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Chapter 7

Non-recyclable plastics: management practices and implications

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7.1 DEFINITIONS AND COMPOSITIONS OF NON-RECYCLABLE PLASTICS

7.1.1 Types of plastics

Plastics are the most widely used products in several applications such as packaging films, wrapping materials, shopping and garbage bags, fluid containers, clothing, toys, household and industrial products, medicinal electrical applications and building materials. Typically, they are organic polymers of high molecular mass and produced by conversion of natural products or by synthesis from primary chemicals generally coming from petrochemicals (SRI India, 2016).

In general, plastic products used in daily life can be classified into thermoplastics and thermosetting plastics, depending on how they react when exposed to heat. The primary difference between these two plastics is the ability to be remolded after initial forming. Thermoplastics can be reheated,

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remolded and cooled as required without losing their chemical properties. Thermosetting plastics, on the other hand, are the opposite since they cannot be remolded once heated. As a result of these physical and chemical properties, thermoplastics have low melting points, while thermosetting products can withstand higher temperatures without loss of structural integrity (Thomas Publishing Company, 2020).

In addition, plastics are also divided into recyclable and non-recyclable. Recyclable plastics are plastic waste that can be introduced into a manufacturing process to make new materials and convert them into new products, while non-recyclables are plastics that can no longer be used as raw materials in the manufacturing process. The majority of non-recyclables are disposed of through landfills, which has a significant risk of polluting the environment. The summary of types of plastics is presented in Figure 7.1.

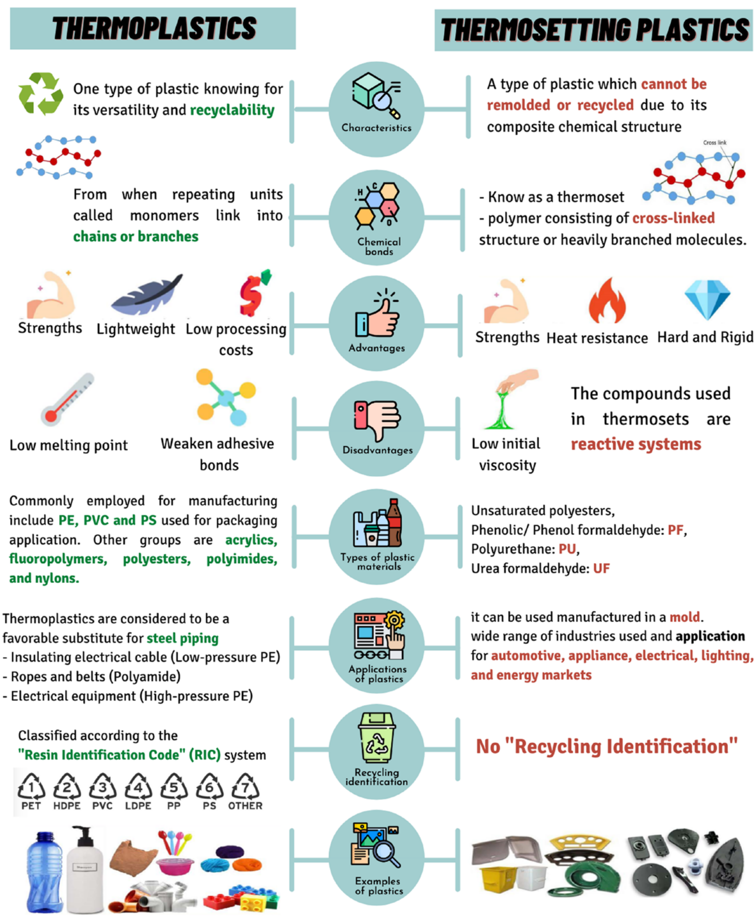

Figure 7.1 Plastic types: thermoplastics vs thermosetting plastics.

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7.1.2 Definition of non-recyclable plastics

In terms of recyclability, non-recyclable plastics are plastics that cannot be reprocessed as raw materials. Non-recyclable plastics are often contaminated or for which no current recycling system exists (Bottone, 2019). The definition of non-recyclable plastics is based on different aspects, which can be considered as follows.

7.1.2.1 Original properties

Given the thermal behavior of plastics, thermoplastics are known for its versatility and recyclability. The polymers form when repeating units called *monomers link into chains or branches*, as shown in Figure 7.2. The chains are held together by Van der Waal forces, weak attractions or interactions between molecules. This characteristic allows thermoplastic material to be repeatedly melted, remolded and recycled without negatively affecting the material's physical properties.

Several kinds of thermoplastic resins offer various performance benefits. However, most of them have high strength, shrink-resistance, and high flexibility. Depending on the resin, thermoplastics can serve low-stress applications such as plastic bags or can be used in high-stress mechanical parts. Examples of thermoplastic polymers include plastics that are listed as numbers 1–6 in the Resin Identification Code (RIC) system such as polyethylene (PE), polyvinylchloride (PVC), and polypropylene (PP), and other plastics (number 7 of RIC) such as acrylonitrile butadiene styrene (ABS) and nylon.

Thermoset polymer is a material that cannot be remolded or recycled because of its composite chemical composition. They set in their physical and chemical characteristics after the formation process, as implied by their name, and are no longer affected by subsequent heat exposure. The chemical change in thermosetting plastics that occurs during molding, which is triggered by temperature and pressure, is a result of a curing process. Once heated, thermosets form permanent chemical bonds or crosslinks with each

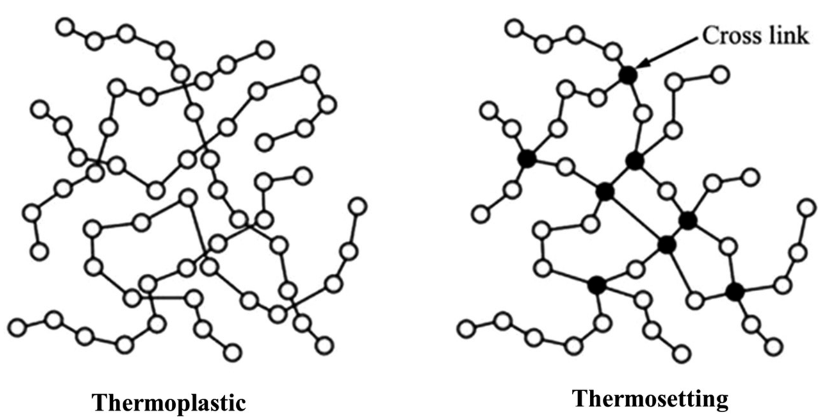

Figure 7.2 Polymer structure of thermoplastic and thermoset plastics (*Source*: Karuppiah, 2016).

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other (Figure 7.2). A high crosslink density will result in a very stiff, hard, and sometimes brittle material. Thermosetting plastics are non-recyclable because they cannot be remolded into new products.

After initial heat treatment, thermoset materials can withstand heat, corrosion and mechanical creep. This makes them perfectly suitable for use in components that require tight tolerances and excellent strength-to-weight characteristics while being exposed to elevated temperatures (Central Pollution Control Board, 2018). Examples of thermoset plastics are epoxy, phenolic, urea-formaldehyde and unsaturated polyesters.

Box1: Curing of Resin

Curing is a chemical process applied in polymer chemistry and process engineering that produces the toughening or hardening of a polymer material by cross-linking of polymer chains. This process is dependent on the types of resin. It can be originated by heat, radiation, electron beams, or chemical additives (Chambon & Winter, 1987).

1. Room temperature curing

The goal of curing polymers is to make the materials structurally stable. There are three main components, namely catalyst, cross-linking agent and accelerator, all of which are used together with the resin. The most used catalyst is methyl ethyl ketone peroxide (MEKP) while the common accelerator is cobalt naphthenate or cobalt octoate. For cross-linking agents, styrene is the most common agent used in this process. Mostly, 24 hours of curing time is required for room temperature curing. After this, the material can be removed from the mold and sent for further processing, such as post-curing at elevated temperatures (Biswas *et al.*, 2019).

2. High-temperature curing

High-temperature curing is used for compression, injection, and pultrusion molding techniques. In this process, free radical chain growth co-polymerization reactions occur between the cross-linking agent and the polymeric chains. The initiator first breaks and generates free radicals. These free radicals link with, for example, unsaturated polyester resins (UPR) chain molecules through the styrene oligomer. Many researchers have observed the effects of temperature on the curing process of UPRs at 30–50°C throughout the whole conversion range. It was found that, at the start of the reaction, co-polymerization occurs. Then, styrene conversion takes place, followed by the opening of C=C bonds. Eventually, the reaction of styrene and the side chain takes place (Biswas *et al.*, 2019).

Example: UV curing of thermosets by photopolymerization

- Curing by polymerization rather than vaporization
- Photopolymer: Light-sensitive resin that cures when light hits it
- UV light of 320–400 nm

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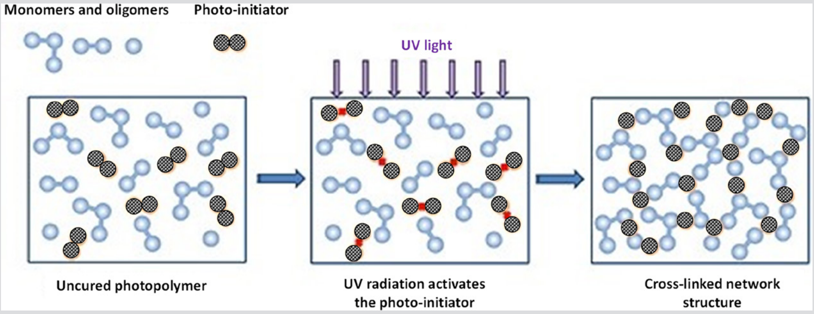

(*Source*: Jeffrey, 2016).

7.1.2.2 Composite materials

Composite materials are made by combining two or more materials that have significantly different physical or chemical properties. The components of composite materials include resin matrix, fiber reinforcements, core materials, additives and surface finishes (American Composites Manufacturers Association, 2022). The first modern composite material is fiberglass or fiber-reinforced polymer (FRP), and the most common FRP manufacturing process is hand lay-up or wet lay-up. Sheet molding compound (SMC) and bulk molding compound (BMC) are the later developed form of FRP composites which are widely processed by compression or injection molding (Forenge Technologies, N.D.).

Composite materials are high quality and have a long lifespan. Their higher strength, lower weight and less maintenance have led to many engineering applications, especially in the transport sector, for significantly reduced energy consumption and impact on the environment (Yang *et al.*, 2012). Three types of composite materials are developed and widely used in numerous kinds of engineering applications including polymer–matrix composites (PMC), metal–matrix composites (MMC) and ceramic–matrix composites (CMC). Regarding the reinforcement types, composite materials can be classified into particulate composites, fiber-reinforced composites, and structural composites. The classification of composite materials is presented in Figure 7.3.

For all types of composite materials, polymer–matrix is holding the largest share in the market, in which thermoset composites accounted for 72.0% of the overall revenue share in 2019. This is due to the growing demand for transportation and aerospace, and defense applications (Grand View Research, 2020). However, thermoplastic composites are also growing more rapidly in recent years.

The major application sector is automotive and transportation which accounted for 21.1% of the global market revenue in 2019. The aerospace and defense industry is also one of the most important to the composite market. In addition, composite materials are used in sports and recreation facilities,

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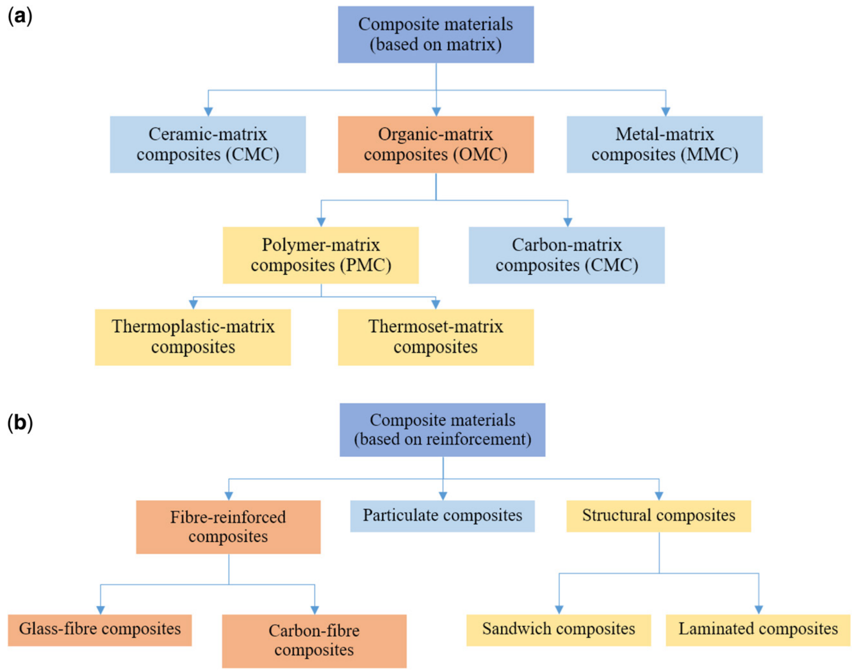

Figure 7.3 Classification of composite materials. (a) Based on matrix materials and (b) based on reinforcement materials (*Source*: modified from Ibrahim *et al.*, 2015).

boat and shipbuilding, wind energy generation for wind turbine blades, as well as in oil and gas offshore exploration. The examples of composite materials in different applications are shown in Figure 7.4.

Western European countries have the highest demand for composite materials, with Germany taking the largest market in 2018, and it is expected to continue its dominance over the forecast period (Grand View Research, 2019). In addition, the well-established automotive, aerospace and defence, construction, and electrical and electronics industries are anticipated to continue the growing trend in the European market. Increasing demand for cost-effective and high-performance composites in the renewable energy industry is also expected to drive the regional market. Figure 7.5 shows the statistics of the market value of composite materials worldwide in 2015, 2017 and 2019, with a forecast figure for 2027. It is estimated that the global market size for composites will increase upto 160.54 billion U.S. dollars in 2027.

Commercial recycling of composite materials remains limited due to technological and economic constraints. The basic problem is the difficulty in separating homogeneous components from composite materials. The presence of fibers and other types of reinforcement, as well as binders in composites, especially thermosets, is an obstacle to the recycling of this type of material. Because of these limitations, most of the recycling activities for composites are

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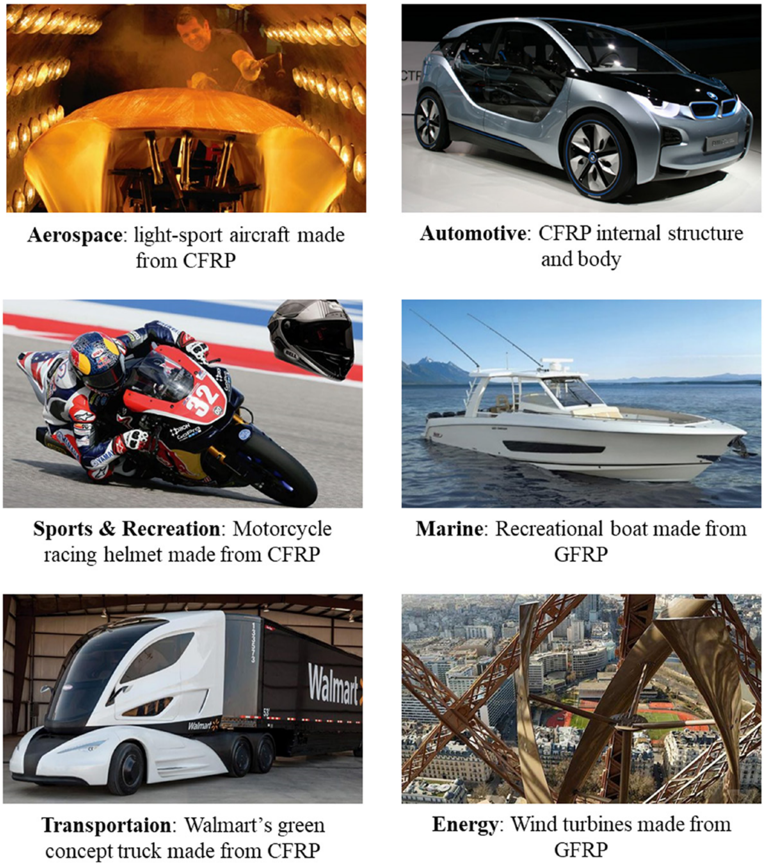

Figure 7.4 Applications of composite materials, CFRP is carbon fiber-reinforced polymer and GFRP is glass fiber-reinforced polymer (*Source*: http://compositeslab.com/where-are-composites-used/).

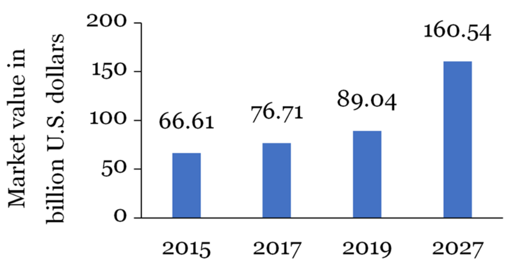

Figure 7.5 Market value of composite materials worldwide from 2015 to 2027 (*Source*: https://www.statista.com/statistics/944471/global-market-value-of-composites/).

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limited to down recycling such as energy or fuel recovery with little materials recovery such as reinforcement fibers. Additionally, the lack of markets, high recycling cost, and lower quality of the recyclates compared to the virgin materials also impede the use of recycled composite materials in many applications such as automotive, aerospace, and other engineering products. Environmental regulations, as well as long-term technology improvements, are essential to support recycling (Yang *et al*., 2012).

(a) Resins
Resins are used to transfer stress between reinforcing fibers. They are also used as glue to hold fibers together and protect the fibers from mechanical and environmental damage. Resins employed in reinforced polymer composites can be thermoplastic or thermoset.

(b) Reinforcements
Various reinforcements can be used to give the composite materials the desired properties according to their application. Natural and man-made materials, such as cellulose in wood, can be used as reinforcements. However, in commercial applications, most reinforcements are man-made. There are many commercially available reinforcement forms to meet the design requirements of the user. The ability to customize the fiber architecture allows for optimized performance of a product which translates to weight and cost savings.

Many forms of fiber are used as reinforcement in composite laminates, such as glass fibers, carbon fibers, aramid fibers (polyaramids), and polyester and nylon thermoplastic fibers. However, glass fibers are the most commonly used, which account for more than 90% of the fibers used in reinforced plastics. They are generally inexpensive to produce and have an excellent strength-to-weight ratio.

(c) Additives and fillers
Additives and modifiers are used to expand the usability of polymers by increasing their processability or extending product durability. They are generally used in relatively low quantity by weight compared to other components such as resins, reinforcements, and fillers. However, they perform critical functions. Although additives and modifiers often increase the cost of the basic material system, they always improve cost and performance.

- Additives
  There are several additives used to modify and enhance resin properties.
  - *Thixotropes*: Fumed silica or certain clays can be used as thixotropic agents in the hand lay-up or spray-up. In a standstill state, resins containing these agents have a high viscosity, reducing the liquid resin's tendency to flow or drain from vertical surfaces. The viscosity of the resin is reduced when it is sheared, making it easier to spray or brush on the mold.
  - *Pigments and colorants*: They can be added to resin or gel coat for cosmetic purposes or to enhance weatherability of products.

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  - *Fire retardants*: Most thermoset resins are combustible and produce toxic fumes when burned. Combustion resistance can be improved by selecting an appropriate resin type and using fillers or flame-retardant additives.
  - *Suppressants*: In open mold applications, styrene emission suppressants are used to prevent evaporation for air quality compliance. These wax-based materials form a film on the resin surface and reduce styrene emissions during the curing process.
- Fillers
  Fillers are used to improve mechanical properties of materials such as fire and smoke performance. The resins combined with fillers will shrink less than the unfilled resins, thus improving the dimensional control of molded parts. The composite properties can be improved for various applications by selecting the appropriate fillers. The important properties include water resistance, weathering, surface smoothness, stiffness, dimensional stability and temperature resistance.
  The use of inorganic fillers in composite applications is increasing. When used in composite laminates, this type of fillers can account for 40–65% by weight. Several inorganic filler materials are used with composites.
  - *Calcium carbonate*: It is the most widely used inorganic filler due to its low cost and is available in a wide range of particle sizes.
  - *Kaolin (hydrous aluminium silicate)*: It is the second most commonly used filler with its common name, clay. This filler is also available in different sizes.
  - *Alumina trihydrate*: This filler is usually used to reduce fire and smoke problems. When exposed to high temperatures, the filler gives off water (hydration), thereby reducing the flame spread and development of smoke.
  - *Calcium sulfate*: It is a low-cost filler used for flame and smoke retarding purposes, often used in the tub and shower industry.
- Core
  The core materials are used to produce rigid and lightweight composite products. The properties such as thermal conductivity, sound insulation and fire resistance can also be improved by use of the proper core material. The use of the core is called *sandwich construction* which consists of a face-skin laminate, the core material, and the back-skin laminate. The use of the core makes the laminate thicker, which results in a more rigid material.
- Surface finishes
  Mostly, surface finishes are used for UV protection, corrosion resistance and aesthetics. They can be critical to the long-term appearance of composite products. The examples of surface finishes are listed below.
  - *Gel coat*: It is used to improve weathering, filter out ultraviolet radiation, add flame resistance, provide a thermal barrier, improve chemical resistance, improve abrasion resistance, and provide a moisture barrier.

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- *Surface veils*: They are designed to improve the surface appearance and ensure the presence of a corrosion resistance barrier for typical composite products such as pipes, tanks and other chemical process equipment. Other benefits of the surface veils include increased resistance to abrasion, UV and other weathering forces.
- *Adhesives*: They are used to bond the composites to themselves and other surfaces. The three most common adhesives used in various applications include acrylics, epoxies and urethanes.
- *Ultraviolet protection*: Some materials are sensitive to UV degradation; thus, they should be protected from UV by an opaque gel-coated surface or by painting the exposed surfaces.
- *Painting*: Painting systems are widely used in both architectural and marine fields. Applying paints on the surface of composites requires proper abrasion and removal of residual mold release agents without special surface preparation.

7.1.2.3 Properties for non-recyclable plastics adjustment

From the viewpoint of recycling, waste can be classified into three groups (Sabău, 2018).

- Most of the manufacturing waste is in the form of a *single material*. As it is not contaminated with other materials, recycling is then easier. Usually, these wastes are reintroduced into production lines.
- *Easily separated waste* is made up of one to two polymers or contaminated materials like fillers (on a macroscopic scale). These materials are separable, at least in theory.
- *Microscopic mixtures* or intimately connected (soldered, interpenetration) are considered as the most difficult case for treatment since the separation of components is very difficult or even impossible, requiring complicated operations. The organic matrix composites are the sample materials that are classified in this category. The most representative example is the waste from the automotive industry. In this case, the blend will find materials (resins) thermoplastic, polymer mix, fibers, fillers and multilayer composite materials.

However, the first two types of plastic waste are currently common in waste recycling. For the composite materials, landfilling and incineration are the common methods for disposal of this kind of materials. Although there are initiatives for mechanical recycling, organizing a practicable collection/transportation/processing system for the waste and finding markets for the recyclates are two main barriers to this approach (Jacob, 2011).

In the case of the microscopic mixtures, multilayered plastics are commonly found in some packaging industries. The multilayered packaging is any material used for packaging which has at least one layer of plastic as the main ingredients, and it is combined with one or more layers of other materials such as paper, polymeric materials, or aluminum foil. The combination can be in the form of a laminate or co-extruded structure (Central Pollution Control Board,

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Table 7.1 Sources and uses of non-recyclable plastic waste.

No.	Sources	Examples
1	Food packaging	Multilayer films are used for packing of biscuits, chips, and juices
2	Pharmaceutical and cosmetic products	Multilayered packing is used for packing of medicines, tablets and cosmetics
3	Electrical and electronic goods	Multilayer films such as bubble raps, laminates are used for packing of electrical and electronic items
4	Items used for food storage and serving	Thermocol products such as plates or cups are used for serving food, tea, or coffee. They are also used as fillers in packing of goods and items

Source: Adapted from Central Pollution Control Board (2018).

2018). It is marked with the symbol '7' and 'other' in the resin identification code (RIC) system.

Multilayered plastics are generally used in the packaging industry since they provide good barrier properties which are required for the products such as food, pharmaceuticals and electronic products. Several goods are made of multilayered plastics as shown in Table 7.1 and Figure 7.6. Although this type of plastic is produced from thermoset or thermoplastic material, due to its complex structure, it is very difficult to separate from each other, thus considered as *non-recyclable*.

The packaging industry is the largest sector of plastic consumption, accounting for 36% of total global plastic production in 2015 (Malhotra, 2020). In addition, more than 45% of plastic waste generated in the same year was from packaging materials. Furthermore, among packaging films produced, the

Figure 7.6 Examples of multilayer plastics in daily life (*Source*: https://packagingsouthasia.com/she-safety-health-and-environment/sustainability-health/why-multilayered-plastic-structures-are-indispensable/).

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multilayer materials account for approximately 17% (Lahtela *et al.*, 2020). The increasing demand for this type of plastic is also expected to be about 7%, and during 2018–2026, the global market value is predicted to expand by 4.4% with CAGR (compound annual growth rate). PE and PP films are the common manufactured films used for the production of multilayered packaging, either for use as a package or as a coating material. Both PE and PP account for 60–65% of the total quantity of the produced films.

The growing demand for packaging materials due to packed products' safety and quality requirements has resulted in the significant development of advanced packaging techniques (Tartakowski, 2010). Economic and environmental considerations have led to a replacement of single-layer films by multilayer films. Compared to common single-layer films, the multilayers provide special properties, including high barrier for water vapor, gases and aromatics, as well as high mechanical strength, good sealability and resistance at low temperatures. These properties result from the synergy of basic properties of the materials used such as PE, PP, polyethylene terephthalate (PET) and polystyrene (PS) and the use of ethylene vinyl alcohol (EVOH) and ethylene vinyl acetate (EVA) as a barrier and adhesion layer. An example of using multilayers instead of single-layer plastics for resource-saving purposes is EVOH in packaging products. The EVOH barrier layer with a thickness of 4–20 μm has the same barrier properties as polyamide (PA) with a thickness of 400 μm. An overview of commonly used materials and their particular functions are shown in Table 7.2 (Kaiser *et al.*, 2018).

Table 7.2 Overview of common functional layers.

Mechanical Stability	Oxygen Barrier	Moisture Barrier	Light Barrier	Tie Layers	Sealant
HDPE	EVOH	PE (LD, LLD, HD)	Aluminum	Polyurethanes	LLDPE
PP, OPP	PVDC	PP, OPP	TiO_2 filled polymers	Acid/anhydride grafted polyolefins	LDPE
OPET	Polyamides (nylon, BOPA)	EVA	–	–	EVA
PS	Polyesters, OPET	Ionomers	–	–	Ionomers
Paper	Coatings (SiO_x, Al_2O_3, PVOH, nano particles)	PVDC	–	–	PP, OPP
–	Aluminum	–	–	–	PA, OPA
–		–	–	–	PET, OPET

Source: Kaiser et al. (2018).
Note: Abbreviations: BOPA, biaxially oriented polyamide, EVA, polyethylene-vinyl acetate, OPA, oriented polyamide, OPET, oriented polyethylene terephthalate, OPP, oriented polypropene, PVDC, polyvinylidene chloride, PVOH, polyvinyl alcohol, PE, polyethene, LD, ow-density, LLD, linear low-density, HD, high-density.

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The recycling of multilayer packaging is available for certain products such as liquid packaging boards (LPBs), in which their end-of-life recycling option is already established on the market. The components of LPBs include 21% of PE, 4% of aluminum, and about 75% of cardboard. The cardboard layer is used to provide stability of the product, while the PE layers provide protection against moisture from the outer and the inner sides of the packaging. For aluminum, it acts as a gas barrier.

Furthermore, in order to recycle multilayer post-industrial waste, a delamination process may be required. Nevertheless, for polymer–polymer multilayer materials, no industrial solution has been available until now (Kaiser *et al*., 2018). The recycling of multilayer films is still an important challenge due to several reasons.

- Various materials used for each layer
- Large differences in the processing properties of the materials used for multilayer films
- Lack of systems for identification of multilayer film (e.g., PS/PE, PET/PE, etc.)
- Lack of system solutions for the collection of these materials, which results in contamination with other materials with similar visible characteristics (color, thickness, stiffness)
- Lack of standard research of the properties, processing and applications of composites based on recycled multicomponent materials
- Lack of economically viable systems of segregation of the various materials

Due to the similar appearance of multilayers and single-layer films, it is possible that the target films will be processed with other films as a result of inappropriate segregation and false characterization of properties. This contamination leads to the production of material with undefined properties, which prevents the proper processing of the material and its application as a desired device (Tartakowski, 2010).

The multilayered plastics hold a large percentage in the packaging market, and mostly they are treated by incineration or landfilling due to the difficulty in recycling. However, in order to recycle these materials, the replacement of multilayer packaging by monomaterials can be a potential option for some multilayer systems. Nevertheless, it is expected that the monomaterials can substitute not all kinds of multilayers. In addition, functionality, costs and marketing are still the main factors of the packaging market. Therefore, it may be worthwhile to have a closer look at the recycling strategies of this type of material (Kaiser *et al*., 2018).

7.2 FACTORS AFFECTING RECYCLABILITY OF THE PLASTICS

7.2.1 Degree of contamination

Currently, many recycling plants are optimizing their systems so that they can efficiently sort and process recycled materials. However, in some situations, it has been found that recyclable products are mixed with non-recyclable waste. This is because the recyclables are put in the incorrect recycling bins, causing

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the recyclable items to be contaminated with other unwanted materials such as food, grease, or liquid. Hence, the recyclable materials cannot be processed or recycled effectively. In addition, the recyclable plastics can become dirty non-recyclable waste through the contamination by their own product such as dirty food box, or the contamination from storage, collection, and transportation processes. Also, partly recyclable items such as children's car seats, where certain components are recyclable and others are not, can contaminate the recycling system as well (Rabbit Waste Management, 2020). The contamination of recycling streams by other non-recyclable waste or different recyclable waste results in the rejection of recyclable items, causing the entire waste to be disposed of by landfills.

The average recycling contamination rate is about 25%, meaning that out of every four items there is one contaminant presented (Cleanriver Recycling Solutions, N.D.). The high concentrations of non-recyclable items or contamination of other forms such as food waste in the recyclable stream may happen for several reasons (Stephenson, 2018).

- People are confused about what goes in which bin.
- People are not always very careful about what they put in.
- In areas where all types of recyclable waste are collected in one bin, one type of waste can contaminate another.

However, even in cases where plastic contamination could be dealt with, it is sometimes more economically feasible to divert some loads to landfills. The cost for processing poorly sorted or contaminated plastic waste is more expensive, in some cases outweighing profits from recycled materials (Ritchie, 2018).

Plastic contamination is related to the amount of plastic waste sent to landfills. For example, in the UK, most bottles will usually be managed for reprocessing in the country, but plastic waste that is less valuable which is about two-thirds collected for recycling goes overseas as shown in Figure 7.7. In 2017, the UK exported more than 600 000 tons of plastic waste, and all could be highly contaminated, as reported by The National Audit Office (Rabbit Waste Management, 2020; Stephenson, 2018). This means that with the large number of contaminated plastic waste, the entire load of waste may not be reprocessed and may end up in landfills or contribute to environmental pollution.

7.2.1.1 Contamination of non-recyclable waste or other recycling in plastic waste flow

Waste separation at the source is very important for the effective recycling process. Some recyclable plastic waste becomes non-recyclable waste when contaminated with non-recyclable plastics or food waste, as shown in Figure 7.8. The non-recyclables can lead to contamination of the supply. Although many facilities have automated and/or manual procedures for removing non-recyclables, they are not always 100% effective. If waste streams contain a significant number of non-recyclables, the facilities may not be economically feasible to sort. The same applies to food or liquid waste, uncleaned plastics can contaminate the supply, and the disposal of these loads must be taken directly

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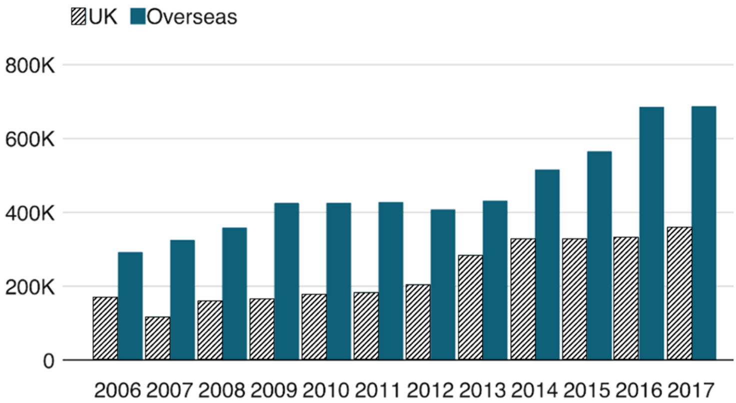

Figure 7.7 Tons of plastic sent for reprocessing (*Source*: https://www.bbc.com/news/science-environment-45496884).

Figure 7.8 Examples of contaminated plastics (*Source*: https://www.bbc.com/news/science-environment-45496884).

to landfills (Salt Lake City, 2019). The contamination of non-recyclable waste into recyclable plastic streams makes the whole stream unsuitable for recycling. All this plastic waste will become non-recycled plastics which are defined as plastics that are not redirected for recycling and remain in municipal solid waste (MSW) or in materials recovery facility residue. Table 7.3 illustrates the

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Table 7.3 Global composition of non-recycled plastic waste consisted in MSW.

Plastic Material	Malaysia Plastic Waste[a] (%)	US plastic Waste[a] (%)	UK Plastic Waste[a] (%)	Thailand Plastic Waste[b] (%)	Global Plastic Waste[a] (%)
PET	16.2	12.4	15.3	5.9	15.4
HDPE	26.2	17.8	13.5	57.4	17.0
PVC	3.9	5.5	3.5	2.2	3.1
LDPE	31.1	19.6	25.0	17.4	34.0
PP	8.2	13.9	22.2	7.3	15.4
PS	13.0	8.7	4.0	4.8	12.4

Source: [a]Sharuddin et al. (2017); [b]Areeprasert et al. (2017).

percentages of plastic materials that are presented in MSW. This table can imply that although there is recyclable waste such as PET, when it is contaminated with other non-recyclable waste, all must be taken to landfills.

The examples of contaminants in the plastic recycling stream are listed below.

(1) Non-recyclable plastics
Types of non-recyclable plastics depend on several factors such as market and city government. If there is a demand in the market, then recyclers and companies will pay for the post-consumer recyclables, and they will become economically valuable materials (Sedaghat, 2018). In addition, the types of recyclable plastics can vary significantly between countries depending on recycling policies, targets and the effectiveness of recycling separation methods. However, mostly plastic bags, shrink wrap, bubble wrap, newspaper bags or trash bags are considered as non-recyclables since they have a high possibility to damage or tangle the machines. In addition, PS is also not usually accepted in recycling program due to its lightness that easily is blown away and creates litter during collection. Moreover, its bulky characteristic is also one of the reasons that PS is not preferred as it requires high transportation cost. Also, PS is hazardous to be in contact with any food as some studies have found that PS can create health problems. Therefore, it is often not profitable to recycle PS (Sharuddin *et al.*, 2017).

(2) Other recyclable items
The combination of different types of recyclable waste can create a complication in waste sorting system. For example, it creates more work to the recycling workers, and the workers can be exposed to hazardous waste through leachate if there is some liquid from bottles and e-waste in the recycling stream. Moreover, plastics can be contaminated with heavy metals from the electronic device. This potentially affects the quality and applicability of reprocessed plastic, as it might be unsuitable for use in certain applications such as food packaging due to elevated metal concentrations (Eriksen *et al.*, 2018).

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(3) Other wastes
Food waste and bio-hazardous waste such as tissue paper or diapers are also contaminants found in recycling stream. In addition to complicating the sorting system, they can create unsafe conditions for workers in recycling facilities (Recyclebank, 2014). Most recyclable waste must be switched to landfill when contaminated with organic waste.
Due to the contamination with other wastes as well as thermal breakdown or destruction in processing, the quality of recycled plastics is degraded, resulting in the limitation of repeated recycling. For most recyclable plastics, they are typically only suitable for recycling once. As a result, most recycled plastics eventually reach landfills even if they go through an additional use cycle as another product. The recycling process typically delays rather than prevents plastic disposal to landfills or incineration (Ritchie, 2018).

7.2.1.2 *Contamination of different recyclable plastics*

In addition to the contamination with non-recyclable waste, the contamination of different types of recyclable plastics also needs to be considered in the recycling process as the contaminants can affect the quality of the target recycled plastics. When the waste is contaminated with another type, the quality of the material will drop. For example, a small amount of PVC contaminant presenting in a PET recycling stream will degrade the recycled PET resin due to the evolution of hydrochloric acid gas from the PVC at a higher temperature which is required to melt and reprocess PET. On the other hand, PET plastics in a PVC recycling stream will form solid lumps of undispersed crystalline PET, which significantly reduces the value of the recycled material (Hopewell *et al.*, 2009). For this reason, multi-layer or multi-component articles which consist of several types of polymers, are also not recycled.

Another example is the contamination of biopolymer on the recycling process of petroleum-based plastic waste (Gere & Czigany, 2020). Small amounts of polylactic acid (PLA) have a significant negative effect on the properties of PET plastics when they are mixed together (PET/PLA:95/5% by weight) (La Mantia *et al.*, 2012). At the processing temperature of PET, PLA will be degraded, which leads to the yellowing of the product. In addition, since PET and PLA are thermodynamically immiscible, holes, peaks or clusters can appear in the products. Moreover, the glass transition temperatures of the two polymers are also different, resulting in opaqueness or haziness in PLA-contaminated PET products. These are important problems as optical and surface properties may be even more important than mechanical properties in mass production.

7.2.2 Market value

The selection of recyclable or non-recyclable plastics in each location also depends on the market value of plastics. Although many types of plastics can be recycled, they are not always economical. The price of used plastics depends on both supply and demand of recycling market (Milios *et al.*, 2018). Generally, the plastics that have good quality and sufficient amount and easy processing will be

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Figure 7.9 Maximum price per ton in November 2018 of used plastic waste (*Source*: https://www.bbc.com/news/science-environment-45496884).

selected by plastic manufacturers. Therefore, recycled PET and high-density polyethylene (HDPE) are more expensive than other plastics. Manufacturers often believe that transparent plastics are often desirable since they can be dyed to transform into new products, resulting in greater flexibility, unlike pigmented or dyed plastics with lower market value. In addition, recyclers also prefer rigid containers made of a single polymer as they are simpler and more economical to recycle over multi-layer and multi-component package (Hopewell *et al.*, 2009).

Normally, high-priced plastics will be collected whereas the plastics that cannot be sold will not be collected and become non-recyclable plastics. Figure 7.9 shows the price of some types of used plastics, in which natural HDPE has the highest price, and the colored PET has the same price as mixed plastic waste.

Based on polymer types, the price of used plastics is presented in Table 7.4. The most recycled plastic worldwide is post-consumer PET, followed by HDPE, low-density polyethylene (LDPE), PP and others. The recycled PET is dominating the market due to its widely used applications such as packaging, electronics, construction and others. In addition, recycled PET and PE accounted for 70% of total post-consumer plastics recycling (Future Market Insights, 2018; Market Research Future, 2019).

Table 7.4 Price of plastic waste based on polymer types.

Type of Plastics	Recycling Rate (%)	Price (Baht/kg)[d]	Recyclability
PET	26.8[a]	1.1 (screened)–9.0 (pure color)	High
HDPE	29.3[a]	1.5–5.0	↓
PVC	<1.0[b]	0.4 (bottle)–13.0 (pipe)	
LDPE	2.4[c]	1.3	
PP	3.0[b]	1.0–3.0	
PS	–	0.5–1.5	
Other	–	1.0–2.0	Low

Source: [a]USEPA (2020); [b]Seaman (2012); [c]Harper (2003); [d]Wongpanit International Company (2020) (30 Baht = 1US$).

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Additionally, the reasons that make some plastics become recyclable or non-recyclable plastics are as follows:

7.2.2.1 PET

PET plastic is recyclable because the polymer chain breaks down at a relatively low temperature, and also there is no degradation of the polymer chain during the recycling process. These properties allow PET plastic to be recycled a large number of times before it becomes unusable. Normally, PET attracts the high prices, especially clear bottle. However, colored plastic is less desirable as the color cannot be removed, thereby complicating the recycling process. For PET plastic, it is suggested for single-use applications. Repeated use can increase the risk of chemical leaching and bacterial growth.

7.2.2.2 HDPE

HDPE is the most commonly recycled plastic and is considered as one of the safest forms of plastic. The recycling process of HDPE is relatively simple and cost effective (Seaman, 2012).

7.2.2.3 PVC

Mostly, PVC products are not acceptable for recycling. Two major problems are the high chlorine content in raw PVC (~56% of the polymer's weight) and the high levels of hazardous additives added to the polymer to achieve the desired material properties. As a result, PVC requires separation process from other plastics before mechanical recycling (Rubio, 2019).

7.2.2.4 LDPE

LDPE plastics are less toxic than other plastics and are relatively safe for use. However, in the recycling process, plastic wrapping and thin plastic bags can create the risk of clogging the processing machinery if they are collected along with larger, heavier and more rigid recyclable plastics. Also, products made from recycled LDPE are not as hard or rigid as those made from recycled HDPE plastic. Therefore, LDPE is not commonly recycled.

7.2.2.5 PP

PP is considered as a recyclable plastic in some curbside recycling programs. However, it is difficult and expensive to get rid of the smell of the product that the recycled PP housed in its first life. Some scents are particularly offensive, such as gasoline or moldy yogurt. In addition, the recycled material ends up having black or gray color, which makes it difficult to be reused in packaging. Therefore, the recycling rate of PP plastics is still lower than PET or HDPE plastics.

7.2.2.6 PS

PS plastic is not generally recyclable and accounts for about 35% of US landfill material. Because PS is structurally weak and ultra-lightweight, it breaks up easily and is dispersed readily throughout the natural environment. In addition, PS may leach styrene, a possible human carcinogen, into food products. The

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chemicals present in PS have been linked with human health and reproductive system dysfunction. Therefore, most curbside collection services do not recycle PS plastics.

7.2.2.7 Other plastics

Because the plastics labelled as no. 7 under RIC system tend to be mixed plastics, combined with other layers of materials such as foil, or contaminated by food waste, these plastics are nearly impossible to be recycled. An effort to recycle this type of low-quality plastic by melting and reprocessing is a costly process that yields lower-value materials that are unlikely to be profitable to recyclers (Ho, 2020).

7.3 ADVANCED SEGREGATING TECHNOLOGY AND PLASTICS WASTE MANAGEMENT

7.3.1 Current situation

The quantity and demand of plastics steadily increase every year since they can be applied to various applications. However, this fact reflects that plastic waste generated will also increase. About 10% of global plastic production is thermoset plastics (Patoski, 2019), and approximately 17% of packaging film production is multilayer materials (Lahtela *et al.*, 2020). These two types of plastics are considered non-recyclable, most of which ends up in landfills and eventually contaminates the environment.

Globally, only 9% of plastic waste is recycled (Parker, 2018). However, the recycling rates of plastics vary significantly across different countries, waste streams and polymer types. Some polymers are more widely recycled than others. For example, recycling rates for PET and HDPE plastics commonly exceed 10%. This is because of the high-volume and relatively clean waste stream of these plastics, making them relatively easy to recycle (OECD, 2018). According to the USEPA report (2019), 8% of 35 370 tons of plastic waste generated in U.S. in 2017 was recycled whereas about 76% was dumped into landfills. Meanwhile, around 6% of plastic waste from India is non-recyclable which accounts for approximately 0.56 million tons per year (Central Pollution Control Board, 2018).

Practically, some of the theoretical recyclable plastics are not accepted by most recycling centers such as plastic bags. This is due to the possibility of machine clogging during recycling and blown-away residuals into the neighborhood near the facility. Several curbside recycling programs do not allow putting plastic bags or films and Styrofoam into the recycling bins, such as in Salk Lake City, San Diego, Bowie, U.S.A. and Ottawa, Canada (Salt Lake City, 2019; The City of San Diego, N.D.; City of Bowie, 2022; City of Ottawa, N.D.). Therefore, in this context, these plastics are considered as non-recyclable waste. Meanwhile, the plastics are recyclable when they are in Los Angeles, U.S (City of Los Angeles, N.D.). The curbside bins in this city allow residents to dispose of any types of cleaned plastics, including plastics labelled as numbers 1–7, including plastic bags and PS products. In the City of Toronto, Canada, PE film plastic bags are accepted in the City's blue bin recycling program where they are separated using hand sorting and a vacuum system from the rest of the

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recyclable materials such as glass, metals, paper, other plastics (City of Toronto, 2020). Film plastics are then baled and shipped to reprocessors where they are converted into flakes and pellets that can be used to produce new film plastic products. Another example of the city that collects plastic bags is the recycling program in Madison, U.S. (City of Madison, N.D.). The clean and dry plastic bags made from HDPE or LDPE are acceptable, but food wrap, bubble wrap or the shopping bags, which are often thick white or gray bags, are still an exception. For multilayered plastics, mostly they are non-recyclable plastics. However, in Japan, some of them are collected for recycling to make products such as toy blocks, and the rest are sent to incinerators (Thejapantimes, 2019a).

7.3.2 Non-recyclable plastic waste management

The presence of non-recyclable plastics in the plastic recycling stream results in the rejection of the whole waste. All cannot be reprocessed and become garbage which must be diverted directly to landfills or the incineration process. In addition, the contamination of MSW or other non-recyclable waste in the recyclable plastic stream leads to a loss of opportunity to recycle the good plastics. However, with the proper separation of recyclable plastics from general waste, the number of recyclable plastics contained in the total waste will be reduced which means more plastic waste can be reprocessed. Also, the remainder that needs to be disposed of to landfills will be reduced as well.

However, non-recyclable plastics currently are handled in the same manner as general waste, in which they are sent to landfills or incinerators for final disposal. For example, the Japanese government categorizes non-recyclable plastics including dirty plastics as combustible waste and combines them with other combustible items such as food waste and paper waste. Then, all wastes are sent to incinerators for energy recovery (Thejapantimes, 2019b).

Since approximately 6.3 billion metric tons of plastics have become waste (Parker, 2018), and 79% of this (5 billion metric tons) is accumulating in landfills or spreading into the natural environment as litter, this means that at some point, much of it will end up in the oceans, causing significant pollution and threatening aquatic life, especially in coastline-rich nations with less-developed waste management strategies (Benavides *et al.*, 2017).

7.4 CASE STUDIES OF NON-RECYCLABLE PLASTICS MANAGEMENT AND LESSONS LEARNED

Recently, non-recyclable plastics have become a big challenge worldwide. Both developed and developing countries face the problem of how to deal with the residual or non-recyclable plastics waste after segregating processes. To overcome these problems, the government agencies may have to introduce a solid waste policy starting from minimizing plastic waste generation, implementing effective management and conducting proper disposal/recovery methods.

In the case of developing countries, Thailand has become a major plastic polluter of the ocean, with the majority of the plastic debris found in rivers and seas being single-use plastics that are difficult to recycle using conventional methods. Most non-recyclable plastic waste or contaminated plastic waste

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is combined and managed together with solid waste. The government has implemented the National Solid Waste Management Master Plan (2016–2021) to promote materials recycling and increase the waste collecting and sanitary landfill rate. In addition to that, the government has also been promoting the usage of alternative energy from the residual or non-recyclable plastics waste by 30% within 20 years (2015–2036). This plan to convert residual plastics waste to generate power promotes this alternative energy for the small and medium local administration in Thailand. The first management method has been applied to adjust the ratios of plastic wastes in waste collecting (increasing waste-collecting rate by 40%), recycling (having recycling rate of 21% in industrial waste and 30% in MSW) and disposal (obtaining 40% of sanitary landfill rate), and these are also expected to reduce the ratios of residual or non-recyclable plastics in plastics waste stream. The second management method has been introduced during 2015–2036 to use residual or non-recyclable plastic wastes generating power. The energy recovery rate and alternative fuel used will increase by recovering the electricity generation from industrial waste and MSW, thermal energy from waste and pyrolysis oil. As a result of both managements, in 2020, the plastic material flow analysis (MFA) showed the ratios of plastics in landfill, open environment and recyclable plastics to consumption as follows:

- Baseline figures were 30.55%, 15.78%, and 23.22%, respectively,
- Figures from the implementation of the first management method were 31.88%, 9.47%, and 29.13%, respectively, and
- Figures from the implementation of the second management method were 32.17%, 10.46%, and 22.13%, respectively.

There was an increase in all three ratios when the baseline situation and the implementation of first management method are compared, benefiting the recycling section. However, an increase in the amount of plastic wastes to landfills indicated that some recyclable plastics cannot be included in recycling processes. This would be due to insufficient understanding, lack of cooperation among the relevant stakeholders and some issues in market prices of plastic materials and a degree of contamination. For the second management method, a large amount of plastic waste was disposed of in landfills because a number of plastic wastes cannot be converted to power generating substances or combustible materials. Additionally, the cost of investment for energy recovery facilities and energy price are the main obstacles that prevent the long-term implementation of the energy recovery. To achieve effective management of non-recyclable plastics, sustainable development plans and goals should be promoted by the government sector (Bureecam *et al.*, 2018).

As for developed countries, alternative recycling pathways were conducted in the United States (2017) with effective management approaches, and waste to fuel and waste to energy are frequently applied as a solution to issues related to residual or non-recyclable plastic wastes. However, these processes have specific technical challenges, and it is important to determine the amount of energy recovered from plastic wastes. If all plastic wastes in the US (32.1 Mt) were recovered to energy, a low generation rate of electricity (0.6 EJ or 0.6 quads) would be observed, equivalent to only 4% of total electricity net

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generated in the US. Also, another concern of CO_2 emission is that combustion of plastics typically results in greater CO_2 emissions than disposing of plastics in the landfill. Alternatively, converting all the landfilled plastics (28.2 Mt) into fuel via pyrolysis could generate more than 26 gigaliters (6.8 billion gallons) of liquid fuels. These equal to 15% of the distillate fuel oil (diesel) consumed annually in the US. The life cycle for the greenhouse gas emissions from plastic-derived diesel fuel is estimated to be 1%–14% lower than conventional diesel, and the plastic to fuel pathway also has lower emissions per ton of plastic than conventional disposal (landfill and waste to energy) (Heller *et al.*, 2020).

Another case study of how the recovery systems can support mechanical recycling is observed in Japan. In 2018, 2080 kt (kt = thousand tons) of plastic waste was used in mechanical recycling (the process for manufacturing new plastic products using recyclable plastic waste as a raw material). Of this amount, 710 kt was domestic plastic waste (17%). Meanwhile, 1370 kt of industrial plastic waste (30%) was found in the mechanical recycling, which was 2 times greater than that of the domestic plastic waste. This is because of its quality and comparative stability in the plastic waste supply in the mechanical recycling as well a large proportion of generated industrial plastic waste. In the mechanical recycling of the plastic waste, used plastic products and the plastics loss in production and processing were observed to be 1470 and 620 kt, respectively. The 1470 kt of used plastic products consisted of 530, 240, 210, 80, 70 kt of PET bottles, wrapping film, home electrical appliance housings, agricultural plastics and electric-wire covering materials, respectively. The success of the mechanical recycling in Japan can be attributed to law enforcements and efficient cooperation among relevant stakeholders in the recycling mechanisms (Plastic Waste Management Institute, 2019).

REFERENCES

American Composites Manufacturers Association (2022). Materials. http://compositeslab.com/composite-materials/ (accessed 23 November 2020).

Areeprasert C., Asingsamanunt J., Srisawat S., Kaharn J., Inseemeesak B., Phasee P., Khaobang C., Siwakosit W. and Chiemchaisri C. (2017). Municipal plastic waste composition study at transfer station of Bangkok and possibility of its energy recovery by pyrolysis. *Energy Procedia*, **107**, 222–226, https://doi.org/10.1016/j.egypro.2016.12.132

Benavides P. T., Sun P., Han J., Dunn J. B. and Wang M. (2017). Life-cycle analysis of fuels from post-use non-recycled plastics. *Fuel*, **203**, 11–22, https://doi.org/10.1016/j.fuel.2017.04.070

Biswas B., Bandyopadhyay N. R. and Sinha A. (2019). Mechanical and dynamic mechanical properties of unsaturated polyester resin-based composites. In: Unsaturated Polyester Resins, S. Thomas, M. Hosur and C. J. Chirayil (eds.), Elsevier, Amsterdam, Netherlands, pp. 407–434.

Bottone G. (2019). Start-up of the day: Turning non-recyclable plastics into synthetic gas. https://innovationorigins.com/start-up-of-the-day-tuning-non-recyclable-plastics-into-syngas/ (accessed 30 October 2020).

Bureecam C., Chaisomphob T. and Sungsomboon P. Y. (2018). Material flows analysis of plastic in Thailand. *Thermal Science*, **22**(6 Part A), 2379–2388, https://doi.org/10.2298/TSCI160525005B

Downloaded from http://iwa.silverchair.com/ebooks/book/chapter-pdf/1234760/9781789063448_0285.pdf
by guest

Central Pollution Control Board (2018). Guidelines for the Disposal of Non-Recyclable Fraction (Multi-Layered) Plastic Waste. Ministry of Environment, Forest and Climate Change, Government of India, Shahdar, Delhi.
Chambon F. and Winter H. H. (1987). Linear viscoelasticity at the gel point of a crosslinking PDMS with imbalanced stoichiometry. *Journal of Rheology*, **31**(8), 683–697, https://doi.org/10.1122/1.549955
City of Bowie (2022). Residential Recycling. https://www.cityofbowie.org/1026/Residential-Recycling (accessed 7 December 2020).
City of Los Angeles (N.D.). Blue bin collection (recycling). https://www.lacitysan.org/san/faces/home/portal/s-lsh-wwd/s-lsh-wwd-s/s-lsh-wwd-s-r/s-lsh-wwd-s-r-rybb?_adf.ctrl-state=qo8a8u6q5_5&_afrLoop=19684233644286427#! (accessed 12 November 2020).
City of Madison (N.D.). Plastic bag recycling. https://www.cityofmadison.com/streets/recycling/plasticbag.cfm (accessed 7 December 2020).
City of Ottawa (N.D.). Recycling. https://ottawa.ca/en/garbage-and-recycling/recycling (accessed 7 December 2020)
City of Toronto (2020). Plastic bags – recycling process. https://www.toronto.ca/311/knowledgebase/kb/docs/articles/solid-waste-management-services/processing-and-resource-management/processing-recycling/plastic-bags-recycling-process.html (accessed 7 December 2020).
Cleanriver Recycling Solutions (N.D.). What is Recycling Contamination? 4 Ways to Reduce Contamination and Recycle Right. https://cleanriver.com/how-to-reduce-recycling-contamination/ (accessed 27 November 2020).
Eriksen M. K., Pivnenko K., Olsson M. E. and Astrup T. F. (2018). Contamination in plastic recycling: influence of metals on the quality of reprocessed plastic. *Waste Management*, **79**, 595–606, https://doi.org/10.1016/j.wasman.2018.08.007
Forenge Technologies (N.D.). SMC & BMC Composites. http://www.forenge.com/bmc.html (accessed 10 November 2020).
Future Market Insights (2018). Plastic Recycling Market. https://www.futuremarketinsights.com/reports/plastic-recycling-market (accessed 5 December 2020).
Gere D. and Czigany T. (2020). Future trends of plastic bottle recycling: compatibilization of PET and PLA. *Polymer Testing*, **81**, 106160, https://doi.org/10.1016/j.polymertesting.2019.106160
Grand View Research (2019). Europe Composites Market Analysis Report by Product (Carbon Fiber, Glass Fiber), By Resin (Thermosetting, Thermoplastic), By Manufacturing Process, By End Use, And Segment Forecasts, 2019–2025. https://www.grandviewresearch.com/industry-analysis/europe-composites-market (accessed 23 November 2020).
Grand View Research (2020). Composites Market Size, Share & Trends Analysis Report by Product (Carbon, Glass), By Resin (Thermosetting, Thermoplastics), By Manufacturing Process, By End Use, And Segment Forecasts, 2020–2027. https://www.grandviewresearch.com/industry-analysis/composites-market (accessed 23 November 2020).
Harper A. C. (2003). Handbook of Plastics Technologies: The Complete Guide to Properties and Performance. The McGraw-Hill Companies, Inc., New York, USA. https://www.globalspec.com/reference/64215/203279/8-6-recycling-of-low-density-polyethylene-ldpe-and-linear-low-density-polyethylene-lldpe (accessed 5 December 2020).
Heller M. C., Mazor M. H. and Keoleian G. A. (2020). Plastics in the US: toward a material flow characterization of production, markets and end of life. *Environmental Research Letters*, **15**(9), 094034, https://doi.org/10.1088/1748-9326/ab9e1e

Downloaded from http://iwa.silverchair.com/ebooks/book/chapter-pdf/1234760/9781789063448_0285.pdf
by guest

Ho S. (2020). Global Waste Crisis: Let's Talk About Low-Value Plastics. https://www.greenqueen.com.hk/global-waste-crisis-lets-talk-about-low-value-plastics (accessed 6 December 2020).

Hopewell J., Dvorak R. and Kosior E. (2009). Plastics recycling: challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **364**(1526), 2115–2126, https://doi.org/10.1098/rstb.2008.0311

Ibrahim I. D., Jamiru T., Sadiku R. E., Kupolati W. K., Agwuncha S. C. and Ekundayo G. (2015). The use of polypropylene in bamboo fibre composites and their mechanical properties–A review. *Journal of Reinforced Plastics and Composites*, **34**(16), 1347–1356.

Jacob A. (2011). Composites can be recycled. *Reinforced Plastics*, **55**(3), 45–46, https://doi.org/10.1016/S0034-3617(11)70079-0

Jeffrey G. (2016). UV Curing of Thermosets Part 11: Using UV Rheology to Monitor Curing – 2. https://polymerinnovationblog.com/uv-curing-thermosets-part-11-using-uv-rheology-monitor-curing-2/ (accessed 8 December 2020)

Kaiser K., Schmid M. and Schlummer M. (2018). Recycling of polymer-based multilayer packaging: a review. *Recycling*, **3**(1), 1, https://doi.org/10.3390/recycling3010001

Karuppiah A. V. (2016). Predicting the Influence of Weave Architecture on the Stress Relaxation Behavior of Woven Composite Using Finite Element Based Micromechanics. Doctoral dissertation, Wichita State University.

Lahtela V., Silwal S. and Kärki T. (2020). Re-processing of multilayer plastic materials as a part of the recycling process: The features of processed multilayer materials. *Polymers*, **12**(11), 2517, https://doi.org/10.3390/polym12112517

La Mantia F. P., Botta L., Morreale M. and Scaffaro R. (2012). Effect of small amounts of poly (lactic acid) on the recycling of poly (ethylene terephthalate) bottles. *Polymer Degradation and Stability*, **97**(1), 21–24.

Malhotra M. (2020). Multilayered Plastics: A Persisting Problem in Plastic Pollution. https://medium.com/age-of-awareness/multilayered-plastics-a-persisting-problem-in-plastic-pollution-4015d95230 (accessed 23 November 2020)

Market Research Future (2019). Global Plastic Recycling Market. https://www.marketresearchfuture.com/reports/plastic-recycling-market-2859 (accessed 5 December 2020)

Milios L., Christensen L. H., McKinnon D., Christensen C., Rasch M. K. and Eriksen M. H. (2018). Plastic recycling in the Nordics: A value chain market analysis. *Waste Management*, **76**, 180–189, https://doi.org/10.1016/j.wasman.2018.03.034

OECD (2018). Improving plastics management: trends, policy responses, and the role of international co-operation and trade. *Environmental Policy Papers*, **12**, 20.

Parker L. (2018). A whopping 91% of plastic isn't recycled. https://www.nationalgeographic.com/news/2017/07/plastic-produced-recycling-waste-ocean-trash-debris-environment/ (accessed 11 November 2020).

Patoski A. (2019). Why Is Most Plastic Not Recycled? https://repurpose.global/letstalktrash/why-is-most-plastic-not-recycled/ (accessed 7 December 2020).

Plastic Waste Management Institute (2019). An Introduction to Plastic Recycling. https://www.pwmi.or.jp/ei/plastic_recycling_2019.pdf (accessed 14 December 2020).

Rabbit Waste Management (2020). The problem with contamination and recycling. https://www.rabbitgroup.co.uk/news/the-problem-with-contamination-and-recycling/ (accessed 27 November 2020).

Recyclebank (2014). Why Can't I Recycle Stuff with Food on It? https://livegreen.recyclebank.com/column/because-you-asked/why-can-t-i-recycle-stuff-with-food-on-it (accessed 2 December 2020).

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by guest

Ritchie H. (2018). FAQs on Plastics. https://ourworldindata.org/faq-on-plastics (accessed 27 November 2020).
Rubio R. M. (2019). Recycling of PVC – Prospects and Challenges. https://www.ecomena.org/recycling-pvc/ (accessed 6 December 2020).
Sabău E. (2018). Recycling of polymeric composite materials. In: Product Lifecycle Management–Terminology and Applications, R. Udroiu and P. Bere (eds.), IntechOpen, London, UK, pp. 103–121.
Salt Lake City (2019). What Can I Put in My Curbside Recycling Container? https://www.slc.gov/sustainability/waste-management/curbside/recycling-can/ (accessed 12 November 2020).
Seaman G. (2012). Plastics by the Numbers. https://learn.eartheasy.com/articles/plastics-by-the-numbers/ (accessed 5 December 2020).
Sedaghat L. (2018). 7 Things You Didn't Know About Plastic (and Recycling). https://blog.nationalgeographic.org/2018/04/04/7-things-you-didnt-know-about-plastic-and-recycling/ (accessed 11 November 2020).
Sharuddin S. D. A., Abnisa F., Daud W. M. A. W. and Aroua M. K. (2017). Energy recovery from pyrolysis of plastic waste: study on non-recycled plastics (NRP) data as the real measure of plastic waste. *Energy Conversion and Management*, **148**, 925–934, https://doi.org/10.1016/j.enconman.2017.06.046
Stephenson W. (2018). Why plastic recycling is so confusing. https://www.bbc.com/news/science-environment-45496884 (accessed 27 November 2020).
Sustainable Recycling Industries (SRI) India (2016). Co-processing of non-recyclable hazardous plastic waste in cement kiln. https://www.sustainable-recycling.org/wp-content/uploads/2018/03/Co-Processing-Non-Recyclable-plastics-in-cement-kiln-25-11-2016.pdf (accessed 5 December 2020).
Tartakowski Z. (2010). Recycling of packaging multilayer films: New materials for technical products. *Resources, Conservation and Recycling*, **55**(2), 167–170, https://doi.org/10.1016/j.resconrec.2010.09.004
The City of San Diego (N.D.). Curbside Recycling Tips (FAQs). https://www.sandiego.gov/sites/default/files/legacy/environmentalservices/pdf/recycling/recyclingfaqs.pdf (accessed 12 November 2020).
Thejapantimes (2019a). Addressing disposal and recycling systems in Japan. https://www.japantimes.co.jp/2019/04/29/special-supplements/addressing-disposal-recycling-systems-japan (accessed 7 December 2020).
Thejapantimes (2019b). Japan to ask municipalities to dispose of industrial plastic waste as trash piles up due to China ban. https://www.japantimes.co.jp/news/2019/05/17/national/japan-ask-municipalities-dispose-industrial-plastic-waste-piles-due-china-ban/ (accessed 8 December 2020).
Thomas Publishing Company (2020). Comparison of Thermoset Versus Thermoplastic Materials. https://www.thomasnet.com/articles/plastics-rubber/thermoset-vs-thermoplastics (accessed 8 October 2020).
USEPA (2019). Plastics: Material-Specific Data. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data (accessed 11 November 2020).
USEPA (2020). Facts and Figures about Materials, Waste and Recycling. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data (accessed 5 December 2020).
Wongpanit International Company (2020). Price Sunday 6 December 2020 (Retail Price). http://www.wongpanit.com/ (accessed 6 December 2020).
Yang Y., Boom R., Irion B., van Heerden D. J., Kuiper P. and de Wit H. (2012). Recycling of composite materials. *Chemical Engineering and Processing: Process Intensification*, **51**, 53–68, https://doi.org/10.1016/j.cep.2011.09.007

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