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Plastic recycling

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ABSTRACT

This review covers the options for recycling of plastic waste and provides a general overview of the main issues associated with plastic disposal. It provides a summary of the quantities and type of plastics in the waste stream and also the main effects of recycling on the plastic material itself. The four types of recycling: primary, secondary, tertiary and quarternary, the requirements each places on the feed stock, and the uses of each are given.

Keywords: *plastic, polymer, recycling, processing, incineration, landfill avoidance*

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1. Introduction

Historically recycling in the plastic industry was carried out within manufacturing companies as part of the standard production process. In extrusion for instance, often where material and contamination constraints allowed, in-house scrap would be reprocessed with virgin material, to improve final material production yields. Plastic waste both commercial and post consumer going to landfill.

Therefore, it is only relatively late in the development of the plastic industry that focus and public perception has shifted towards the problems of plastic waste. This has been driven by two factors; a growing concern about the costs, both financial and environmentally of land filling, and the sheer amount of plastic waste finding its way into that waste stream.

This overview will provide a general introduction to the issues affecting plastics recycling materials from end of life to disposal and overview the main methods in landfill avoidance associated with plastic waste.

2. The scale of the problem

The amount of plastics ending up in the waste stream seems to be ever increasing. In Western Europe it is currently estimated to be rising at 4% a year[1]. This is due to the fact that plastics are an extremely useful and versatile set of materials. They have found use in a whole range of products such as consumer goods, packaging, automotive and construction. The use of plastics in the automotive industry for example has been increasing due to the drive to make cars more energy efficient and lightweight. The overall distribution of plastic materials usage by industrial sector within the UK is shown in Figure 1.

As a percentage of the domestic waste stream, plastics make up only about 7%; however because of their light weight they can seem to be contributing a much higher percentage of the bulk and are therefore more visible in the waste stream than heavier materials such as metals. Annually plastics contribute about 3 million tonnes, 56% of this comes from packaging materials.

This may be surprising since in Figure 1 only 35% of plastics are used in packaging. This can be explained by considering not only the product type but also the product lifetime. The lifetime of a product is an important concept in recycling.

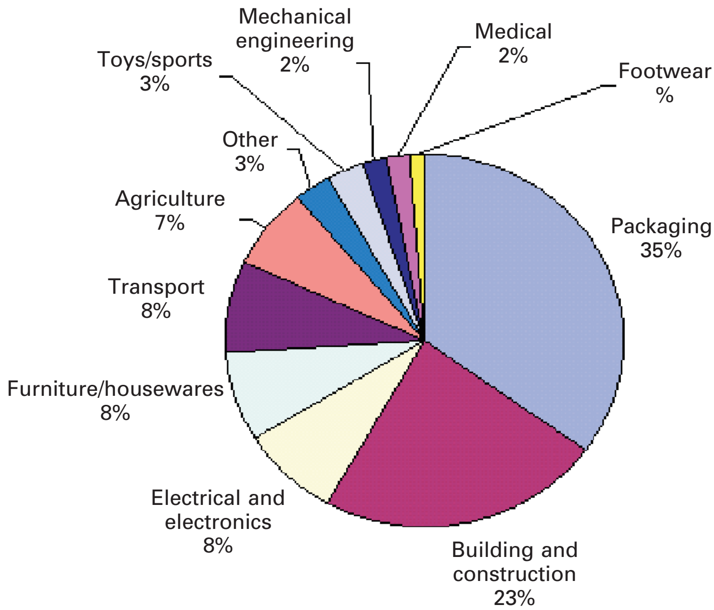

Fig. 1. *Uses of plastics within the UK. [http://www.wasteonline.org.uk/resources/InformationSheets/Plastics.htm accessed 4.4.07]*

Consider for example a polypropylene bumper on a car. This may well be on the same car for in excess of 10 years. In contrast, a polyethylene wrapper on a fresh chicken may be discarded (have a lifetime) of just a few days. Likewise, a supermarket carrier bag may be discarded as soon as it has served its purpose of carrying the shopping home. Plastics from the packaging sector tend to have a much shorter lifetime. The lifetime of a product will affect when it ends up in the waste stream.

We have seen that packaging has a very short lifetime; however it has been estimated that supermarkets give these away at a rate of over 290 bags for each person a year in the UK. If this does not make environmental sense why do it?

The answer is economics. The supermarkets are in competition with each other for customers and to keep their market share they must give their customers the service that they want. The conflict between the environment and the economy can be a major barrier in recycling. One solution is legislation; this is beyond the scope of this paper but is further considered by Meech, 2006[2].

(Interestingly, it is the same consumer pressure that may soon cause the supermarkets to cease this particular practice.)

3. Plastic materials

In order to understand how best to recycle a plastic material it is necessary to know what the material is and how it is likely to behave. Plastics are made up of polymers and additives. The percentage of a polymer contained within a plastic material can vary widely from virtually 100% to less than 20% and depends on the application for which it is intended. In the USA alone over 18,000 different grades of polymer based materials are available. For the purposes of discussing recycling, these plastics can be subdivided into two main categories: thermoplastics and thermosets. This distinction relates to the basic molecular structure and affects which processing route as well as which recycling route can be applied. A plastic in first use is termed a virgin material.

Common thermoplastics and their uses are shown in Table 1.

When heated they melt and flow and when cooled they solidify. This process of heating and cooling can be repeated many times and therefore to reprocess a thermoplastic material is it necessary to re-melt them. HDPE, LDPE, PP and PS materials are used in vast quantities to make many consumer items such as lids, carrier bags and fast food packaging. PET is used for carbonated drinks bottles. PVC is used to make flooring, shoes and bottles.

Thermosets whilst initially processed by melting in a similar manner to thermoplastics cannot be re-melted and will decompose rather than melt. This is because they are chemically cross linked during a process called curing. This produces a highly dense chemical structure which imparts stiffness and brittleness. Examples of thermosets are epoxy resins (adhesives, electrical insulation), melamine-formaldehyde resin (heat resistant laminate surfaces such as kitchen worktops) and phenolics (heat resistant handles for pans, toasters, irons).

Since thermosets cannot be recycled by re-melting they are much more difficult to re-process. However they also tend to have longer service lives (10 years+) and are used in smaller quantities to thermoplastic materials. Much research has been done looking for ways to dispose of thermoset materials, a number of which will be discussed later in this paper.

It was stated earlier that plastics are made up of polymer and additives, before we move on to a more in depth look at recycling it is necessary to briefly discuss additives and their affect on this

Table 1. *Common thermoplastics and their use in packaging*

Polymer	Application	Products
Low-density polyethylene (LDPE)	Film, coatings	Carrier bags, bin bags
High-density polyethylene (HDPE)	Film, bottles	Milk and fruit juice bottles, washing up liquid bottles, fabric conditioners. (Bottles are *not* transparent as per PET)
Polyethylene terephthalate (PET)	Bottles	Transparent drink bottles *e.g.* cooking oil, cordials, carbonated drinks
Polyvinyl chloride (PVC)	Film, containers	Chemical bottles (weedkiller, car polish sprays)
Polystyrene (PS)	Containers	Clear when unfoamed for food containers, also often foamed (fast food packaging)

process. There are numerous additives commercially available for plastics and a full discussion is beyond the scope of this review[3]. However eight of the most common additives can be found in Table 2.

Not only can numerous additives be put into plastics; they can also be added at a range of percentages. Glass fibre for instance may be incorporated at ranges from 5%–80% producing a plastic with vastly different properties and uses.

It is this sort of versatility which has allowed plastics success in markets traditionally using materials with such different properties as glass, metal or wood. However this versatility can also be a drawback when considering recycling. If one single polymer is considered, a considerable amount of possibilities for additives and combinations of additives exist.

4. Melt processing of thermoplastics

The focus will now switch specifically to thermoplastic material and their processing. Processing can be simplified to three stages: melting, forming and solidifying.

There are a number of processes used to manufacture plastic components performing these three simple steps for example extrusion, injection moulding blow moulding and film blowing[4]. Each is used to manufacture specific types of products.

Table 2. *Common additives for plastics*

Additive	Purpose
Calcium carbonate	Filler: generally used for cost reduction as much cheaper than polymer
Pigments	Give the plastic a colour. Generally for aesthetic properties
Glass fibre	Increased strength and stiffness
Flame retardants	Increase fire resistance
Heat stabilisers	Increased resistance to heat exposure
Light stabilisers	Increased resistance to light exposure
Plasticisers	Process aid which reduces viscosity
Foaming agents	Lightness and stiffness

Extrusion is used to mix polymer with other additives (called compounding). It can also be used to produce simple shaped articles such as sheets of plastic and window profiles for instance.

Injection moulding can produce more complex and intricate articles and can quickly mass produce them. Examples include buckets, automotive door handles, mobile phone cases and TV housings.

Blow moulding is used to produce hollow articles such as bottles.

Film blowing is used to produce thin films for wrapping or carrier bags.

The feed stock for all of these processes is usually plastic pellets of sizes similar to the range of pea sizes. For materials to be reprocessed they will usually have to undergo a process to return them back to this sort of feed stock.

During all of these processes, the plastic will undergo the following:

Heating and heat transfer: the polymer will be heated to melt and flow and must loose the heat to solidify.

Deformation: enables the product to form during manufacturing. Polymers are also susceptible to damage from shear force that can occur during standard manufacturing processing as well as subsequent processes such as granulation. This action is accelerated by the high temperatures involved. The result is chemical degradation due to molecular damage in the form of chain cleavage, crosslinking or the formation of a series of double bonds.

Heating and shear are the main causes of the two biggest problems associated with re-processing plastics from post consumer products are:

(1) The degradation of the plastics due to processing and service life.
(2) Getting acceptable properties from processing mixed plastics[5] and therefore finding applications for recyclate.

While in service the influence of the environment can also cause deterioration in the polymer. This could be due to the action of light, heat and weathering. This aging process is accompanied by a change in visual properties (illustrated in Figure 2 and commonly seen as a yellowing of white carrier bags or white PVC window frames). The mechanical properties of both virgin and recyclate materials are also affected.

Waste plastics, therefore, will have degraded to some degree following their original usage. The level of this degradation depends on the polymer type, on thermal and shear stress history and on the initial stabilisation. To inhibit plastic degradation, stabilisation additives can be used. Other additives such as fillers can also be introduced into the compound to improve the properties of the recyclate.

The amount of degradation undergone by these materials will be dependent on the processing conditions under which they were subjected to and the levels of stabilisation present. For a second application, it will be possible to re-stabilise them. For this to work satisfactorily, knowledge of the type and amount of stabiliser originally used is required. In the process of protecting the plastic some stabilisers are used up. To ensure continued protection these materials need to be kept at optimum levels. Further testing may be required to assess the stability (both processing and long-term) if required.

5. The need for separation of plastics

The reasons that thermoplastic and thermosets need sorting from each other will hopefully be quite clear since thermosets cannot be remelted to reprocess them. However, individual thermoplastics families *i.e.* PP, PET, PVC also need to be separated from each other before they can be reprocessed. If all the various thermoplastics were mixed together and recycled the properties of the new

Fig. 2. *The colour change in HDPE can be clearly seen after 10 process cycles. Virgin material (top left), material injection moulded and re-granulated 10 times (bottom left).*

mix would not be very good. This is because of the chemical composition of polymers. They are all different and do not mix well with each other. Instead of getting a single polymer mixture of one single set of properties, the mixture would consist of lots of small discrete areas of different polymers with no bonds between them. An egg consisting of not one but many smaller individual yolks encapsulated but not connected to a thin egg white is a simple analogy.

Therefore, not only is separation necessary for good properties, single polymers mixtures can also command a higher price in the market place and be used alone or in blends with new materials.

6. Reprocessing thermoplastic recyclate

The most common method of recycling is called mechanical recycling. In the first instance collected plastics are ground down to a suitable size to be reprocessed. This has long been practiced by the plastics industry in production facilities. This in-house recycling called primary recycling makes considerable economic sense as manufacturers not only use up their own waste but production yields are also improved.

For a re-processor to reclaim used material from other sources requires greater effort. Material may come in a variety of forms: bales, mouldings, large plastic lumps. It may also require all or some of the following: size reduction, cleaning, sorting, and re-granulating to a suitable feed stock size. Recycling activities of this type are termed secondary recycling.

A further complication is that the history of the material may not be known and therefore the properties of the resultant recyclate produced may be substantially different to the properties of the virgin material even if the original grade is known. For high quality products, high quality plastic materials are required. It is therefore difficult for recycled materials to compete in such markets where there properties can be variable.

For example properties could vary depending on:

- How many times has it been re-processed previously.
- How much thermal degradation has it been exposed to.
- Whether it is a single polymer or mixed.
- If it is contaminated with other materials *i.e.* dirt, oil, wood, metals.
- What it was used for previously.
- Whether it has been damaged by its service life (prolonged light exposure, water exposure, steam, high temperatures *etc.*).

Within a closed loop cycle, these answers are usually known which is why primary recycling is so common place. With this knowledge comes confidence in the quality of the materials being used.

Creating closed loop infra-structures and recyclate materials standardisation schemes therefore have and are major drivers in improving confidence in using recyclate in the automotive sector, packaging and waste electrical and electronic equipment sectors. These industrial sectors have been heavily legislated to drive improvements in recyclability, forcing manufacturers to act.

7. Recycling techniques

A material can be considered reclaimable when both a technology for waste treatment and a market for the products are available[6]. Despite increasing research effort to find technical solutions, it is not yet economical to separate the wide variety of plastic that end up in the waste stream. The ideal solution would be single plastic waste streams, which present little technical effort in order to recycle. However a typical household waste stream may contain a variety of plastics in the form of packaging, carrier bags, bottles,

Fig. 3. *Symbol for plastic identification.*

plastic lids, and food and household containers. Not only are these plastics mixed they are also contaminated with items such as food waste, residues, labels and glue. Plastics may be mixed with other materials such as aluminium linings or metal closures.

One easy solution is for them to be sorted at source by the householder and a number of local councils in the UK (alas the authors own council is not yet one of them!) collect plastic bottles which have been washed and dried and separated by the householder. At present only PET, HDPE and PVC bottles, tubs and pots are regularly collected and recycled from consumers in the UK. What you are able to recycle in curb side schemes at the moment unfortunately depends where in the UK you live. However, specialist recycling companies will collect other types of plastic from businesses, usually in bulk.

The plastics in a household waste stream should each be individually marked with an identification code such as shown in Figure 3. This was developed by the Society of the Plastics Industry in America and is used throughout Europe. The number relates to the type of plastic as shown in Table 3.

The largest fraction of the various plastics in household waste is made up of polyethylene (PE) which makes up about 55%. This includes LDPE and HDPE and a less common material called LLDPE. Polypropylene is the second largest at 15%. 7% of waste is made up of 'other' plastics. These are designated with the symbol number 7.

It has been shown that mixed plastics are not compatible with each other chemically. Another important factor when remelting them is the differing temperatures required to melt and process them. One plastic may melt while another is still solid. Again this can seriously affect the properties of the final component.

For example PET melts at 245°C whereas PE needs only 135°C. In fact at 245°C, it is likely PE will start to degrade. Whereas at

Table 3. *Society of the Plastics Industry Inc. (SPI) packaging codes*

Polyethylene terephthalate	PET also seen as PET(E) or PETE	1
High-density polyethylene	HDPE	2
Polyvinyl chloride	PVC	3
Low-density polyethylene	LDPE	4
Polypropylene	PP	5
Polystyrene	PS	6
Other		7

150°C, at which PE would be molten for processing, PET would be completely solid. Recycling a mixture of the two is therefore not recommended.

A typical mechanical recycling route may be split into two types of processes.

- Physical methods to homogenize the waste (*i.e.* storage, shredding, washing and sorting).
- Melt processing (*i.e.* re-granulation and reprocessing).

Size reduction may be necessary because the feed stock must be of a compatible size to fit into reprocessing machinery. Large items may first have to be shredded to about 25–50 mm and then flaked.

Washing using a detergent will remove residues and contamination. It improves the purity of the feed stock and in some cases will increase the efficiency of some further sorting processes. Labels, glue, dirt *etc.* are removed and then the material is dried.

Often sorting will need to be carried out. Using identification codes this can be done manually. However this is obviously very labour intensive and final purity relies on human accuracy. If manpower is cheap this can be an economic method. However in the developed world mechanized sorting is preferred. There are a variety of sorting technologies in use that take advantage of the differing properties of plastics for separation[7].

One such technique for separating the polyolefin fraction of waste, which in household waste accounts for a majority fraction of 70% is to use density differences. A polyolefin includes all polymers made from monomers with linear C=C double bonds. The different types derive from differences in polymer chains, which in turn give variations in other properties such as melting

Table 4. ***Melting point and densities of common polyolefins***

Polyolefin	Melting point (°C)	Density (g/cm^3)
LDPE	115	0.92
LLDPE	123	0.92
HDPE	130	0.95
PP	170	0.90

points and densities as shown in Table 4. Unfortunately you cannot use these differences in melting point to separate different fractions. However there is a method to remove them from other material types.

All the polyolefins have densities under $1\,g/cm^3$; this is the density of water. Therefore polyolefins will float like sponges. Other plastics have densities above that of water and will sink (like soap). Separating polyolefins from other plastics can therefore be achieved in a similar manner to sorting a bag of sponges and soap. By tipping them into a bath and scooping the sponges off the surface. In plastic recycling this process is done in float-and-sink separators.

This principle will not work for all plastics. PVC and PET for instance are both used to manufacture bottles and end up mixed in the waste stream. However their densities are both $1.40\,g/cm^3$. In this case a technique called X-ray fluorescence (XRF) can be used. This is because PVC contains chlorine atoms within its chemical structure whereas PET does not. Therefore PVC can be detected and separated by the identification of chlorine.

An example of an entire waste stream is shown in Figure 4. Some of the processes may be omitted depending on the type of waste. (Energy recovery will be dealt with later.)

When discussing processing techniques it is important to distinguish between the types of waste we wish to process. A homogeneous waste stream made up of a single polymer type can usually be reprocessed on the same machinery that virgin materials are processed on. A heterogeneous mixed plastic waste (MPW) stream may also be processed in some cases on these machines but a number of specialised reprocessing techniques may be applicable. It is not possible to cover all processing possibilities within this remit, many volumes have been written on polymer processing techniques. However the most common process; extrusion[8] will be

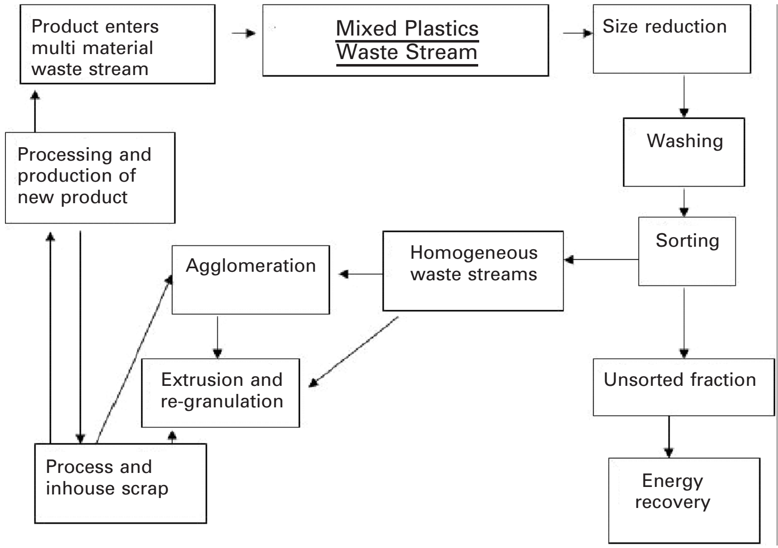

Fig. 4. *Waste process cycle for plastics.*

covered in more depth. First however a brief view will be given of how other countries are tackling the problems of plastic waste.

In Europe, Germany has very much been at the forefront of plastics recycling and its development; mainly in mechanical recycling and the logistics of collection. Germany was very heavily legislated internally by the Government as an incentive to manufacturers and very ambitious recycling targets were set.

How individual countries in Europe have approached the problem of packaging waste varies. Italy for instance put a 10% charge on PE, the raw material used for film production. Finland placed charges on non-refillable containers. Sweden placed a product charge on plastic packaging fillers and importers, whilst some other countries were still preparing legislation. Likewise Government targets for recycling or recovering packaging waste were equally variable from 30% to 85%. On the whole Europe mechanically recycled 17.8% of its plastic waste in 2004.

The emphasis government's place of mechanical recycling compared to other forms of disposal also impact heavily on how countries react to the problems of waste in general. For instance Japan, which does not have space for landfill sites concentrates heavily on Energy Recovery (discussed later) from waste rather than other forms of recycling. Japan currently treats 78% of its waste in this way.

8. Extrusion and compounding

At some point in a plastics life chances are it has passed through an extruder. In turning from a polymer to a plastic (through the addition of additives), the polymer undergoes a process of extrusion called compounding. The term compounding in general plastic processing terms, covers a variety of process steps between the production of the polymer and its final forming in a process machine. This could include the conveying or feeding of the material into a machine, metering the correct quantity of material and mixing it in as a blend of polymer with other materials such as additives. Finally, this would include pelletizing or cutting of the final plastic material for use in other processes such as for injection moulding or blow moulding machines. The typical compounding route is outlined in Figure 5.

There are two types of extruder namely a single screw and a twin screw. They perform slightly different tasks but work on similar principles. In recycling, it is to perform compounding that an extruder is most applied.

Compounding will begin with a quantity of virgin base polymer such as polypropylene and from this a number of different formulations and grades can be created to supply materials that can meet the specific requirements of their end use applications. In considering the thermal history of plastics, most material will already have passed through some kind of a processing cycle like this before it even goes to manufacture a saleable components.

When considering recycling a similar supply chain may operate. Recyclate materials may be utilised by either the polymer supplier or the compound supplier to produce grades containing all recyclate, a mixture of recyclate and additives or a mixture of recyclate and virgin material.

In Figure 5, a five step compounding route was illustrated beginning with feeding or conveying. Generally mechanical conveyors such as feed screws, conveyor belts or vibrating shutes are utilised. Larger operations may use pressure or vacuum operated silos to deliver material to the extruder or mixing stations.

Feeding or conveying	***Metering***	***Hot or cold mixing***	***Plastication***	***Pelletizing***

Fig. 5. *A plastic compounding route.*

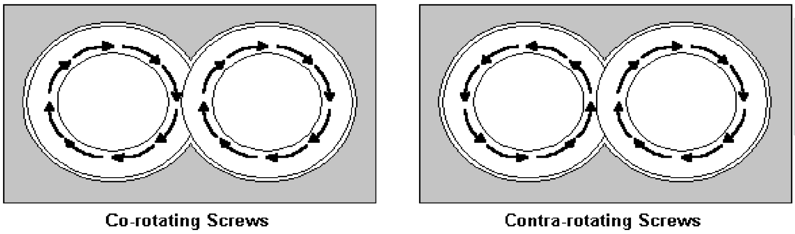

Fig. 6. *Co-rotating and contra-rotating screws.*

Accurate metering is required in many cases and gravimetric or volumetric type feeders can achieve this. Of these, gravimetric systems lend themselves to automation, have higher accuracy but a higher price. Once the required compound ingredients are metered they need to be mixed.

The aim of mixing is to disperse the ingredients to produce a homogeneous mixture. This can be done at room temperature by simply tumble blending to produce a *dry blend*, or they can be hot mixed. Generally hot mixers are situated directly above the extruder where the melted mixture can be poured into the extruder.

A twin screw extruder can have either contra-rotating (also known as counter-rotating) or co-rotating screws.

This depends on the way the screws turn relative to each other and is illustrated in Figure 6.

The aim of the screw is *plastication*, that is, to produce an easily formable melt stream. The temperature of extrusion will fall between the melting point of the polymer as a minimum, (otherwise the polymer simply will not flow as it will be solid), but below the onset of any thermal degradation to prevent excessive damage to the plastic compound. The heating of the material is done by means of external heating zones, which are incorporated into the body of the machine. The number of zones will depend on the size of the extruder being used. Generally they are positioned along the length of the machine; for example at the point of input, the centre region of the screw and the point of output. These positions correspond to the feeding and conveying section, the melting and metering region, and finally the exit die region. This allows temperature to be varied and controlled across the length of the screw. Generally the temperatures will be profiled, to be coolest at the point of input, to aid with material feed, and hottest at the point of exit. This is to compensate for extra heat that will be lost from the material in this region as it hits ambient air temperature or cooling water. The twin-screw extruder is a very effective mixer design and also ensures both a evenly dispersed mixture and an even temperature profile across the exiting material.

Because of the combination of feeding and screw action, twin-screw extruders can produce compounds with very low levels of polymers, in some cases less than 20%. The single screw extruder cannot cope with such high levels of non-polymeric materials. However for melt blending of virgin and recyclates or adding relatively low levels of additives the single screw extruder is an effective method for mixing and compounding a plastic mixture.

As the name suggests, the single screw extruder has a single Archimedian screw that rotates in a heated metal barrel. Unlike twin screw machines, which require material to be metered into the screw to prevent a screw torque overload, solid material enters the barrel through a gravity feed hopper at the feed throat. This material is melted and conveyed along the extruder barrel by the action of the screw. The material is plasticated during this conveying action and then passes through a breaker plate before exiting at the die. A breaker plate is used to take the rotation out of the melt. Without a breaker plate, the material would spiral out of the die in line with the movement of the screw. This breaker plate, which resembles a sieve, also helps to build up pressure in the melt.

Extruders can also be used to make finished or semi-finished goods such as solid profiles (bars), hollow profiles (window frames), pipes, films, sheets and filaments. The type of extrusion manufactured depends on the shape of the die through which the plastic exits. Depending on the product, downstream equipment (after exiting the extruder) may include a water bath for cooling the plastic and a pelletiser to cut it into pellets. Profiles and pipes may utilise a haul-off system with a cutting device to cut the plastic into lengths.

If the product is a granular material, it will find use as feedstock for other processes for example injection moulding, blow moulding or film blowing. Other melt processes for recycling plastics and their tolerance to contamination is shown in Table 5.

Whilst primary mechanical recycling will continue to be common practice amongst plastics processors, secondary recycling is subject to both practical and economic limits for use beyond 15% waste utilisation. Success depends primarily upon the economics of sorting for production of single polymer materials and knowledge of material provenance and degradation history. Processes adapted from conventional machinery to take more highly contaminated feedstock exist, however they are limited in application to wood-replacement type profiles and panels and cannot overcome the

Table 5. Overview of selected plastic processing techniques

Process	Complexity of parts	Forming action	Mould	Plastic types	Tolerance to contaminants
Blow moulding	Complex	Inflation	Closed	Single	Very low
Multi-layer blow moulding	Complex	Inflation	Closed	Single layers	Very low
Extrusion	Fairly simple profiles	Extrusion	None	Single	Low
Film blowing	Simple	Inflation	None	Single	Low
Injection moulding	Complex	Injection	Closed	Single	Low
Co-injection moulding	Complex	Injection	Closed	Single layers	Low
Intrusion moulding	Simple	None	Open	Mixed	High
Sinter moulding	Simple	Compression	Open	Mixed	Very high
Transfer moulding	Simple	Compression	Open	Mixed	High

inherent limitations in the make-up of their feedstock. Even these processes also generally require feedstock to have undergone some preliminarily sorting.

9. Other routes of recycling or recovery

For materials for which reprocessing is uneconomic or not possible such as with thermosets, other process routes exist. These are shown in Table 6.

Thermosets are cross-linked, meaning they cannot be re-melted and re-processed in the same way as thermoplastics. Until relatively recently thermosets were considered non-recyclable but with recyclability becoming an ever increasing criteria for material selection, the thermoset business faced a serious threat if ways could not be found to overcome this hindrance to market potential. To tackle

Table 6. *Standard names for processes for plastics recycling*[9]

Definition	Type of recycling
Primary recycling	Mechanical recycling
Secondary recycling	Mechanical recycling
Tertiary recycling	Chemical recycling (feedstock recycling)
Quarternary recycling	Incineration (energy recovery)

these technical challenges a series of companies and trade associations across the globe were set up to develop recycling methods for these materials. These groups were known as ERCOM (Germany), VALOR (France), SMC Alliance (USA) and the FRP Forum (Japan).

One possible use for thermosets is as a filler material for thermoplastic materials. Fillers are cheaper than polymer and can help reduce the cost of the final compound. Powdered thermoset scrap can find use as a material held by adhesive resins, as filler in thermoplastics or as part of a new uncured thermoset matrix.

Using thermosets as raw materials in this way are further examples of mechanical recycling. The economics for the success of mechanical recycling usually depend on the cost of the washing and sorting stages. In using recycled thermoset merely as a cheap filler rather than in 'added value' applications, it is unlikely the costs of recovering and grinding can be met. However, there are other methods available for recycling and recovery using chemical means.

Chemical recycling technologies, like mechanical recycling, place their own restrictions on the quality of feedstock that they can handle. Energy recovery (incineration) is less demanding on the requirements of sorting of individual plastics. These disposal methods offer an alternative to the use of land filling.

9.1 Chemical recycling

Chemical recycling is a process where the polymer is broken down into smaller molecules that can be easily separated from impurities. This process also known as feedstock recycling creates raw materials for petrochemical processes or feedstock that can be used to produce the monomer for new polymers or other petroleum

Table 7. *Examples of polymers made from two different polymerisation mechanisms*

Polymers from unsaturated monomers	Condensation type monomers
PE (polyethylene)	Nylon 66 (polyhexamethylene adipamide)
PP (polypropylene)	PET (polyethylene terephthalate)
PS (polystyrene)	PU (polytrimethylene urethane)
Reaction mechanism: breaking of double bond	Reaction mechanism: reactive end groups that join, expelling water

products such as waxes and paraffin. Common examples of such processes are cracking and hydrogenation.

Processes like these place restrictions on the types of materials they can handle and each method has slightly different restrictions and tolerances. Generally however they cannot handle untreated waste and sorting is necessary to remove fractions containing heavy metals, fillers and halogen compounds.

Chemical recycling is especially suited to polymers formed by condensation reactions such as PET, PU and Nylon* as the process is the reverse of the one used to create them. However, for this it means that the waste must be reasonably free from other polymers or impurities.

These technologies are exploited in industry. For example, the depolymerisation of Nylon 6 has been particularly well researched and has been practiced since the sixties[10]. Commercial depolymerisation units for polyurethanes using a process called glycolysis operate in Germany, Austria and Denmark[11]. The basic chemistry involved in these reactions is presented by Ehrig[12] for those who require further details.

9.2 Thermal conversion technologies

Thermal processing can be defined as the conversion of solid wastes into conversion products with a release of heat energy. It can serve two purposes: volume reduction and energy recovery.

*There are various types of materials termed nylons, designated by a number *i.e.* nylon 6, 10, 12, 66 related to different chemical structures. These materials are also termed polyamides.

There are a number of different categories usually distinguished by their air requirements.

1. Pyrolysis: thermal processing in absence of oxygen.
2. Hydrogenation: pyrolysis but in a high hydrogen or carbon monoxide environment.
3. Gasification: partial combustion in which a fuel is deliberately combusted with limited air.

Compared to simply burning polymeric materials by combustion, these methods can offer significant benefits.

- Environmentally cleaner process routes producing significantly lower emissions.
- The reduction in density enables cost reduction for subsequent transport and handling.
- Increased energy density.
- Conversion to fuel results in higher overall efficiencies than standard combustion.

9.2.1 Pyrolysis

In a German study published in 1999[13] it was found that difficult electrical and electronic waste could be successfully recovered by pyrolysis at temperatures of 700–900°C in the absence of air. Halogens in the waste were destroyed and complied with German dangerous materials regulations. The resulting oil and gas products were found to have high calorific values, which although found to be unsuitable for use as feedstocks, could replace the fossil fuels used to heat the kiln. The same study also compared the cost of mechanically treating this waste to recover the metal with the pyrolysis technique. The treatment costs for both processes were found similar.

9.2.2 Hydrogenation

This is a very similar process to Pyrolysis but in this process, the mixed plastic waste (MPW) is heated with hydrogen. As the molecules are cracked, (the process is often termed hydrocracking), they are saturated with the hydrogen molecules to produce a saturated liquid and gaseous hydrocarbons. The synthetic crude oil produced is of a very high quality. It is necessary to keep the pressure of the hydrogen sufficient to suppress repolymerisation or undesirable by products.

In 1992, a coal-oil plant in Bottrop, Germany, successfully trialed hydrogenation technologies with plastic waste. Some restrictions on feedstocks were necessary to optimise the efficiency of the plant and for its success it requires close collaboration with suppliers to ensure suitable feedstocks.

9.2.3 Gasification

Gasification technology is based on the use of partial combustion. It was originally developed for use with coal and oil. There are a number of variations, depending upon the type of gases used. These include oxygen in the form of air, steam, pure oxygen, oxygen-enriched air or carbon dioxide. The temperature required also depends on the type of fuel. It generally falls in the range 800–1600°C. Gasification is favoured for fuel gas production since a single gaseous product is formed at high efficiency without requiring expensive and potentially dangerous air separation plants. The synthetic gas produced can be classified according to its composition, heat value and application. The bulk of the carbon present in the waste feedstock is converted to gas leaving a virtually inert ash residue for disposal.

9.3 Energy recovery

Energy recovery can be defined as incineration to recover inherent energy.

Given that polymers are made from oil, it is not surprising that they are quite good fuel sources when they are burnt. The amount of energy that can be recovered depends on a materials calorific value. Literature values tend to give an average calorific value of mixed plastic waste as 35 MJ/kg. When compared to paper (16 MJ/kg) and organic waste (3 MJ/kg), it can be seen that plastics give a relatively high energy return when incinerated.

There are a variety of methods used for energy recovery. One pyrolysis has already been discussed. Incineration, production of waste-derived fuel and gas recovery from landfill site emissions are three examples of energy recovery in action.

The UK tends to lag behind mainland Europe, Japan and the USA when it comes to using energy recovery technologies. For example, Japan uses around 78% of its municipal waste for energy generation, Denmark 58%, whilst the UK uses only 9%. This difference is mainly due to the acceptance of landfilling as a waste disposal option. However, with the cost and restrictions imposed on such disposal expected to increase, alternative disposal methods will come to the fore.

Many countries throughout Europe routinely use municipal solid waste combustors with state of the art energy recovery and flue gas cleaning technology to produce high percentages of domestic electricity requirements. Energy recovery is even more efficient if the combustor is linked to a municipal localised heating system for the supply of hot water and process steam. In Paris, France, residential buildings in some areas are equipped with combustors. Thereby domestic waste is incinerated locally and used to provide low cost heating for the residents.

The world's first electricity generating plant to run on nothing but waste plastic fuel was built in Japan. The plant was designed to consume 700 tonnes of waste plastic a day and provide power for 30,000 Japanese homes[14].

10. Conclusion

For the most effective disposal method for plastics recycling it is necessary to consider a number of factors. The most important of these is the composition of the waste. If this is known then the viability for mechanical recycling can be easily ascertained. If mechanical recycling is not possible, then chemical recycling and finally energy recovery both present viable alternatives to offset the usage of oil reserves in the creation of the plastic material. However the best way of waste disposal will always ultimately remain one of waste minimization through best practice by both manufacturers and the general public ensuring maximum environmental benefit.

11. Outlook

World wide, the prospects for improved rates of recycling look good. Brazil has seen a surge in mechanical recycling rates comparable to Europe and balances are being found between collecting high value materials for mechanical recycling, whilst accepting this will not always be the only viable option. Energy from waste schemes and mechanical recycling are likely to go hand in hand in plastic waste disposal routes in the near future.

Similarly new infrastructures are being established to future enable recycling activities on a broader scale. The first HDPE milk bottles recovered from the same (closed loop) waste stream have currently gone on trial in the UK. Other similar schemes should also follow.

The differences in the economic development of countries world wide tends to mean that richer countries export their waste to poorer countries. Hopefully, as the third world developments practices such as these will stop as they de-stabilize internal recycling markets within individual countries and pollute the poorer nations less able to afford technology to deal with the waste stream in the first place.

In the longer term plastics you can throw on the compost heap called biodegradable materials should ease many if the problems of plastic waste. These materials are already widely available and becoming more common for short term packaging applications. These plastics can be made from natural materials such as vegetable oils which may mean that in the future, not only do we throw our waste vegetables on the compost heap but also all the materials they were packaged in.

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