [3].

Plastic products applications vary from one sector to another. There exist a wide range of polymers, each one with specific properties that make them ideal for each application. Polymers such as PE, PP, PVC, and PET are the materials most in demand, followed by polystyrene (PS) and PUR. The packaging sector has become the most important application representing almost 40% of the total [2]. Polyethylene is one of the most versatile polymers owing to a changeable degree of chain branching. The polymerization conditions can be altered to produce the desired structure. Low-density polyethylene (LDPE) has a branched structure that makes the material clear, flexible, easy of processing, and with good heat sealability. It is widely used in secondary and tertiary packaging (shrink and stretch wrap films), reusable bags, and agricultural films. Fewer branches increase the density of the material. This is the case for medium-density polyethylene (MDPE) which is slightly stronger, stiffer, and less permeable than LDPE. On the other side, there is the high-density polyethylene (HDPE), which is a linear and crystalline PE. It has a good water vapour barrier (better than LDPE), resistance to different chemical compounds, and good tensile and impact strength. Also, it is a non-transparent material with poor gas barrier characteristics. HDPE is widely used in hard packaging (e.g. milk, juice, water bottles; cosmetic containers; pharmaceutical bottles) and flexible food packaging (e.g. cereals, snacks, crackers). PE materials can be also produced by copolymerization to obtain, for example, ethylene vinyl acetate (EVA) or linear low-density polyethylene (LLDPE). The second most commonly used thermoplastic after PE is PP. It has a lower density, a higher melting point and a higher rigidity. It is also a good barrier to moisture, so it is used for dry food and bakery packaging. Hard PP can be found in automotive parts, microwave containers, and pipes. The optical, mechanical, and barrier properties can be improved by orientation methods [4]. There is a wealth of information on plastic's properties and applications, but it is beyond the scope of this chapter. Therefore, only a few of them have been described.

High production rates and a lack of consumer awareness have led to uncontrolled plastic waste generation. Globally, around 150 million tons are released every year [5]. In the USA, 34.56 million tons of post-consumer plastic waste (including residential, commercial, and institutional sources) was generated in 2015. Recycling rates remain low (slightly higher than 9%), while almost 76% of plastic solid waste (PSW) is disposed in landfills [6]. The remaining fraction is used as an energy source. In 2016, the European Union countries plus Norway and Switzerland generated 27.1 million tons of post-consumer plastic waste. Of this, 31.1% was recycled, 41.6% was recovered as energy, and 27.3% ended up in landfills. It was the first time that recycling overtook landfilling. The rates, however, vary among countries. For instance, Switzerland, Austria, or Germany has committed to recycling and energy recovery by implementing landfill restrictions. Meanwhile, Bulgaria, Greece, or Malta still buries more than 70% of their waste in landfills [2]. In developing countries, the percentage of plastics in municipal solid waste (MSW) streams is on the increase, mainly due to changes in people's lifestyle. The summary of annual PSW generation in some Asian cities (from Indonesia, India, Thailand, Malaysia, Iran, and Bangladesh) can be estimated around 1 million tons [7]. However, accurate data are difficult to obtain. Seven major cities in India produce nearly 500,000 tons of plastic waste per year, representing 4% of the total MSW [8]. In a recent study, researchers estimated that in 2015, the Asian continent was the largest contributor to global plastic waste, generating 82 million tons. The following regions are Europe (31 million tons), North America (29 million tons), Latin America and Africa (19 million tons each), and Oceania (0.9 million tons) [9].

Waste treatment methods can be divided into mechanical recycling, chemical recycling, and energy recovery. Here a distinction is drawn between post-industrial and post-consumer waste. The former is generated during the converting operations (rejects and offcuts), and it is usually clean and homogeneous. The latter consists of a mixture of products at the end of their service lives. There are two types of post-consumer waste. On one hand, there is the so-called commercial waste which is mainly secondary and tertiary packaging from retail industry area. The composition is usually known and homogeneous, and the amount of physical impurities and chemical contaminants is low. On the other hand, there is domestic post-consumer waste coming from kerbside collection. This waste is dirty, highly contaminated, and heterogeneous.

2 Waste Management in Developed Countries

A number of actions are necessary to properly manage the waste produced by human activity, such as collection, transportation, sorting, and disposal or treatment. The European Union Waste Framework Directive [10] states that operations intended to manage waste must not cause any damage to the environment or human health. The waste hierarchy has been established to determine priority among waste treatment processes (prevention or minimization, preparing for reuse, recycling, recovery as energy, and lastly disposal). However, the waste hierarchy cannot be strictly applied because it depends strongly on waste composition and characteristics.

2.1 Collection

Plastic recycling always begins with waste collection whether at households or in the industry, and the ratio of collected plastics will severely impact the recycling efficiency of a locality and will undoubtedly keep from diffuse pollution of plastic litter leaking into the environment. In Europe (EU28 + NO/CH), the average plastic waste collection rate increased by 12% between 2006 and 2016. Germany contributed with a 41% improvement and Poland with 40%. Other European countries did not match these figures (the UK 13%, France 9%, Italy 2%). Actually, in Spain, waste collection decreased by 7% [11].

Regarding commercial and post-industrial plastic waste collection, companies are responsible of segregating the different waste fractions, and these are more likely to do so if incentives are given in return by the local authorities. Even so, companies usually recycle their plastic waste as it is virtually clean and, therefore, highly valuable for recyclers. Moreover, specialized recycling companies generally offer a collection and recycling service for purchasing the post-industrial and commercial plastic scrap [12].

Concerning municipal solid waste, there are multitudes of schemes when it comes to collection, but most of them can be summarized in four main groups: kerbside collection, drop-off collection, buy-pack centres, and deposit collection methods [13].

– *Kerbside collection* of plastic solid waste is referred to waste disposal within communities, meaning buildings and individual houses, that separate plastic and metal container packages from the rest, organics, paper, etc., and dispose them in either plastic bags or containers to be collected on a specified day of the week or the month, according to the municipality regulations [14] (Fig. 3a).
– *Drop-off or bring point collection methods* consist of different containers, the use of which is clearly indicated and where organics, paper, rest of food, and plastic are disposed separately (Fig. 3b). Generally, these containers are placed near residential areas in order to be accessible for citizens to dispose their household plastic waste among other recyclable materials. However, nowadays, the use of

Fig. 3 Different waste collection options. (**a**) Kerbside collection in Erlangen (Germany). (**b**) Bring point collection in Alicante (Spain). (**c**) Multi-material collection system in Lausanne (Switzerland). Pictures by Andrea Cabanes and Oksana Horodytska

drop-off collection is increasing not only in neighbourhoods but also in public areas such as parks, schools, universities, etc., so that all the waste disposed can be separated and recycled, not only at homes. In populated areas, bring points are more frequently seen than kerbside collection, since the amount of disposal points and transportation resources are significantly reduced [14].

- *Buy-pack containers*. The operability of buy-pack containers is similar to the drop-off collection systems, with the exception that this scheme aims to encourage more citizens to separate their plastic fraction by means of an incentive that is received for the disposal of each plastic container, e.g. PET bottles. At the same time, the separation avoids an extra contamination in the plastic package and subsequently facilitates the recycling process. This kind of collection system is normally placed in supermarkets [14].
- *Deposit programmes* aim to reduce plastic waste pollution and impel citizens to return their recyclable containers. The way it works is quite similar to buy-pack containers, but in this case the end-user has to pay an additional cost for the plastic container that will be refunded after taking it back to the so-called reverse vending machine. Consequently, most of packed food stuff in the supermarket will have an added cost, driving citizens whether to buy non-packed food or to return the package in order to get the deposit back [15, 16].

This collection scheme seeks to increase the recyclability not only of the plastic waste produced at home but also of the waste produced outdoors. Meaning that, for example, there is a greater chance that people will contribute to return the plastic bottles consumed outside home to get the deposit back instead of discarding them in the general containers placed on the street. In the last years, this collection scheme has been growing across European countries, North America, and Australia [17].

Nevertheless, in both *kerbside and drop-off* collection methods, plastic is not always collected separately, and, in some cases, all municipal solid waste is collected in the same fraction to be sorted later in the corresponding facilities. However, the single-fraction collection system is decidedly more inefficient in terms of materials recovery and, therefore, yields in a lower recycling ratio of plastic packaging due to the increase of contaminants attached to the material, which are originated as a consequence of being in direct contact with rests of food, care products, cleaning products, and so forth. Regardless the inconveniences for plastic recovering, there exist several solid waste collection systems ranging from zero separation fraction to specific materials separation, as would be the case of PET bottles [18].

– *Single fraction – mixed solid waste*: all solid waste is disposed in one single bin, and the mixed waste-processing facilities are responsible for collection, transporting, and separation of plastic, metal, paper, and organic fractions.
– *Two fractions – dry waste and organic*: in this case citizens are responsible for separating the organic biodegradable fraction from the rest of waste. This scheme would decrease the level of contamination in the packages, but still a complex sorting process is required to recover the different types of materials.
– *Three fractions – organic, paper and cardboard, and rest of dry waste*: in this case paper and cardboard will result in a lower level of contamination which may facilitate the recycling process, and the rest of dry waste contains mainly plastic and metal packaging. This is the most usual system found around Europe.
– *Multi-material collection systems* are applied, for example, in Switzerland separating PET bottles, aluminium, and paper from the rest of waste (Fig. 3c). The aim of multi-material collection is to recover valuable materials while minimizing the content of contaminants.

Once the waste is fractionated, there are mainly two types of trucks that can be utilized for waste transportation: multisection or single section trucks [18]:

– Multisection trucks offer the possibility of collecting all waste at once, which seems an efficient option for multifraction systems. However, there is a clear limitation to consider, as the truck must discharge whenever one of the chambers is completely full, even though the rest of compartments remain empty. Therefore, if the amount of waste is not balanced among the different fractions to be collected, this would not be an appropriate solution for waste transportation.
– The other option is to use single section trucks. In this case, if each waste fraction has to be transported in a different truck to avoid contamination in recyclable materials (such as plastics and cardboard), then the inconvenience would be the

necessity of a larger number of vehicles, which also involves a higher initial investment in the collection system.

The frequency of collection in both cases varies depending on the local authorities, but in general, it mostly depends on the weather conditions. For instance, Southern Mediterranean countries in Europe collect the household waste almost daily, since the elevated temperatures favour the decomposition of organics and lead to unpleasant odours emitted to the environment [18].

2.2 Sorting

Sorting of waste is carried out in so-called material recovery facilities (MRFs) and depends on the existing collection schemes. In general, there are two types of MRFs. On the one hand, facilities that receive mixed waste from single stream collection are called mechanical-biological treatment (MBT) plants (in EU) or dirty MRFs (in the USA). On the other hand, there are dual-stream or clean MRFs where only potentially recyclable materials are treated.

Technologies and equipment used vary among facilities and depend on the input waste characteristics. Some commonly used technologies are bag splitters, ballistic separation, air separators, and optical detection systems.

Single-stream MRFs require a previous sorting operation to separate the fibres (paper and cardboard) and containers or packaging (plastics, glass, and metals). A trommel screen and disc screens are typically used for this purpose. After that, different materials follow their own sorting process. Plastics recovered for recycling are mainly rigid containers. Plastic films, wraps, and shopping bags from commingled waste are usually considered contaminants and sent to landfills or energy recovery. Additionally, magnetic separation is used to remove ferrous metals, and eddy current systems are used to remove non-ferrous metals.

Plastic sorting processes consist of several mechanical operations. First, bag opening takes place, and materials are released onto a downstream conveyor. Lightweight (2D) and heavier (3D) products are separated using ballistic or air separators. Ballistic technology consists of an inclined screen where the heavy rigid products roll downwards and lighter films and papers are pushed upwards. Air separation is based on the difference in material density since lighter materials can be removed from the conveyed stream using air at relatively low velocity. Optical sorting is used to distinguish between different materials, for instance, plastic and paper. Near-infrared optical detection (NIR) is a burgeoning technology based on the wavelength reflected after light is incident upon the material. Sorting of a range of polymers (e.g. PE, PP, PET) is a big advantage. However, there are still several limitations associated with NIR. Multilayer, coated, or black plastics pose specific challenges and lead to missorting. Rigid plastics from different sources (WEEE, packaging, bottle caps, etc.) can be sorted into pure polymer fractions using electrostatic plastic separators. These systems operate on the principle of the different tribo-electric behaviour of involved plastic materials.

Effective sorting is the key to increasing plastic recycling rates. However, it is still underdeveloped especially for flexible plastics recovery. Rejected plastic from sorting facilities are usually sent to landfill and can end up in nature.

2.3 Treatment

Plastic recycling processes can be divided into different groups based on polymer classification (thermosets or thermoplastics), waste source (post-industrial or post-consumer), and plastic type (rigid or flexible).

Thermosetting plastics (ABS, epoxy and polyester resins, etc.) cannot be recycled using temperature owing to their ability to withstand heat. Therefore, the most common waste treatment is energy recovery through combustion or pyrolysis. Alternatively, mechanical recycling is carried out via grinding or pulverization. In this case, the plastic flakes produced can be utilized as fillers in new products. Finally, several chemical recycling technologies have been developed to depolymerize plastic materials using solvents and supercritical fluids. For instance, Connora Technologies has developed a low-energy recycling technology for thermosetting resins recovery including the conversion of thermosets into thermoplastics [19].

Thermoplastics have excellent mechanical properties, lightness, versatility, and relatively low processing costs. Accordingly, they are used in many applications such as packaging, agriculture, and building and construction. Thermoplastics have become single-use or short-life products due to the ease of production and low costs. This has led to an increase in the volume of thermoplastic waste, and it is more likely to escape from municipal collection schemes. Waste treatment methods for these materials are described hereafter.

Post-industrial waste can be successfully recycled through mechanical recycling processes. Direct re-extrusion is used when the input material contains a minimal level of contamination. The quality of the recycled products is similar to the original material, and, thus, it can be used for the same application. This is known as closed-loop recycling or in-house recycling since converting companies can recover their own scrap without leaving their facilities. However, when some contaminants are present, such as ink or adhesives, more complex technologies are required. Usually, plastic washing lines are used to remove the contaminants and extrusion machines with ultrafine filtration, homogenization, and degassing might be needed. As a result, the materials suffer degradation and some loss of properties. Hence, it is suitable only for less demanding applications. This is known as open-loop recycling.

Both closed-loop and open-loop systems contribute to reduction of virgin plastic consumption. However, closed-loop recycling is a preferred option from an environmental point of view because of higher quality of the recycled pellets. This means that these products can be used during several life cycles. On the contrary, products made of more degraded recycled pellets from open-loop system are more likely to end up in landfills or incineration plants after the use phase.

Post-consumer waste is more difficult to recycle through mechanical operations mainly due to high levels of contamination. Usually, only commercial and separately collected or efficiently sorted plastic waste (e.g. PET bottles, shopping bags, etc.) can be recycled using open-loop systems. Generally, the process consists of several mechanical operations such as grinding, washing, drying, and pelletization. The recycled pellets can be used only for nondemanding applications (trash bags, pipelines, flowerpots, etc.). Chemical recycling can be used for highly contaminated mixed plastic waste. However, these processes are not fully developed and can be energy intensive. Therefore, post-consumer domestic waste usually goes to landfills or, at best, to energy recovery plants.

Rigid and flexible plastics undergo different recycling processes. Properly collected and sorted rigid plastics (e.g. water bottles, pots, and trays) can be easily recycled through mechanical recycling methods. PET bottles closed-loop recycling is one of the most successful material recovery systems. This can be attributed to high-grade resins used in original products manufacturing, inert character of PET, and efficient collection schemes that ensure that the contamination level is minimized. Mechanical recycling consists of grinding the material into small flakes, washing (or decontaminating) with detergents, and re-extrusion. Recycled PET is suitable for new bottles manufacturing, but sometimes it is used for production of new products different from the original one. Depolymerisation of PET residues (chemical recycling) is also applied to reuse the monomers in new polymerization processes [20].

Mechanical recycling of flexible plastics is somewhat more challenging particularly due to their low bulk density and low thickness. Washing and drying efficiencies are lower than with hard plastics because the equipment has not been adequately designed to handle flexible plastics. Only post-industrial and selectively collected monolayer plastic films are currently mechanically recycled. The quality of the recovered materials depends on the input waste characteristics. For instance, the presence of ink on the plastics surface leads to coloured pellets suitable solely for nondemanding applications (downcycling). In recent years, several technologies have been developed to remove the ink before extrusion [21]. The University of Alicante has patented an innovative process based on an aqueous solution of nonhazardous chemicals. This is an environmentally friendly technology that produces clear pellets of high quality which can be used for the same application as the original products (upcycling) [22].

Currently, monolayer films recycling shows good results, whereas, multilayer films cannot be recovered yet at the industrial scale. The problem lies in the combination of noncompatible materials (polymers, aluminium, paper, etc.) that produces severe defects during extrusion. There are three main branches of research focused on multilayer films recycling. The first one is the use of compatibilizers to improve the interactions between different polymers inside the mixture. The second one is delamination (separation of the layers) and recovery of the different materials individually. Lastly, there is the technique of dissolution-precipitation, which involves the use of solvent or non-solvent systems to selectively dissolve one of the materials and separate them afterwards [23].

3 Waste Management in Developing Countries

All successful waste management scenarios begin with collection and sorting operations. The problem of environmental pollution and waste accumulation in developing countries can be precisely attributed to the lack or inefficiency of municipal collection strategies. Unfortunately, inexistent waste collection services and limited capacity of landfills force the inhabitants and authorities to throw the waste directly to rivers and canals.

One clear similarity among different developing countries is the presence of an informal recycling sector. This is an unregulated waste management activity performed by local individuals or groups to improve their economic situation. The so-called waste pickers collect potentially recyclable materials directly from the streets and dumps and sell them to local recycling companies [24]. Sorting technologies are almost non-existent, and classification and separation are carried out by hand. Recyclable waste from the informal waste recycling sector can be sorted in situ. Although in some cities this is the only way to recover recyclable materials because there is no formal separate collection system, from the social perspective, informal recycling is usually associated with atrocious working conditions. Fortunately, in some countries of Latin America (Brazil, Colombia, and Argentina), municipal authorities are starting to recognize the labour of these waste pickers and to integrate them in formal waste management strategies [25]. Mechanical recycling is the preferred option and PET, and polyolefins are the most recycled materials. Recycling processes, as in developed countries, consist of grinding, washing, drying, and re-granulation. To increase the profitability, some companies invest in sophisticated equipment from reputable European machinery manufacturers.

3.1 Latin America

In countries with emerging economies such as Brazil, waste generation has increased over the last decades mainly due to the rise of the average income. Consequently, national authorities were forced to implement MSW regulations (Lei 12305, 2010) [26]. Several big metropolitan areas (e.g. Rio de Janeiro, João Pessoa) count with separate collection systems and material recovery facilities [27]. In general, the plastic recycling sector in Latin America is experiencing considerable growth in recent years. Several recycling companies exist in different countries (e.g. Mexico, Brazil, Peru, and Honduras) aimed mainly at food-grade PET production. Recyclers usually receive sorted materials directly from industries or from intermediates that work with waste pickers. Kerbside collection of domestic waste remains a weak point for most cities and regions. Furthermore, even if a municipal collection strategy exists, mixed domestic waste is usually sent to landfills (controlled or uncontrolled). Only a small fraction ends up in sorting facilities where the predominant method is still manual separation.

3.2 Asia

Within the Asian region, China is the country with the highest ratio of plastic debris leaking into the marine environment, followed by Indonesia and the Philippines. These countries have experienced an economic growth in the last years, which has been directly reflected on an increase of solid waste pollution, and the plastic leak is basically the result of a scarce waste collection system or a lack of it [28].

For many years China has been the destiny of not only their own plastic waste but Europe's and America's plastic waste, resulting in the generation of roughly 440 million tons yearly. In China the overall collection rate is under 40%, leading to 260 million tons of uncollected plastic waste leaking into the environment, which contributes to 84% of the global plastic pollution. Nevertheless, there is a significant difference between urban and rural areas. In urban areas, the collection rate of plastic waste is reaching 65%, while in rural areas, more than 95% of plastic waste is totally uncollected, and residents resort to traditional waste management habits, such as uncontrolled waste disposal, burning, or dumping in the river, which leads to a high load of contamination in both land and oceans. In urban areas, the most common recovery system for plastics is at incinerators or sanitary landfilling. All in all, only 11% of all plastic waste generated is collected by waste pickers to be recovered in recycling facilities [29].

On the other side, the collection system in the Philippines is, at least initially, considerably more efficient than in China; specifically, the mean rate of plastic waste collection is nearly 85%. In this case, the collection system efficiency differs between rural and urban areas too, although the collection rate drop-off in rural areas is not that high when compared to China, above 40%. Cities with high population density, e.g. Metro Manila, reach 90% of plastic waste collection. The waste management success in the Philippines is due to the regulation "Ecological Solid Waste Management Act of 2000" (Republic Act No. 9003), which targets zero waste and recycling of all valuable products by promoting the segregation of materials at source, dividing them into four main groups: compostable, recyclable, nonrecyclable, and special waste. The objective is to collect them separately and make the most of plastic materials. However, in 2009, there was no evidence of a realistic change in the country, and almost every city continued to perform uncontrolled landfilling and open incineration. Fortunately, owing to the Global Alliance for Incinerator Alternatives (GAIA), the regulation Waste Management Act of 2000 was implemented in 25 localities, and after 2011, open burning and dumping was totally banned. Domestic waste is nowadays segregated for composting and recycling [30]. In spite of the progress made, the Philippines greatly contributes to plastic litter in the ocean. Surprisingly, the issue of plastic waste management in the Philippines is not at the collection point but after collection. It has been reported that 74% of the plastic leakage in the Philippines is originated from the collected fraction. Moreover, the main treatment to plastic and household waste is open burning and uncontrolled landfilling. Only 25% of the plastic waste stream is recovered, although the recovery ratio changes significantly from PET bottles (90%) to flexible packaging (<5%). The plastic recovery is mainly done by waste pickers at different points: at household, during collection while the trucks are moving, and at material recovery facilities. The waste officially collected is discarded in open dump sites (600 available) and sanitary landfills (70 available) [29].

By 2014, it was estimated that Indonesia recycled and composted only 7% of its household waste, 5% was treated with uncontrolled incineration, 10% was illegally landfilled, and 9% of MSW was leaked to the environment, which includes land regions as well as rivers and oceans. The 69% left was landfilled, which is the most common treatment for household waste in this region [31]. More specifically, in Jakarta, waste pickers are the major force in segregating plastics from the rest of waste, since the official collection system only considers dumping plastics into the landfill without any treatment. However, there is an alternative to municipal waste management called "waste bank", where citizens can deliver their presorted waste separated in paper, metals, plastic, and organic fractions in return for cash refund. Companies responsible for the waste banks gain profit by selling the sorted waste to recyclers [32]. This waste is then recycled in the case of plastics, metals, and paper or composted in the case of organic fractions. However, the municipality does not take part in these waste banks, and there are only individuals who are interested in sorting their household waste to increase their income. A recent study estimated that Jakarta recovers 34% of all plastic waste through waste pickers and the waste bank but only 24% of the total plastic waste generated is recycled. The rest remains in landfills or leaks into the environment [33].

The situation in India is similar to the rest of the Asian countries mentioned above. Waste pickers are also a relevant figure in the waste management system, contributing to 20% of the total waste collection. In this region, their practice is not only picking and sorting MSW but also managing waste pickers associations, where valuable materials such as plastics are recycled. On the other side, the official waste collection system in India consists mainly of collection and transportation to dump sites, where organic and valuable materials are burnt together [8].

3.3 Africa

In Africa's developing countries, the same scenario is repeated: waste management basically means transportation from household collection points to open dump, where the waste is either burnt or just landfilled and plastics recycling is only a future project. On top of it, most of these countries are running out of landfilling space; besides, their waste management plan is not able to cope with all the waste generated by their growing population [34].

4 Circular Economy and Weaknesses

The current economy model based on extraction, use, and disposal is not sustainable from the environmental point of view, especially for fossil-based non-biodegradable plastics. Several associations and academic institutions have joined forces to develop the idea of a new economy model, the circular economy (Fig. 4). The fundaments lie in trying to mimic the natural ecosystems. Zero waste, diversity, use of renewable energy, and interaction between systems are the main principals of this economy approach. Regarding plastics and other non-biodegradable materials, the following actions should be taken after the product's service life (in order of preference): maintenance, reuse, refurbishment, and, finally, recycling. Closed-loop mechanical recycling and upcycling provide the highest economic and environmental benefits. Therefore, recycled pellets should be suitable for high-demanding applications. On the contrary, energy recovery and landfilling must be minimized.

The selection of the most appropriate recycling method depends on the quality of plastic waste and the degree of degradation. Currently, upcycling is feasible only with clean, non-contaminated waste. Contamination and inappropriate use of plastic goods significantly diminish material's quality. Furthermore, degradation also occurs during recycling operations. There are different types of plastic contaminants. For example, coating, inks, adhesives, and additives, intentionally added (IAS)

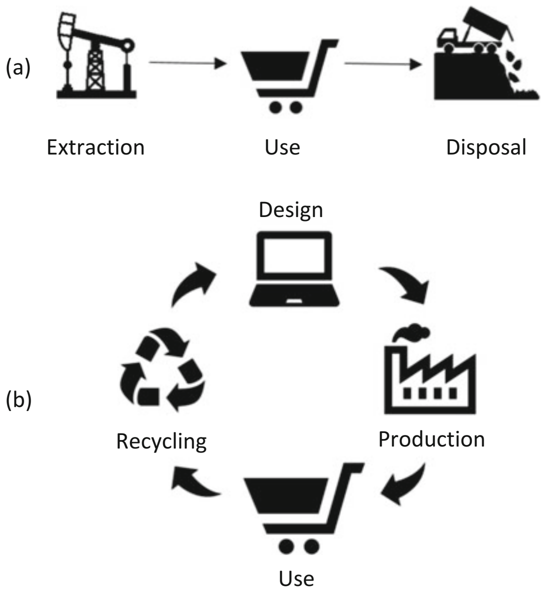

Fig. 4 Schematic representation of the linear economy model **(a)** and the circular economy model (**b**) [35]

during manufacturing, produce defects (bubbles, voids, gels, etc.) when the material goes through re-extrusion at a high temperature. Other contaminants (labels, missorted noncompatible polymers, etc.) and dirtiness adhere to the plastics during the use phase and collection. These are denominated non-intentionally added substances (NIAS). To ensure effective recycling into value-added secondary products, plastic waste requires decontamination.

Both IAS and NIAS pose serious problems for the implantation of closed-loop recycling processes. The packaging sector generates an enormous volume of plastic waste, which cannot be recycled into new packages (especially food packages) due to high consumer's safety requirements. The NIAS, which can be degradation or reaction products, impurities, etc., can migrate from the packaging layer into the food and may constitute a hazard to human health. These substances are hard to detect, and, if detected, it is difficult to establish their origin. High sensitivity advanced analytical techniques are required. Headspace solid phase microextraction (HS-SPME) and gas chromatography-mass spectrometry (GC-MS) are common techniques used to identify volatile and semi-volatile organic compounds. Liquid extraction and GC-MS are used to identify semi-volatile and non-volatile compounds. And, finally, liquid chromatography (HPLC) and high-resolution mass spectrometry (HRMS) techniques such as time of flight (TOF) identify non-volatile compounds when mass spectra libraries are not available [36]. Some plastic manufacturers try to minimize the generation of NIAS during their processes by optimization of manufacturing parameters. In the recycling sector, there is little progress, but the elimination of undesirable substances might be the key for recycled products upgrading.

The fraction of volatile NIAS that confer an aroma to the plastic represent a barrier for the circular economy. Even if post-consumer recycled plastic is intended to be only used for non-food packaging applications, the unpleasant odour produced as a consequence of food and cosmetics contamination among others permeates into the polymer matrix and is not removed through the current recycling process. For this reason, this kind of materials is nowadays downcycled rather than recycled, since consumers are likely to refuse any package made of post-consumer recycled plastic. To put it simply, none would buy a shampoo bottle releasing a cheesy aroma, which presents a roadblock for the plastics recycling industry [37]. As evidence of this, a recent study revealed that the volatiles released from post-consumer high-density polyethylene (HDPE) confer a soapy and citrus-like odour to the recycled plastic, while virgin HDPE do not emanate this kind of odours at all. The study also compared the input plastic waste from the kerbside collection with the resulting pellet after a conventional recycling process, showing that odours are still present at levels of perception in the output material, and therefore, indicating that odours are not mitigated with the current recycling technologies [38].

The techniques used for identification of odorants include gas chromatography coupled to an olfactometer (GC-O) for both identification and sensory characterization of the volatile organic substances causing malodours. Additionally, there exist sensory analyses that do not involve any equipment and in which the only requisite is to have a trained panel of human evaluators comprised of a minimum of eight individuals. In this case, the analysis is based on odour description and hedonic and intensity rating. For the odour description, the panellist has to agree with a list of odour attributes by sniffing the headspace of the sample to be analysed, and then each attribute has to be scored. In the case of hedonic rating, each panellist has to decide whether they like it (maximum score) or dislike it (minimum score); and, last but not least, the odour intensity of the sample is rated from 1 (low intensity) to 10 (high intensity) [39].

Deodorization of recycled plastic would undoubtedly open new market opportunities in the packaging, building, and construction sectors, contributing, thus, to the introduction of plastics in the circular economy. The technologies developed until now are at a research or pilot scale rather than at an industrial scale, which are mainly based on supercritical CO_2 extraction and oxidation of volatile organic compounds (VOCs) attached onto the polymer surface [37].

5 Conclusion

Plastic production will continue growing worldwide because of the excellent properties, ease of production, and low costs. It also contributes to diminishing some negative environmental impacts. For instance, plastic packaging helps to reduce the amount of food waste produced globally. The negative side is that millions of tons of non-degradable waste are generated every year. However, plastic waste should be perceived as a resource rather than a problem.

In general, developed countries are more committed to sustainable waste management. A number of strategies, which include collection, sorting, and waste treatment operations, have been developed. Collection systems vary from one country to another, and there is no consensus on which one offers the biggest environmental benefits. Separate collection of potentially recyclable materials increases the quality of the waste steam. Unfortunately, operating costs also increase, decreasing the profitability of the entire system. Sorting processes are necessary to avoid contamination and improve the recycling rates. Waste treatment methods can be divided into mechanical recycling, chemical recycling, and energy recovery. Landfilling is considered the least preferred option. In fact, several European countries have banned plastic waste going to landfills.

Regarding developing countries, the informal recycling sector significantly contributes to the recovery of valuable materials. Waste pickers collect recyclable materials from the streets, houses, and landfills and sell them to recyclers. Generally, they work in atrocious conditions and do not get the credit that they deserve. Latin America is making a lot of progress in waste management. Plastic recycling has become a business opportunity and existing recycling companies compete with their European and American counterparts. In Asia and Africa, waste management strategies only exist in big cities and metropolitan areas. The costs of sorting and recycling processes are usually too high; therefore, collected waste is merely landfilled.

Although much progress has been made, recycling rates are far from achieving the goal of a circular economy. Materials should flow in a closed-loop cycle. That means that the waste generated by one system should be used as feedstock in another system. Currently, the value of recycled materials decreases due to contamination and degradation. As a result, recovered products are used in less demanding applications (downcycling). The European Union is trying to force the plastic manufacturers to introduce a minimum recycled material content in their products. But, the quality of recyclates must be significantly improved to achieve that. The NIAS and odours pose a serious problem, since current technologies are not prepared to meet the required degree of decontamination.

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