Plastics Waste Management: Processing and Disposal

Dr. Muralisrinivasan
Natamai Subramanian

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A Smithers Group Company

Shawbury, Shrewsbury, Shropshire, SY4 4NR, United Kingdom
Telephone: +44 (0)1939 250383 Fax: +44 (0)1939 251118
http://www.polymer-books.com

First Published in 2016 by

Smithers Rapra Technology Ltd
Shawbury, Shrewsbury, Shropshire, SY4 4NR, UK

A catalogue record for this book is available from the British Library.

ISBN: 978-1-91024-296-4 (hardback)
978-1-91024-297-1 (ebook)

Typeset by Integra Software Services Pvt. Ltd.

Preface

Plastics are increasingly used in modern-day life due to their wide-ranging properties which can be used in a variety of applications. '*Plastics Waste Management: Processing and Disposal*' is primarily written from an industrial point-of-view and relates waste management to understanding the correct processes for dealing with the growing issue of plastics waste.

This book mainly focuses on plastics waste, though plastic materials, additives and processing are dealt with to some extent; thermosetting materials are also briefly covered. It would be impossible, in a volume of this size, to cover all the plastics and additives in detail.

Plastics and the environment are also discussed and, although limited to a few pages, provides information which is extremely useful. The section on plastics processing management describes the methods of manufacturing plastic products and the chapter dealing with case studies gives practical guidance as well as considerable information regarding recycling and disposal. This book contains a wealth of information and a comprehensive approach to waste management.

Similarly, the sales and marketing of recycled plastics are discussed and is followed by a section on the management of recycled plastics. This book will be of great interest to professionals within the environment and plastics industries who want to contribute to progress within this field. This book gives a clear and comprehensive exposition of the many facets of plastics waste management. The bulk of the information concerns the concepts and fundamentals of waste management, and offers fresh ideas to consider when addressing the problems of plastics waste.

This book contains references to research and methods of plastics waste management, which will be invaluable to students, engineers, academics, technologists, plastics processors and management personnel. This unique new book is a methodical statement, in clear, technical terms, of what is actually known, in the scientific sense, about plastics waste management. This book is designed to accompany management or technology courses in business schools and universities, as well as being relevant to academic research departments. Due to its subject matter and technological detail it is also a valuable reference work.

The section regarding the future of the plastics waste industry covers the development and possibilities of a number of activities, and is highly suited for personnel in the plastics waste industry and people concerned with waste management.

I would like to thank the small army of support who helped to write the book, my wife Himachalaganga, my sons Venkatasubramanian (Studying in KLN College of Information Technology) and Sailesh (Vellammal College of Engineering and Technology), and the encouragement of professors to get the job done. Special thanks also to Mrs Helene Chavaroche and Mrs Eleanor Garmson of Smithers Rapra. Above all, the almighty is to receive my sincere gratitude.

Dr Muralisrinivasan Natamai Subramanian

Madurai

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Introduction

Plastics waste can be used as a raw material for recycling operations or can be treated prior to disposal, resulting in the waste being transformed into material which can be safely disposed of or reused. The proper management of plastics waste starts at the production stage. Plastics waste has an economic advantage, in comparison with many other solid wastes, as it can be regularly recycled. Current processing technology enables the efficient conversion of waste into new recycled end products.

Plastics waste is closely linked to population type and size, and the degree of urbanisation and material comfort. It remains a major challenge for municipalities to collect, recycle, treat and dispose of increasing quantities of plastics waste in most developed and developing countries. Most technologies for plastics waste management are immature and have been difficult to implement in many countries.

Global postconsumer waste generation totals approximately 900–1,250 metric tonnes per year [1, 2]. In an underdeveloped country, the per capita solid waste generation rate is less than 0.1 tonnes per capita per year as opposed to developed countries where it is greater than 0.8 tonnes per capita per year in high-income industrialised countries [3–10].

Industrialists should know the type and quantity of waste produced by their operations and processes, whereas a waste generator should know the composition, properties and environmental impact of the waste. Without this knowledge industrialists cannot properly manage their operations and cannot discharge their responsibilities to protect the health and safety of employees, i.e., the nature of the waste they are exposed to must be known, otherwise they are not in full control of their operation; in addition, if the quantity of waste is unknown the cost, material balance and efficiency cannot be determined [11].

Plastics waste management does not exist in a vacuum; waste plastics are affected by and impact upon many different aspects of national life, i.e., there is a balance between the utilisation of plastics waste and its production and processing. The majority of plastics waste generation is related to material comfort items; however, recycling/ reuse initiatives for mixed plastics are limited [1].

In particular, it is crucial that plastics waste management is linked to the parallel development of production and processing, otherwise there is a risk that controls to limit the environmental pollution of one operation will lead to an increased level of pollution in another, hence:

- Plastic processes and activities should be chosen which produce the lowest amount of waste.

- The production of hazardous waste from antimony and lead and so on, should be kept to a minimum.

- All feasible and reasonable steps should be taken to recycle and reuse materials from plastics waste and convert this waste into useful marketable products.

- The waste disposal process should include arrangements for the disposal of plastics waste that cannot be reclaimed, such as degraded polyvinyl chloride. Disposal should reduce the level of risk to public health, water supplies and the environment to acceptable levels.

- All types of solid waste should only be disposed of at sites suitable for the disposal of that particular waste, which will not be reclaimed. The site can stipulate upon acceptance, any special requirements regarding the method of deposal which includes preparation to receive the waste, the methods involved in disposing of the waste and so on.

- Plastics waste treatment and the methods to be used for the disposal of the residues from the treatment should be included in the waste disposal process.

- Waste generators are responsible for their waste, which is a very important aspect for plastics waste. Generators of waste must be assumed to have adequate knowledge of its composition, form, and of the potential hazards to public health and the environment, to ensure disposal of the waste is not detrimental to the environment. The waste generator is responsible for ensuring that only appropriate disposal methods are used for their waste.

- Future planning needs to include the proper management of plastics waste.

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2 Plastics and Additives

Plastics are extraordinarily persistent in the environment after disposal and are capable of resisting physical, chemical and biological degradation for decades and longer. Plastic is included in a wide variety of applications which are used in everyday life, as they are light-weight, tough and cost-effective. A large amount of plastic is used for packaging and container materials as these applications make the most of the unique properties of plastic; the use of any other material for these applications would lead to a three-fold increase in weight resulting in increased transportation and disposal weights, and further environmental loading due to the higher energy demand involved in their production and disposal [1]. Polymer formation processes have led to the development of plastics with properties tailored to specific applications. The addition of elements such as carbon, hydrogen, nitrogen, oxygen, fluorine, silicon, sulfur and chlorine, has enabled the production of thousands of types of plastic.

Polymers are produced *via* polymerisation techniques, such as anionic, cationic, step-growth and so on, which result in the formation of large molecules from monomers. The use of one type of monomer results in a homopolymer, whereas the use of two or more different monomers leads to the formation of copolymers. Polymerisation is usually controlled by the addition of a catalyst or initiator, and polymers produced by these techniques are thermoplastic in nature.

Plastics generally consist of macromolecules called polymers and additives which are used to modify the properties of the material; polymers rarely consist of pure polymer. Additives are used in the production of plastics to enhance the appearance, improve strength and change certain characteristics. Plastics continue to advance into many applications that are used in a range of sectors from automotive and aerospace to medical and electrical. Plastics are synthetic materials composed of chemical compounds called monomers, which are chemical units that react together to form long chains of repeating units. Plastic is in a gas or liquid state at the start of the production process and is converted into a finished solid state *via* a liquid forming state, which can be achieved *via* heat, pressure or a combination of the two. Composites are made by the addition of reinforcing material.

Synthetic polymeric plastic materials accumulate in the environment at a rate of 25 million metric tonnes per annum. Polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP) and polystyrene (PS) are all used globally in large quantities. In terms of consumption, PVC is the third most important thermoplastic material with widespread applications ranging from packaging to healthcare devices, toys, building materials, electrical wire insulation, clothes and furnishing [2].

2.1 Thermoplastics

Thermoplastics are created from monomers and, upon the application of heat and pressure, in the presence of a catalyst, a polymer is produced. During the process, monomers join with each other and the chain length grows until the reactive ends combine, which stops chain growth at that point. During the polymerisation reaction, the polymer chains simultaneously grow in length. The addition of predetermined inhibitors (chain growth stoppers) can produce polymers with a consistent average chain length, which is a key factor in determining many properties of the plastic and its processing characteristics. Increasing the chain length increases toughness, creep resistance, stress-crack resistance, melt temperature (T_m), melt viscosity and leads to processing difficulty due to the non-degradable nature of the polymer.

It is possible to manufacture polymer molecules with an average molecular weight(s) (MW) distribution and there can be either a broad or narrow spread between the MW of the largest and smallest molecules.

A narrow MW distribution provides more uniform properties and a broad distribution material is easier to process.

Thermoplastics soften or melt during heating and regain rigidity when cool. Various processing techniques have been developed for moulding a specific shape by exploiting the properties of thermoplastics. No chemical change or crosslinking of molecules occurs during processing. As thermoplastics will soften during reheating, prior to being reformed, the finished polymer chains from the completed polymerisation process are thermoplastic, i.e., heat mouldable.

2.1.1 Polyolefins

The bulk properties of polyolefin(s) (PO) can be tailored *via* catalyst design. PO are important polymers which are derived from relatively inexpensive feed stocks and are generally hydrophobic in nature. PO require surface modification to improve certain properties such as adhesion, wettability, printability and biocompatibility. Upon exposure to light or heat, PO usually exhibit an induction period, during which minimal oxygen uptake or changes in physical properties are observed [3]. PO are subject to thermal and oxidative degradation and cannot be used in practical applications, such as automotive parts, unless they are protected with efficient antioxidants [4].

2.1.1.1 Polyethylene

PE is one of the most degradation-resistant plastics when disposed of in the environment. Even in and on the soil, it does not display any visible changes and has been used for long-term exposure in the sea for applications such as cable covering and sonar devices. It continues to be the most important plastic in terms of volume used for manufacturing. The low-density polyethylene (LDPE) market continues to dominate with approximately 75% consumption for packaging film manufacturing, followed by extrusion coating and injection moulding products; LDPE comprises 64% of the global plastic material manufactured in the form of packaging and bottles, which are usually discarded after only brief use[5].

In theory, PE should be structurally stable against photooxidation; however, it may undergo loss of mechanical properties upon outdoor exposure if it includes branching, impurities or residual catalytic species. Plastic bags accumulate in the environment due to their low degradability, hence generating pollution and taking space in landfills. In addition, as they generate very small mass and are usually contaminated, recycling is economically unfeasible [6, 7]. Their elimination at composting plants is not complete, therefore, fragments of bags end up contaminating the compost which ultimately requires screening or other processes to remove it. **Table 2.1** illustrates some of the physical properties of PE.

Table 2.1 Physical properties of PE

Physical parameters	**Value**	**Units**
Specific gravity	0.91–0.94	–
Melting point	110–135	° C
Tensile strength	10–60	Mpa
Elastic modulus	550–1,000	KPa
Hardness	45–70	Shore D

PE represents the largest constituent of plastics in the municipal waste stream and the fraction is mainly composed of high-density polyethylene (HDPE) packaging materials. Recycling this type of waste packaging material yields a stream of recycled plastic that is highly homogeneous and consistent [8].

The high volume usage ensures that there are large quantities of postconsumer HDPE, plastics bags, homopolymers (e.g., milk and juice bottles) and copolymers (e.g., shampoo bottles) for recycling. The resultant recyclate has essentially the same rheological properties as the virgin resin since it does not undergo any appreciable thermal degradation during recycling [9].

2.1.1.2 Polypropylene

PP has an excellent balance of physical and mechanical properties, and the products based on PP are economical and can be easily recycled. The bulk properties of PP are attractive and can be varied *via* synthesis conditions; however, the surface properties are not easily controllable [10]. Due to its low surface energy, the adhesion of PP to other polar materials is generally low, which significantly limits its engineering applications. To increase the surface energy, surface modification *via* chemical or physical means is necessary [11].

PP is widely used in various applications requiring good impact properties. Using various elastomers, the required impact strength and ductility are achieved *via* chemical modification or mechanical blending. PP belongs to the group of commodity thermoplastics and produces a large amount of waste; considerable effort is required to upgrade the characteristics of waste PP in order to recycle it [12].

PP is a highly hydrophobic and non-polar polymer and can be used for the preparation of nanocomposites only after a compatibilising process in which polar groups are introduced [13]. PP belongs to the semicrystalline PO family and is resistant to chemicals and abrasion; its advantages include higher rigidity over other PO and due to the presence of tertiary hydrogen in the backbone chain, PP is very susceptible to degradation [14]. **Table 2.2** illustrates some of the physical properties of PP.

Table 2.2 Physical properties of PP

Physical parameters	**Value**	**Units**
Specific gravity	0.905	–
Elastic modulus	1,140–1,550	KPa
Impact strength by Izod method at 23 °C	65	J/m^2
Hardness (Shore D)	73	–
Melting point (T_m)	178.1	°C
Tensile strength	23.49 ± 0.23	MPa

PP is light-weight, which is an important factor for material substitution in automotive engineering. It allows greater freedom of design due to its impact strength and can replace many conventional materials. PP can withstand higher temperatures than PS and PE, which makes it suitable for use in automotive components [15].

PP is extensively used in the packaging of consumer goods, which increases the amount of discarded PP packaging material in the waste stream. Postconsumer waste from PP is therefore abundant and recycling is a viable option for solid waste management. The recycling of PP is dependent on its structure and properties, and thermal properties are of particular importance when processing waste PP [16].

2.1.1.3 Polystyrene

PS is currently widely used due to its good mechanical properties and ease of processing, as well as its relatively low cost [17]. As a result of its chemical stability and ubiquity, a large amount of plastics, including PS, have accumulated in the environment causing a phenomenon termed 'white pollution' [18]. In order to reduce the accumulation of PS in the environment, new recycling/disposal processes should be sought. Among them is the possibility of converting PS into a more easily biodegradable material, though this is a challenge for the materials and microbiological sciences. Although PS is hardly crystalline, its molecules have high molar masses and are non-polar, existing in the glassy state at room temperature (RT); as such, enzymatic attacks are very difficult [19]. Moreover, the phenyl side groups, which are distributed in space in a disordered manner, are biodegraded very slowly [20].

New component housing materials made from PS for equipment in the fields of office systems and information technology exhibit a marked improvement in toughness and, with approximately 40% of the market, it is the most important market segment followed by injection moulding, electrical and electronics, and refrigerator manufacture. In packaging, the trend is for highly transparent, sparkling and/or tough film. **Table 2.3** illustrates some of the physical properties of PS.

Table 2.3 Physical properties of PS

Physical parameters	Value	Units
Specific gravity	1.04	–
Limiting oxygen index	17.8	%
Solubility parameter	15.6–21.1	$(MPa)^{1/2}$ in various solvents
T_g	100	°C

T_g: Glass transition temperature

In the case of PS, the weak sites of the polymer chain are the tertiary carbon atoms attached to the phenyl groups, which are vulnerable to attack by free radicals. At these weak sites, a series of chemical reactions can lead to cleavage of the chain and initiate the formation of carbonyl groups [21, 22]; the presence of carbonyl groups, as well as moieties capable of forming free radicals, such as peroxides, accelerates degradation [18, 23].

2.1.1.4 Polyvinyl Chloride

PVC is the second largest volume of plastic used worldwide and plays an important role in the plastic industry. Due to its compounding versatility, PVC can be processed into many long-life products, such as appliances and pipes. PVC is an integral part of plastic recycling opportunities and can be processed into many short-life products, such as beverage packaging. About 40% of PVC is used for making pipes and recycled PVC material containing virgin grade PVC is an appealing prospect to make new pipe products [24–27]. **Table 2.4** illustrates some of the physical properties of PVC.

Table 2.4 Physical properties of PVC

Physical parameters	Value	Units
Specific gravity	1.35–1.4	–
Tensile strength	56.6	MPa
Elongation	85	%
T_g	71	°C
Melting transition temperature	200–300	°C (decomposition occurs)

Despite all the environmental debates, PVC is still one of the most important commercially used plastics. Rigid PVC accounts for the major share of PVC production and is used primarily in the construction industry for the manufacture of pipes, fittings and profiles; the outstanding price performance of this material results in the continual displacement of wood and aluminium.

PVC is one of the primary thermoplastic polymers used for the production of biomedical disposable devices owing to its compatibility with a large number of additives (i.e., plasticisers, impact modifiers, heat stabilisers), its wide-ranging mechanical properties which yield rigid to flexible end products and, last but not least, the ability to produce relatively low-cost materials [28].

2.1.1.5 Acrylonitrile-butadiene-styrene

Acrylonitrile-butadiene-styrene (ABS) is one of the most frequently used polymers in the production of electrical and electronic equipment, it also has widespread applications in automobiles, communication instruments and other commodities. Within the electrical and electronic sector, the quantity of recycled plastics could be increased *via* the recycling of ABS to reduce environmental, economic and energy issues. **Table 2.5** illustrates some of the physical parameters of ABS.

Table 2.5 Physical properties of ABS

Physical parameters	**Value**	**Units**
Specific gravity	1.01–1.05	–
Tensile strength	6,000	psi
Elongation	5–20	%
Hardness	103	Rockwell R

ABS is sensitive to oxidation due to the presence of polybutadiene components, which act as oxidation sensitisers and lead to the formation of carbonyl groups, which absorb at 1,680–1,750 cm^{-1} [29].

2.1.1.6 Polyester

Polyester resins are widely used due to their versatility and economic cost. Polyester exhibits a good combination of resistance to softening and deformation at elevated temperatures, good electrical properties and high resistance to corrosion as well as excellent weatherability [30, 31]. Structural applications, such as reinforced polyester containing glass fibre, comprise more than 80% of the market. **Table 2.6** illustrates some of the physical parameters of polyester.

Table 2.6 Physical properties of polyester

Physical parameters	Value	Units
Specific gravity	1.26–1.49	–
Tensile strength	6,780–8,860	psi
Elongation	1–13	%
Hardness	86–122	Rockwell R
Melting transition temperature	157–164	°C

2.1.1.7 Polycarbonate

Polycarbonate (PC) has excellent mechanical strength, particularly impact strength, good electrical properties and transparency, and is widely utilised in a variety of fields including office machinery, electric and electronic machinery, automobiles, architecture and so on. Many applications require that a PC composition be flame retardant(s) (FR) and combine ease of processing with good optical properties. **Table 2.7** illustrates some of the physical properties of PC.

Table 2.7 Physical properties of PC

Physical parameters	Value	Units
Specific gravity	1.18–1.22	–
Tensile strength	8,120–9,940	psi

Table 2.7 *Continued*		
Elongation	4.9–9.4	%
Hardness	70–121	Rockwell R
Melting transition temperature	165–212	°C

2.1.1.8 Polyamide

Polyamide(s) (PA), the first engineering thermoplastic, was originally developed in the form of high strength textile fibres, which were basically hygroscopic in nature and required drying before processing. Its highly crystalline nature, which can be controlled to some degree during processing, has a major effect on all properties and results in higher strength, higher stiffness, a high heat deflection temperature and so on. PA are sensitive to ultraviolet (UV) radiation and exhibit good resistance to creep and cold flow compared with many less rigid thermoplastics. **Table 2.8** illustrates some of the physical properties of PA.

Table 2.8 Physical properties of PA

Physical parameters	Value	Units
Specific gravity	1.03–1.05	–
Tensile modulus	161,000	psi
Flexural modulus	41,800–200,000	psi
Hardness	78–108	Rockwell R
Melting transition temperature	94	°C

2.1.1.9 Biodegradable Polymers

Fully biodegradable polymers are completely converted into small molecules, such as carbon dioxide, water, minerals and biomass, by microorganisms and do not have any environmental impact or ecotoxicity. The time taken for degradation to occur is measured using the life cycle time. Many polymers that are claimed to be 'biodegradable' are in fact 'bioerodable', 'hydrobiodegradable', 'photodegradable', undergo slow degradation or just partially biodegradable.

The development of a substantial volume of the municipal solid waste to be commercially viable biodegradable plastics is an important effort towards the preservation and revitalisation of our global environment. In waste management, biodegradable polymers with a controllable lifetime are becoming increasingly important. Biodegradation is described as degradation by microorganisms and its chief advantage is that it enables the currently considerable volume of waste to be assimilated by the natural environment [32, 33].

2.2 Thermosets

The production of thermoset plastics is quite different to that of thermoplastics; thermoset polymerisation occurs *via* a two-stage curing process using a material and moulding technique. It is polymerised *via* a reaction between two chemicals in the presence of peroxide and an accelerator, with or without heat, and the resulting pressure depends upon the reacting molecules. The majority of linear molecules are formed at the initial stage and even the linear chains contain unreacted portions which are capable of flowing under heat and pressure.

The final stage of thermoset polymerisation occurs in the moulding press. Under pressure, the partially reacted compound undergoes crosslinking reactions between the molecular chains. Thermoset monomers with three or more reactive ends lead its molecular chains to crosslink in three dimensions. Flexible thermosets have longer chains with fewer crosslinks.

A thermoset plastic has strong, interconnected permanent bonds which are not heat reversible. After curing, reheating does not cause remelting, therefore, thermoset materials cannot be remoulded. Continuous heating may lead to breaking the crosslinks which in turn leads to degradation.

Many thermosets are polymerised *via* the condensation reaction in which a by-product, such as water and so on, is created during the reaction in the mould. Volatile by-products cause dimensional instability and low part strength unless they are removed during moulding. In some thermoset materials, the reaction occurs *via* the addition reaction where there is no formation of volatile by-products; permanent crosslinks occur even at RT. Thermosets, due to their crosslinking nature, are resistant to higher temperatures and provide greater dimensional stability than most thermoplastics.

2.2.1 Phenol-formaldehyde

Phenol-formaldehyde resins, the workhorse of the thermosets, are moulded *via* compression, transfer and injection methods, and are principally compounds which contain fillers. They are high-performance engineering plastics used as bonding and impregnating materials, which exhibit good heat resistance and heat deflection temperature, in addition to high electrical and flame resistance properties. It is a low-cost material with excellent mouldability and dimensional stability, along with good water and chemical resistance.

2.2.2 Unsaturated Polyester

Unsaturated polyester resins are dissolved in styrene to enable free-radical chain growth copolymerisation between the resin and styrene monomers. Styrene serves as an agent which links the polyester chains resulting in the development of a crosslinking network. Approximately 7% shrinkage by volume occurs during the curing and crosslinking stages [34, 35]. Shrinkage is one of the main disadvantages of this process as it leads to a lack of dimensional stability of the end product as well as poor surface quality.

The inclusion of a thermoplastic additive to the formulation decreases the extent of shrinkage.

Products containing unsaturated polyester resins are not widely recycled due to poor material characteristics, long processing times, and non-uniform shape and composition. Even though polyethylene terephthalate (PET) is low cost, the recycling of wastes of clear or coloured PET is limited. High-performance PET is a thermoplastic polyester with excellent thermal and mechanical properties which is widely used as an economical, ecological and consumer-friendly material for video and audio tapes, X-ray films, food packaging, soft-drinks bottles and jars. The demand for PET has increased year-on-year with the subsequent increase of PET waste.

PET recycling technologies have become well known and represent one of the most successful and widespread examples of polymer recycling. There are two methods of recycling PET waste: one method involves physical recycling to produce PET flakes which are reused in a resin, and the other method involves chemical recycling *via* the depolymerisation of PET wastes.

2.3 Additives

Additives are chemical compounds that are added during polymer production, typically during compounding, to impart desired properties without modifying the molecular architecture of the base material [36]. Without exception, all plastics contain additives which are used to impart a variety of functionalities. Additives, such as antioxidants, nucleating agents and so on, can modify the bulk properties of a polymer and need to be uniformly dispersed in the polymer to be effective.

Plastics contain additives such as heat and light stabilisers, antioxidants, UV-absorbers, lubricants and plasticisers, which cannot be used in any device/item to be placed inside the body. However, these additives are absolutely necessary for the processing and stability of plastics; in addition, they are required to achieve the desired mechanical properties of the final plastic products.

Several thousand different additives exist which can be added to plastic polymers in order to create compounds to be used for specific plastic products. The use of additives is not evenly distributed among the different types of plastic; PVC production alone accounts for 73% of the global consumption of additives by volume followed by 10% in PE and PP, and 5% in styrenics [37].

Additives are commonly used in thermoplastics and thermosetting plastics in order to achieve specific properties, such as stiffness and prevent heat distortion, and to aid processing to produce an economic end product. Various combinations of additives and stabilising agents are used during a particular compounding process in order to meet the requirements of a desired application, in addition to preventing thermal oxidation or degradation and discolouration during the melt process, and impart long-term heat and light stability. The selection of additives and compounding process to be used depends on the end applications of the compounded products. The presence of additives in the polymer, particularly antioxidants and UV-stabilisers, may reduce the service lifetime of the end product [38, 39]. The migration of additives depends not only on the low MW and high mobility of the additive but also on the density of the plastic, the additive concentration, contact time and temperature in the system [40], and on the physico-chemical properties of the system components. The number of additives used in the processing of polymers is large and each one has a specific role [41].

Chemical additives are incorporated into plastics to enhance the service lifetime of the end product and improve the processing and physical properties of the material. Different additives modify different properties such as, improving the optical properties, resist aging, enhancing the bulk mechanical properties or for a variety of other reasons. Additives are not chemically bonded with the plastics but are dispersed in the matrix. The leaching, omission or chemical transformation of additives results in product failure.

2.3.1 Antioxidants

Antioxidants are used as radical scavengers, i.e., to inhibit oxidation by donating a hydrogen atom, in order to compete with the polymer substrate to either form peroxy radicals or breakdown peroxides to form intermediate products, as oxidation reactions regenerate the antioxidant. PP is particularly sensitive to oxidation and requires large amounts of antioxidants and UV-stabilisers, as does PE but to a lesser extent [42].

The use of stabilisers to combat thermooxidative phenomena is a key factor in preserving the polymer's properties. PP may undergo degradation during processing at high temperatures or prolonged use in adverse conditions, such as in the presence of heat, light and chemical agents. Degradation of the polymer results in an increased melt index, lower MW and reduced mechanical properties; therefore, the addition of antioxidants to PP is strongly recommended.

2.3.2 Slip Additives

Slip agents are additives that facilitate the free movement of adjacent plastic sheets in sliding contact, often by causing microscopic surface roughness. Antiblock agents inhibit the sticking (welding) of plastics to each other upon contact or under moderate pressure. The properties that control the effectiveness of amides as slip and antiblock agents have been related to their mode of action [43, 44]. Amides are commonly used as slip agents which help reduce the coefficient of friction and allow the molecules to flow easily.

Amides dispersed in melted PE at RT, at levels exceeding their solubility, migrate to the PE surface during and after the blowing of films. Exuded amides form random aggregates on the film's surface that reduce the close contact and cohesion between adjacent sheets. Slip or antiblock activity increases upon increasing the amount of amide on the PE surface until a critical level is reached; thereafter, further increase of the surface amide concentration does not improve the slip or antiblock properties and may produce an undesirable oily layer on the film.

The most effective amides are solids at RT, which may form crystals on the film surface and diffuse rapidly from the PE surface.

The fatty amides used in PE production include: erucamide (EA) (*cis*-13-docosenoic acid, amide), behenamide (docosenoic acid, amide), oleamide (OA) and stearamide (SA) [43]. Unsaturated amides, such as EA and OA, provide superior slip properties, whereas saturated amides, such as behenamide and SA, provide acceptable slip and superior antiblocking properties. EA displaced OA as the preferred slip agent for the production of PO film because it melts at a higher temperature and is more stable at extrusion temperatures; EA can be used as a slip and antiblock agent [45]. SA also provides useful slip properties, although it is slower acting it has superior antiblock properties to those of EA and OA.

Primary fatty amides are the preferred slip agents and are added at an approximate level of 0.1% during the production of LDPE film materials (in the USA, PE film production was 6.3 billion pounds (lbs) in 1991) [46]. They are less frequently used as antiblock and mould release agents in the manufacture of other flexible and rigid plastic products. EA, OA and SA are very cost-effective for these applications and hence are widely used; however, other saturated and unsaturated amides with a chain length of 18–22 carbon atoms may be equally effective [47].

2.3.3 Ultraviolet Stabilisers

For outdoor applications, additives such as UV-absorbers and light stabilisers are generally used during compounding and are transparent to solar radiation but immune to the destructive effect of UV radiation.

2.3.4 Heat Stabilisers

PVC, for instance, requires heat stabilisers to prevent the polymer from degrading during processing, and needs plasticisers to impart flexibility [42].

2.3.5 Plasticisers

Plasticisers are added to polymers in order to increase their flexibility and improve certain processing characteristics [48]. In rigid polymers, adding plasticisers leads to an important increase of processability but to only a marginal increase of flexibility [49].

There are a large number of commercially available plasticisers and include both micro- and macromolecular compounds [41]. The micromolecular compounds are characterised by good compatibility and high effectiveness but have a low permanence due to their migration towards the surface of the product. The omission of plasticisers during polymer processing results in the loss of favourable material characteristics. Using macromolecular plasticisers for the processing of polymers avoids the disadvantages of micromolecular plasticisers but their effectiveness is much lower [49]. Plasticisers make material soft and pliable, and examples include epoxidised vegetable oil, butadiene and so on.

Polymers which contain macromolecular plasticisers are difficult to process but result in products of high rigidity, whereas using micromolecular plasticisers, though a good flexibility and processing is realised, the permanence of the properties is considerably reduced as a consequence of plasticiser migration followed by its evaporation or extraction. As a result, in recent years, both types of plasticisers are usually used simultaneously, with the micromolecular plasticiser content ranging up to approximately 20% [49, 50].

2.3.6 Lubricants

Fifteen per cent of the global lubricants and mould release agents market is consumed by the demand for PVC additives. Most developmental work involving lubricants and mould release agents is concentrated on tailoring existing technology for specific applications which is, in part, a result of the relative maturity of the industry. The largest developmental area involves lubricating agents that increase productivity through cleaner-running systems. The goal is to extend the cleaning period beyond one week, to address excess build-up on the tooling. In addition, faster production speeds are being sought by processors and are the product development focus of many suppliers. The North American market is a global leader, by volume, of the consumption of lubricants and mould release agents. This high demand is due to emphasis being placed by plastic processors on capital avoidance and incremental throughput margins gained from tailoring lubricants to existing processing equipment.

As lubricants and mould release agents are frequently used in combination with other additives during the production of PVC, developments occurring in the additives market, such as heat stabilisers and impact modifiers, have a resultant impact on the combination and amount of lubricants and mould release agents used. For example, increasing the use of calcium/zinc heat stabilisers, at the expense of lead and mixed metal stabilisers, has led to the need for better performing lubricants; for lead, PO waxes are generally used, whereas for calcium-zinc, it can be either wax or an ester. Lubricant loading levels have increased and new one-packs, which contain all the ingredients for one formulation, are being offered. Changes in the use of plasticisers can potentially lower the amount of lubricants used and there are a large number of lubricant suppliers who offer a wide range of products and technical services in order to meet industry demands. The global sales of the 20 largest suppliers of metallic stearates, petroleum and PO waxes, fatty amides, esters/alcohols/acids, and silicones/fluoropolymers/others are available in the literature.

2.3.7 Flame Retardants

The antimony concentration in industrial waste is considerably higher than in urban waste, which explains the different antimony concentrations found in the various input waste streams.

Typically, where small household waste is concerned (vegetables, fruits, paper, plastics, glass, bread and carpets), the average concentration of antimony present in dry waste is 5.2 mg/kg [51]. In 1996, a concentration of 7.6 mg/kg of antimony was estimated to be present in household waste in Japan and more than 80% was derived from FR used in plastics, clothes, curtains and textiles [52].

Twelve per cent of the global FR market is consumed by the demand for PVC additives. The PVC production process is a major user of non-halogenated phosphate esters and chlorinated paraffins, in the form of FR/secondary plasticisers, and a minor user of brominated FR. PVC uses significant amounts of aluminium trihydrate or antimony oxide as a synergist which reacts with the halogen contained in the PVC. When FR are added to PVC, they are used as an FR/plasticiser combination; loading levels of the non-halogenated triaryl phosphate esters comprise up to 25% of the total plastic. FR PVC can be used to produce various items such as wire and cable jacketing, items for rigid components to be used in the building and construction industry, flexible films and coated textiles. One driver that is very clear is the shift of FR demand towards Asia-Pacific and China, and away from Europe and North America.

Europe and North America currently account for just over 50% of global FR consumption, but China is poised to challenge for the highest consumption. This situation is largely due to the growing volume of PVC used for lower end plastic items and the increasing requirements for exports to meet overseas flammability requirements. There has been an extensive increase of FR consumption in China and Asia, while demand for non-halogenated organophosphorus FR in North America and Europe has been negatively impacted. The health and environmental scrutiny of FR that has impacted halogenated FR continues to shift towards banning individual classes of products, as opposed to broad-based bans of all FR products. The type of plastic chosen for an application affects the growth and development of individual FR additives.

FR consist of three main components: an acid source, a carbon source and a gas source. FR form a charred-like cellular layer on the surface and this layer acts as a barrier to prevent the transfer of heat to the condensed phase. FR depend not only on their stability but also on their decomposition rate, char-forming rate and char yield.

2.3.8 Mould Release Agents

During the processing stage, every problem that is encountered has many solutions. It is expected that during moulding, in particular, the frictional and adhesive forces which contribute to the high level of sticking that arises due to the lack of a mould release agent will constrain material/product formation, resulting in more strain as the required forces developed in the polymer melt would have to overcome these frictional and adhesive forces [53].

Mould release agents and processing additives are engineered to improve the production process and product quality. They facilitate optimum demoulding of the contents from the mould and the release agent should not transfer from the mould surface to the moulded part. Parts that are easily removed from the mould exhibit an attractive mirror-like finish and with less mould maintenance and wear, less cleaning of the part is required.

During the resin transfer moulding technique, the internal mould release agents can greatly enhance the resin flow and glass fibre wet out. Even during hot and cold press making and pultrusion, internal mould release agents reduce the pulling force and improve glass fibre saturation.

Internal mould release agents are materials that are mixed directly into the resin to improve the release properties and the moulding or processing characteristics. Internal release agents require heat to function, which originate from an exothermic reaction of the resin, heated mould surfaces or *via* selected process temperatures. These agents can reduce the use of external release agents, the time taken to apply the mould release and cleaning of the moulds, and contribute to better gloss and improved wet out of reinforcements and fillers, in addition to improving pultrusion line speeds leading to increased output. External release agents are used to seal the porosity of the mould during the production of fibre-reinforced plastics, and internal release agents help to reduce porosity in the gel coat.

A wide variety of mould release agents are known to effectively keep the contents of the mould from adhering to it; however, many of these agents subsequently remain on the surface of the moulded product and are extremely difficult to remove [54].

No 'ideal' release agent exists that can provide acceptable non-stick characteristics and also reduce the surface porosity of the moulded product. By their very nature, release agents invariably increase the surface porosity, as they reduce the force that attracts the polymer to the mould [55].

Internal release agents improve the physical properties of the material and enable crosslinking with the resin during curing, the balance of internal release agent solvent is emitted as vapour, creating the release interface between the part and the mould.

Silicon grease and fluorocarbon mould release agent lubricants appear to convert the stick-slip motion into nearly constant slip behaviour, and further reduce the dynamic friction coefficient. This loss of stick-slip motion and reduction in the friction coefficient when using lubricants is considered to be a useful indication for engineers who deal with the process equipment and mechanics [56].

Internal release agents will:

- Enable better wet reinforcement
- Improve resin flow
- Eliminate build-up
- Make mould release easy
- Improve dispersion of colours and fillers

- Eliminate stress and flow marks
- Improve cosmetic surfaces
- Yield clean parts, ready for finishing

In pultrusion, they help:

- To reduce the pull force
- Improve line speed
- Eliminate chalking, scaling and scumming

In injection moulding, they help:

- To increase the melt flow index/reduce resin viscosity
- Quicker production cycles
- Easy mould release
- Improved dispersion of colours and fillers
- Easy cavity fill
- Eliminate stress and flow marks
- Improve cosmetic surfaces
- Reduce the coefficient of friction
- Keep the parts clean, ready for finishing

Pentaerythritol tetrastearates are used as external lubricants in PVC and ABS formulations, where they act as mould release agents or antiblocking agents during the manufacture of plastic films and sheets. Lecithin is also used as a mould release agent [57]. Magnesium soaps are used in the plastics industry as lubricants and mould release agents for thermosetting plastics and thermoplastics. The incorporation of concentrated silicone fluids improve the material flow and act as a mould release agent to overcome the high rate of product rejection. Mould release problems can be overcome by using stainless steel moulds with polished surfaces and mould release agents such as silicone oils.

The moulding lubricant in the ABS resin should act in two ways to aid processing. First, it should lower the viscosity of the resin and thereby facilitate moulding and second, the mould lubricant should serve as a mould release agent as a result of being more concentrated on the plastic surface while solidifying in the mould [58].

2.3.9 Nucleating Agents

Semicrystalline polymers comprise over two-thirds of the products used in our daily life. Adding a nucleating agent to a semicrystalline polymer is a common way to control the degree of crystallisation and tailor mechanical and optical properties [59–61]. The interface between the nucleating agent and the polymer melt has a high surface energy, which reduces the energy barrier associated with the formation of a nucleus. Introducing a large amount of nucleating agent particles therefore greatly increases the nucleation density and consequently the rate of crystallisation [62]. In general, a higher nucleation density leads to more desirable material properties; nucleating agents improve hardness, elasticity, optical properties and transparency.

2.3.10 Fillers

Fillers are simple or complex substances of mineral, animal or vegetable origin, which are used for altering polymer properties and lowering cost. These kinds of additives may reduce crack formation and deformation of plastic material, and also improve the surface characteristics, abrasion, temperature and humidity resistance, and flowing properties in cold conditions. At the same time fillers may increase dimensional stability and reduce moulding pressure and processing temperature [41, 45, 50]. Fillers improve stiffness, strength and electrical properties; talc, chalk, clay and so on, are used as filling material.

The type and amount of filler have an effect on shrinkage and sink marks; more filler reduces both, but at the same time increases the mixture viscosity, which is critical when working with moulding compounds. A combination of coarse and fine particles produces the optimum results. Fillers, such as clay, calcium carbonate and wollastonite, judiciously selected and in relatively high concentrations, can also impart flame retardancy and serve as a stress transfer medium, as well as reduce the total material cost. It should be pointed out that fillers strongly influence the flow characteristics of moulding compounds.

2.4 Plastics – Applications

Plastics are an attractive manufacturing material due to the fact they can be used in a wide range of applications and exhibit high performance characteristics, including good mechanical strength and toughness, strong dimensional stability and processing advantages. Plastics are used in a variety of sectors including:

- Education: computers, mobile communications, fibre optics and the Internet all rely on plastics.

- Healthcare: hygienic, safe plastics, advance medical technology and are critical in life-enhancing and life-saving surgery.

- Construction: light-weight doors, windows and so on.

- Maximising natural resources: plastics enable water/food preservation and distribution, using less to do more, e.g., light-weight plastic packaging.

- Energy conservation and efficiency: light-weight plastic vehicle components maximise fuel efficiency and insulation prevents domestic heat loss.

- Renewables: plastics are key to solar and wind power generation.

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3 Plastics and the Environment

The generation of plastics waste has been stimulated by increased production coupled with an increasing population, and it is responsible for the world's present environmental crisis. The rapidly increasing demand and production of plastics has led to increased pollution and the replacement of many non-plastic items in the market place.

Every year, a large amount of plastics waste is generated worldwide, however, waste plastics data are lacking for many countries. Even though annual usage is often well quantified, the data quality is variable [1].

3.1 Plastics and Conventional Materials – Comparison

The relatively rapid growth of the chemical industry is largely due to the increase of plastics production. On a weight basis, the recent production of plastic and ferrous materials is roughly equal. The manufacture of finished plastic components is increasing by the same degree of magnitude as competitive products made from other materials.

Reassessment of the competitive position of plastics is a result of the recent dramatic increase in crude oil price, i.e., plastics must be competitive on a price basis as well as their overall technical performance [2]. **Table 3.1** illustrates the energy required for the production of PE and other common materials.

Table 3.1 shows the energy required for the production of some common materials on a weight and volume basis, and reveals that the energy necessary to produce 1 volume unit of PE is much less than that of steel. The energy saving realised when using plastics instead of steel or other materials has led to traditional materials being substituted by plastics.

Table 3.1 Energy required for the production of PE and other materials

Materials	By weight		By volume	
	MJ/kg	KWh/kg	MJ/kg	KWh/kg
PE	21.35	5.93	22.86	6.35
High-density PE	27.32	7.59	25.92	7.20
Low-density PE	53.10	14.75	48.35	13.43
Cement	8.57	2.38	26.82	7.45
Glass	17.39	4.83	45.04	12.51
Steel	30.89	8.58	241.88	67.19
Aluminium	169.09	46.97	446.83	124.12
Copper	55.01	15.28	490.10	136.14

PE: Polyethylene

3.2 Plastics and the Atmosphere

The energy required to break chemical bonds usually comes from ultraviolet (UV) light, stress, heat or pollutants, and oxygen [3]. The main cause of polymer degradation is oxygen, hence an atmosphere lacking oxygen would have a detrimental effect on the degradation of plastics as oxidation would not occur [4]. The weak chemical bonds of polymer chains can also be broken due to poor manufacturing techniques or during the use of the material.

3.3 Plastics and the Chemical Environment

Polymers are subject to degradation which is caused or accelerated by chemical agents. Many polymers are actively attacked by pollutants such as ozone, sulfur dioxide and formaldehyde. In addition, water can break the bonds along a polymer backbone and this hydrolysis reaction is catalysed when acidic pollutants are present [5].

Sulfur dioxides, hydrocarbons, nitrogen oxides, and particulate matter such as sand, dust, dirt and soot are known to be common air pollutants. These atmospheric pollutants may cause degradation in combination with solar radiation and other weather factors. Sulfur dioxide is a pollutant that arises from industrial sources and soot is acidified by the interaction with moisture and other particles in the presence of sulfur dioxide and oxygen.

Acrylic, nylon and polyester are especially susceptible to hydrolysis and metals, such as iron and copper, catalyse this degradation. Metal impurities which are present as a result of the manufacturing process, or in a composite material, accelerate degradation. Many polymers are alkali and acid sensitive, and acid can cause the hydrolysis of polymer chains. Organic vapours and fumigants can dissolve or swell plastics.

3.4 Plastics and the Marine Environment

In the 1970s, biologists first reported that seabirds were voraciously eating plastic. Around 50 species of seabirds appear to seek out plastic pellets mistaking them for the small, shrimp-like crustaceans they normally they eat [6]; it has also been reported that fish, turtles, whales and so on, consume plastic. Animals that consume plastic may die of starvation as their digestive tracts become blocked or ulcerated. The toxic chemicals present in some plastics exert a range of effects from the thinning of eggshells to death [7].

Plastics in the marine environment have become inescapable and include everything from fishing nets to tampon applicators to household waste. Commercial fisherman alone purposely dump 52 million lbs of plastic packing into the ocean every year and lose an additional 298 million lbs in the form of plastic nets, lines and buoys [8].

Plastics are manufactured to be durable, which is an important aspect of their resistance in the marine environment. Common plastic wastes are reported to have a life expectancy of 450 years in seawater. Plastic debris in the marine environment is unsightly and threatens tourism at many of the world's beaches. Plastic causes the deaths of perhaps 2 million seabirds and 100,000 marine mammals every year according to the Entanglement Network, a coalition of 18 environmental groups in Washington, DC, USA [9].

In addition to raw plastic, plastic packaging also enters the marine environment in enormous quantities. In 1982 it was estimated that merchant ships alone dump some 639,000 plastic containers into the ocean every day [10]. Most plastics are buoyant and eventually wash up onshore where they slowly disintegrate into small pieces.

The long-term welfare of the marine environment demands greater control over the manufacturing and disposal of plastics. In the overall solid waste stream, plastics are highly visible, particularly as litter on beaches and roadsides. The shipping and fishing industries are a major source of plastic litter in marine environments. An estimated 1 million birds and 100,000 marine animals die each year as a result of ingestion of, or being trapped by, plastics in the oceans [11].

3.5 Plastics and Agriculture

The use of plastics in agriculture results in an increased accumulation of plastics waste in rural areas. Part of this plastic waste may be recycled, particularly greenhouse films, silage films and fertiliser packaging, sacks, pipes and other plastic products. Other portions of agricultural plastic waste are difficult to recycle for technical and/or financial reasons. In some cases, thin mulching films, thin low tunnel and direct cover films are classed as waste of low recyclability; very thin films are usually heavily contaminated by soil and foreign materials [12]. Furthermore, the use of plastics for mulching in agriculture has increased the plastic litter problem in rural communities.

The most common current disposal practices for non-recyclable agricultural plastics waste are burying in the soil (mulching films), burning, or disposing of it in open fields or landfills [13]. All of these practices have serious negative consequences for the environment, and for the health of farmers and consumers, and impact on the quality and market value of agricultural produce.

The process of recovering and recycling agricultural films is difficult as approximately 80% of the weight of the recovered waste plastic is made up of foreign materials such as soil, sand and so on [14–17]. The cleaning of such films results in a higher recycling cost [18].

3.6 Life Cycle Assessment

Life cycle assessment(s) (LCA) is a tool for assessing the environmental aspects and potential impacts associated with products or services. LCA involves compiling an inventory of inputs and outputs of the relevant product system, which are then evaluated, along with interpretation of the results of the inventory analysis and impact assessment in relation to the objective of the study, to determine the potential impact of the product/service on the environment [19].

LCA considers the entire life cycle of products or services from raw material acquisition through to production, use and disposal. LCA is a method of assessing products or services and has been proven to be a valuable tool to document the environmental considerations that need to be part of the decision-making process with regards to environmental sustainability [20].

LCA avoids the problem of moving the consequences of a process change, i.e., an apparent improvement in one part of a life cycle can merely lead to further problems at another time or place in the life cycle [21]. **Figure 3.1** illustrates plastics waste management in terms of the life cycle of polymeric products. The disposal phase in LCA is often neglected or indicated as kilogram waste; however, it has been established that the disposal phase should be included in

LCA studies [22]. The risk of decisions shifting burdens from the production or use phase to the disposal phase because of data gaps can therefore be diminished.

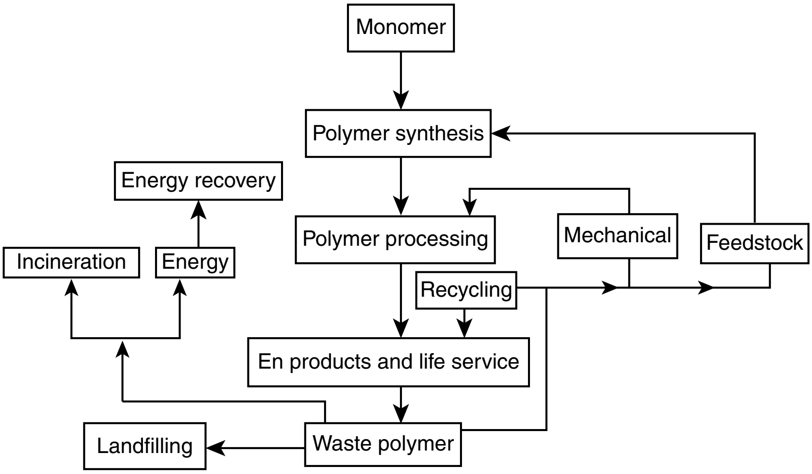

Figure 3.1 Plastics waste management in terms of the life cycle of polymeric.

LCA have been successfully utilised in the field of plastics waste management, for example, to assess differences in environmental performance between different waste incineration strategies [24] or related activities such as the flue gas cleaning process of plastic waste incinerators [25], to compare the environmental performance of different scenarios for the management of mixed plastics waste as well as that of specific plastic waste fractions [25–32].

3.7 Degradation of Plastics

The degradation of plastic materials, contained in items of everyday use, is a result of the sum of all the weathering effects which occur during the product's life cycle [33, 34]. Degradation occurs by:

- UV degradation as a result of the action of UV rays in natural daylight.
- Environmental factors can cause significant changes to the chemical structure of plastics and result in the loss of properties during use over a period of time.
- Oxidation.
- Hydrolysis.

3.7.1 Structure and Degradation

Plastics undergo both chemical and physical changes during their processing and service life. Throughout the life cycle of the plastic, oxidative reactions constantly occur and the new groups formed during these reactions may enhance the sensitivity of the recyclates to further thermal-and photodegradation. Both degradation during the manufacturing process and weathering during the product's use change the properties of the items to be recycled.

Usually, peroxy radicals are formed at the beginning of polymer degradation in the presence of oxygen [35]:

$$\begin{aligned} RH + O_2 &\rightarrow R^{\cdot} + HOO^{\cdot} \\ R - + O_2 &\rightarrow ROO^{\cdot} \end{aligned} \tag{3.1}$$

The oxidative reaction forms new oxidative moieties due to the utilisation of a substantial amount of stabilisers, leading to a consequent decrease of long-term stability and deterioration of mechanical properties. For an effective recycling process, it is necessary to know the extent and effect that degradation has on the structure, mechanical properties and long-term stability of recyclates. Plastics face prolonged use before being discarded as waste [23].

Polyolefins containing tertiary hydrogen atoms are vulnerable to oxidative degradation *via* the peroxidation chain reaction [36]. This reaction is accelerated by the influence of sunlight and the elevated temperatures used during processing, and results in the material becoming discoloured and embrittled. A continual low level of oxidative degradation eventually leads to mechanical breakdown.

PP is a semicrystalline polymer, the oxidation of which is confined to the amorphous phase. Photooxidation takes place on the surface, leading to extensive recrystallisation and the production of surface cracks which can propagate through the product [37]. Embrittlement occurs because of the preferential scission of the tie molecules linking the crystallites in the polymer which causes a disproportionate amount of applied stress [38].

Polymers are, in the main, hydrocarbons or hydrocarbon-like and as a consequence they are combustible. For many consumer applications, agents to control or suppress this combustibility must be incorporated into the polymeric formulation [39]. Organohalogen compounds, particularly brominated aromatics, continue to be among the most widely used [40]. They function by liberating, upon thermal decomposition, hydrogen halide or halogen atoms which interrupt gas phase flame propagating reactions. Other agents act in the solid phase to promote the formation of a char layer at the surface of the polymer, which protects it from the heat of the flame and prevents polymer degradation and the generation of the volatile fragments which fuel the flame [41, 42].

3.7.2 Process Degradation

Plastics processing involves high temperatures and mechanical shear. During thermal processing, chemical reactions occur at elevated temperatures [43–48]. During the extrusion and injection moulding process, the molten polymers experience relatively high rates of shear and hence non-uniform heat generation, which may result in polymer degradation and/or the formation of crosslinks.

3.7.3 Environmental Degradation

Natural weathering encompasses the effects of most types of degradation phenomena, which lead to embrittlement or catastrophic failure of the mechanical properties of the polymer [49–53]. Degradation is usually governed by the combined effect of the mechanical properties of the polymer and weathering. Microcracks which develop on a UV-irradiated surface provide pathways for the rapid ingress of moisture and chemical agents. Moisture condensation can remove soluble products of photooxidation reactions leading to further degradation.

UV light contains energy needed to break the carbon–carbon or oxygen–carbon bonds in the polymer chain. Plastics exposed to UV become brittle or develop a chalky surface as they degrade. Stress can also provide the energy needed to break chemical bonds. Stressed plastics will degrade more rapidly due to the chain-breaking process and are subjected to stress cracking. Certain chemicals and solvents in the environment can aggravate the problem, causing some plastics to crack with minimal stress. Cast acrylic, polycarbonate, polystyrene and PE are subject to stress cracking. UV radiation causes polymer crosslinking and is responsible for the rapid loss of colour.

The durability of plastics has been considered to be a positive attribute, but it is now commonly perceived by society as negative. Although photodegradability has been suggested as a solution for plastic litter, photodegradation has a limited practical application because UV light will not penetrate landfills [54].

3.8 Present Trends

There is an increase in the volume of solid plastics waste. In recent decades, due to the worldwide use of plastic products, plastics waste has come to be a major component of both industrial and municipal wastes. In many countries, incineration is a traditional and available method to reduce different plastic wastes. When considering the reduction and destruction of waste, incineration is a valuable means of waste disposal with the advantage of being highly effective in reducing the volume of waste.

The management of waste plastics has become a serious issue as a result of the recent increase of consumer goods made of plastic. Waste plastics are treated by combustion or placed into landfill. Careful control is necessary during the incineration of waste chlorine-containing plastics, as they are converted into toxic compounds during certain thermal reactions [55–58]; hence, the establishment of optimum operational conditions for the combustion of this plastic waste is urgently required [59–61], in order to limit the emission of volatile chlorinated organic compounds [62]. However, volatile or low-molecular hydrocarbons and chlorinated organic compounds are currently emitted from the incineration of this type of plastic waste.

The alternatives for the treatment of plastics waste are landfilling, incineration, and mechanical and chemical recycling; the most promising seems to be chemical recycling. The mechanical recycling of plastics waste, known as secondary recycling, is an important resource for reuse in manufacturing plastic products [63]. However, mechanical recycling is limited to single-polymer plastics, thus excluding the use of more complex and contaminated plastics waste for recycling.

3.9 Future Threats

Plastics waste management focuses on limiting the detrimental effect of this waste on the environment, which is of global concern. The rate of waste generation increases as a result of human activities, i.e., changes in lifestyle, consumption and an increase in the population and degree of urbanisation. Plastics waste is generated *via* industries, manufacturing units and municipal solid waste processes [64].

Wastes of durable and non-durable plastic-related goods, packaging, containers, scraps and trimmings from residential, commercial and industrial sources are collectively known as plastics waste. Improper plastics waste management can lead to serious health threats, resulting in fires and the contamination of air, soil and water [65–70]. Even mixing plastics waste with tar materials to lay the road causes environmental pollution. Due to the non-degradable nature of plastics, if disposal is not managed properly this environmental pollution will become permanent leading to greater problems in the future and expensive clean-up operations.

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4

Plastics Processing Management

4.1 Background

Plastics processing emerged as a separate, identifiable engineering discipline in the late 1950s and 1960s. The most exciting developments can be attributed to important advances which took place in the late 1980s and 1990s, which include [1]:

- Catalysts were used in the polymerisation process to improve the material characteristics, particularly in the case of polyolefins.
- Progress in the field of high-performance plastics.
- Production of polymers with improved properties as a result of scientific compounding.
- Research and practices were enhanced by enormous computational power due to the computer revolution.
- Instruments to measure quantitative properties during flow and deformation, and physical properties to the molecular level as well as determination of the chemical composition of the material.

4.2 Management – Plastics Processing

Plastics processing started with the development of thermoplastics. Traditional processing techniques such as extrusion, injection moulding, thermoforming and rotational moulding have, and continue to, benefit from significant technological progress [2]. In plastics processing management, the optimum conditions depend on machine size, resident time of the material in the machine and other features of the process.

Processing often requires external heat for the melting step and results in frictional heat which impacts the quality of the product. During processing, plastic materials are usually in a molten state and exhibit high viscosity. The melt flows through complex geometries and undergoes viscous dissipation, shrinkage and warpage to take the shape of the mould after deformation. The level of viscosity adds more challenges to the processing and shaping of plastic materials during the stages of deformation, flow and solidification of materials. Viscosity plays a central role during processing until the final stage when the material cools down and solidifies into the final product. During the moulding of plastics, temperature is one of the most important parameters and temperature distribution has a significant effect on the properties of the final part.

An important aspect of plastics processing management is to obtain products with the required end-use properties such as melt viscosity, softening temperature, mechanical strength and so on. Therefore, plastics processing depends on:

- Material characteristics
- Temperature settings
- Specific output per screw revolution
- Melt temperature
- Melt pressure
- Machine output

4.3 Technology

The processing of thermoplastics mostly involves changing pellets, granules and powders into different forms. The type of polymer determines the structure–property relationship of various physical properties, i.e., the properties of the material dictate the complex structure of plastics [3]. The commonly used techniques for product fabrication are:

- Injection moulding
- Blow moulding
- Extrusion
- Thermoforming
- Rotational moulding

The processing technique to be used depends on the material type, product shape and size, production requirement, accuracy and quality, and design load performance. Injection moulding is used to form different shapes and sizes of intricate design. The extrusion process is used to manufacture pipes, sheets, profiles and so on, during a continuous process. Blow moulding and rotational moulding are used to manufacture hollow parts. Thermoforming transforms extruded products in sheet form into various shapes and sizes.

Processing techniques involve:

- Mixing, melting and plasticising
- Melt transporting and shaping
- Drawing and blowing
- Finishing

Plastics processing can shape material and improve the properties of end products. The use of plastic enables parts to be manufactured which have various characteristics including: light-weight, high strength, high precision, high efficiency and low cost. The development of packaging and other consumer products, in addition to automobile, aerospace and hi-tech industry parts, all include plastics processing.

4.3.1 Injection Moulding

Injection moulding is one of the most widely employed methods for the manufacture of plastic products. Injection moulding can be achieved using either a reciprocating-screw-type machine or a plunger-type machine. Reciprocating screw injection moulding has been commercially exploited on a large scale.

During the manufacture of plastic products there are five basic stages involved in injection moulding: plasticisation, injection, packing, cooling and finally ejection. During the plasticisation stage, the raw material in solid form is transformed into molten material through the combined action of the friction provided by a rotating screw and the heat provided by external heating elements. The retraction of the screws during rotation forces the molten material to accumulate at the front of the screw. When a sufficient amount of material has accumulated, the screw moves forward, causing the molten material to fill the cavity. During filling, the hot polymer melt rapidly fills a cold mould, reproducing a cavity of the desired product shape. **Figure 4.1** illustrates the stages of the injection moulding process.

Once filling is complete, additional material is packed into the cavity in order to compensate for the shrinkage which occurs during the cooling stage. During the packing and holding stage, the pressure is raised and extra material is forced into the mould to compensate for the effects of temperature decrease and crystallinity development, which determine the material density during solidification. The cooling stage starts with the solidification of a thin section at the cavity entrance or exit of the mould impression and holding pressure is released. When the solid layer on the mould surface reaches a thickness sufficient to assure the required rigidity, the product is ejected from the mould [4].

After solidification, the moulded article is ejected and the sequence of events is repeated in a cyclic manner. The cooling time constitutes a major portion of the moulding cycle due to the poor thermal conductivity of plastic materials. The choice of mould and material delivery system will depend on the characteristics of the part being moulded as well as on the material.

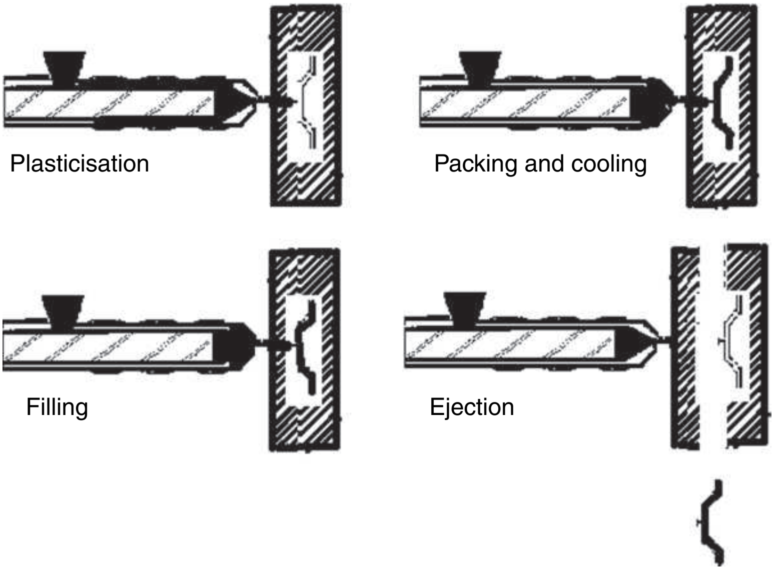

Figure 4.1 Stages of the injection moulding process

4.3.2 Blow Moulding

During extrusion blow moulding, the material in the form of a pellet or granule, is fed into a plasticising extruder. The plastic is melted *via* external heating and the hot melt is transferred through the barrel by the shearing motion of the extruder screw, which has solid conveying, melting and metering sections to ensure a uniform homogeneous melt at the screw tip. The helical flights of the screw configuration change along its length from input to output.

The screw feeds the melt directly into the head-die assembly within a continuous extrusion blow moulding machine. The melt flows around the mandrel and into an annular die of either convergent or divergent type. Parison, which is a hollow tube, can be continuously extruded and the extruded hollow tube is cut at preset time intervals for transfer into the blow moulding stage. **Figure 4.2** illustrates the stages of a continuous extrusion blow moulding machine.

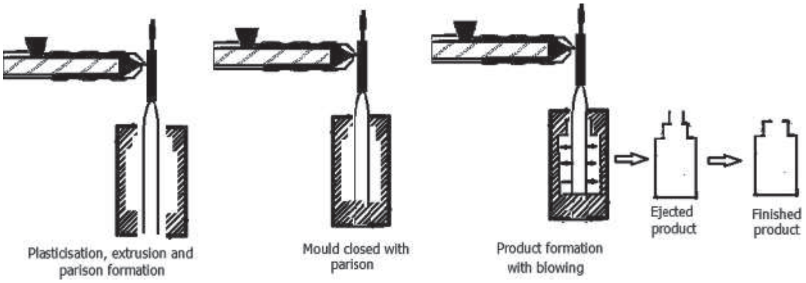

Figure 4.2 Different stages of continuous extrusion blow moulding

In a ram- or plunger-type machine, the extruder feeds the material to an accumulator/head device. The plunger pushes the material rapidly through the head-die assembly once the desired volume has accumulated. The transfer of material does not need to occur *via* a blowing station in the mould clamp mechanism. The part is blown, cooled and removed from the mould, and the next parison is only extruded after the part has been removed.

When the desired length of the parison is reached, the mould is closed and the parison is inflated by internal air introduced *via* the die-head assembly. The mould walls are vented and a vacuum may be applied. The molten plastic is thus forced to conform to the shape of the mould cavity. The article is then cooled, solidified and ejected from the mould.

The annular die can be designed to incorporate a hydraulic mechanism to vary or programme the annular gap size in both extrusion- and plunger-type blow moulding. With extrusion blow moulding, a specific wall thickness distribution or controlled weight of the parison can be programmed.

Injection-stretch blow moulding is a two-stage process. The material is injection moulded around a core rod to create a preform during the first stage. The preform is then stretched through the action of the core rod, inflated and cooled, similarly to the extrusion blow moulding process. Injection-stretch moulding yields lighter products with biaxial orientation and increased tensile strength.

Figure 4.3 illustrates the various stages of injection-stretch blow moulding. The biaxial orientation also provides permeation to gas, liquid and odour due to an increased molecular alignment. This process produces bottles or containers which are scrap-free, and have close tolerance, i.e., a complete finish which does not required any secondary operations.

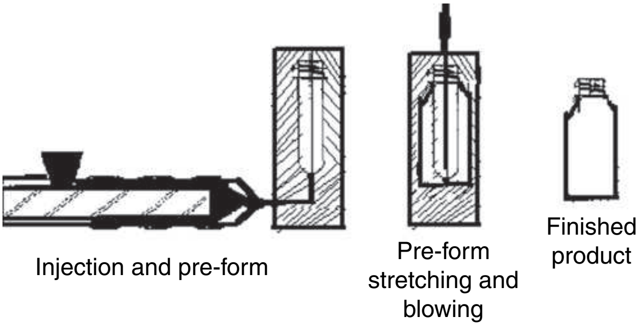

Figure 4.3 Various stages of injection-stretch blow moulding

4.3.3 Extrusion

The extrusion process is usually divided into three stages: solid conveying, melting or plasticisation, and melt conveying or metering. An extruder consists of a threaded shaft or screw rotating in a fixed cylinder or barrel, plus a feed port and a die. The screw channel constantly changes its position relative to the barrel and the advance of the polymer melt through the barrel of the extruder follows a helical path, which is a mirror image of the extruder screw. During the extrusion process, pellets or granules are compacted and fluxed in the extruder barrel with the help of external and friction heat. The molten material is extruded inline under pressure through a die opening designed to yield the required pipe, profile or sheet. The hot extrudate is immediately passed through a calibrator which has a water circulation channel in a vacuum environment. Passing through the water channel, the extrudate develops sufficient strength to be pulled away from the die by a suitable puller or take-up equipment. The resultant extruded product is either cut to length or reeled as required.

Dies should be heated using electrical band heaters which are specially shaped to give complete and close conformation to the outside die dimension. The die opening should be 20–30% oversized to accommodate the drawdown caused by the constant tension necessary to draw the molten material away from the hot die and is commonly known as the swelling ratio. The extruded product is normally cooled by immersion in water, water spray or a combination of the two.

Figure 4.4 illustrates the different types of extrusion processes. In the blown film process, extrusion is carried out using standard side- and bottom-fed die types, both rotating and stationary. Rotating dies are preferable because of their ability to minimise gauge bands.

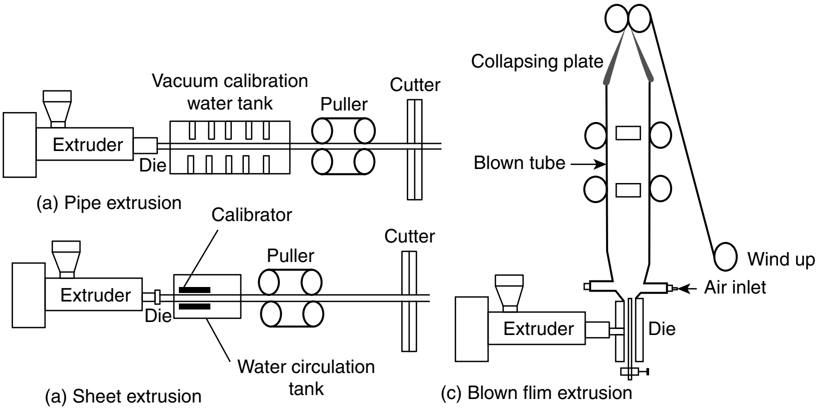

Figure 4.4 Different types of extrusion (a) pipe extrusion, (b) sheet extrusion and (c) blown film extrusion

Conventional bubble-cooling methods and take-off equipment are used to cool and form the film.

Due to process/product requirements, extrusion requires plastic material of higher molecular weight for better melt strength. During extrusion, the material is heated and pumped into a permanent mould, which is called a die, where it takes shape and cools. The extrusion process involves continuous material heating, shaping and cooling. The screw design plays an important role and optimum processing conditions maximise product quality.

4.3.4 Thermoforming

Thermoforming is a process of deformation by heating the plastic sheet to its rubbery solid state. A plastic sheet is heated to a suitable temperature in order to undergo deformation by temporarily draping the softened sheet over a rigid mould until the material takes on the desired finished shape; this process includes a variety of ways to produce rigid articles from a flat sheet. Of special concern during the thermoforming process is the thinning of barrier materials at high draw ratios, with the potential loss of barrier properties.

Plastic materials have low thermal conductivities, hence during heating, even relatively thin sheets can have surface temperatures that are substantially higher than the interior temperatures. Therefore, plastic sheets must be heated to an optimum forming temperature in order to achieve uniform and repeatable drawdown. **Figure 4.5** illustrates continuous sheet forming extrusion *via* the thermoforming process.

Common stages of heating thin-gauge sheets involve conduction, convection and radiation. During the conduction stage, the energy interchanges between the layers in multilayer sheets. During convection, heat transfer occurs between the hot air and the sheet. During thermoforming, the radiation energy is between the electrical oven elements and the sheet, and the preferred choice is thin-sheet thermoforming.

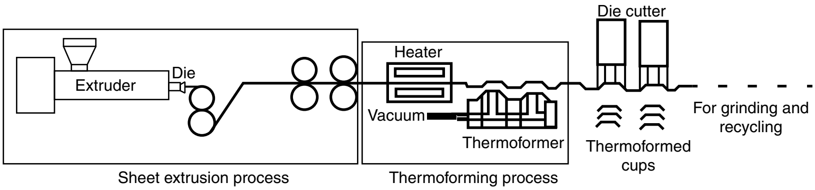

Figure 4.5 Continuous sheet forming extrusion *via* the thermoforming process

4.3.5 Rotational Moulding

Rotational moulding is one of the plastic processing methods for the production of hollow plastic products. Plastic powder is charged and subjected to biaxial rotation in an oven at a temperature of 200–400 °C. The plastic powder melts inside the mould by heat transferred *via* convection through the mould wall. All the powder melts and the mould is moved out of the oven while maintaining the biaxial orientation. Exposure to air, or using a fan or water shower are usually employed to cool the mould.

Once the product has reached sufficient rigidity in the mould after cooling, preferably below the melting temperature of the plastics, the mould is opened and the product is removed. The rotational moulding process involves material charging, heating and rotation, cooling and rotation, and finally demoulding. **Figure 4.6** illustrates the rotational moulding process.

The rotational moulding process requires a long cycle time compared with other process such as injection and blow moulding. The main attraction of this process is that in addition to being an alternative to injection and blow moulding processes, it is inexpensive and can handle complex shapes with variable thickness and a wide range of part sizes. By rotating the mould, heating and cooling are commonly achieved by convection to the external surfaces of the mould using air as the transfer medium.

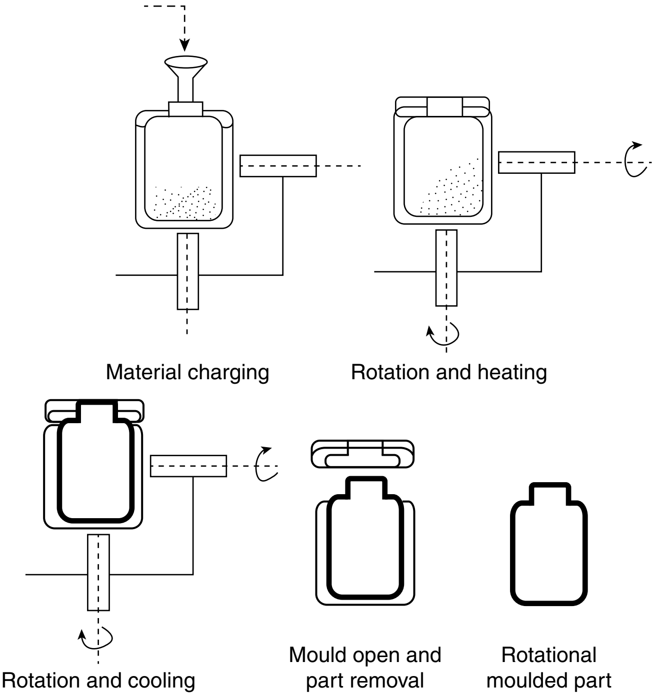

Figure 4.6 Rotational moulding process

4.4 Challenges and Opportunities

As the production and processing of thermoplastic materials occur with the material being in a molten state, knowledge of the flow behaviour of the material is essential [5].

A complete understanding of the plastic process from production to the properties of the end product has become increasingly important in view of the increasing speed of material development resulting from rapidly changing customer requirements [6]. To achieve the desired end-product characteristics, plastic processing technology depends upon a balance of material selection, processing parameters and mechanical property requirements; in addition, an important factor of plastic production is its ease of processing.

Plastics processing faces challenges and opportunities in order to develop advanced techniques, and innovative materials are needed to achieve this; hence, plastics processing requires hi-tech involvement and extending current knowledge [7].

4.5 Management – Waste Processing

Plastics waste processing, in particular, has direct links with the conservation of energy and natural resources, and the development of technology is the best solution to deal with plastics waste material. Plastics processing is used to recycle waste, which is driven by the potential depletion of raw materials and socio-economic factors. However, the direct reprocessing of plastics waste is limited due to contamination or the mixture of different kinds of materials.

Current development activities are focused on the processes and practices of reprocessing plastic waste materials, with emphasis on the processes and practices that reduce emissions and integrate the LCA of technologies and materials. Plastics processing management involves the reuse of plastics waste from industry, and primary and secondary recycled material, to limit the environmental impact and preserve natural resources.

The most suitable plastics processing technique used for the production of any component will depend upon the shape, size and quantity required; in addition, the cost of plastics waste, obtained by different processing methods, must be taken into account. The product may need to be altered to make it suitable for an individual process and may even include material change.

Plastics waste processing depends upon technology. The overall share of processing waste in combination with virgin material is negligible in plastics processing management. Processing waste has a strong focus on experimental research as the use of 100% recycled material may lead to a deterioration in material properties.

The choice of processing method employed when managing plastics waste material depends on the time and money available. As there are numerous ways to consider shaping a plastic melt, the cost and capital involved tend to dictate the available options of plastic processing methods. Plastics processing involves using moulds or dies and processes such as injection, extrusion, calendering and so on, which are all aspects of processing that have to be managed.

Many processes are available for the production of plastic products and the choice depends upon the relationship between material properties, processing method and end-product properties, in addition to the choice of forming method, which all have technical and economic aspects. Three important features of plastic melts during processing are shear viscosity, melt flow index (MFI) and melt elasticity. MFI is the quantity of polymer extruded under specific load and temperature conditions in a given time. The elastic properties of the melt are a major factor in determining the residual strain and moulding defects [8].

4.6 Productivity and Task

Productivity improvement is the primary objective of the plastics processing industry and developments include the entire process. The results of these developments have been implemented in terms of the utilisation of plastics waste, additives and machinery. The role of plastics processing management has expanded, from simply executing to implementing, and requires industries to continue to provide and develop efficient systems and techniques. Improvements are driven by respective solutions to process problems and the development of productivity can be achieved by implementing further waste reduction, which is the primary aim of the processing industry.

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5 Recycling Management

Recycling is a process referred to as 'value from waste', which indicates the recovery or reuse of material *via* the extraction and reprocessing of raw materials from recycled products. Methods are constantly being developed which allow more effective ways of recycling waste materials. As advanced technologies are employed to research and develop man-made polymers, it is necessary to invest considerable effort, energy and cost; however, these developed polymers should be strong, stable and durable. Polymers have become important materials for scientific and technological development, and contribute to maintaining a high standard of living; modern society depends upon polymeric products in everyday life, from toothbrushes to computers.

Polymers are designed to exhibit durability and strength, however, an unfortunate consequence is that they create environmental pollution after use, i.e., synthetic polymers do not easily degrade in the outdoor environment and accumulate at dump sites causing litter. The required properties for the end use of synthetic polymers results in their relative resistance to environmental degradation, which includes biodegradation.

The recycling of plastics waste provides an ecologically acceptable way of reutilising the energy content of the waste. The plastics processing operation is damaging to the environment and inefficient if the polymer composition of the waste is unknown. It is necessary to conserve and dispose of plastics waste as there is no alternative solution, hence it should be considered as a resource; disposal techniques depend on the type of waste and location.

Plastics waste disposal poses a research challenge and on a global scale, plastic products are considered to be non-degradable. The majority of plastics waste is not produced from petroleum waste, but from natural gas that could be used for a different purpose or not extracted at all [1]. The landfilling of plastics waste is a short-term solution, which does not allow the recycling and recovery of any resource. The main purpose of recycling management is to save resources: recycling reduces the need for virgin raw material, however, the contamination of plastics within the recycling stream by foreign materials is a major obstacle to recycling efforts.

With ever-increasing oil prices, recycled plastics are becoming an economical alternative for the production of a wide range of commodity plastic parts. Polyolefinic polymers, such as polyethylene (PE) and polypropylene (PP), contain approximately 14% hydrogen; these materials could provide the hydrogen required for thermal coprocessing with biomass, which could lead to an increase of the liquid production of oligomers or short chain polymeric materials.

It has been suggested that polymer recycling is the only sustainable solution to the rapidly increasing amount of plastics waste. Among the various polymer recycling methods, the thermal and/or catalytic degradation of plastics waste into fuel show the greatest potential for a successful future commercial polymer recycling process, especially as plastics waste can be considered as a cheap source of raw materials in times of accelerated depletion of natural resources. The catalytic degradation of plastics waste offers considerable advantages [2].

5.1 Plastics Waste – Stream

Figure 5.1 illustrates the industrial recycling of discarded waste into raw material. In municipal waste, postconsumer plastic represents a small percentage; however, it occupies about 25% of the waste stream volume. Recycled plastics can be transformed into pellets which can be used as raw materials to either partially or fully replace virgin material in many plastic manufacturing operations.

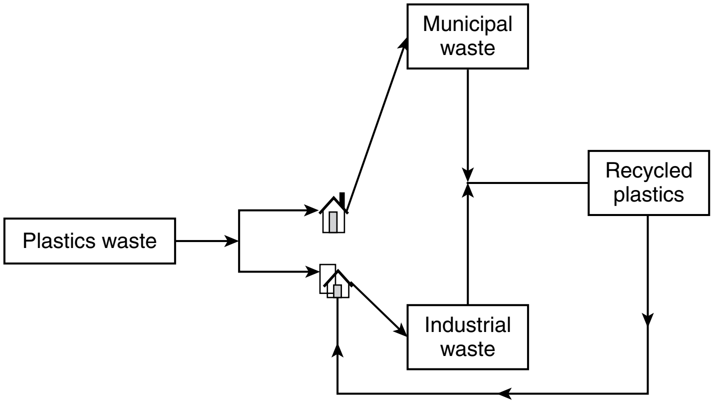

Figure 5.1 The recycled plastics stream

Recycling involves collecting, separating, processing, marketing and ultimately using material that would have been discarded and is associated with community roadside programmes. The in-house reuse of process waste has been common industrial practice for many years, however, it does not always divert waste from landfills. As disposal costs increase, the reuse of previously discarded waste from one industry by another is becoming more common. During processing, significant amounts of product end up in recycling bins and dumpsters, which is problematic.

5.2 Recycling – A Resource

During the plastic material life cycle, plastics waste is recycled as a resource. The amount and type of recyclable plastic depends upon the composition and quantity of waste from the municipal and industrial waste streams. Industrial waste from the manufacture of plastic products is regarded as a manufacturing loss; the reduction of plastics waste, as a result of recycling the material, increases productivity and reduces the manufacturing loss.

Many plastic components are used as refuse-derived fuel or as a reducing agent for blast furnaces. Plastics waste recycling can help protect the environment and improve manufacturers' profitability. When plastics waste is recycled it is a valuable resource for manufacturing products, with a similar status to virgin materials [3]. There is considerable profit in recycling plastics waste and the marketing of recycled plastics is not a problem due to the eagerness of end users to utilise the material.

5.3 Recycling Requirements

Plastics recycling has become more and more common for two different reasons [4, 5]; the first is driven by cost, which requires the reprocessing of faulty parts and scrap from moulding methods. The second is environmental, which is crucial in the case of commodity plastics due to the large production volume.

During plastics recycling, the recycled material has to be initially subjected to recognised testing methods as it is necessary to know the properties of the plastics in various products. The processing of plastics waste requires methods of disposal which track the flow of material as it is essential to quantitatively evaluate if the recycling method employed is feasible or not. There is even a possibility that recycling may result in negative environmental loading.

The composition of plastics waste is closely monitored prior to recycling as many plastics are not recyclable due to the presence of mixed plastics waste. The mass recycling of materials is not suitable due to a loss of material properties. The contamination of plastics within the recycling stream, by foreign materials, is a major obstacle to recycling efforts as the recycling of plastics is only economically viable when the processing system is highly efficient and cost-effective [6].

Successful material recycling is dependent upon the purity and uniformity of the plastics waste. The properties of the recycled material depend upon the history of the synthesised polymer, the primary processing and application, and finally the recovery methods/equipment. Sorted, single polymer waste exhibiting low contamination stands a good chance of being recycled. If small amounts of other polymers, such as PE produced using a Ziegler- or Philips-type catalyst, PP [7], even lower amounts of polystyrene (PS), polyethylene terephthalate (PET) and polyvinyl chloride (PVC) are present, the waste cannot undergo commercial recycling [8]. In the future, engineering plastics such as Nylon, polycarbonate or polyphenylene oxide will be present in waste in increasing amounts.

5.4 Limitations

The recycling of plastics waste is often limited by the degradation which occurs during processing. The effects of degradation include: reduced physical properties, surface defects, process instability resulting in machine downtime and wear, and increased quality control costs. Several types of degradation are known to occur during processing, namely: thermal, mechanical, chemical and oxidative.

Thermal degradation in polymers occurs at elevated temperatures. Mechanical degradation is due to excessive shear during processing. Chemical degradation is caused by a reaction between the polymer and a chemical. Oxidative degradation arises as a result of heat, oxygen and mechanical parameters [9]. Due to adverse weather conditions and transportation problems, recycled plastics may quickly become depleted due to the rate of waste collection and sorting of the municipal waste streams.

5.5 Recycling Management

Recycling addresses the needs of small industries in remote or emerging markets by enabling the development and progression of this sector. If the recycling process does not move forward, these organisations will have insufficient recycled plastic and consequently lower productivity.

The success or failure of an organisation can be influenced by the type of innovations and developments which are available in the field of recycling plastics waste. Innovative recycling methods enable the transformation of plastics waste into new products and additional applications. Most proposals for the recycling or disposal of plastics waste require human and financial resources.

Mechanical and feedstock recycling involve material recovery from plastic waste streams and combustion procedures for heat production with controlled emissions, respectively, which are included in recycling management as energy recovery options. The mechanical recycling of waste entails a physical means of producing new plastic products. During feedstock recycling, plastic wastes are cracked and depolymerised, *via* chemical means, into a series of petrochemical products or monomers, which can later be transformed into new polymeric products *via* synthesis.

Energy recovery options utilise plastic waste streams as fuel for energy production, exploiting the high calorific content of plastics. The life cycle assessment (LCA) governs how the successful recycling of waste plastics is managed, i.e., recycling management is driven by the technological process used to recycle waste plastics.

An effective industrial recycling programme not only reduces the environmental impact, but sends a positive message to its end users. The plastics waste produced in a manufacturing facility is the result of its processing operations and the easiest way to reduce waste is, most likely, to alter the process. The hierarchy of reduce, reuse and recycle is also applied to process waste. Making process changes, in order to reduce waste, usually requires an investigation of costs, alternatives and results.

The success of recycling depends on the continued high participation of householders and other waste generators. Sociological, institutional and technological advances are needed in order to increase participation and yields [10].

5.6 Selection of Plastics to be Recycled

The main difficulties encountered in recycling postconsumer plastics are: 1) most postconsumer wastes are soiled and 2) they exist in a dilute form in terms of quantity in the community [11]. Although the technology for washing and separating the various types of plastic is available, the number of facilities with this capability will continue to be extremely small until a sufficient supply of raw material, at an appropriate cost, can be assured. One remedy would be to develop material collection processes that are resource efficient.

The recycling of mixed plastics waste has attracted considerable interest because of the economic and ecological advantages compared with separately compounding each component, i.e., virgin polymeric materials and their additives [5, 12]. In general, deterioration of material properties, caused by the incompatibility of the components, is one of the major problems in reprocessing mixed plastics waste. Almost 85%, by volume, of global plastics consumption is comprised of four thermoplastic resins, PE, PP, PVC and PS [13].

The first step starts with determining the types and quantities of discarded materials. The selection of plastics recycling streams involve:

- Observation of the types and amounts of waste produced.
- Identification of waste-producing activities and equipment.
- Detection of inefficiencies in operations or the way waste moves through the organisation.
- Assessment of space and equipment that can be used for storage, processing recyclables and other activities.
- Assessment of current waste reduction efforts.

5.6.1 Mixed Plastics Waste

Plastics waste recovery, with the exception of PET, from the waste stream is to be made compulsory. Plastics waste is subjected to a series of sensors that sort the type and colour; further inspection ensures no PVC contamination.

Any waste which is contaminated by soil, or contains dirty plastics, cardboard and so on, cannot be recycled. Small quantities of low-density materials such as low-density PE and PP can be mixed with high-density polyethylene (HDPE); a negligible quantity of PS is not an issue [14]. **Figure 5.2** illustrates the separation of plastics from the mixed waste collection.

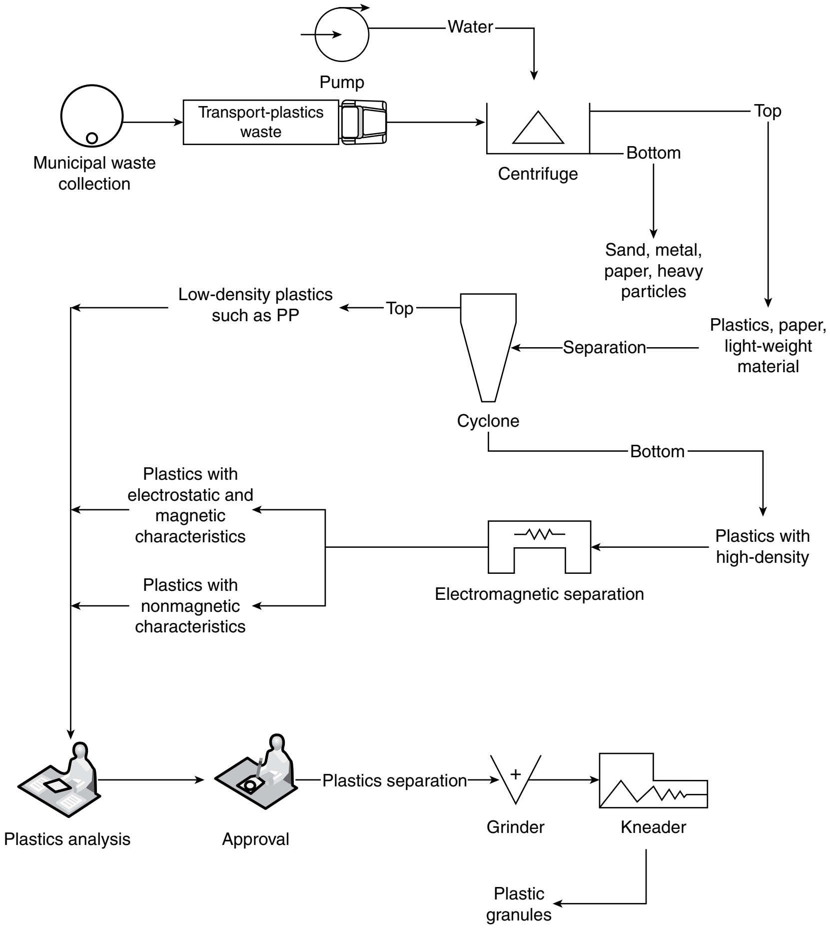

Figure 5.2 Plastics waste separation

5.6.2 Mechanical Recycling

Mechanical recycling is performed by physical means and involves separation, washing, grinding, remelting and processing plastics waste, and is a clean and homogeneous route for waste plastics. LCA studies indicate that mechanical recycling is preferable to other management procedures in terms of optimising overall energy use and minimising the emission of gases that contribute to global warming [15]. Recycled products are exposed to the mechanisms and effects of degradative processes throughout their life cycle. Using analytical strategies, the quality assessment of recycled plastic includes determining the degree of mixing (composition) and degradation, such as chemical and morphological alterations, changes in the mechanical and rheological properties, and the presence of low molecular weight (MW) compounds, such as contaminants, additives and degradation products [3, 16]. Waste plastics with improved properties can be realised by the restabilisation and rebuilding of the molecular structure and compatibilisation of mixed waste plastic blends. Effective mechanical recycling takes into account specific management- and technology-related issues.

Upgrading the plastics waste process is a necessity both for environmental protection and sustainable development. The incineration of waste plastic is declining due to operating costs and descending credibility in the environmental protection scenario. Copyrolytic techniques have received considerable attention in recent years as they provide an attractive way to dispose of, and convert, polyolefins (PO) and coal into higher value fuel; the specific benefits of this method potentially include the reduction of waste volume, the recovery of chemicals and substitution of fossil fuels [17–19]. Studies have shown that mixed plastic wastes can be used as a minor component in coal blends without any detriment to coke quality [20]. Recently, Nippon Steel Corporation (Chiyoda, Japan) began the industrial application of PVC-free plastic waste recycling at the Nagora and Kimutsu Works (Aichi, Japan).

5.6.3 High-density Polyethylene

It is well known that the effective recycling of polymers in general, and of HDPE in particular, requires information regarding the polymer's properties [21]. The properties, in comparison with their virgin counterparts, depend upon the polymer type and the number of cycles and conditions that occur during reprocessing.

5.6.4 Polyvinyl Chloride

The mechanical and processing properties of recycled polyvinyl chloride (rPVC), collected from bottles and pipes, blended with pipe-grade unplasticised polyvinyl chloride (uPVC) were found to be acceptable. Two important factors which control uPVC processing are the particle size and restabilisation. The impact strength and processing behaviour of uPVC improves upon the addition of rPVC due to the presence of modifier agents in the rPVC pipes which slightly lowers the thermal resistance [22].

5.6.5 Polyethylene Terephthalate

PET waste is recycled using various methods for use in several applications. Chemical recycling enables sustainable development and leads to recovery of the raw materials from which the polymer was made, as well as secondary value-added products [23]. Chemical recycling is generally based on breaking the ester bonds of waste PET using a chemical degradation process such as [24]:

1. Methanolysis: converting PET into dimethyl terephthalate and ethylene glycol (EG). The products of methanolysis are the raw materials needed for the production of PET. The reaction conditions for methanolysis are 2–4 MPa and 180–280 °C [25–28].

2. Glycolysis: chemical recycling using EG, diethylene glycol, propylene glycol, butanediol and triethylene glycol [29, 30]. The

temperature range of the glycolysis process is 180–250 °C [24]. Glycolysis results in the production of specialised products, such as unsaturated polyester, polyurethane and polymer concrete; glycolysis is primarily used for this type of recycling due to its low cost [31].

Glycolysis consists of the transesterification of PET and the destruction of its polymer chain, resulting in the decrease of its MW. When glycols are used for the depolymerisation of PET, the oligomers obtained have two hydroxyl end groups, i.e., oligoester diols are formed.

Unsaturated polyester resins are complex polymers resulting from a crosslinking reaction of a liquid unsaturated polyester with vinyl-type monomers, most often a styrene monomer. The unsaturated polyester is formed *via* the condensation reaction of an unsaturated dibasic acid or anhydride, a saturated dibasic acid or anhydride, and a polyfunctional alcohol [32].

3. Hydrolysis: acids react with PET producing dicarboxylic acid and diols which yield raw materials that can be used in production.

4. Ammonolysis: anhydrous ammonia reacts with PET producing terephthalic acid amide. Reaction conditions include a temperature range of 120–180 °C, 2 MPa and 1–7 h duration [33].

5. Aminolysis.

6. Other processes.

5.7 Present Trend

Waste plastics disposal is a complex process and requires active participation by industry, the public and governments. The recycling and reprocessing of waste plastics is driven by the awareness and concern of the detrimental environmental impact of discarded plastics waste. It is an important issue due to the need for resource conservation, and costly and limited energy and feedstock availability. Discarded polymers represent a colossal waste of the energy which is locked within them and if they are not recycled it results in a greater strain on already limited natural resources/ feedstocks. Polymer recycling is related to the national economy due to hydrocarbon feedstocks. The high price of virgin polymers and cheap labour are the driving forces for the recycling of waste plastics.

There has been an increase in virgin resin production at the same time as the promotion of recycling. Postconsumer recyclables are of rather low value in the market place, competing with mass-produced and low-cost virgin materials; therefore, the manufacture of virgin plastics has considerably outstripped plastic recycling.

Plastic recycling needs to understand the market availability of recycled materials. Petroleum prices are rising globally and considerable emphasis is being placed on the manufacturing of plastic materials. The volume of plastics waste to be recycled is becoming a major problem, because huge amounts of synthetic polymers are manufactured every year for many different purposes. Polymer scraps are gathered from the municipal solid waste streams and within the waste streams there are several different PO – such as PE, PP and PS – all incompatible with each other [34].

The treatment of scrap and postconsumer waste both pose economical and technical problems, as the amount of recycled material has increased much faster than the reprocessing capacities and market utilisation. The cost-effectiveness of the process and ability to adequately solve problems on an industrial level govern any perceived environmental benefit; in addition, the market must be able to utilise the new materials arising from recycling [35].

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6

Solid Waste Management

The use of plastics and the subsequent generation of plastics waste are both increasing rapidly worldwide. Solid waste refers to the amount of materials and products generated prior to recycling, landfilling and incineration, which is governed by the density and living standard of the population [1], income level [2], economic growth, consumption pattern, and waste collection and recycling framework.

Solid waste generation is an inevitable consequence of production and consumption activities related to the level of income of a population and degree of urbanisation [3]. The quantity and characteristics of solid waste are the two major factors which govern the design of an efficient, cost-effective and environmentally compatible waste management system. Integrated systems involve a number of management techniques which maximise the recovery of resources from the waste.

6.1 Solid Waste – Plastics

Solid waste is defined as discarded material which is no longer used in its present form or condition; however, it is a resource which is potentially useful. In reality, certain types of waste may render recovery and reuse impractical, inadvisable or even unfeasible. Solid waste management reduces the negative impact that non-degradable plastics waste could have on the environment.

Discarded plastics deemed unsuitable for recycling require waste treatment management which includes an alternative route of disposal. Life cycle assessments rarely incorporate limiting the impact of plastics solid waste in a detailed manner in the prevention activities section. The management of solid waste optimises the infrastructure system for managing a given amount and composition of plastics waste [4]. The outcome relies on identifying management techniques which result in the lowest environmental emission and impact.

6.2 Advantages of Plastics Waste

Due to the carbon- and hydrogen-rich nature of plastics waste, in solid form it can be used as a reducing agent in blast furnaces for the production of iron and steel; therefore, coke can be replaced with plastics waste. Other advantages of plastics waste include thermal recycling, i.e., waste is incinerated, together with other combustible waste, and the heat is used to produce electricity. As plastic has an average heating value of more than 8,000 kcal/kg it makes a reasonably good fuel without any other treatment. In addition, the waste gasifying and melting process seeks to reduce the volume of waste material without producing harmful gases, such as dioxins, while effectively recovering the heating value of the waste in the form of a fuel gas [5].

The recycling of plastics waste is thought to be ideal for handling the separation of plastics from mixed waste and the problems of solid waste. It is also argued that today, plastics waste is needed more than ever as petroleum resources are being overwhelmed by demand. In Checkland's words, the management of plastics waste is 'the use of a particular set of ideas, systems ideas, in trying to understand the world's complexity' [6].

6.3 Solid Waste Management

Solid waste management involves the process of disposal, i.e., managing the transformation of waste into products or services. The concept of solid waste management extends beyond the processing function of the plastics industry.

Solid waste management is related not only to reuse, recycling, energy recovery and landfilling, but also prevention and/or minimisation [7]. Technological changes in plastics processing have led to products being thrown away as or before performance declines. Solid waste generation is the result of a ‘throw-away’ society with a penchant from consumption; therefore, it is the responsibility of local governments to encourage and develop recycling, recovery and reuse.

Public authorities play a crucial role in the proper management of plastics waste in all countries, no matter what political or economic system exists, as proper waste management can only exist on a foundation of good practice.

The successful planning of a waste management programme relies on the availability of reliable information regarding the quantity and type of material being generated, and an understanding of how much of that material the collection programme managers can expect to prevent or capture. The effective waste management of municipal solid waste (MSW) can be achieved by taking into account: the need to estimate material recovery potential, identifying sources of component generation, facilitating the design of processing equipment, estimating the physical, chemical and thermal properties of the waste, and maintaining compliance with national laws and European directives. The composition of generated waste is extremely variable as a consequence of seasonal, lifestyle, demographic, geographic and legislative factors. This variability makes defining and measuring the composition of waste more difficult and at the same time essential.

It is impossible to reduce solid waste to zero level of pollution. As long as society lives in a culture of consumption, the plastics waste problem will reach crisis proportions and pose a challenge to public policy-making systems and governance [8].

Solid waste management needs to develop a reliable method of estimating waste composition. Certain variations can be observed, which can be attributed to specific social activities. Statistical data should be used to establish a baseline for monitoring progress in achieving waste management objectives.

6.4 Waste Management and the Environment

Solid waste management is an important facet of environmental conservation and encompasses planning, organisation, administration, financial and legal aspects of various activities associated with the generation, collection, transportation, storage, processing and disposal of solid waste. Solid waste management is required to be environmentally compatible and employs the principles of economy, aesthetics, energy and conservation [9].

Unscientific waste management aggravates different types of environmental pollution such as air and water, including groundwater and soil quality, which can impact public health as waste is a breeding ground for various diseases [10].

Developing countries spend more than 0.5% of per capita gross national productivity on urban waste services, which covers only approximately one-third of the overall cost [11]. Correct planning for the primary and secondary collection, and subsequent disposal, of MSW has become crucial to ensure a clean, healthy and pathogen-free urban environment.

6.5 Solid Waste Generation

Plastics waste arises from everyday activities of human existence in residential areas or commercial and industrial centres. The entire generation of plastics waste is subject to value judgment, i.e., when industry or consumers decide to dispose of a plastic item. The critical factors to consider in making projections of future plastics waste quantities are:

- Population
- Population growth rate
- Per capita waste generation

The solid waste management process involves collection, transportation, processing and disposal, and each step of the operation requires expertise and equipment.

The inadequate management of plastics waste produced by people at home, work and during leisure activities can result in environmental pollution, aesthetic insult and the destruction of useful resources. Household plastics waste is more uniform than industrial waste and varies in composition according to the time of year, however, the fundamental nature of the plastics waste and its components do vary greatly. The nature of household plastics waste will also change as individual wealth, method of packaging and so on, alter. In developing countries, the composition, density and biodegradability of the plastics waste varies considerably.

Unfortunately, over the years, solid waste management has mainly consisted of illegal dumping; however, over the last decade, the solid waste management strategy was designed and started being implemented in developing countries. The final disposal or exploitation of plastics waste should not endanger or cause any damage to the environment.

6.6 Process Update

Solid waste management currently requires the simultaneous consideration of seven factors, which include:

1. Collection
2. Segregation
3. Scientific thinking
4. Waste quantity estimation
5. Qualifying the waste

6. Separation and cleaning
7. Recycling into product

Solid waste management is essentially the planning and utilisation of waste in a better manner. It allows a problem or issue to be considered in terms of a pattern of behaviour over time and results in considering the current situation in the context of timescale; the strategy should thus have a historical segment, a current state and one or more future paths [12].

Solid waste management is rooted in cognitive processes. The concept of solid waste as a paradigm requires considering the process holistically; however, translating the solid waste paradigm into 'measurable' elements has remained a research challenge. In order to optimise waste management, the seven factors listed above remain the fundamental elements to be considered.

The management of solid waste seeks to identify causality, i.e., determine how the waste is generated. Generally, people have a tendency to think in terms of 'correlation' or 'influence'. The solid waste operation looks at the structure or 'physics' of relationships, at how one variable affects another; not just that they affect each other. Solid waste management helps to recognise the concept of interdependence; that generally within a system, there is a web of relationships [13].

6.7 Dynamic Thinking

Solid waste management builds on dynamic thinking, i.e., seeing the bigger picture. It requires the ability to 'rise above' functional silos and 'view' the recycling process that links the recycled products. The plastics waste process enables the determination of plausible explanations to be identified, i.e., relationships that are not under the control of a decision within a system should be eliminated from consideration. Essentially, this perspective means viewing plastics waste as a component of solid waste and as such under the control of recycling decisions.

The plastics waste process helps to identify closed-loop structures and the process of recycling plastics waste does not run in just one direction, but an ‘effect’ usually feeds back to change one or more of the ‘causes’, and that the ‘causes’ themselves affect each other. It is an important part of the recycling process not to prioritise ‘causes’ as being most or least important, but rather to understand how waste composition and quantity may change over time.

6.8 Insensitive Feedback

As is clear in this chapter, the recycling of plastics waste has increasingly been accepted as a response to a complex situation and the default understanding of this situation has not led to adequate action. However, despite the accepted value and ease of recycling plastics waste, most individuals have a great deal of difficulty in systemically recycling waste.

In addition, it has been found that solid waste processes are insensitive to feedback and underestimate time lags between actions and responses. This insensitivity to feedback reflects a failure of the decision-making process to correctly assess the nature and significance of the solid waste management system, particularly the link between the decision and the environment.

Solid waste management personnel have been astonished by how hard it is for firms to repeat their success when technology or markets change. For instance, no leading plastics manufacturer has been able to replicate its initial success when more advanced technologies were developed and their corresponding markets emerged.

The failure of solid waste management can sometimes be ascribed to managerial myopia or organisation lethargy, or to insufficient resources or expertise. Many developed countries have great competitive awareness, aggressively invest in recycling and technologies, and listen astutely to industrialists.

Solid waste management involves the manner in which waste is transformed into materials, innovation, technology, information, products or services. Here, innovation refers to a change in technology and technology refers to how an organisation transforms labour, capital and materials [14].

6.9 Competitive Advantages

The economy of the major industrial nations is now entering its fourth stage and is determined by many factors including limited fossil fuel resources and solid waste management. Many industries are in this postindustrial economic stage due to their handling of solid waste management skills, and competitive advantages will result from the most effective processes. A process-centric management focus and organisation will replace a task-centric perspective and management style [15].

A clear understanding of solid waste management requires an organisation to be process-centric and involves many interlocking processes – some functional and some cross-functional, and the latter will be built upon the foundation of strong waste management skills and processes [15].

6.10 Environmental Impact

The environmental impact of disposable plastic wastes is growing rapidly worldwide [16]; however, current disposal methods are insufficient. Incineration can generate toxic air pollution, and satisfactory landfill sites are limited. The cost of petroleum-based plastics is also steadily increasing and most countries must import these resources; therefore, focus should be directed on disposal, renewable resources and the recycling of plastic materials [17, 18].

Discarded material from industries and society can be utilised *via* the following methods for disposal:

1. Landfill
2. Thermolysis

Plastics solid waste has become a serious problem when considering the disposal alternative dictated by the sequential hierarchy of sound solid waste management. A rapid growth in population and expanding urbanisation have caused an increase in the amount and type of waste which is generated. Many cities and towns in developing countries face serious environmental decline and health risks due to inadequate solid waste management. The effective planning of waste management relies on elucidating reliable information regarding the quantity and composition of MSW, especially household solid waste [19, 20]. Further potential uses for household solid waste, which is compostable and recyclable, are yet to be identified.

6.10.1 Landfill

Landfill is a common solution to the problem of solid waste and, along with sanitation, is the cheapest means of disposal. It requires waste collection, economic land and transportation cost [21], and is the least preferred method.

6.10.2 Thermolysis

Thermolysis plays an important role in dealing with the enormous amounts of plastics waste produced all over the world and decreases the negative impact of waste on the environment. Plastics waste may be converted into economically valuable hydrocarbons, which can be used both as fuels and feedstocks in the petrochemical industry. End-product yields and properties depend on the composition of the plastics waste.

In the case of polyethylene (PE), there is an increased alkane content in the end product, whereas polystyrene leads to a higher aromatic content. Alkene formation benefits from the presence of polypropylene (PP) in the waste. The desired end products can be obtained by the adequate blending of plastics waste; however, it is not always technically or economically possible to obtain the quality required. The addition of a catalyst not only improves the quality of the resultant end products, but also enables selection of the product type.

Processes such as pyrolysis and combustion reduce the volume of solid wastes and, in particular, plastics waste. Solving the problem of the vast volume of plastics waste is often the key to successful solid waste management. Low-density polymers such PE, PP and so on, require costly storage at the point of waste generation, which greatly affects the cost and the logistics of collection and handling. Incineration is an attractive process to decrease not only the volume of solid waste but also reduce the burden on landfill and other disposal operations. Incineration is not a final disposal method as it requires landfill or other means to receive the solid residues.

Advantages:

- Reduces the volume of solid waste.
- Detoxification of combustible toxins and sanitation of pathologically contaminated plastics waste.
- Reduces the environmental impact related to the leaching of organic material such as plasticisers.
- Provision of an energy resource.

Disadvantages:

- High capital and operating cost.
- Environmental impacts such as air pollution.
- Adverse public reaction in many cases.

6.11 Socio-Economic Factors

Rapidly expanding urban activities, including commercial and industrial development, along with improved lifestyles, due to socio-economic development, have resulted in an enormous quantity of solid waste. The world is facing a crisis in MSW management as there is no suitable permanent site to dump the waste or an integrated scheme for its sustainable management. In addition, information on the status of MSW management is insufficient. The practices and sources of segregation, primary and secondary collection, including composition and characterisation, and disposal practices are summarised below.

Effective solid waste management requires knowledge of factors such as:

- The source of waste generation.
- The existing status of waste collection, transportation and segregation of waste.
- Waste characteristics and disposal activities.

6.12 Environmental Progress

The basic operation of solid waste management involves: waste collection, transportation, storage and treatment. Although these functions remain similar, as environmental management progresses, the roles and applications of products may change; therefore, an ideal waste management system is function oriented, not product oriented [22–26].

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7

Industrial Waste – Plastics

Improving the quality of life is a continuing global goal for many people, which results in an increased consumption of plastics and produces large amounts of waste. Maximising the efficiency of energy utilisation at every step of the waste disposal process is necessary to achieve sustainable growth, which is an enormous and complex task. Waste can exist in any form namely, solid, liquid and gaseous, or a combination of the three.

Since the 1950s, 1 billion tonnes of plastic has been discarded which can persist in the environment for hundreds or even thousands of years [1]; hence, plastics waste has become an ever-increasing and widespread problem over the last few decades. There are many routes for the recycling and recovery of plastics solid waste including; chemical recycling (including pyrolysis, gasification and hydrogenation), through which plastics can be broken down to a feedstock state, and energy recovery *via* the combustion of plastics waste as an alternative fuel source. The recycling and recovery routes of plastics waste [2] contribute to the plastic fraction of the total amount of waste produced, hence there is an urgent need for the proper management of waste plastics [3].

The increasing annual production rate of polymers is governed by rising demand, which is dependent upon several factors including the economy, while the advancement of polymer technology depends on research. It has become imperative to produce polymers with better properties at reduced cost using improved processes and larger capacity production units.

Different groups of polymers exhibit a wide variety of physical properties and even within the same class of polymer, small differences in the preparation method or constituent proportions can result in marked physical differences. The physical properties of polymers are determined by the internal molecular structure as well as the cohesion between long chains or the packing of closed rings.

Plastics waste produced by an industrial facility is the result of processing activities and the reuse of industrial plastics waste has been a common industrial practice for many years. Processing changes, in order to reduce waste and maximise processes, usually require an investigation to determine the costs, alternatives and potential outcomes.

7.1 Plastics Waste

Plastics technology is pivotal in delivering products and services which fulfil the needs of the population, both now and in the future. Technological input requires resources which are withdrawn from the environment to manufacture products, which society uses and then discards as waste products, i.e., technology requires input which results in products, but finally produces waste [4].

The planning or development of an industrial waste management system requires knowledge of the quantity of waste which is generated. Any exploitation of the potential for industrial waste recycling relies on detailed knowledge of industrial waste production; however, many problems arise when trying to ascertain the type and quantity of industrial waste. The environment is a key factor that impacts an individual's quality of life and plays a pivotal role in current waste disposal/recycling processes. Industrial waste is a term which refers to all waste produced by industrial operations or derived from manufacturing processes [5]. The global economy has undergone radical changes which have significant implications for industrial development. The plastic industry has generated mixed waste not only in terms of the quantity of waste, but also its composition. Economic loss from industrial waste must be restricted as discarding plastics waste is detrimental to the economy of industries and society.

7.2 Recovery of Plastics

The recovery of plastic materials from industrial processing is both environmentally necessary and economically feasible. Developing practical methods to enable the utilisation of plastics waste after processing is necessary for two reasons: the diverse applications of recycled products for a number of consumer and industrial applications, and to ensure the waste generated is recycled or has an alternative use.

The development of the plastic industry has generated a large quantity of solid waste, especially non-degradable waste. Plastics waste from industrial activities contains additives; hence, the practice of segregating plastics waste reduces potential environmental, health and safety impacts, and ensures recycling facilities are cost-effective. The essential step involves cleaning and recycling.

In many countries, the treatment infrastructure is inadequate. The main practices for plastics waste are currently:

- The collection of plastics waste from industries and disposal at domestic landfill sites without any segregation.
- Recycling at waste generation sites.
- Disposal within the waste generation stream.
- Reuse and informal recycling.

7.3 Industrial Waste Management

Industrial waste is an important source of energy and material; hence, many industries are engaged in extensive environmental audits and evaluate their own waste management activities. There are large economic as well as environmental benefits when appropriate waste management is implemented. The existing system within industry requires an energy-optimisation alternative for the plastics waste produced during processing in order that this waste is recovered or reused in terms of optimal material recovery. The economic analysis may include fuel costs, the cost of raw materials, the waste disposal and treatment of internal waste handling, income from material and energy recovery, and so on. **Figure 7.1** details the method of waste assessment.

Within some industries, industrial waste management efforts have extended from pollution control measures, to the identification of industrial ecology linkages, in which waste stream information must be made available for analysis and evaluation. The collection and analysis of information contributes to the success of a waste management system; therefore, the system can be used to assist in the integration of energy, economic and environmental considerations when determining product life cycles [6].

7.4 Industrial Ecology

Rapid economic development has resulted in greater complexity in the management of industrial waste which, in the plastics industry, includes the recycling, reuse and final disposal of unusable material. Industrial waste from the plastics industry contains additives which may be in a concentration high enough to endanger human beings or pollute the environment due to the volume generated. As a result of the additive content of industrial waste, it can be considered hazardous if the extract concentration exceeds the maximum allowed concentration of contaminants. Industries also generate waste other than hazardous industrial waste.

Industrial ecology is a recent concept in engineering and management, and is an attempt to manage an industrial unit as an ecosystem, with feedback loops and the minimal use of resources and production of waste [7]. Life cycle assessment, which was designed to take into account the environmental impact of waste, can help achieve cleaner production technologies and sustainable waste management practices which are all important aspects of

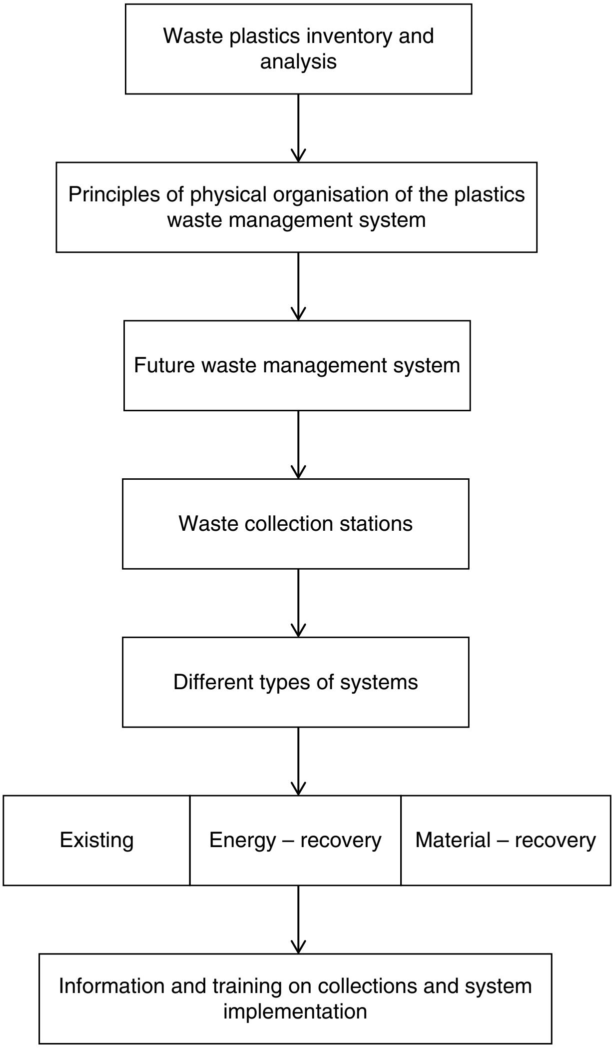

Figure 7.1 Schematic illustration of the waste assessment method

industrial ecology. The concept of industrial ecology will help industries to minimise the use of resources and production of waste, from resource extraction to manufacturing, and final consumer use to recycling of the product.

7.5 Environment and Industrial Waste

Various factors drive the demand for the recovery of material from industrial waste. The economic value of the plastics industry relies on virgin and recycled material, the technology of using virgin material, the substitution of recycled material for virgin material and the market structure. The lack of record-keeping within industrial sectors presents a major challenge for the verification of the actual amounts of materials that are eventually recycled; knowledge of the energy saved as a result of the reuse of recycled materials is a key factor in the utilisation of industrial waste.

Due to the rapidly increasing growth of the plastics industry, a large quantity of plastic products become obsolete every year; therefore, out-dated plastic products, including end-of-life plastic products, are the most rapidly growing plastics waste problem worldwide [8]. As a result, many plastic materials, such as polyvinyl chloride, acrylonitrile-butadiene-styrene and so on, along with heavy metals and flame retardants, create serious pollution problems during the recycling and disposal process.

The open burning of waste plastic causes the emission of gases and chemicals which are toxic [9], and the recycling activities of plastics in electronic waste (E-waste) have resulted in high levels of pollution in the ambient environment. These activities threaten the ecosystem [10]; therefore, driven by profit from the increased cost of plastics, primitive waste recycling processes are now extremely active.

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8 Case Studies

Case study methodology is well suited for many types and aspects of plastics waste management. Research into plastics waste is a contemporary development and is complicated by the fact that waste components/processes are difficult to study in isolation. Therefore, case studies do not generate the same results on recycling as controlled experiments; however, they provide a deeper understanding of the phenomena under study.

A case study begins with a description of the background of the problem and the situation is then analysed. In a manufacturing plant, a problem regarding quality requires changing various parameters and mapping input to output data as no accurate theoretical model for solving interrelated process problems exists; input and output problems occur due to machine and operator performance.

Therefore, case studies are a very effective tool, but have limitations, and differ from analytical and controlled empirical studies. Case studies have been criticised for being of less value, impossible to generalise from, being biased by researchers and so on; hence, case studies require methodology in order to review and judge the situation properly.

8.1 Plastics Waste Management

8.1.1 Europe

The sustainability of municipal solid waste (MSW) management has been predominantly driven in Europe. The European waste and natural resources policy is governed by the need to protect human health and the environment, and aims to reduce any negative impact on the environment *via* economic, technological and social constraints.

Waste generally means any substance or object which the holder discards, intends to or is required to discard, and waste management means the collection, transport, recovery and disposal of waste, and includes the supervision of such operations and aftercare of disposal sites [1].

The European Council encourages the prevention or reduction of waste production as the preferred solution. In 1994, acceptable levels of plastics waste recycling and recovery were established by the European Union (EU) regarding packaging and packaging waste; for all packaging waste streams, including plastic, a minimum recycling target of 15 wt% was set [2].

Later it was amended to 22.5 wt% for plastics, which included material that was recycled back into plastic with no distinction among the various streams of plastic waste, such as industrial, commercial, office, service or household [3].

The European Commission's '*Thematic Strategy*' on the prevention and recycling of waste established new aims and objectives for EU waste policy. In addition, it put forward a vision of an EU 'recycling society' as its long-term goal [4].

8.1.2 India

MSW can aggravate different types of environmental pollution such as air, water, including groundwater, and soil pollution, which affects public health as the waste forms a breeding ground for various disease-carrying vectors such as flies, mosquitoes, rats and others, and indicates inappropriate and unscientific management [5].

There are numerous deficiencies in many of the current practices of plastics waste handling in India. During the rainy season, waste management cannot be carried out properly which impacts public health. This situation is mainly due to limited human and financial resources, and the fact that machinery cannot effectively carry out various activities; to overcome this problem effective strategies and guidelines must be established.

Furthermore, the collection and composition of packaging waste gathered by impoverished people, in exchange for money, varies and segregation adds to the cost of recycling. Waste dumping sites create a nuisance to the public and harbour disease due to the lack of landfilling sites. In addition, waste dumping sites attract animals which cause further health hazards. The majority of cities in India have landfill sites within the city limit, as elevated transportation prices and roads with potholes mean it costs more to carry the waste beyond the city limit; hence the disease rates are unfortunately increasing on a daily basis.

The Government of India needs to come up with a holistic approach to waste management by collecting the segregated waste at source, and characterising and processing the waste in order to produce value-added products. Household waste contributes a major portion to the total MSW; in addition, waste from commercial establishments, hospitals and hotels, sweepings from the street and construction activities add to MSW. Creating awareness through the participation of local people in programme- and community-based waste management systems would be a useful tool in the management of plastics waste. Monitoring the generation of plastics waste and characterising and assessing the physical and chemical characteristics of the waste yield essential information.

8.2 Use of Case Studies

Cases and case studies can be powerful aids. Both can be used to train professionals in fields such as education, public administration, management, medicine, social work and caring occupations. Case studies can be an engaging way to evaluate the feasibility of possible solutions [6].

Furthermore, existing work on the empirical research methodology of plastics waste management has a strong focus on experimental research. Statements, ideas, points-of-view and research decisions are surprising, perhaps outrageous; however, they are challenging and enlightening. All research has a tendency towards quantitative approaches, hence, the literature involving case studies of waste plastics and qualitative methods is limited.

The type of learning that occurs when immersed in situations and experiences varies from situation to situation. Case studies are commonly used in the fields of psychology, sociology, political science, social work, business and community planning, [7]. To increase our knowledge regarding plastics waste management, case studies are conducted for social, community and related phenomena, which allows comparison with the research objectives in plastics waste management.

The use of environmental case studies, related to plastics waste, enables analysis of the extent to which contamination may adversely impact property value through the effect previously referred to and defined as ‘environmental stigma’ [8].

Case studies, as a tool for generating and testing theories, have provided the general management field with some of its most groundbreaking insights [9, 10].

Therefore, a case study is:

- Not simply a data-gathering technique.
- A method which incorporates a number of strategies.
- Incorporated with sources of evidence [11] including documents such as agendas, meeting minutes, reports, diaries with archival records, calendars, service records, direct and participant observation, and interviews which may be focused or open ended [7, 12, 13].

- The triangulation of data that results from the use of multiple methods and data sources to examine one phenomenon [14].
- Serving different purposes which may be exploratory, explanatory or descriptive [7, 11].

8.3 Property Value

With regards to plastics waste, there can be three effects on property value that may result from environmental contamination:

- Cost: a lowering of house price due to the costs to remediate a contaminated property to appropriate regulatory standards.
- Use: limitations on the use of properties that may be impacted by environmental contamination.
- Adverse effects on value due to increased perceptions of environmental risk by relevant market participants.

The most difficult to analyse and quantify, due to a lack of supporting evidence, is the effect on the property market. Risk or adverse effects can be quantified with clear and convincing market data [15].

8.4 Case Study 1: Plastics Waste from the Electric and Electronic Field

8.4.1 Concept

Typically, the plastics waste created by the electric and electronic field is 15–30%, hence, the recycling quotas cannot be fulfilled solely by state-of-the-art metal and glass recycling. The European ‘Waste Electric and Electronic Equipment (WEEE) Directive’ defines strict recycling and recovery quotas (EC2003a) namely, 70–80% for recovery and 50–75% for recycling strategies, which will eventually apply to all countries and will increase in the future; therefore, it is imperative to provide and develop economic recovery systems for plastics. In Europe, more than 6 million tonnes of WEEE is produced annually, which contains more than 1 million tonnes of plastic [16].

8.4.2 Objective

The separation of solvents from specific plastics, e.g., polyvinyl chloride (PVC) is separated from other polymers such as polyethylene (PE), polyoxymethylene, polycarbonate (PC) and so on, within electrical and electronic waste materials is achieved using its density and solubility *via* the cyclohexanone process. The following points need to be assessed when using a solvent process method:

1. The economic benefit of different material recycling approaches.

2. The presence of additives such as brominated flame retardants (BFR), including brominated biphenyls and polybrominated diphenyl ether [17].

3. Determination of polymer properties such as the density and solubility.

8.4.3 Methodology

The first stage of the cyclohexanone or CreaSolv® process involves density separation, which allows the separation of PVC or styrenics, respectively, from other identified polymers in waste originating from electrical and electronic equipment. The density of PVC or styrenics overlaps with filled polypropylene (PP) and rigid polyurethane, and PVC and styrenics even overlap each other; therefore, density-based polymer separation alone will not permit pure recycled polymers to be obtained.

The majority of electrical and electronics waste contains PVC as it is used in electrical and electronics wiring as a sheathing material and insulator, and in electrical fittings along with other materials such as PE, polyoxymethylene, PC and so on, which form part of the waste material.

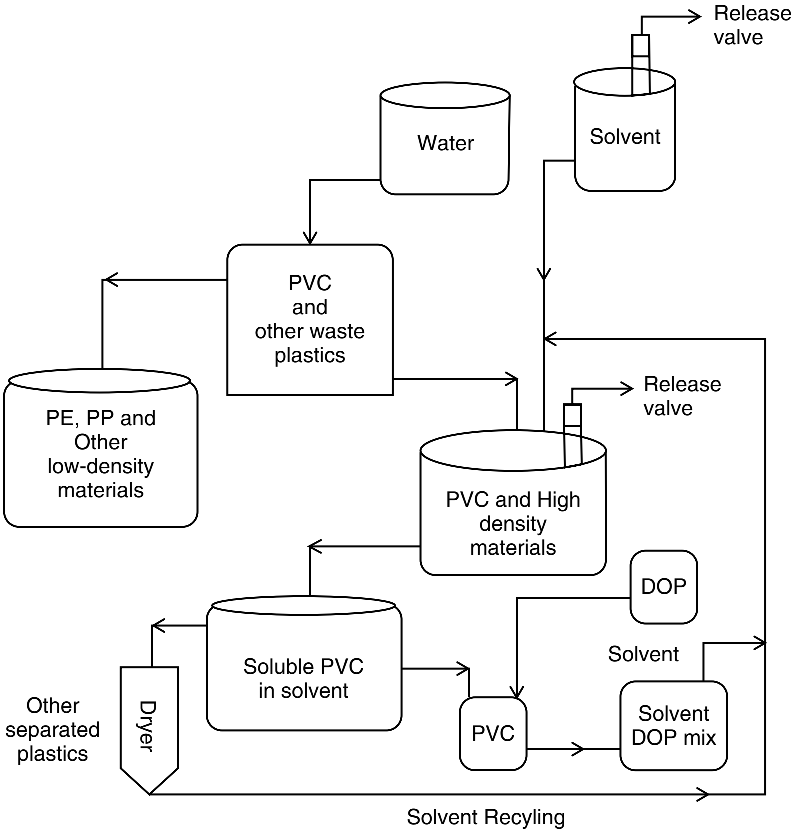

Figure 8.1 Separation of PVC from other plastics using the solvent technique. DOP: dioctylphthalate

8.4.4 Experimental Method

Figure 8.1 illustrates a flow diagram of the density and solvent separation of PVC from other plastic materials. During density separation, there is the possibility that materials of similar density may separate and settle along with the PVC. Using this method 5–8% of the PVC is soluble, and therefore a 12 kg sample can be used for the separation of PVC, which is a major quantity in comparison with other plastics.

After the separation of PVC from the mixture of waste originating from electrical and electronic equipment, the occlusion of plasticisers needs to be addressed.

If the above process is used, as opposed to a similar method using shredder residues produced during processing, WEEE is excluded from recycled material due to the variety of polymeric materials and presence of BFR; in addition, WEEE might also contain banned polybrominated diphenyl ethers or toxic polybrominated dioxins and furans [16]. The separation of residual non-styrenic polymers can be achieved using the CreaSolv® process, a solvent-based technology. In addition, this process allows the removal of non-polymeric materials, such as dust, metals and glass splinters, as well as unwanted additives and contaminants, such as BFR, polybrominated dibenzo-*p*-dioxins and polybrominated dibenzofurans, from the polymer solution [18]. Both density and solubility methods enable the separation of PVC from other materials [16]. **Figure 8.2** illustrates the two-stage density separation of a medium density styrenics fraction followed by the extractive CreaSolv® process; this method uses a 11.5 kg sample.

8.4.5 Results

In both methods, the separated plastic materials are not in pure form. ABS and HIPS are present in the mixture and the two cannot be separated from each other. This styrenics fraction can be recycled either as it is or added to virgin material. With regards to PVC, DOP is present but it is not possible to separate the two; therefore, PVC can be used as a recycled material in flexible applications.

The solvent separation technique is quite costly and the separation of even small quantities of waste material requires high levels of solvents. As the solvent contamination increases, the solvation power of the recycled solvent decreases and become less effective, until it finally becomes a pollutant and requires special disposal as it contains toxic materials eluted from the waste plastics.

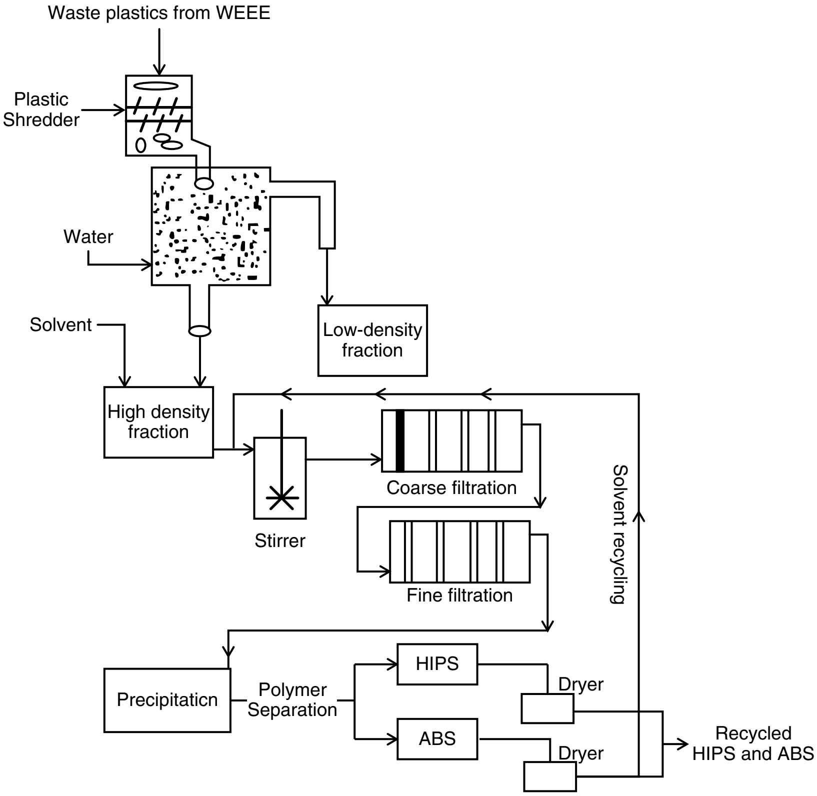

Figure 8.2 Illustration of density separation of WEEE waste. ABS: acrylonitrile-butadiene-styrene and HIPS: high-impact polystyrene

8.4.6 Conclusion

The plastic material separated from WEEE *via* density separation is used in blends along with other polymeric materials which are compatible with each other. Even for the separation of styrenics or PVC, the technological cost is higher using the solvent technique. This case study reveals that there may be a possibility for the separated plastics to be a valuable raw material for polymer recycling. The intermediate fraction from low-cost density separation serves in both methods as an appropriate input for the extraction of specific plastics from mixed plastics. Furthermore, there is also the requirement to prove the cost-effectiveness on a larger scale using different separation techniques.

8.5 Case Study 2: Plastics Waste from the Automobile Industry

8.5.1 Background

Today, plastic used in the automobile industry is receiving some attention from academics; however, the majority of the focus on waste plastics is by the automobile company along with the utilisation of waste plastic in its products. The automobile industry has improved production using process development; one step involved the utilisation of plastics waste to create economic models for the automobile market. Economy can be realised by implementing the recycling of waste as opposed to its disposal.

8.5.2 Design

Design attempts to combine the elements of art and science. The first consideration in any design and optimisation problem is to decide the boundaries of the system. Optimised process design in plastics waste recycling considers the costs of manufacturing, processing technique and the minimisation of waste.

8.5.3 Disposal and Recovery

8.5.3.1 Recycling of Bumpers

The plastics waste from an automobile is around 10% of the total weight of the automobile; bumpers account for 10% of the total weight of plastic, making this an important target for recycling. The performance of bumper recycling depends on the complete removal of paint. Recycling will become a prerequisite in products such as automotive components. Crushing and pulverising results in limited noise and dust; in addition, pulverising is comparatively easy and enables recycled products to maintain certain properties including strength.

The evaluation of automotive materials involves recovering parts from cars which have been used for a long period and determining the properties of the plastics waste. **Figures 8.3** and **8.4** illustrate the disposal of polymer parts which are present in automobiles and the recycling of bumpers, respectively.

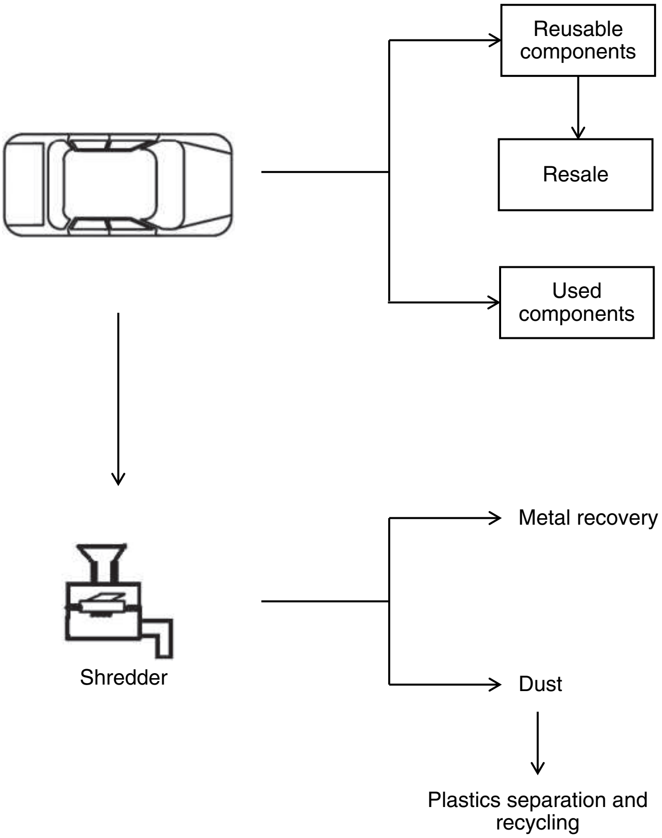

Figure 8.3 Disposal of automobiles

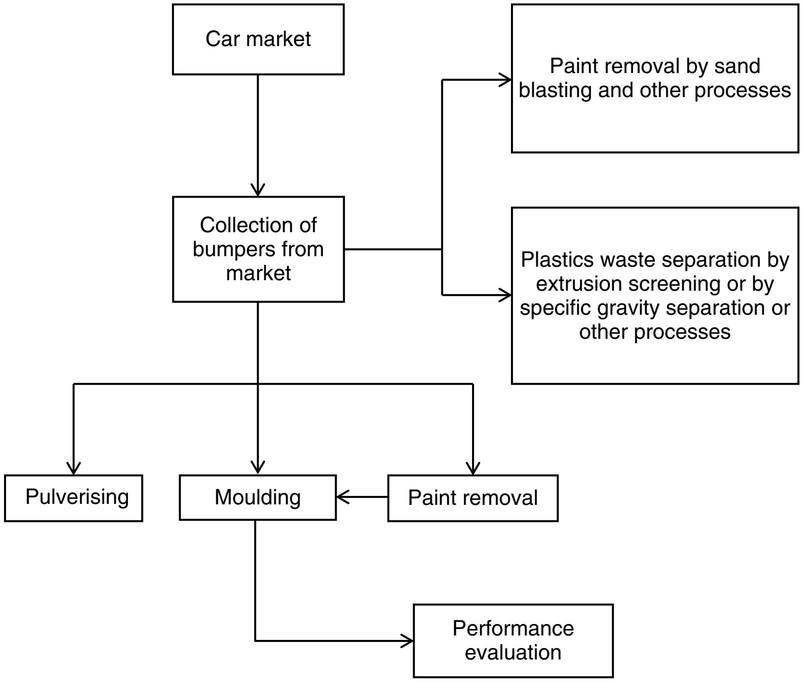

Figure 8.4 Recycling of automotive bumpers

The parts obtained from scrap automobiles are sorted through for plastic parts. The appearance and weight of the parts are measured and then subjected to crushing and pelletising. Test specimens are prepared by moulding or cutting the parts and the test pieces are evaluated.

8.5.4 Inference

ABS is widely used for the interior and exterior parts of automobiles, and parts such as the console box, glove box, radiator grill, door mirror and others are recycled. Non-painted ABS parts exhibit good properties and surface appearance. Acrylic painted parts exhibit good properties but are partially rough in appearance. Urethane painted parts have low-impact resistance with poor surface appearance. The application of new technology or adoption of mass production may not always be possible in order to achieve productivity improvements in the processing industry. The most practical approach is to review and redesign the processing method and apply automation and mechanisation.

8.6 Pros and Cons

8.6.1 Positive Thinking

In 2007, the analysis of plastics waste in Europe reported [19]:

1. The generation of 24.6 million tonnes of postconsumer plastic waste concentrated in the packaging, construction, automotive, and electrical and electronic equipment sectors.

2. 20% was recycled and 30% was recovered as energy.

8.6.2 Negative Effects

There are negetive effects if the recycling process is not performed in a thorough manner. Some of the effects are mentioned below:

1. 50% of the waste is disposed of in landfill sites [19].

2. The new 'Waste Framework Directive' has set a 50% recycling target for household waste. The directive does not stipulate what waste should apply to the municipal waste stream as a whole or individual material fractions within this stream [20].

The established hierarchy is prevention, preparation and reuse, recycling and other recovery, such as energy recovery, and disposal. It allows specific waste streams to depart from the waste hierarchy when justified by life cycle thinking [20].

Plastics waste separated from a MSW plant has a high energy content and is therefore considered useful for cogasification with coal, which has been detailed by Romey [21].

To make the large-scale (200–600 MWe) coprocessing of waste economically feasible, sufficient quantities have to be available on a continuous basis for a prolonged period of time and the energy content should not be too low. A substantial amount of plastic waste can be collected through the separation of MSW. Approximately 210 million tonnes of MSW are produced annually in the USA and the same amount again in Western Europe, of which the majority (70–90%) is landfilled [22]. The plastics component of MSW makes up, on average, 8.5 wt% in the USA and 7 wt% in Western Europe (APME 1994). MSW is sifted through in a sieve drum to remove the light material.

8.7 Research and Case Study

Case studies on plastics waste are one of several acceptable methods for analysing the impacts of environmental contamination and estimating the decreased value of a contaminated or previously contaminated property [23]. The areas of plastics waste involve recycling, reuse and disposal; hence, research on waste plastics is, to a large extent, aimed at investigating how this waste is generated, recycled and reused under different conditions. Plastics waste management is carried out by groups and organisations and the consideration of the impact upon society is important for this development.

Plastics waste management is a multidisciplinary process involving areas where case studies are of benefit. Many research questions in plastics waste management are suitable for case study research and the case study methodology is well suited for many types/aspects of plastics waste management. Research into plastics waste is a contemporary development and is complicated by the fact the waste components/processes are difficult to study in isolation.

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9

Market and Sale of Recycled Plastics

Due to increased competition, cost reduction and economic uncertainty, industry is seeking to manufacture products from a combination of recycled and virgin material. The competitive situation in world markets has led to a move away from the use of pure virgin material; hence, the time has come to use plastics waste in large quantities. The role of marketing plastics waste involves finding new strategies and infrastructures for novel market opportunities.

Due to the realisation that solid waste contains valuable plastics waste, there has been increased focus on the collection or separation of plastic waste from other mixed wastes; hence, the recycling of plastics waste is part of a huge, billion dollar market. The pattern of buying dictates the use of resource required and hence prioritises the type and amount of recycled plastic that is targeted [1]. Recycled plastics are used in small amounts by a multitude of industrial firms all over the world and the waste plastics market is used by many small-scale industries.

Plastics waste adds value when recycled alone or with a certain percentage of virgin material as long as the essential properties of the end product are not negatively impacted. The recycling of waste plastics may have to look beyond its initial application in order to alleviate any detrimental environmental impact. A crucial strategy in the management of plastics waste will be the collection, segregation and effective handling of the whole process from the solid waste stage.

9.1 Virgin Material – Market Uncertainty

Plastic products made from virgin material are facing increased competition and a depletion of natural sources of raw material. Economists who are critical of classical and neo-classical economics state that an important element in any theory of economics is uncertainty [2]. Plastics waste has become a recognised source of recycled material sales based on market uncertainty.

The recycled plastics market would increase in the future if industries changed their state of ignorance regarding their collective concepts on the use of waste plastics material. Risk taking and innovation through the separation of plastics waste from other solid waste material will characterise the market trend.

The separation of plastics changes the recycling utilisation structure and strategies involved, which impacts the development of the recycled plastics market by allowing new opportunities to be sought, errors and constraints to be overcome, and planning to be implemented. This would result in changes within the market place [3] brought about by industries seeking to increase the use of plastics waste in order to reduce cost and increase knowledge, which would result in reducing the market uncertainty with regards to non-degradable plastics waste. In order to survive, industries must expand their knowledge, which requires them to enter into networks of competition with key players in their sales and marketing chain. The future of the plastics waste market is unknown as it is characterised by high levels of competition between industries.

9.2 Industrial Strategy

The industrial strategy is to highlight the importance of competition; intense competition is a result of numerous competitors, slow growth, high-level fixed costs, lack of differentiation amongst products and quality, ease of product substitution and the existence of industries with a high stake in achieving success [4].

Marketing, when properly understood and practiced, is the very soul of enterprise; it gives meaning to and permeates all aspects of it. A business enterprise has two functions: marketing and innovation, the remainder involves cost [5]. If a clear understanding of waste management is critical to success, then a clear understanding of the marketing process is fundamental. Marketing and sales have supplanted manufacturing as the primary aspect of industrial competition. The development of products containing waste plastics has become the battleground as the postindustrial stage begins.

9.3 Marketing Strategy

In the marketing of plastics waste, markets grow explosively requiring multinational organisations to develop new strategies to manage the change. However, the changes required in the organisational structure are slow to follow, resulting in people and processes struggling to keep up with manufacturing demand, which has a detrimental impact on the brand image. Today, the acceptance of plastics waste as a useful resource contributes to increasing knowledge of its potential. The analytical research paradigm is not sufficient for investigating complex real-life issues involved in managing the recycling of plastics waste.

9.4 Recycled Plastics Market

There is a growing interest in increasing the recovery and recycling of waste plastics. The basic arguments regarding productivity activity are [6]:

- An increased willingness to recognise that the raw materials used for the manufacturing of plastics are limited.

- Many major industrial nations are extremely dependent on overseas sources for primary raw materials, which causes potential economic and political disadvantages.

- The social and environmental costs brought about by many cost-cutting industrial practices are becoming politically unacceptable.

Plastics waste can vary considerably from industry to industry as does the degree to which recycling can benefit individual industries.

In the field of recycling plastics, the industry faces two major hazards:

1. Failing to take economic advantage offered by new market possibilities.
2. Assuming the recycling market automatically has a profitable market outlet.

Promising trends have been noted relating to marketing strategy being a primary tool in the recycled market, which has highlighted the diminishing levels of natural resources and unavailability of virgin plastic materials. Some promising introductory work has taken place with industries mixing waste plastics in varying proportions with virgin material without affecting product quality; however, the recycling of plastics has received little attention and the sale of recycled products is still at an early stage of development.

9.5 Industry and Recycled Plastics

Recycled plastics provide the primary point of differentiation between competitors and as such, they are increasingly critical to the success of many industries and rely on:

- The economic view which suggests that products made using recycled plastics are of acceptable quality and reliability.
- The strategic view considers that the recycling of plastics acts as a mobility barrier to competition.
- The marketing view links recycled plastics with favourable views of product quality.

- Industrial considerations, in terms of mixing recycled plastics with virgin materials.
- The sociological view focuses on social networks and connections in terms of product quality.
- The accounting view considers waste plastics in terms of recycling as a capital asset.

9.6 Industrial Marketing

Industrial marketing is highly likely to be affected, in business and domestic activities, by the antipollution lobby. Some industries could be adversely affected by the environmental crisis, whilst others could grasp new marketing opportunities resulting from financial support and new legislation.

The balance between population growth and natural resources is, in a sense, a problem that has always been with us, and also affects all the other species on the planet. Comparatively recent trends of the rapid growth in population, growth in exploitation of the earth's resources and growth in every parameter which characterises the status of mankind, have led to comprehension of the fact that we live on a finite globe of limited resources. The finiteness of the earth is within sight of imposing the ultimate confrontation between man and nature: between human systems whose influence has now grown worldwide, and the natural ecosystems that have arisen and maintain the biosphere as a place suitable for life [7].

9.7 Product Development and Market

Product development using plastics waste is an example of a cross-functional process that is largely composed of functional engineering skills and the developing of manufacturing processes. Product development includes many important marketing activities, and to be successful must be closely coupled with integration process. There are many products which are currently under development and are examples of excellent product development processes – which is a considerable accomplishment, but not enough. Additional development of products using waste plastics is urgently needed.

As markets move closer together in the global economy and worldwide logistics becomes more accessible, the geographical reach of technologies has increased. If a technology for manufacturing products or services can be offered in various parts of the world this leads to financial benefits for both the producer and consumer.

This line of reasoning is limited, however, to cases of products and services where consumer demands are independent of geographical location and cultural context. The field of environmental engineering and management addressed in this book is very sensitive to geography and culture. As a consequence of researching environmental management in South America, the author was approached by European manufacturers to discuss the transfer of solid waste handling technology and corresponding equipment procurement. Although in principle, this transfer of knowledge appears pertinent, the success of such an enterprise depends heavily on correct management procedures tailored to the specific location where the technology is to be employed.

Efforts to translate technical success into commercial success are full of pitfalls. Waste plastics recycling is a billion dollar market in which a few companies sell recycled products to a multitude of industrial firms worldwide. The waste plastics market is voluminous and small firms order this resource in large quantities only when it is needed.

Two functional processes that are fundamental and critical for any business are product development and marketing.

A growing trend in today's business environment is understanding the value of waste management. Plastics processing industries include an increasing number of firms which offer marginal customisation of products and services, which highlights the fact that industries emphasise the importance of production and marketing interactions.

9.8 Recycled Product Sales

It is not an overstatement to say that there is a palpable sense of transformation in both the virgin and recycled product sales sectors, and rapid changes have been observed in the way recycled product sales are achieved. An increasing global environmental awareness, has been catalysed by the sudden end to years of economic growth and some changes outside the realms of the sale of recycled products.

Rapidly changing and highly complex plastics business environments are affecting the trading process. Sale is a strategic value-creating process and often attracts high-level management involvement particularly in the field of recycled products. Profit is an important factor for sales, yet when considering recycling, attention has to be devoted to the budget in terms of cost reduction, processing and so on [8].

9.9 Successful Sales

The successful sale of recycled plastics requires familiarity with the concept of profit gap analysis, profit planning and new product development as three interlinked stages which ensure that requisite corporate profitability is attained. Modern marketing philosophy cites profit-seeking activity as opposed to sales volume activity as the distinguishing feature.

With regards to the sale of recycled products, planning and monitoring is linked to expenditure on sales activities, emotions, customer demands and future prospects. Remuneration schemes and plans for rewarding increases in the sale of recycled products are common, however, processes and techniques for predicting volume of sale and trends are essential.

Passage through these three stages, however, has increasingly been shown to encounter a series of organisational problems which few attempts have so far been made to overcome. Therefore, exploration of the relevant concepts in the marketing sector must be embraced if these problems are to be faced and overcome [9].

Today's competitive landscape has not changed significantly over recent years [10]. Many of the pressures on recycled products seem to be related to changes in customer expectations, which require rapid changes and persistent pressure to achieve the necessary sales quotas [11]. Customer expectations, rising buyer power and fierce competition are all factors in the trading of recycled products.

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10

Future Trends

Science and technology have combined to make our everyday life comfortable, but has placed a burden on the environment in the following ways:

1. Global warming
2. Depletion of natural resources
3. Atmospheric pollution
4. Increase in solid waste
5. Destruction of the ozone layer

Current regulations aim to preserve the environment *via* recycling materials. Solid waste, particularly plastics waste, is non-degradable and requires economic disposal techniques.

Burning waste is sometimes seen by consumers as a convenient way to avoid trips to landfill sites, and the municipal corporation is a serious threat to air quality in some developed and developing countries. Pollutants have been linked to many health concerns, including cancer, disruption of endocrine function, developmental problems, endometriosis, cardiovascular disease, asthma and diabetes. Burning the waste also causes fire hazards, unpleasant odours and chemical fog; in addition, the toxic ash can contaminate water supplies [1].

10.1 Environmental Advantages

As a result of the growing awareness of the need for clean air and water, there has been an increased use of pumps which contain plastic parts, such as the casing, casing cover and impeller, as opposed to metallic pumps. A study by pollution engineers revealed that the advantages of plastic pumps are superior corrosion and abrasion resistance, ease of maintenance and scrubbing systems for odour control for use in, e.g., water recovery projects, neutralisation of acidic or alkaline solutions, and the treatment of a wide range of liquid wastes or toxic fumes to satisfy government regulations [2].

Worldwide, 129 million tonnes of plastic is produced annually, 60% of which is disposed of as fuel oil. If the total amount was recycled, it would fill up 350 tankers of 200,000 tonne capacity [3]. However, there is a growing consensus that plastics waste faces challenging operational environments. Due to increasing demand and the subsequent increase of consumer and industrial waste, the amount and composition of plastics waste needs to be characterised prior to disposal.

10.2 Plastics Waste – Challenge

50% of waste is disposed of in landfills [4]; however, the new 'Waste Frame Work Directive' has set a 50% recycling target for household waste. The directive does not stipulate what waste can enter the municipal waste stream as a whole or individual material fractions within this stream [5].

Disposal of waste is the act of abandoning items, i.e., placing the waste item somewhere with no intention of moving it anywhere else. Waste disposal is, or should be, a managed activity requiring: the selection of an appropriate site, the design and engineering of the site and ensuring the processes employed are appropriate, proper management of the entire operation, assessment of the likely consequences and monitoring to confirm acceptability.

Increasing concern regarding the impact of chemicals on health and the environment may have significant impact on the use and disposal of plastics that, in turn, may translate into strict legislation. Environmental regulations require the change of design, manufacture, disposal and use of plastic products in many countries.

10.2.1 E-Waste

E-waste contains lead, mercury, cadmium, flame-retardant plastics and other materials, and its disposal can pose a threat to human health and the environment. Out of the 10 million computers that are discarded every year in the USA, only 10% are recycled [6]. According to the European Union, the producers must either take back used equipment or phase out hazardous materials from electronics. In the decade 1997–2007, 500 million computers became outdated with plastics waste reaching 70–80%. Among the collected plastics E-waste, between 50–80% is recycled by the USA; the remainder is exported to Asia, and 90% of that is destined for developing countries [7]. Asia accumulates the greatest amount of E-waste in the world [8].

In the electronics sector, design cycles and product life spans are short, unit builds are high, and manufacturers design, produce and sell globally. Expanding volumes, short life cycles and an ever-growing waste stream impact on waste disposal resources – both landfill and incineration capacity are a practical concern for many governments. Plastic is a diverse material and is used in a wide range of industries and product types, including electronic devices and electrical appliances, which results in the production of a large amount of waste. It is necessary to improve material choices and create better designs with waste recycling as a mandatory factor.

10.2.2 Medical Waste

The predominant constituent of plastics waste in medical waste is polyvinyl chloride (PVC), an inexpensive and common polymer used for both medical and commercial products. Iatrogenic dioxane pollution can be largely eliminated by avoiding the incineration of PVC. The group of dioxin-like compounds includes all substances with a similar chemical structure and biological effect, which makes them particularly troublesome. PVC contributes to approximately 80% of the organically bound chlorine found in municipal incinerators and about half of the total chlorine (organic plus inorganic) [9]. During incineration, the chlorine liberated from the incineration process kills the majority of germs present in the municipal waste.

10.2.3 Packaging

Plastic materials are being used globally as packaging material as a result of favourable cost factors and suitability for the chosen selling and distribution system. Plastic packaging materials once discarded are the major source of plastics waste. Approximately 380 billion plastic packaging items are produced as bags worldwide and only about 5.2% are recycled; the remainder of the bags end up in landfill, are incinerated, or get clogged in waterways, pipes, drains and ditches [10].

Plastic bags are the most visible form of pollution; cheap, thin plastic bags are found everywhere, including rivers, streets and treetops, in most developing and underdeveloped countries. Plastic bags clog waterways and create bacteria-infected cesspits which further contaminate the water. As plastic bags litter the ground and can become buried under layers of mud during the rainy season, they leach further toxic waste into the soil.

10.2.4 Construction

Construction and demolition waste in the USA reaches approximately 143 million tonnes and according to the ‘Waste Business Journal’, only 25% of that waste is recycled. In fact, 40% of all waste in landfill is construction and demolition waste. The plastics waste generated by construction and demolition projects includes vinyl sidings, doors, windows, floor tiles and pipes [11].

10.3 Environmental and Social Problems – Prevention

Plastics waste is becoming an environmental and social problem. Industry can avoid the increasing cost of waste disposal, and potential financial difficulty, by not allowing it to accumulate, which would also benefit the environment. At the same time, in terms of the consumer point-of-view, it is the responsibility of industry to dispose of plastics waste properly. Hence, the plastics industry can incorporate the use of recycled plastics and improve its chances of surviving by:

- Reduce/avoid plastics waste generation by using an efficient manufacturing process.
- Recycle plastics waste by investigating new areas of product application.
- Avoid landfill and the burning of plastics waste by considering environmental and social factors.

10.4 Future Trends

Biobased plastics are not always biodegradable and biodegradable plastics are not always biobased. Biodegradable plastics cannot be considered as a general solution to the litter problem. Biological degradation is very slow and depends on environmental conditions, such as microorganisms, temperature and humidity. Biodegradable plastics may even add to the litter problem due to limitations including the time required for degradation, the use of enzymes, climate change and so on [12].

For use in primary applications, the recycling of plastics waste must be engineered in a clean and segregated closed-loop process [13]. Even packaging material such as film wrap can be collected in bulk from industrial waste; therefore, packaging waste can be economically recycled [14].

Analytical considerations for plastics waste, in terms of an environmental point-of-view, include:

- Plastics processing should result in optimal physical properties such thermal, mechanical and so on.
- Chemical composition of the plastics material.
- Extraction and migration properties with respect to the environment.

Consideration of the above factors prevents the generation of plastics waste and at the same time helps in the preparation and reuse of plastics waste in addition to recycling and energy recovery. In the sea and on the seashore, it is necessary to ensure the ability of waste plastics to photodegrade and/or biodegrade [15]; the disposal of unusable plastics wastes requires defined processes, which allow the plastics waste stream to be driven by life cycle thinking. Many plastics have a higher calorific value than coal, therefore they can be logically mixed with fossil fuels or used individually in a furnace, which avoids the danger of toxic pollution as a result of not burning waste in a furnace.

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Conclusion

The manufacturing of plastic products is a very good use of energy and resources as it ‘borrows’ energy and the energy within the manufactured product is then recovered, resulting in a 100-fold saving of energy which is a beneficial investment for society. Plastics are essential modern-day materials which improve the day-to-day quality of life through telecommunications, computers, transport, health, sanitation, education, housing and so on. Plastic products originate from the petrochemical, coal or gas industry, and can be moulded into any shape. Some plastics have excellent corrosion and impact resistance, and new plastic materials are designed to suit a multitude of novel applications.

Plastics waste management can help industries maintain profit and enable growth. In 1980, the waste material business in the USA reached almost $50 billion and has been increasing by 20% year-on-year [1]. The increased consumption of plastics results in a larger accumulation of unrecovered energy, i.e., plastics are stocked, e.g., in households, cars and buildings; however, plastics are released as waste when the service period of these goods is over, hence increasing plastics consumption will lead to higher plastic waste volumes.

There is a widely held belief that plastics waste increases the complexity of the environments in which we live and work. However, there is little empirical evidence to support the notion that the method of disposal is indeed effective in dealing with the composition and volume of waste plastics. Despite some notable research, there is a curious gap in the literature regarding plastics waste and its disposal. Many claims have concerned the ability to change the nature and quality of plastics waste using complex methods.

There seems to be a strong link between the expectations and needs of the recycling process and type of motivation within the industry, therefore resources are necessary for the development of recycled products. The recycling markets targeted by industry will ultimately determine the commercial success or failure of the venture.

It could be some time before the consumer movement demands the recycling of waste materials. The plastics material sector is the same as other industries, in that recycled plastics can be easily translated into profit. There is the potential to transform millions of tonnes of plastics waste into products leading to worldwide economic gain; however, the argument against this concept concerns the question over the consistent supply of recycled products of sufficient quality to satisfy customers.

The environment clearly displays the dangers and problems of plastics waste, which has resulted in communities demanding either it is reused and recycled or converted into energy. The need for solutions to plastics waste are driven by environmental concern and awareness. The proper management of waste plastics can minimise the negative impact on the environment and encourage new projects which could enhance the economy of the country. Therefore, the plastics industry should consider scenarios based on social, political, economic and technological factors to ensure success in the future. Recycled products should be assessed on their compatibility with, and impact on, the environment.

Plastics are utilised to improve the living conditions of the majority of the global population and, due to technological advancement, the industry has demonstrated tremendous growth along with ecomomic success. The solution to any plastic waste problem must be defined both qualitatively and quantitatively. Using expert knowledge, plastics waste can be transformed into materials which can be used in a wide range of practical applications. Plastics waste should be used to develop new products tailored to the end use, which should be both technically and economically feasible.

The practice of plastics waste management differs between developed and developing countries, and waste plastic is generated by residential and industrial activites in urban and rural areas. The aim of plastics waste management is to facilitate the recovery of resources and energy from the waste material, which can be achieved using different methods and fields of expertise based on a specific type of processes to provide new paradigms for waste management.

Large amounts of plastic are produced and used in various spheres of human activity, which are ultimately discarded as pollutants containing residues such as plasticisers, solvents and harmful products which can migrate out of the materials. Therefore, the toxicological properties of plastics can be characterised as migratory or derivatives formed under the influence of the environment. Plastics contain many additives which alter its properties and it is important to know the level of these constituents to regulate by maximum concentrations allowable in the plastic [2–6].

Plastics are increasingly important from a global perspective and increase the amount of waste needed to be discharged into the environment. Discarded plastics waste is dumped in the countryside or burned in the open air and the resulting pollution causes hygiene and environmental problems. The correct management of plastics waste is essential to reduce the amount of waste and possible environmental and health risks.

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Abbreviations

ABS	Acrylonitrile-butadiene-styrene
BFR	Brominated flame retardant(s)
DOP	Dioctylphthalate
EA	Erucamide
EG	Ethylene glycol
EU	European Union
FR	Flame retardant(s)
HDPE	High-density polyethylene
HIPS	High-impact polystyrene
LCA	Life cycle assessment
LDPE	Low-density polyethylene
MFI	Melt flow index
MSW	Municipal solid waste
MW	Molecular weight
OA	Oleamide
PA	Polyamide(s)
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene terephthalate
PO	Polyolefin(s)

PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
rPVC	Recycled polyvinyl chloride
RT	Room temperature
SA	Stearamide
T_g	Glass transition temperature
T_m	Melt temperature
UV	Ultraviolet
uPVC	Unplasticised polyvinyl chloride
WEEE	Waste electric and electronic equipment

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ISBN 978-1-91024-296-4
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Published by Smithers Rapra Technology Ltd, 2016

This book details the utilisation of a wide range of plastics waste in terms of optimising the processing and disposal of polymers, which plays an important role in the success of the plastics industry. In addition, the environmental impact of the plastics industry is also discussed.

Several thousands of compounds are associated with polymers in the form of additives such as antioxidants, fillers or lubricants, and so on, which aid the processing of plastic but can cause problems once the plastic items have come to the end of their service life, i.e., become waste. The plastics waste sector also has to take into account that some technology used to process waste plastic is incompatible with the recycling process.

Plastics waste management is essential due to the large volume of degradable plastics; however, plastics waste is required in certain markets hence its impact on the plastics industry has been limited. This book details a different approach to the management of plastics waste which has many advantages. In addition, this book discusses the use of waste plastics in many applications and covers the major routes of plastics waste disposal and litter control; an area which has previously lacked information.

This book is essential reading for any technical individual needing a comprehensive and authoritative review of the entire plastics waste field. Polymer chemists and environmental scientists will find useful and important information which could inspire a large audience of industrial and academic polymer scientists. In summary, specialists in the plastics and environmental sectors will find this book a useful and important reference source.

SMITHERS
RAPRA

Shawbury, Shrewsbury, Shropshire, SY4 4NR, UK
Telephone: +44 (0)1939 250383
Fax: +44 (0)1939 251118
Web: www.polymer-books.com