

Abstract: This chapter presents a review of the properties and uses of the common packaging plastics, and some of the materials used for specialist applications.

Key words: plastics packaging market, tensile strength, elongation, tear strength, impact strength, surface friction, viscoelasticity, transparency, chemical stability, environmental stress cracking, barrier properties, glass transition temperature, melting temperature, heat sealability, density, polyethylene family, ethene, low density polyethylene, linear low density polyethylene, high density polyethylene, metallocene, collation shrink film, pallet shrink film, pallet stretch film, stretch hooding, ethylene vinyl acetate, plastic sacks, ethylene vinyl alcohol, polyvinyl acetate, polyvinyl alcohol, ethylene acrylic acid, ionomers, polypropylene, isotactic, atactic, syndiotactic, nucleating agents, biaxial orientation, thin wall containers, cast polypropylene, polarity, polyvinyl chloride, polyvinylidene chloride, plasticiser, polystyrene, general purpose styrene, high impact polystyrene, expanded polystyrene, polyethylene terephthalate, polyethylene terephthalate glycol, polyethylene naphthalate, styrene copolymers, styrene acrylonitrile, acrylonitrile butadiene styrene, Barex[®], polyamide, nylon, polycarbonate, fluoropolymers, thermoplastic elastomers, cyclic olefin copolymers, liquid crystal polymers, thermosets, phenol formaldehyde, urea formaldehyde, cellulose film, cellulose acetate, bio-based polymers, biodegradation, biomass, oxodegradable, starch-based polymers, cellulose-based polymers, polylactic acid, polyhydroxyalkanoates.

13.1 Introduction

Plastics are an essential part of modern life. Major industries depend on them and products as varied as cars, aeroplanes, electronic equipment, textiles, furniture, household goods, jewellery, shoes and clothing all use increasing quantities of plastics in their construction. Plastics used in packaging are just as widespread, from the commonly used plastic bottles and caps for milk and soft drinks, to the films used to pack a range of goods such as bacon, confectionery, nuts and bolts and textiles, and the rigid boxes/cases used for CDs and computer games. This chapter follows on from the basic principles of polymer chemistry discussed in Chapter 12, and it is essential to refer back to it when working through this chapter. Of particular importance is the section on factors affecting the characteristics of polymers, as this contains many examples relevant to individual material properties discussed here.

13.2 Market overview

Plastic is the most rapidly expanding sector of packaging materials, despite being the newcomer when one reviews historical development. From Table 13.1 it can be

Table 13.1 Overview of the development of plastics

Date	Material
1907	Phenol formaldehyde ('Bakelite') thermosetting resins
1927	Polyvinyl chloride (PVC)
1927	Cellulose acetate
1936	Polyvinyl acetate (PVA)
1938	Polystyrene (PS)
1938	Nylon 66
1939	Polyvinylidene chloride (PVdC)
1941	Polytetrafluoroethylene (PTFE)
1942	Low density polyethylene (LDPE)
1944	Polyethylene terephthalate (PET)
1948	Acrylonitrile butadiene styrene (ABS)
1955	High density polyethylene (HDPE)
1957	Polypropylene (PP)
1957	Polycarbonate (PC)
1960	Linear low density polyethylene (LLDPE)
1964	Ionomers, e.g. Surlyn
1970	Thermoplastic elastomers (TPEs)
1972	Ethylene vinyl alcohol (EVOH)
1994	Polyethylene naphthalate (PEN)

Table 13.2 European polymer demand for packaging vs. other markets, 2007 (000s tonnes)

Material	Packaging	Other markets	Packaging as % of total market
Low density/linear low density polyethylene	5,976	3,110	66
High density polyethylene	3,357	2,609	56
Polypropylene	3,414	5,789	37
Polyvinyl chloride	748	5,707	12
Polystyrene	1,511	2,218	68
Polyethylene terephthalate	3,096	147	95
Other	132	3,084	4
Total	18,204	22,664	45

Source: Applied Market Information Ltd (www.amiplastics.com).

seen that the first plastics were developed in the early years of the twentieth century. However, it was not until the 1950s that their use became widespread, when the relatively low cost polyethylenes brought plastics out of specialist applications and into the mass market. These 'new' materials became increasingly popular due to their ready availability (made from by-products of the oil industry); easy processability (most of those listed in Table 13.1 are thermoplastics, which soften at relatively low temperatures compared with materials such as glass and metal, and are easy to form into a range of different shapes); and the ability to tailor their properties closely to the intended end use, leading to a wide range of market applications.

Packaging is not the only market for plastics, but it is certainly a significant one. Table 13.2 shows the European market for plastics in packaging was just over 18 million

tonnes in 2007, which is double the 1987 tonnage. Of this 18 million tonnes, 58% is used in rigid packaging (bottles, tubs, caps, etc.) and 42% in flexible applications, i.e. films and laminates. Not surprisingly, 70% of all plastics packaging is used for food and drink, the remainder being used for household chemicals, pharmaceuticals, cosmetics and toiletries, and a range of other non-food uses, plus industrial products such as shrink and stretch film, and carrier bags.

13.3 Key properties for packaging applications

Compared with other packaging materials, plastics are generally lighter in weight, more easily formed into different shapes, and extremely versatile. This versatility is largely responsible for their growth in usage: the ability to carefully tailor the performance of a plastic container to the needs of the product, the market and the demands of the supply chain means that there is a 'plastic' solution to almost all packaging problems.

When considering the performance of plastic materials, the properties of most interest in packaging applications, and their relevance in use, are summarised as follows.

Tensile strength and elongation are probably of most practical relevance in flexible packaging, especially during form, fill and seal machine operations. Films and laminates must withstand the tension of being pulled through a forming station without stretching or breaking, and bags/sacks must withstand the force of the product weight being dropped into place without distortion. For pallet stretch wrapping, a film with high elongation is required, the most commonly used material being linear low density polyethylene. Tensile strength is a directional property and specifications will state values in machine and cross direction.

Tear strength is also relevant in flexible packaging applications, both in terms of resistance to tearing during machine forming and subsequent handling. Tear properties also influence consumer convenience in ease of opening. In general, plastics have good resistance to tearing, compared, say, with paper, and if the consumer is expected to tear open a pack it is advisable to facilitate this by using a paper/film laminate and/or incorporating an easy-open device in the pack, such as a laser cut.

Impact strength is a measure of a material's resistance to breakage when subject to a sudden impact, such as a falling object. It is probably more meaningful to evaluate the impact strength of a filled plastic component, e.g. a drum or a sack using a series of drop tests, than to rely on data generated from impact tests on the plastic materials.

Surface friction influences the ease with which a packaging material or component will travel through the packaging line, such as a film moving over a forming collar. It also influences the stability of palletised loads during transit and of primary/secondary packs on display. Surface friction can be modified to the desired level by the use of additives during film manufacture.

Viscoelasticity or 'creep' is a major consideration when deciding which plastic to use for a given application. All thermoplastics exhibit some degree of permanent deformation under load. This typically manifests itself when filled containers are

stacked on pallets during storage. Stacking tests under load, using actual packaging components, are essential to evaluate the true extent of a material's suitability.

Optical properties such as transparency and gloss mainly influence pack aesthetics. If the product has an attractive appearance and is stable on exposure to light, then a highly transparent pack may be desirable. Totally amorphous polymers are transparent; as the degree of crystallinity increases, transparency decreases and the materials become hazy and, eventually, opaque.

Chemical stability describes the extent to which a polymer is suitable for direct contact with a range of different product types, such as organic solvents, oils, acids or alkalis. Table 13.3 provides guidance on the general suitability of the common packaging plastics with a selection of such products, although this must be verified in each specific case, preferably using actual packaging components and products.

Environmental stress cracking is the failure of a plastic component under the combined effects of stress and an aggressive environment. Stress in plastic mouldings will bring about mechanical failure over time, but the presence of stress cracking agents such as detergents and oils can dramatically accelerate this failure, sometimes with catastrophic results.

Moisture and gas barrier properties of plastics determine their suitability to provide the required shelf life of the product. The data shown in Table 13.4 may be used as a starting point in selecting which plastics may be suitable, but again, storage tests using actual packs and actual products are essential. Refer back to Chapter 3 for more detailed information on this.

Temperature data of plastics has been referred to in Chapter 12, which differentiates between the glass transition temperature (T_g) and the melting temperature (T_m). T_g is the point at which the material changes from a glassy to a rubbery state and it occurs in the amorphous regions of a polymer. T_m is the temperature at which the crystalline regions of a polymer melt and is therefore always higher than T_g . Totally amorphous polymers (e.g. atactic polystyrene with its large benzene ring on the main carbon chain) do not have a melting temperature and thermosets do not have a glass transition temperature (due to their high degree of crosslinking). The temperature information given in Sections 13.4 and 13.5 refers mainly to T_m (except for polystyrene) as this is of most practical importance when selecting which plastic to use for a given application, such as suitability for sterilisation, microwave or conventional oven cooking, and the material's heat sealability.

Heat sealability is an important property to consider for a range of flexible packaging such as sachets, bags, flow wraps and pharmaceutical blister packs, as well as semi-rigid packs such as thermoformed trays and pots. The temperature at which the sealing medium softens and starts to flow must be compatible with what can be achieved by a combination of sealing head temperature, pressure and dwell time on the packaging machine, so that correctly sealed packs are achieved. Pack seals must survive the rigours of the supply chain, i.e. they must maintain the containment, protection and preservation functions, and be openable by the final user.

Density, as shown in Table 13.5, is an important consideration for cost in use. Plastic resins are traded by weight and for applications such as flexible packaging it is the area of material which is of interest, i.e. the number of square metres of

Table 13.3 Chemical resistance of the common packaging plastics

Material	Dilute acid	Dilute alkali	Oils and greases	Aliphatic hydrocarbons	Aromatic hydrocarbons	Halogenated hydrocarbons	Alcohols
LDPE/LLDPE	****	****	** variable	*	*	*	****
HDPE	****	****	** variable	*	*	*	****
PP	****	****	** variable	*	*	*	****
PVC	****	****	*** variable	****	*	** variable	*** variable
PS	**	****	**	****	*	*	* variable
PET	****	**	****	****	**	**	****

**** Very good, *** Good, ** Moderate, * Poor.

Source: British Plastics Federation (www.bpf.co.uk).

Table 13.4 Moisture and oxygen barrier properties of the common packaging plastics

Material	MVTR	OTR
LDPE/LLDPE	15–25	7000–8000
HDPE	5–12	1500–2000
PP	3–7	1800–2500
PVC (U)	20–60	50–80
PS	70–160	4000–6000
PET	16–20	60–120

MVTR = moisture vapour transmission rate for 25 μ film in g/m²/day; test conditions 38°C, 90% relative humidity.

OTR = oxygen transmission rate for 25 μ film in cm³/m²/day; test conditions 25°C, 50% relative humidity, 1 atmosphere.

Table 13.5 Density of the common packaging plastics

Material	Density kg/m ³
LDPE/LLDPE	910–930
HDPE	940–965
PP	880–920
PVC (U)	1230
PS	1070
PET	1360

Exact figures will vary with grade.

material available from 1 kg of resin. For any given thickness of film, this area can be calculated from the data in Table 13.5. It can be seen that material densities vary considerably and this must be taken into account, along with the price per tonne of resin, when comparing alternatives for a given end use.

13.4 The common packaging plastics

The ability to tailor material performance to requirements has already been emphasised as one of the most significant contributors to the growth in use of plastics in packaging and it is the case that most solutions are to be found amongst polyethylenes, polypropylene, polyvinyl chloride, polystyrene and polyethylene terephthalate (see Table 13.2). Even allowing for inaccuracies in data collection, it is clear that these materials dominate the packaging market. This section will review the key properties and uses of these common packaging plastics, while Section 13.5 will address the ‘other’ types of plastics used.

Note that it is not the objective of this chapter to provide fully comprehensive information on every packaging application of every plastic, which would be unrealistic within the space available. Several sources have been consulted in putting together this section (see Section 13.8) and some give quite extensive additional information. This section and Sections 13.5 and 13.6 aim to provide short notes on each material,

sufficient to begin to make informed choices for given end uses, but the reader is required to explore other sources for more detailed information.

13.4.1 The polyethylene family of plastics

Ethene ($\text{H}_2\text{C}=\text{CH}_2$) is a gaseous by-product of the process of cracking of long chain hydrocarbons to produce much sought-after products such as petrol and aviation fuels. The development of polyethylene (original trade name Polythene) and its commercialisation in the 1940s/1950s have already been mentioned as an important milestone in the development of plastics for packaging.

For convenience, polyethylenes are usually classified according to density. The more branched chains in the structure, the less these chains can be packed together (i.e. there is more steric hindrance) and thus the lower the density of the material. As chain packing increases, so does tensile strength, barrier to moisture and gasses, heat resistance and opacity.

Low density polyethylene

Low density polyethylene is produced by a high pressure process, and has a mix of long and short branched chains and around 50–65% crystallinity, making it translucent in appearance. It is soft and flexible with good elongation before breakage and good puncture resistance. It has a fair moisture barrier and poor oxygen barrier and softens at around 100°C (lower for some grades), making it an economical polymer to process and readily heat sealable, but of course unsuitable for cook-in packs. In common with all the polyolefins, it is non-polar and must be surface treated prior to printing or laminating.

Linear low density polyethylene

Linear low density polyethylene is a copolymer of ethylene and other alkenes such as butene, hexene or octene. This results in an essentially linear chain arrangement, with the comonomer (i.e. the butene, hexene or octene) forming short, regular chains on the main carbon backbone. It has similar properties to LDPE although it is tougher with slightly better barrier properties. It requires slightly more energy to heat seal and its operating range for sealing is narrower than LDPE, making control of seal temperature on the packaging machine more critical. It is also a little more transparent than LDPE. As already stated, it has very high elongation before break, which accounts for its widespread use in pallet stretch film.

Around 70% of all LDPE and LLDPE is used as film. This includes secondary/tertiary packaging such as pallet stretch film, collation and pallet shrink film, as well as primary packaging such as sacks, retail carrier bags, produce bags and frozen food bags. Film manufacturers are now using blends of LDPE and LLDPE for these applications, the inclusion of the latter offering opportunities for increased strength and decreased gauge, and thus the consumption of LLDPE is increasing at the expense of LDPE.

Metallocene catalysed grades of LLDPE are also now readily available, offering high puncture resistance and good clarity, and these are finding particular application in the high performance end of the pallet stretch film market, especially for pre-stretch machines. Most stretch film is produced by the cast process (see Chapter 14). The choice of comonomer in LLDPE depends on performance required; octene and hexene offer superior strength but are more expensive than butene LLDPE, hence they are used for more demanding applications.

Collation shrink film for secondary packs uses LDPE and LDPE/LLDPE blends, as well as coextrusions to impart specific slip characteristics and thus ensure the stability of a palletised load. If transparency is an important factor, e.g. for collation packs of bottles of mineral water and soft drinks which are sold directly to the consumer, metallocene grades are suitable, offering opportunities for significant down gauging with no loss of strength.

Pallet shrink wrap film uses mainly LDPE, which may be blended with LLDPE and/or HDPE for improved strength and down gauging. In Europe, pallet stretch wrapping is far more common than pallet shrink wrapping, as the latter requires higher capital investment and is more expensive per pallet due to the amount of film used and the need for energy in the form of heat. However, there are some specific applications where it remains the optimum choice, e.g. securing heavy loads such as glass bottles in transit from the producer to the packer/filler, or for providing good protection against dust contamination for palletised sheets of paper/board in transit from the paper mill to the printer/converter.

One further application of LDPE/LLDPE film in secondary/tertiary packaging is that of pallet stretch hoods. Stretch hooding uses highly elastic film to form a hood which is stretched over the palletised load and pulled down to be secured onto the pallet. It requires no heat (unlike pallet shrink wrapping) and is a faster process than stretch wrapping. Films are usually coextrusions including EVA (ethylene vinyl acetate) copolymers and elastomers.

Plastic sacks are used mainly in the horticulture market (for compost, etc.) and for chemicals, fertilisers, building materials and animal feed. LDPE is widely used, often blended with LLDPE for puncture resistance, and MDPE (medium density polyethylene) and HDPE for added stiffness to aid performance on the filling line. Coextrusions are used to impart the required levels of slip and heat-sealing characteristics.

Apart from film uses, both LDPE and LLDPE are used as heat seal coatings, extruded onto paper, board, other plastic films and aluminium foil, as well as for lamination. One significant market is liquid packaging cartons (see Chapter 10). Rigid packaging uses of LDPE include small, squeezable bottles, tubes, push-in and push-on closures.

High density polyethylene

High density polyethylene is made using a low pressure process and Ziegler-Natta or Phillips initiators to control the chain formation, resulting in a highly linear (unbranched) structure. Metallocene catalysed variants are also available. HDPE

is more crystalline than LDPE, and hence is more opaque, more rigid and has a higher tensile strength. It has a good moisture barrier and fair oxygen barrier. T_m is around 135°C and thus it withstands boiling water, which makes it suitable as a heat seal coating for steam sterilisable pouches and as a film for boil-in-the-bag foods.

Most of the applications of HDPE are in rigid packaging such as bottles for milk and household chemicals, as well as heavy duty items such as pallets, drums, crates and intermediate bulk containers. It is prone to environmental stress cracking and this should always be checked prior to selection. In the past it has been used widely for bottles for toiletries, although PET tends to be preferred in this sector due to its excellent transparency. It is also used for short-life screw caps, e.g. for milk and soft drinks bottles. Where screw caps are required for multiple uses, e.g. products such as shampoo and other toiletries, HDPE is liable to break in use and PP is a much better option. HDPE is also used for heavy duty sacks and bags, e.g. fertiliser, sand and aggregate.

Ethylene copolymers

The following ethylene copolymers are included here as part of the polyethylene family, although in usage they fall into the more specialised category of materials considered in Section 13.5.

Ethylene vinyl acetate

Ethylene vinyl acetate (EVA) is a random copolymer of ethylene and varying amounts of vinyl acetate (VA). The VA comonomer interferes with chain packing, reducing crystallinity and thus lowering T_m and improving transparency when compared with LDPE. As the VA content increases, crystallinity decreases, until at 50% the EVA is totally amorphous. Flexibility and toughness at low temperatures are also improved making it a good choice for frozen food bags. It has good hot tack and adhesive strength and a wide sealing temperature range, accounting for its uses as a heat seal layer and in hot melt adhesives.

Ethylene vinyl alcohol

Ethylene vinyl alcohol (EVOH) is another ethylene copolymer, this time using the comonomer vinyl alcohol (produced by the hydrolysis of vinyl acetate). It has excellent barrier to oxygen (less than 2 cc/m²/day) but the –OH groups make it hydrophilic, i.e. it attracts water, which decreases the oxygen barrier. For the oxygen barrier to be effective, EVOH must be ‘sandwiched’ to protect it from moisture. This is commonly done by coextrusion, examples being PET/EVOH/PET for bottles for sauces and mayonnaise and/or PET/EVOH/EVA for modified atmosphere packs for processed meats.

Polyvinyl acetate and polyvinyl alcohol

Polyvinyl acetate (PVA) and polyvinyl alcohol (PVOH) are further examples of ethylene copolymers. PVA is used as an emulsion adhesive for bag, sack and carton making. PVOH is produced by hydrolysis of PVA and the strong hydrogen bonding imparted by the $-OH$ groups means that pure PVOH is water soluble. The degree of water solubility is controlled by the amount of hydrolysis. Specific packaging uses for PVOH are in unit doses of detergents, where the entire pack is placed in the washing machine, and for agrochemicals, where the pack is placed into a tank of water and mixed. In both of these examples the advantages are that a measured dose of product is used, with no spillage on decanting and, in the latter case, limited exposure of personnel to what may be a toxic product.

Ethylene acrylic acid

Ethylene acrylic acid (EAA) is, as the name suggests, a copolymer of ethylene and acrylic acid (AA). As the AA content increases, crystallinity decreases (due to interference with chain packing) and heat seal temperature decreases, and the increase in polarity means that adhesive strength increases. Its excellent adhesion to a range of substrates makes it a good choice as the adhesive layer in foil laminates for composite containers, toothpaste tubes and sachets.

Ionomers

Ionomers are unusual in that they have ionic as well as covalent bonds in the polymer chains. They are made by reacting metal salts (commonly Na^+ or Zn^{++}) with acidic copolymers such as EAA or ethylene methacrylic acid (EMAA). The ionic bonds act like crosslinks between the polymer chains, resulting in tough, puncture resistant materials with excellent heat-sealing characteristics over a wide temperature range, and the ability to seal through contamination. Bonding to aluminium foil and paperboard is excellent. Ionomers also have very good resistance to oily products, making them useful as heat-sealing layers for processed meats. They are also used in rigid form for closures. There is a large range of options from which to choose, the main suppliers in the packaging field being DuPont, under the Surlyn[®] brand and Exxon Mobil under the Iotek[™] brand.

13.4.2 Polypropylene

Polypropylene has the lowest density of the common packaging plastics (Table 13.5), which gives it an economic advantage over other materials. It is formed by the polymerisation of propene and thus differs from polyethylene in that it has methyl groups on the carbon backbone chain. The arrangement of these methyl groups can vary and, as already mentioned in Chapter 12, PP exists in three different tacticities:

- **Isotactic:** Methyl groups are all on the same side of the chain.

- Atactic: Methyl groups are arranged randomly on both sides of the chain.
- Syndiotactic: Methyl groups alternate around the chain in a regular manner.

The isotactic form is the one most commonly used in packaging and, unless otherwise stated, this is the form referred to in the literature on PP. It is a tougher and stiffer material than the PE family, with good resistance to creep and to environmental stress cracking, and has a good barrier to moisture (see Table 13.4). It has a higher T_m than HDPE (around 160°C) and can be used where HDPE may otherwise fail, e.g. hot-filled bottles and tubs for soups and sauces and steam-sterilised applications.

In contrast, atactic PP is a soft and rubbery, mainly amorphous polymer. Its chief use is in adhesives, although there is some development of atactic/isotactic block copolymers which form thermoplastic elastomers. The third variant, syndiotactic PP has a T_m of around 130°C. It is softer than isotactic PP but still tough and more transparent. Its resistance to gamma ray sterilisation is being exploited in some film applications for medical packaging.

At very low temperatures PP homopolymer becomes brittle and thus is unsuitable for use in long-term deep freeze conditions. To overcome this problem, propylene is copolymerised with ethylene (typically 1–7%), producing polypropylene random copolymers. As well as improved clarity, other benefits are increased strength and toughness, a broader melting range and a lower melting temperature which improves heat sealability. All of these benefits have led to the widespread use of PP copolymers.

The clarity of PP is also improved by adding nucleating agents (which reduce the incidence of crystalline regions) and this is utilised in making contact-clear ice cream containers, for example. Another way to impede the formation of crystallites is to subject the molten polymer to rapid cooling, as in the cast film process, resulting in highly transparent and sparkling films.

Polypropylene is a versatile material, with important applications in both flexible and rigid packs. As shown in Table 13.6, film is the most significant market, followed by thin wall packaging. PP film is usually biaxially oriented (BOPP) and this has become the material of choice for snacks, biscuits, cakes, confectionery and tobacco products, due to its high strength and adequate barrier properties, even at very low gauges. See Chapter 14 for descriptions of the orientation processes.

BOPP has excellent clarity, and can also be produced in pearlescent and opaque

Table 13.6 Packaging applications for polypropylene

Pack type	
Film	32%
Thin wall containers	30%
Bottles	5%
Returnable transit packs (RTPs)	6%
Closures	13%
Other	14%

Source: Applied Market Information Ltd (www.amiplastics.com).

forms, giving a wide range of aesthetic effects. It is also produced in grades with good surface smoothness for subsequent metallising, which gives a shiny metallic appearance without the use of aluminium foil, and at the same time improves the barrier properties of the base film. Technical performance such as barrier, heat-seal characteristics and printability can also be improved by coating and coextrusion, and most BOPP is multi-layer, with suppliers offering a number of tailored options to suit a myriad of uses.

While BOPP is the most commonly used PP film, CPP (cast, non-oriented PP) film has important applications. As already mentioned, rapid cooling after casting results in a highly transparent film, used for textile bags and flower/plant packaging. Food packaging uses include retortable pouches.

Thin wall packaging describes thermoformed and injection moulded pots and tubs, such as those commonly used in the dairy industry for desserts, yoghurts and spreadable fats. PP offers good forming characteristics and good strength at a lower component weight, compared with polystyrene, which is its main rival in this sector (see Section 13.4.4). Thermoformed containers are made from sheet produced by cast extrusion, and as with film, coextrusions are possible to tailor the properties to the performance required.

Polypropylene belongs to the polyolefin family of polymers and therefore, like polyethylene has very low surface polarity and thus must be surface treated before printing.

13.4.3 Polyvinyl chloride (PVC)

PVC is made by the polymerisation of vinyl chloride (chloroethene) which is itself made by the chlorination of ethene. The chlorine atoms on the carbon backbone chain account for the much higher weight per unit volume of PVC compared to the polyolefins (see Table 13.5) and their syndiotactic arrangement means that the polymer is largely amorphous, and hence has good optical clarity. It has a good gas barrier and although the moisture barrier is poor, this is improved by coating with polyvinylidene chloride (PVDC) which has the added advantage of being readily heat sealable, a property utilised in blister packs for pharmaceutical tablets. PVC also has very good grease and oil resistance, and hence was the first alternative to glass bottles for cooking oil, and is still used for bath oils. It has a low T_m (around 90°C) and is thus easy to form, leading to its widespread use for thermoformings such as display trays. It also accepts ink readily. See Table 13.7 for the main uses of PVC in packaging.

Table 13.7 Packaging applications for polyvinyl chloride

Pack type	
Thin wall containers (including trays)	49%
Film	44%
Bottles	7%

Source: Applied Market Information Ltd (www.amiplastics.com).

Unplasticised PVC is naturally brittle, and as the proportion of plasticiser increases, so does flexibility. Plasticisers lower the glass transition temperature, thus improving processability, although they also decrease barrier properties, hence there is a wide range of grades available to suit end uses, from rigid bottles for oily products to highly flexible films such as 'cling' film. There is concern about the possible effects of plasticisers migrating into food products and this has led to a decline in the use of PVC in food packaging. A further contributor to this decline is the considerable environmental opposition to PVC because of the production of hydrochloric acid and dioxins on incineration (although these emissions can be abated, given the right choice of technology). Given these concerns, several companies have taken the decision to move away from PVC for packaging applications, although it continues to be widely used in the construction sector (window frames, pipes and cables) and for flooring.

13.4.4 Polystyrene

Polystyrene is the addition polymerisation product of phenyl ethene (commonly known as styrene). It is a highly transparent, glossy material, with a poor barrier to moisture and gases and limited chemical resistance. It softens at around 75°C and is liquid at around 100°C, and is thus easy to form. It accepts ink readily and thus is easy to print using flexographic or gravure printing for films, and dry offset letterpress or screen printing for three-dimensional components. General purpose styrene (GPS), sometimes known as crystal styrene is very brittle and most polystyrene used in packaging is the high impact variant (HIPS) which is a styrene-butadiene copolymer. The butadiene provides flexibility and lowers the softening temperature, and these two improvements account for the use of HIPS in thermoformed thin-wall containers for the dairy market. It is also thermoformed into sandwich packs and trays for salads, and made into biaxially oriented film for bags for fresh salads and other produce. The poor barrier properties are beneficial for products which respire, e.g. fresh fruit and vegetables, as they help to prevent a build-up in the pack of moist air which is conducive to mould growth.

A further application in packaging is expanded polystyrene (EPS). This is a lightweight material with fairly good compression strength and resistance to moisture. It is a good insulator against both temperature change and shock and is used for fast food trays, boxes for fresh fish and for home delivery of chilled and frozen foods, cell-packs for growing plants and as both loose-fill and pre-formed shapes in packaging fragile items such as china and glassware, domestic appliances and electronic goods.

Specialist copolymers of polystyrene are covered in Section 13.5.

13.4.5 Polyethylene terephthalate (PET)

PET is a condensation polymer made from a diacid (e.g. terephthalic acid) and a dialcohol (e.g. ethane 1,2-diol, commonly known as ethylene glycol). The acid and the alcohol first react together to form ester molecules, which are then polymerised,

hence the common term 'polyester'. This term refers to a large family of compounds with many diverse applications; PET is the common thermoplastic polyester used in packaging.

PET is available in both amorphous (APET) and crystalline (CPET) forms, with the former being more commonly used. Moisture barrier is about the same as that of LDPE, but gas barrier is higher than most of the common packaging plastics and this can be further improved by metallising with aluminium or by coating with, for example, PVDC or silicon oxide (SiOx). Almost 90% of the PET used in packaging is for bottles, primarily for soft drinks and mineral water which are now routinely packaged in PET rather than in glass, due to the weight savings and associated transport cost savings available. PET bottles are also being increasingly used for household chemicals such as laundry products, where the transparency of APET is often seen as an advantage over both HDPE and LDPE.

A significant growth market for PET is in bottles, jars and other components such as lipstick cases in the cosmetics sector, where the good oxygen barrier provides protection against degradation of oily products and loss of perfume. Early uses tended to be for lower-price products such as shampoo, but now thick-walled jars in transparent and coloured forms are widely used instead of glass for expensive creams. The materials used in this sector are mainly copolyesters such as polyethylene terephthalate glycol (PETG), made by varying the starting diacids and dialcohols and variants are available for injection and extrusion blow moulding, as well as for thin-wall and thick-wall containers.

A potential growth market for PET is in beer bottles, with the commercial availability of surface coatings and multi-layer technology to improve gas barrier. At the current time the use of PET for beer is mainly confined to outdoor events, where safety is the main driver, but developments such as PET/PEN (polyethylene naphthalate) blends and coextrusions could bring PET into the mainstream beer market as a realistic alternative to glass.

Flexible packaging uses of PET include biaxially oriented film for pouches and lids for ovenable ready meals. The orientation improves stiffness and the high clarity enhances visual impact, especially in laminates where the PET is reverse printed. PET sheet is thermoformed into trays for salads. The crystalline (CPET) variant is opaque and is used for trays for ovenable ready meals, due to its high temperature resistance.

Uses of recycled PET (r-PET) for primary packaging are increasing, both for food and non-food products. As with all developments, compatibility and shelf life studies are essential. A recent study in the Cosmetic Science department at the London College of Fashion showed encouraging results using PET bottles containing 30% post consumer recyclate (PCR) in contact with common cosmetics such as baby oil, shower gel and shampoo (Talarek, 2011). It is thought that higher PCR content would also be compatible with these products, although the decrease in bottle clarity may be aesthetically unacceptable.

13.5 Specialist polymers used in packaging

Table 13.8 lists the materials which fall into this category. Most of these materials are engineering polymers and their main uses are in markets such as automotive, aeronautical, electronic and others, with packaging end uses representing a small percentage of overall consumption. They are invariably much more expensive than the commodity polymers discussed in the previous section, and are selected for packaging applications only when the commodity polymers do not have the required technical performance, and the product value justifies the additional cost. (Note that EVA, EVOH, PVA, PVOH, EAA and ionomers have already been discussed in Section 13.4.)

13.5.1 Styrene copolymers

In this category the main copolymers used in packaging are styrene acrylonitrile (SAN) and acrylonitrile butadiene styrene (ABS), along with some specialist variants.

SAN is a copolymer of styrene and acrylonitrile ($\text{CH}_2=\text{CHCN}$) in a ratio of around 3:1. It is amorphous, rigid and has good resistance to acids, alkalis, oils and greases. Its high transparency and easy surface printability make it a good choice for cosmetics compacts and jars, and it is available in a range of colours and grades. At this ratio of styrene to acrylonitrile it has a poor gas barrier, but this can be improved by increasing the acrylonitrile content.

ABS is a random styrene acrylonitrile copolymer grafted to butadiene (see Chapter 12). Like SAN, it has good chemical resistance, is readily printable and has good resistance to environmental stress cracking. Many variants of composition are available to suit the required technical performance and aesthetic qualities. ABS is naturally opaque, but the variant methyl methacrylate acrylonitrile butadiene styrene (MABS) is highly transparent. Both materials are used in the cosmetics sector for

Table 13.8 Specialist polymers used in packaging

Ethylene vinyl acetate	EVA
Ethylene vinyl alcohol	EVOH
Polyvinyl acetate	PVA
Polyvinyl alcohol	PVOH
Ethylene acrylic acid	EAA
Ionomers	
Styrene acrylonitrile	SAN
Acrylonitrile butadiene styrene	ABS
Polyvinylidene chloride	PVDC
Polyethylene naphthalate	PEN
Polyamide	PA
Polycarbonate	PC
Fluoropolymers	
Thermoplastic elastomers	TPEs
Cyclic olefin copolymers	COCs
Liquid crystal polymers	LCPs
Thermosetting plastics	
Cellulose materials	

mascara and lipstick cases, compacts and closures. ABS is also suitable for tubs for butter, margarine and desserts such as yoghurt, where it offers improved toughness compared to polystyrene, albeit at a higher purchase price.

As already noted, increasing the acrylonitrile component in these copolymers improves the gas barrier and one example of this is Barex[®]. This is a copolymer of acrylonitrile and methyl methacrylate (75:25 ratio) and nitrile rubber; it has excellent gas barrier, good chemical resistance and good sealability, making it useful for packaging meat and cheese. It also has excellent impact strength, withstands repeated flexing without cracking and is resistant to sterilisation by gamma radiation and ethylene oxide, making it a good choice for demanding applications in the medical and pharmaceutical sectors.

13.5.2 Polyvinylidene chloride (PVDC) copolymers

PVDC is made by the addition polymerisation of 1,1-dichloroethene (vinylidene chloride). The homopolymer is very difficult to process as it decomposes below its melting temperature. It thus has no commercial importance and all the PVDC used in packaging is copolymerised with vinyl chloride or alkyl acrylates (e.g. methyl acrylate). The most useful properties of these copolymers are excellent resistance to oils and fats, high gas barrier and heat sealability. They can be used as surface coatings, in coextrusions and as films. Coatings can be water-based (e.g. PVDC/methyl copolymers) and solvent-based (e.g. PVDC/acrylonitrile copolymers) and provide a cost effective way of improving the barrier properties of PP, PET, etc., films, and of enhancing the performance of paper and board. Coextrusions of PVDC copolymers and polyolefins are suitable for multilayer films for products such as meat and cheese, and single layer PVDC copolymer films can be used alone as food wrapping and in laminates wherever moisture and gas barrier are important requirements.

As with PVC, there are environmental concerns about the use of PVDC and these have prompted companies to seek out alternatives. EVOH is one such alternative, especially with regard to gas barrier although, as already noted, it cannot be used as a coating.

13.5.3 Polyethylene naphthalate (PEN)

PEN is a condensation polymer of ethylene glycol and naphthalate dicarboxylate. It has been available since the 1980s and PEN film is used in electrical insulation. Packaging uses are limited as yet, almost certainly due to its high price, although it has significant advantages over PET in the drinks bottle market, and refillable PEN bottles for beer have been launched in Denmark and for fruit juices in Germany. The advantages of PEN homopolymer over PET are its higher resistance to heat and 4–5 times better barrier to moisture and gases. It also blocks out UV light. If the end use demands an improvement over PET without the full properties of PEN homopolymer, a cost effective solution may be found in the range of PEN/PET copolymers and blends available.

13.5.4 Polyamide or nylon (PA)

Polyamides are condensation polymers made from diamines and diacids and are named according to the number of carbon atoms in the starting materials, e.g. Nylon 6,6 is produced from hexamethylene diamine $\text{H}_2\text{N}-(\text{CH}_2)_6-\text{NH}_2$ and 1,6-hexanedioc acid $\text{HOOC}-(\text{CH}_2)_4-\text{COOH}$ (commonly known as adipic acid). They can also be made from amino acids, in which case they have just one number, representing the number of carbon atoms in the starting substance, e.g. Nylon six is made from caprolactam, a cyclic compound with a total of six carbon atoms and Nylon 11 is made from the straight-chain amino undecanoic acid $\text{H}_2\text{N}-(\text{CH}_2)_{10}-\text{COOH}$.

Polyamides are mostly used in engineering applications, due to their strength and toughness, and good heat and low temperature resistance. Gas barrier is very good, but the material is moisture sensitive and as the moisture level increases the oxygen barrier decreases. Some grades have excellent clarity. Packaging applications mainly utilise the high oxygen barrier properties of Nylon 6, for example in packaging of frozen meat joints, where the low temperature resistance and puncture resistance make this an ideal laminate (with LDPE or EVA for heat sealability). If exceptionally high mechanical strength and heat resistance are important, Nylon 6,6 may be a better option.

13.5.5 Polycarbonate (PC)

Polycarbonate is a polyester made by the condensation of carbonic acid $\text{HO}-\text{CO}-\text{OH}$ and bisphenol A $\text{HO}-(\text{C}_6\text{H}_6)-\text{C}(\text{CH}_3)_2-(\text{C}_6\text{H}_6)-\text{OH}$. It is glass clear and has exceptional impact resistance and good UV resistance, properties which account for its uses in glazing, safety spectacles and in automotive applications such as headlamp lenses. It is also heat resistant and readily sterilisable, which explains its main packaging use for returnable containers for office water dispensers. These large containers are subjected to rough handling and can be repeatedly sterilised without deterioration. Other packaging applications are currently limited, due to the high resin price and the availability of alternatives such as PET.

13.5.6 Fluoropolymers

Fluoropolymers are addition polymers of halogenated alkenes. Perhaps the best-known one is polytetrafluoroethylene (PTFE), better known under its trade name Teflon[®], which is highly crystalline, inert and has a very low coefficient of friction and high melt temperature, accounting for its use as a non-stick coating. Polychlorotrifluoroethylene (PCTFE), under the trade name Aclar[®], is used in pharmaceutical packaging applications such as thermoformed blisters and novel drug delivery systems. It has exceptionally high moisture barrier and when laminated to Barex[®] (noted for its high gas barrier – see above) the combined material can provide the long-term shelf stability demanded in such applications, along with justification for its high cost.

13.5.7 Thermoplastic elastomers (TPEs)

TPEs have already been discussed in Chapter 12. They combine the easy processing of thermoplastics with the elastic properties of rubber. The ability to recover from deformation and good chemical resistance make TPEs highly suitable for closure wads and plugs, and a thin layer of TPE on the outer surface of containers and closures provides a soft, rubbery feel which gives good grip, as well as aesthetically pleasing tactile properties. See Chapter 12 for a review of the different types available.

13.5.8 Cyclic olefin copolymers (COCs)

COCs are produced by addition polymerisation of a cyclic olefin (such as cyclopentadiene) and a conventional straight chain olefin such as ethene, using conventional or metallocene initiators. They have been available commercially since the 1990s, although their high cost has limited their use in packaging to specialist pharmaceutical and medical applications. High strength and clarity, combined with excellent moisture barrier make them viable alternatives to glass for items such as pre-filled syringes, vials and ampoules for injectables. There are grades suitable for film extrusion, bottle blowing and injection moulding and they can be used in blends with polyethylene and in individual layers in coextrusions. Resistance to acids, alkalis and polar solvents is good.

13.5.9 Liquid crystal polymers (LCPs)

Liquid crystal polymers are thermoplastic polyesters copolymerised from rigid and flexible monomers. The rod-like rigid segments are connected by flexible segments which allow the materials to flow on heating. During processing, e.g. into film or injection moulded parts, the rigid segments align in the liquid state and retain their crystal-like spatial arrangement on cooling. This results in materials with high tensile, impact and tear strength, high melting point and excellent barrier to gases and moisture. They have been commercially available since the 1980s and used in applications such as surgical devices, audio visual components and business machines. Flow properties are excellent and thin-walled sections can be moulded to close tolerances. Packaging applications are limited as yet, and are likely to be based on the very high barrier properties, e.g. LCPs are available with an oxygen barrier around six times better than EVOH, without the associated deterioration in humid conditions.

13.5.10 Thermosets

As stated in Chapter 12, in thermosets the polymer chains are arranged in a matrix fashion, with strong bonds called 'crosslinks' connecting them. As a result, they are dense, rigid materials with excellent chemical resistance and high heat resistance. The crosslinking takes place during polymerisation and thermosets cannot be reshaped once formed, hence they cannot be recycled. Thermosets such as phenol formaldehyde were amongst the first plastics used (see Table 13.1) but their usage in packaging declined markedly with the commercial availability of thermoplastic

resins which offered easier processing at lower price. Both phenol formaldehyde and urea formaldehyde are still used for screw-threaded closures especially where high chemical resistance is important, e.g. laboratory reagents such as strong acids and alkalis. Also, unlike thermoplastics, thermoset closures are not prone to creep and the associated loss of torque over time. Other advantages are the minimal shrinkage on cooling, which means that thick-walled sections do not show sink marks, and the fact that the thermoset forming process allows very high precision and dimensional accuracy, along with high definition. This accounts for its use for closures with an embossed, highly detailed brand logo, as used on some alcoholic spirits.

Other packaging applications for thermosets are crosslinked acrylic, polyurethane and epoxy lacquers and adhesives.

13.5.11 Cellulose materials

As mentioned in Chapter 10, cellulose fibre can be made into cellulose film and this was the first transparent packaging film, widely used for confectionery, snack foods, biscuits, cigarette overwrapping, etc. It was also the material of choice for adhesive tape. The advent of polypropylene film in the 1960s changed this due to its lower cost, and the use of cellulose materials in packaging has now declined to a few specialist applications. This section provides an overview of cellulose film and cellulose esters.

Cellulose materials are derived from cellulose plant matter, usually wood pulp from managed forests and thus they can claim to be made from renewable sources. In technical performance they possess many of the properties of paper, such as excellent folding characteristics and the ability to maintain a fold (deadfold), easy printability and freedom from static. Like paper, uncoated cellulose materials have no heat-sealing capability and they absorb moisture (due to the high number of hydroxyl groups), although all these issues can be addressed by the use of appropriate coatings.

Cellulose film is commonly known by its trade name Cellophane™, and is widely used in packaging for twist wrapping of confectionery. This is due mainly to its deadfold properties, although the excellent clarity, sparkle and availability in a range of attractive colours are also important factors. In addition, the fact that the material is static free (unlike polypropylene, for example) is a key benefit for high speed packaging machines which can be running at 1,000 pieces per minute, where the build-up of static would lead to packs sticking together, causing line stoppages.

As stated, cellulose film can be coated to impart specific properties and Cellophane™ is available with copolymer, nitrocellulose or PVDC coatings, depending on the level of moisture barrier, gas barrier, heat sealability and thermal stability required. Films can be used alone or in laminations and typical end uses in addition to confectionery include wrapping of bakery goods and soft cheeses. Microwaveable films are available with semi-permeable coatings which allow some ventilation during heating, making them ideal for pastry products such as pies and quiches where the release of built-up water vapour maintains the product crispness.

NatureFlex™ is a more recent cellulose film which, as well as being based on renewable resources, has the added benefit of being compostable to EN 13432. For

the purposes of this chapter, it is categorised as a bio-based polymer and will be discussed in Section 13.6.

Cellulose esters used in packaging include cellulose acetate (CA) and cellulose acetate butyrate (CAB). CA is used as a clear window in paperboard cartons, especially when moisture permeability is required, such as for cakes where the moisture would otherwise be trapped inside the carton and cause fogging, obscuring the product. It can also be used to make 100% transparent cartons as gift packs for products such as cosmetics. CAB has greater resistance to moisture permeability and is used for clear rigid tubes suitable for a range of products such as confectionery, soap and bath products.

13.6 Bio-based polymers

Most polymers discussed so far in this chapter are derived from crude oil. They are long life materials, destined to provide product protection and preservation, and to withstand degradation. They offer reliability in service and will last for many years, usually far longer than the products they contain. This longevity is desirable in the sense that the consumer can confidently purchase a plastic bottle of milk, shampoo or cooking oil, knowing that the bottle will remain in acceptable condition until the contents are used up. But resistance to degradation becomes a negative property if and when the bottle is taken to landfill at the end of its useful life, where it could remain almost unaltered, probably for hundreds of years. Of course, as already discussed in Chapter 5, there are alternatives to landfill, such as recycling into the same or different end uses and thermoplastics are ideal for this, being readily melted and formed into new structures. Other end-of-life options are reuse (e.g. plastic pallets and drums) and the production of energy from waste plastic.

Returning to the resources used to make most plastic packaging, i.e. crude oil, it should be remembered that plastic packaging is not the major end use of oil-derived products, and should not be held responsible for fossil fuel depletion. Nevertheless, concerns about this have instigated efforts to explore the use of alternative starting materials such as agricultural crops, and it is this category of materials which will now be reviewed.

Bio-based polymers are derived from plant matter, commonly known as biomass (although 'biomass' can also mean animal-derived material). As the crops used, for example maize and sugar cane, can be replanted, these polymers can claim to be made from readily renewable resources, unlike crude oil which takes millions of years to form. Using such renewable resources would appear to be a positive step, although agriculture itself is not free from negative environmental effects. Land has to be prepared for farming, pesticides may have to be used and transport of crops is required, thus generating carbon dioxide emissions. There is also the consideration of using land for the production of polymers, at the expense of food production.

To the general public, the word 'biopolymer' has become synonymous with biodegradable but this is misleading and confuses polymer sourcing (i.e. crop-based) with polymer functionality. This chapter adopts the British Plastics Federation's approach, by using the sub-title 'bio-based polymers' and differentiating between

natural bio-based polymers and synthetic bio-based polymers. For example, sugar extracted from crops is used to make bioethanol which can be used as the starting material for making ethylene and polyethylene. Polyethylene produced by this route is a synthetic bio-based polymer, having the same performance properties as the oil-derived polyethylene already discussed, which is not biodegradable. The claim 'derived from renewable resources' may be made, but not the claim of biodegradability.

Clarification must also be made between oxodegradable and biodegradable polymers. Oxodegradable refers to oil-derived thermoplastics such as PE and PP with the addition of initiators which accelerate the breakdown of the backbone carbon chains when the plastic components, e.g. film or bottles are exposed to air, causing them to break down into fragments. This breakdown starts when the components are produced and takes around six months, depending on the exposure conditions.

Biodegradation refers to the process of breakdown of organic matter into its basic raw materials by the action of microorganisms. The compostability standard EN 13432 lays down a set of standard conditions (e.g. time, temperature, relative humidity) under which biodegradation must take place. It also defines the acceptable level of breakdown in terms of particle size and impact on the compost and the environment (e.g. production of heavy metals) for a material to be declared compliant.

A brief overview of the sources and properties of some of the bio-based polymers currently available now follows, although this is not presented as an extensive study and readers are advised to seek out more detailed information for specific applications.

There are two main ways of treating biomass to make bio-based polymers. Either it is processed to extract the natural polymers such as the polysaccharides starch or cellulose which are present in all plant matter, or methods such as hydrolysis, fermentation, or other microorganism attack are used to produce monomers, which in turn are then synthesised into polymers, e.g. lactic acid to polylactic acid (PLA).

Starch-based polymers are commonly derived from maize, although other crops such as potatoes and rice are also used. Just one example of commercially available starch-based materials in Europe is the Mater Bi[®] range from Novamont. These plant-derived materials conform to EN 13432 with respect to compostability, can be processed using traditional plastics processing techniques such as extrusion and injection moulding, and are readily printable without the need for surface treatment. A wide range of grades is available for food and non-food uses and includes flexible packaging and thermoformed trays, as well as coatings for paper and board, and foams for cushioning against shock. Laminates are available where moisture and gas barrier are important requirements, e.g. for biscuits and snacks.

Reference has already been made to the compostable range of cellulose-based films under the NatureFlex[™] brand, from Innovia. They are made from renewable resources (wood pulp from managed forests) and in their uncoated form have excellent transparency, deadfold, anti-static and easy-tear properties. Coated grades give enhanced performance such as moisture barrier, heat sealability and resistance to grease and oil. Metallised grades are also available, making the range serious competitors to oil-derived polypropylene in the bakery, overwrapping, fresh produce and confectionery sectors, for companies wishing to make both renewable resources and compostable claims.

PLA is produced by fermentation of biomass, using microorganisms to convert the starch to lactic acid monomer. Maize is commonly used as the starting material, although sugar cane/beet and wheat can be used, indeed any crop with a sufficiently high sugar content in the plant starch. Lactic acid exists as two optical isomers, the D and L forms, depending on the spatial arrangement of the groups around the central (chiral) carbon atom. PLA made from 100% L-lactic acid is highly crystalline (known as C-PLA) while copolymers of the L and D forms are more amorphous and thus more transparent. PLA resins are available for extrusion into film, thermoforming into pots and injection moulding, although processing equipment designed for conventional polymers such as PET may need modification. Generally, PLA has similar barrier properties to polystyrene and current uses include bags and thermoformed tubs and pots for fresh produce. Non-packaging uses include disposable cutlery and other catering items.

With regard to product compatibility, initial studies conducted in the Cosmetic Science department at the London College of Fashion showed some softening of PLA bottles and film in contact with shampoo, although contact with baby oil appeared to have no detrimental effects (Talarek, 2011).

At the end of life, PLA is compostable in industrial facilities, but not in home composting due to the high temperature (above 50°C) and humidity required.

A further category of bio-based polymers is the generic class of copolyesters known as polyhydroxyalkanoates (PHAs). These are commonly made up of the simplest PHA, polyhydroxybutyrate (PHB), copolymerised with other hydroxyalkanoates such as hydroxyvalerate (PHBV). PHAs can be made directly by fermentation, without going through the polymerisation stage as used in the production of PLA. They are generally tough materials, with high temperature resistance, and grades are available for film and sheet extrusion, and injection moulding.

13.7 Conclusion

Compared with oil-based polymers, bio-based polymers are in their infancy and are currently used in niche rather than mass packaging markets. Global production is projected to increase from 700,000 tonnes in 2010 to 1.7 million tonnes by 2015, up from 262,000 tonnes in 2007. However, even the 2015 projection represents <1% of annual plastics consumption (tacooper@post.com; www.pcn.org/cooper.htm). Whilst there are sophisticated manufacturing facilities and high levels of capital investment, these are just a fraction of what has been expended over the past 60+ years of oil-derived polymer production; hence resin prices are relatively high. However, as technologies develop and demand increases, prices may become more comparable. Increased demand could be brought about due to pressure on mainstream brand owners by the 'green' consumer and government policies.

13.8 Sources of further information and advice

Baner, A.L. and Piringir, O. (2008) *Plastic Packaging Materials for Food*. Wiley, New York.

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- Nicholson, J. (2011) *The Chemistry of Polymers*, 4th edn. RSC Publishing, Cambridge.
- Talarek, K. (2011) Sustainability in Cosmetic Packaging, undergraduate thesis, London College of Fashion.

In addition to the above texts, the British Plastic Federation (www.bpf.co.uk) is a valuable source of information on all aspects of plastics, including material properties, industry applications and forming methods.

Other useful sources of information include:

- <http://www.britishplastics.co.uk>
- <http://www.incpen.org>
- <http://www.packagingdigest.com>
- <http://www.packagingfedn.co.uk>
- <http://www.packagingtoday.com>
- <http://www.paafa.org.uk>
- <http://www.plasticsinpackaging.com>

Applied Market Information Ltd (www.amiplastics.com) is a recommended source of market data for plastics used in packaging, specifically the following reports:

- *Plastics Packaging Producers – A Review of Europe's Largest Players 2011*
- *European Plastic Industry Report 2011*

Note: Sources used in the preparation of this chapter also include teaching and learning materials written and used by the author in the delivery of courses to a number of organisations, such as the Packaging Society, Loughborough University, University of Warwick, University of Bath and London College of Fashion (University of the Arts London).