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# 11 Bioplastics

Jim Song, Martin Kay and Richard Coles

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## 11.1 INTRODUCTION

Many experts are predicting that the twenty-first century will herald the rise of the carbohydrate economy with a realistic possibility that bioplastics could increase their market share from <1% to around 10% of global plastic consumption, representing 20 million tonnes per annum. Global bioplastics packaging demand is forecast to reach 885 kt by 2020 and a 24.9% compound annual growth rate (CAGR) is expected from 2010–15 slowing to 18.3% in the five years to 2020 (Pira International, 2010).

Plastics accounts for around 40% of the global market for consumer packaging (food and non-food) and plastics packaging is growing faster than any other material (Rexam, 2007/2008). The market growth of plastics is mainly attributable to advances in material properties. Plastics are prized for their lightness, durability, functionality, flexibility of design and ease of manufacture. Source reduction continues to increase the efficiency of plastics in providing product protection and enabling a more sustainable distribution.

Factors encouraging the adoption of bioplastics may be summarised to include:

- *rapidly rising societal awareness of the environmental impact of food and packaging wastes, particularly, with regard to concerns over climate change and water availability*

Landfill of organic waste, whether in the form of food or non-inert packaging, is an important source of greenhouse gases, particularly methane. Food waste forms a large part of the household waste stream in the developed world, much larger than the packaging fraction. In addition to the significant quantities of food waste generated by consumers, packaged food waste is also generated in the retail environment due to damage in the supply chain and product past its 'sell by' or expiry date. Bioplastics packaging enables food waste to be composted without removing the packaging.

Organic waste materials from biodegradable and compostable bioplastics packaging can be treated, along with food, agricultural and garden/park waste, to produce carbon-rich compost (humic material). Compost can be used as a soil improver to enhance water retention and increase the availability of water to plants. Alternatively, in the case of anaerobic digestion (AD), organic waste can also be used to generate renewable energy from biogas (methane).

- *public perception of packaging waste linked to the litter issue stresses the need for the ultimate disposal of used packaging materials in an ecologically sound manner to promote sustainability*

Use of bioplastics can be advantageous in applications where the final packaging could end up as litter, such as packaging from fast food and confectionary products, and where mineralisation to water, carbon dioxide and microbial biomass is advantageous.

- *corporate social and environmental responsibility (CSER) commitment to initiatives actively supporting sustainable development and reducing carbon footprint*

The use of renewable energy and biomass lessens dependence on finite fossil fuel-based resources. The manufacture of bioplastics may involve the use of less energy (and hence a reduction of carbon footprint) in substrate production and conversion, compared to petroleum-based conventional plastics. A 'life-cycle approach' is becoming an important design criterion in the selection of more sustainable packaging materials (Narayan, 2009).

- *a means for retailers and manufacturers to further differentiate their brands and appeal to the consumer through the development of bioplastics that are both functional and offer superior carbon credentials*

A key market advantage for these materials is the common consumer perception that they provide an environmentally sound method of packaging waste disposal as well as being a low carbon option. This is evidenced in the emergence of their application in niche markets, such as 'organic' and premium products.

- *trends in plastics packaging raw material and crude oil prices*

Price rises for petroleum and natural gas increase the price competitiveness of biopolymers, produced on the basis of renewable resources, vis-à-vis conventional petrochemical plastics.

- *regulatory/environmental trends*

Growing global concerns over climate change has brought even greater focus on the key legislation regarding used packaging and landfill. For example, the EU Directive on Packaging and Packaging Waste, (2004/12/EC amending 94/62/EC), and the EU Landfill Directive (99/31/EC as amended in 2003 & 2008) promote the diversion of packaging waste and biodegradable wastes from landfill.

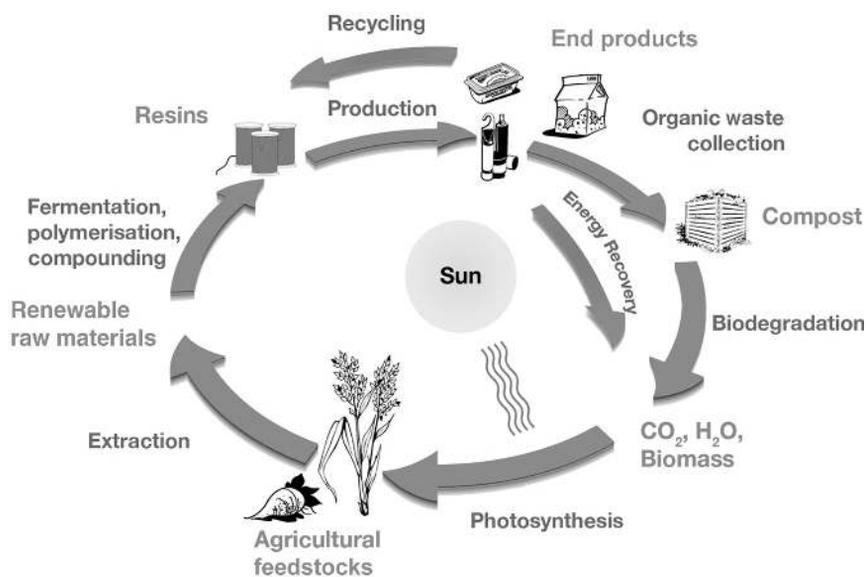
- *diversity/improvement in agro-economy through increased use of compost as a soil improver by providing benefits, such as:*

- increased carbon retention
- improved water and nutrient retention
- reduced need for additional chemical inputs
- suppressing plant disease
- increasing earthworm and micro-organism biomass as much as fivefold

The use of biodegradable packaging creates new choices for its recovery to produce carbon-rich compost that is critical for maintaining the sustainability of the agricultural system. In recent years, soil erosion has become a serious global environmental and agricultural issue resulting in increased use of pesticides, fertilisers and intensive artificial irrigation. These present problems, such as pollution, eutrophication, groundwater contamination/reduction and depletion of organic matter in the topsoil that contains valuable nutrients, including those containing nitrogen and phosphorus.

- *expanding supplier base worldwide and increasing rate of technical development*

After an early pilot plant phase in the 1990s, subsequent upscaling of bioplastic production by both small specialized and established companies since 2000 has now reached an industrial scale with major plastics manufacturers being involved. Bioplastics technology is rapidly advancing to improve cost competitive performance and provide materials with properties and processing similar to common plastics, such as PE, PP, PS, PVC and PET. Significant



**Fig. 11.1** Bioplastics lifecycle (courtesy of European Bioplastics e.V.) (For a colour version of this figure, see Plate 11.1.)

proportions of biodegradable plastics now have renewable rather than petrochemical origins ([www.european-bioplastics.org](http://www.european-bioplastics.org)).

This chapter will define and classify ‘bioplastics’; review life cycle aspects of bioplastics in packaging in relation to the concept of renewable carbon, raw material generation through to consumer packaging, waste collection and final disposal with organic recovery (Fig. 11.1).

## 11.2 DEFINITIONS

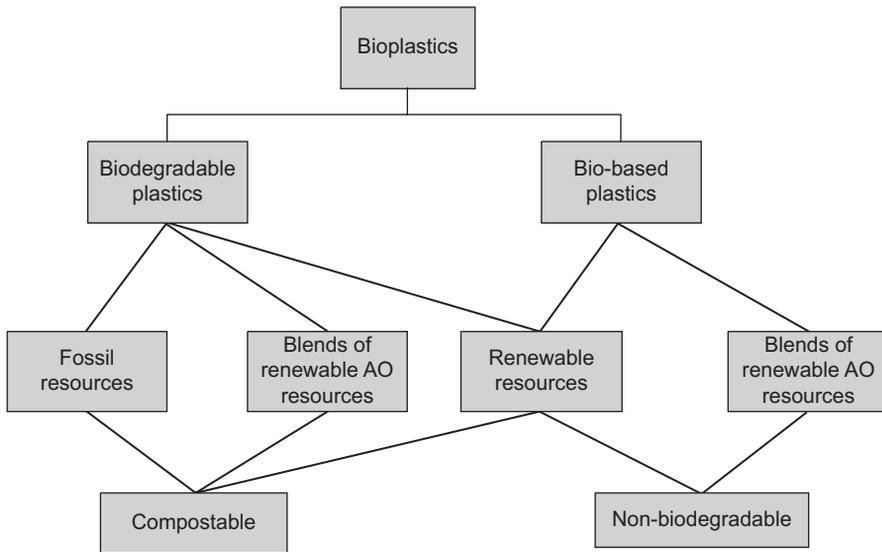
According to European Bioplastics e.V. (2009b), bioplastics is a term used to define two different kinds of plastics (Fig. 11.2):

(i) *Plastics based on renewable (bio-based) resources*

The focus is the origin of the raw materials used. The standard for the material’s bio-origin is yet to be established but it is likely to be based on C14 signature ASTM-D6866.

(ii) *Biodegradable and compostable plastics according to EN13432 or similar standards*

The focus is the compostability of the final products; biodegradable and compostable plastics can be based on renewable (bio-based) and/or non-renewable (fossil) resources.



**Fig. 11.2** Types of bioplastics.

Following these definitions, bioplastics may be:

- based on renewable resources and biodegradable
- based on renewable resources but not be biodegradable
- based on fossil resources and be biodegradable

### 11.3 BIOPLASTICS AND CARBON

Most bioplastics are derived from annually renewable raw materials. Plants grown to produce materials, such as starch, for bioplastics absorb carbon dioxide (CO<sub>2</sub>) as part of the carbon cycle. However, although the overall carbon footprint is typically less – as they cycle carbon from the atmosphere captured by plants during the growing process – it is not zero on account of farming, fertiliser & pesticide production, and other crop-producing activities that have greenhouse gas outputs. Potentially, there may be less of a depletion of fossil fuels when compared with traditional fossil fuel-based plastics. The carbon emission/footprint will depend in part on the level of emissions and amount of fossil fuel used with current production techniques through transport of seed, planting of seed, spraying of crops, harvesting, fertiliser/pesticide manufacture and method of application, transport to processing facilities and production processes. Other environmental impacts also need to be considered, such as nitrogen oxide emissions (highly potent greenhouse gases); groundwater abstraction for the high irrigation requirement of intensive agriculture; the eutrophication potential (the emissions of nitrates and phosphates into waterways) from the fertilising of crops and other pollution effects.

Bioplastics manufacturing also needs fossil fuels to drive the different production steps. However, several bioplastics producers are replacing a part of these fossil fuels by renewable energy. The carbon footprint due to transportation is another factor meriting consideration with some bioplastics or raw materials being imported by ship and truck.

If bioplastics-based packaging materials are incinerated or composted, the renewable or biogenic carbon harvested by the plants during the growing season is returned to the atmosphere. Therefore, renewable carbon is cycled in a closed loop.

In many cases, mixed fossil-based plastic waste fractions are being incinerated with energy recovery. Due to the high level of renewable resources in bioplastics products, renewable on account of their renewable carbon content, they can be used to produce renewable energy if, for example, they are incinerated with energy recovery (also called 'waste-to energy'). This method is applicable to all bioplastics, ([www.european-bioplastics.org](http://www.european-bioplastics.org)).

The composting process itself will release carbon dioxide and low grade heat or, in the case of anaerobic digestion, methane. In the undesirable scenario that bioplastics are landfilled, there is a global warming potential due to methane emissions.

In the future, it is probable that the measurement of carbon footprint associated with the lifecycle of all packaging and packaged goods will play a key role in the selection of sustainable packaging. A number of studies have demonstrated that packaging represents less than 10% of the overall carbon footprint of the whole product life cycle. Such work clearly identifies the importance of packaging functionality in reducing overall environmental impacts. A critical challenge for bioplastics manufacturers will be to demonstrate that their packaging materials meet or exceed functionality requirements whilst being a low carbon option in their own right.

## 11.4 BIOPLASTICS – OVERVIEW OF MATERIAL TYPES

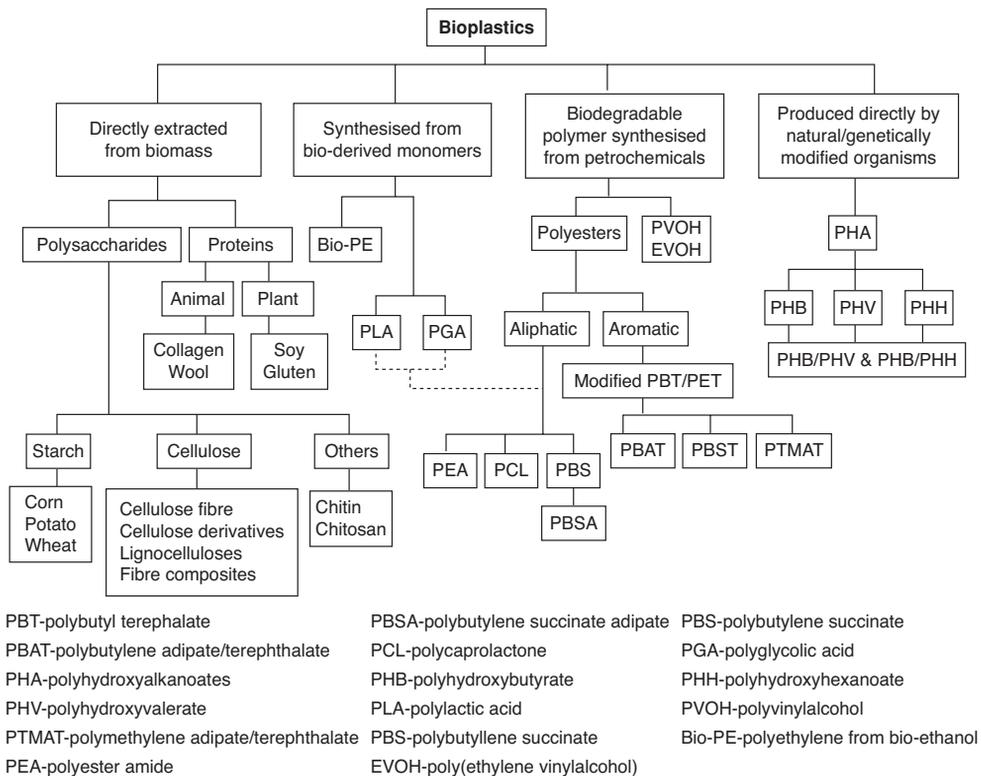
A wide range of bioplastics are now available commercially and new ones are constantly emerging. Information on materials and suppliers is readily available on the internet, e.g. [www.bioplastics24.com](http://www.bioplastics24.com) and [www.european-bioplastics.org](http://www.european-bioplastics.org), or publications (Bioplastics Magazine and Bioplastics 07/08). Details on chemical compositions, production, processing, structural and properties of a wide range of biopolymers can be found elsewhere in literature (Smith, 2005; Chiellini, 2008). A brief overview is given below as a rough guide.

### 11.4.1 Classification of bioplastics

Bioplastics can be classified in many ways based, for example on their origins, chemical compositions, synthesis methods and applications. Fig. 11.3 classifies biopolymers based on origins and methods of production of the materials. Several points are worth mentioning:

- (i) Bioplastics, as defined by European Bioplastics e.V. (2009b), include not only those materials which are biodegradable and compostable (the majority of them in Europe are certified according to EN13432, USA: ASTM D-6400, other countries: ISO17088) "*based on renewable (biobased) and/or non-renewable (fossil) resources*" but also those which are not biodegradable but "*produced on the basis of renewable resources.*" An example of the latter is polyethylene derived from bio-ethanol that is sourced from the fermentation of sugar cane.
- (ii) Copolymers, blends or biocomposites can be made from two or more of these materials. Many commercially available bioplastics are made this way to meet the technical requirements and/or to reduce costs. Typical examples are starch complex (or starch-based bioplastics) where starch is compounded or grafted with other bioplastics.

- (iii) Materials from annually renewable plant fibres, e.g. moulded pulp, are often included in bioplastics but wood-fibre based materials, such as paper and paperboard, are traditionally regarded as a separate group of materials and hence are not included.



Note: Bioplastics can also be produced as co-polymers or bio-composites using two or more of these materials.

**Fig. 11.3** Classification of bioplastics based on origin and method of production.

## 11.4.2 Bioplastics directly extracted from biomass

### 11.4.2.1 Polysaccharides

The polysaccharides or polyoses are a group of carbohydrates polymerised in different forms from monosaccharides (simple sugars classified according to the number of carbon atoms). They exist naturally as starch and cellulose in plants and can be extracted in forms of starch granules or cellulosic fibres for industrial applications.

#### Starch

Starch is an abundant, annually renewable and low-cost source of natural polymer, which makes it an extremely attractive raw material for the production of bioplastics. Starch exists as granules in many plants, such as corn, wheat, rice, tapioca and potatoes, and is a carbohydrate polymer of D-glucose organised in two major constituents: amylose – a linear or sparsely branched polymer with molecular weight of  $10^5$ – $10^6$  and amylopectin – a highly multiple-branched polymer attached on amylose starch with much higher molecular weight of  $10^7$ – $10^9$  (Averous, 2004).

These molecules are readily digestible by micro-organisms leading to excellent biodegradability or compostability of bioplastics containing a significant amount of starch. The hydroxyl end groups of starch, however, means that the starch-based bioplastics are highly hydrophilic, leading to variation of properties with their moisture content. Starch from different origins differs in the ratio of the two constituents, molecular weights, types and degree of crystallinity and size of granules, which give rise to differences in properties. The natural, or native, starch is hardly usable as a bioplastic due mainly to its high melting point and brittleness. It must be 'destructured' and plasticised by application of heat, mechanical shear and the addition of plasticizer, commonly glycerine and polyols, etc. in the presence of water, to produce a thermoplastic material known as *thermoplastic starch (TPS)*. Further modification of starch and improvement of properties can be achieved by compounding with other bioplastics, with or without grafting of the dissimilar polymer chains, to produce a range of materials known as *starch complex (Baastioli et al., 1995)*, *starch blends* or *starch-based bioplastics* as reviewed by Halley (2005). Inorganic additives, such as clay, may also be incorporated, which, when dispersed properly, can enhance the mechanical and barrier properties of starch and produce *starch nano-composites* (Wilhelm et al., 2003).

### ***Thermoplastic starch (TPS)***

Thermoplastic starch should normally contain at least 70 wt% starch (Nolan-ITU Pty, 2002) with the balancing composition being plasticiser, polymeric property modifier and fillers. TPS can be extruded into sheet for thermoforming of food packaging trays, e.g. Plantic<sup>®</sup>, Plantic Technologies, Australia, [www.plantic.com.au](http://www.plantic.com.au), or expanded into foams for cushion packaging, e.g. Bio-flo<sup>®</sup>, Greenlight Products, UK ([www.greenlightproducts.co.uk](http://www.greenlightproducts.co.uk)). At such high starch contents, the TPS products will normally retain the hydrophilic characteristic and high biodegradability in home composters (Song et al., 2009). TPS is thus suitable for short service life packing for foams in transit packaging, or in the packaging of low moisture products, such as confectionary.

### ***Starch complex (starch blends with other bioplastics)***

In order to extend functionality and/or reduce cost, TPS may be combined at various concentrations, typically 30–70 %wt, with other bio-based or petrochemical-derived bioplastics. At lower starch concentration, i.e. less than 60%, starch acts as a weak link in the matrix and provides sites for biodegradation attack. At concentrations exceeding 60%, significant enhancement in biodegradation occurs (Nolan-ITU, 2002). Blending TPS with more hydrophobic polymers produces formulations that are more water resistant and melt flow properties suitable for injection moulding and film blowing.

Starch complexes are amongst the most commercially exploited materials, on the basis of their cost reduction and functionality enhancements, used to produce bioplastics and many patents have been published, as summarised by Averous (2004). A wide range of bioplastics have been blended with TPS, and these include PCL, PLA, PVOH, PBS and PBSA as summarised by Halley (2005) and Clarimval and Halleux (2005) amongst others. Examples of commercially available materials (Bioplastics, 2007/08) include Mater-Bi<sup>®</sup> (Novamont Italy, [www.materbi.com](http://www.materbi.com)), BIOPAR<sup>®</sup> (BIOP Biopolymer Technology, Germany, [www.biopag.de](http://www.biopag.de)), Biograde<sup>®</sup> (Biograde Australia, [www.biograde.com.au](http://www.biograde.com.au)), Bioplast<sup>®</sup> (Biotech Germany, [www.biotec.de](http://www.biotec.de)), Bio-flex<sup>®</sup> (FKUR Germany, [www.fkur.de](http://www.fkur.de)) and VEGEMAT<sup>®</sup> (VEGEPLAST, France, [www.vegeplast.com](http://www.vegeplast.com)) and Biolice<sup>®</sup> (Limagrain, France, [www.biolice.com](http://www.biolice.com))

Due to their multi-phase structures, most of these materials are translucent or opaque, and hence unsuitable for applications where transparency is required. They have been used in the form of films for bags and wrapping, etc. sheet for thermoformed trays/containers, and moulded consumer products by many packaging manufacturers ([www.european-bioplastics.org](http://www.european-bioplastics.org) and *Bioplastics Magazine*).

### *Cellulose*

Cellulose is a linear homo-polymer of glucose, and it is the most abundant natural polymer on Earth. The glucose repeat units are linked in the  $\beta$  configuration by contrast with the  $\alpha$  configuration in starch. This allows the chains to crystallise in linear conformation in the form of highly crystalline, high aspect ratio and sub-micron diameter micro-fibrils that are aligned along the cellulose fibre (known as ultimate or single fibre). Apart from a few exceptions, e.g. cotton, which is almost pure cellulose, plant fibre exists as a natural bio-composite with the cellulose fibres bonded by hemicelluloses and the lignin complex in cell walls of plants to provide structural support.

Direct utilisation of cellulose in packaging can be put in a few categories depending on the refinement of the cellulose ranging from micro-fibrils, pulp (short fibre), textile fibres or engineering fibre (long ultimate fibre or fibre bundles) to relatively unrefined lignocellulosic biomass as in wood flour, straws, etc. Furthermore, cellulose derivatives can be made into films known as *regenerated cellulose film* (RCF) by chemical modification.

### *Cellulose fibre based materials*

Micro-fibril is a bio-based nano-material with much potential in packaging applications, e.g. in transparent films or coatings, gel formulations and as reinforcement in foams and composites (Turbak *et al.*, 1983; Endo *et al.*, 2000; Yano & Nakagaito, 2005; Henriksson *et al.*, 2008). Widespread applications are currently restricted by the high cost due mainly to the difficulties in extraction of micro-fibrils without chain cleavage during enzymic or chemical treatment. When dried, difficult-to-disperse lumps – due to strong inter-molecular forces and entanglement of fibrils – can give rise to problems in its dispersion into biocomposites.

In addition to paper and paperboard products, wood pulp and those fibres refined from plants, e.g. miscanthus, bagasse and palm fibre, have been utilised in *pulp moulding* (or *moulded pulp*) products (Brody & Marsh, 1997). Low grade moulded pulp products are often made from recycled paper or paperboard and used in food packaging, e.g. egg or fruit boxes, fast food service ware, e.g. coffee trays, and general packaging, e.g. for toys. High grade moulded pulp, suitable for food packaging/service, such as trays and clamshells etc., products are made from virgin pulp with good surface finish, mechanical properties and resistance to water and grease. This sector is regulated by the International Moulded Pulp Environmental Packaging Association ([www.impepa.org](http://www.impepa.org)).

### *Cellulose derivatives*

Numerous cellulose derivatives can be produced by dissolution of normally insoluble cellulose, replacement of the hydroxyl groups with different radicals and reclamation from solution to produce films for packaging (or fibre for textiles). These include *regenerated cellulose film*, *cellulose esters*, e.g. *cellulose acetate* (CA), *butyrate* (CAB) or *propionate* (CAP), *cellulose ethers* (such as hydroxyl ethyl/propyl and methyl cellulose), *carboxyl methyl cellulose*, *fatty acid ester of cellulose* etc. (Chiellini *et al.*, 2002). Some of them, such as regenerated cellulose

film, have been lost to petrochemical polymers, such as polypropylene, mainly on commercial grounds. In the past, cellulosic derivative products were also criticised from an environmental perspective because they were energy intensive in production and produced noxious emissions if incinerated. However, advances in technology and the drive for using renewable materials have stimulated the use of cellulose derivatives in recent years. For example, Innovia Cellophane™ (regenerated cellulose film) and NatureFlex™ (cellulose acetate) films are made from renewable wood pulp ([www.innoviafilms.com](http://www.innoviafilms.com)), and they are used in flexible food packaging, window film and wrapping. In addition to their inherent advantages, e.g. they are home compostable, transparent with high gloss, anti-static, good dead-fold and printability properties as well as being oil and grease resistant. Lamination and coating technologies have been employed to enhance heat sealability and reduce water vapour and common gas permeation.

### ***Lignocelluloses***

Lignin is one of the main constituents of lignocelluloses, and it consists of three units of the phenyl propane family: p-hydroxy phenyl, guaiacyl and syringic aldehydes. Lignin is closely associated with hemi-celluloses to form the supporting structure in plants. The complex chemistry and polymer architecture make it difficult to isolate and plasticise lignin by simple methods. For this reason, most unrefined lignocelluloses, e.g. wood flour, sugar cane bagasse, palm fibre; cereal straws and husks, have been incorporated with compatibilisers in conventional plastics, e.g. in wood plastic composites, (WPC), or in bioplastics as low-cost fillers to produce compostable packaging materials, e.g. Ecoplast<sup>®</sup>, Groen Granulaat Netherland. Liquefaction of lignocelluloses (wood in particular) can be achievable by some hard treatments such as treatment at 320–400°C in aqueous or organic solvents, (Widsten *et al.*, 2002), in acidic catalyst solution or concentrated acid solution (Clarimval & Halleux, 2005). The treatments disintegrate the natural lignocellulosic structure and results in 'liquefied wood', e.g. Arboform<sup>®</sup>, Tecmaro, Gemany [www.tecnaro.de/english/arboform.htm](http://www.tecnaro.de/english/arboform.htm), or a blend of lignin, hemi-cellulose and other additives, e.g. starch, protein and other resins, which can be moulded, e.g. Lignopol<sup>®</sup> Borregaard Ligno Tech, Gemany, [www.borregaard.com](http://www.borregaard.com). Some of these materials are not designed for packaging applications and thus care must be taken to conform to standards for food safety when applied for packaging in contact with foods.

### ***Natural fibre bio-composites***

Synthetic, e.g. glass and carbon, fibre reinforced plastics are widely used as high-performance and lightweight engineering materials in construction, automotive and aerospace sectors. High performance natural fibre, e.g. flax, hemp, jute and sisal, have also found applications in building materials and automotive interior components as low-cost alternatives to synthetic fibres. With bioplastics becoming more commercially available, natural fibre reinforced bioplastics have received increasing attention since the 1980s as these 'green composites' can potentially be made entirely from renewable resources and designed to be biodegradable if required. Plackett gave a review of this development (Plackett, 2005). The study covered a wide range of systems of bioplastics and natural fibres, e.g. flax, cotton, jute and abaca in PLA; jute, pineapple and wood in PHAs and flax, sisal ramie and cellulose in starch complexes. Most of the composites were made by melt compounding in which fibre mechanical damage and thermal degradation were studied. The focus was mainly on applications in automotive interior components. However, they may well find applications in secondary packaging, e.g. moulded containers for transport/storage of foods.

### *Others*

Among many other naturally occurring polysaccharides, e.g. gum, dextrin and pectin, chitin and chitosan have been extensively studied for bioplastic applications as reviewed by Arvanitoyannis (2008). Chitin is the most abundant polysaccharide polymer after cellulose and synthesised by a huge number of living organisms. Chitin occurs in nature as ordered crystalline micro-fibrils forming structural components in shellfish or in the cell walls of many fungal species. It can be extracted in concentrated caustic soda, (NaOH), solutions. Chitin is closely related to cellulose except for the substitution of some secondary hydroxyl by acetamide groups, and thus aspects of cellulose technology should be readily applicable to chitin. Chitosan is produced by complete or partial elimination of the acetyl groups. Unlike chitin, chitosan is soluble in weak acids, e.g. acetic acid, and hence more amenable for industrial applications. Both can be extruded into films for packaging applications. They are edible and thus can be used as a thickening or suspension agent, gels and encapsulation for food and cosmetic applications.

#### 11.4.2.2 *Proteins*

Proteins are natural chains of  $\alpha$ -amino acids joined by amide linkages and can be degraded by enzymes, e.g. proteases (Clarimval & Halleux, 2005). Since the 1930s, protein-based polymers have been used for encapsulates, coatings, adhesives and surfactants. From their origins they can be divided into animal and plant proteins. The nutritional value of proteins is particularly attractive for producing edible food packaging. Detailed descriptions can be found in books on protein-based films and coatings (Gennadios, 2002) and edible coatings and films (Krochta *et al.*, 1994).

#### *Animal-based proteins*

*Collagen* is a family of structural proteins abundant in the extracellular matrix of animal tissues (bones, tendons and skin). When degraded by strong alkali, collagen yields *gelatine*, which has been used for food processing and drug encapsulates. The physico-chemical properties can be modulated by plasticisation, e.g. by glycerol, or blending with other polymers, e.g. PVOH.

*Casein* is present in micellar form in skimmed milk and is precipitated from it by acidification. Casein polymers are water soluble and have been used in binder or adhesive formulations. They are good candidates for making biodegradable adhesives, e.g. for labelling, in food packaging and edible films (Beyer, 2002).

#### *Plant-based proteins*

The soybean (US), or soya bean (UK), contains, among other constituents, about 38% protein and 18% oil. Both have been used to produce soy-based polymers. Soy protein and oil can be used to produce biodegradable high stiffness thermoset polymers as replacement for urea formaldehyde (UF) adhesive in the production of wood fibre boards, e.g. Soyad<sup>®</sup>, Heartland Resource Technologies, USA, [www.heartlandresource.com](http://www.heartlandresource.com). Soy oil has been used to produce polyol in the manufacture of bio-based polyurethane (SOYOL<sup>®</sup>, Urethane Soy Systems, USA, [www.soyoyl.com](http://www.soyoyl.com)) for flexible and rigid foams, coatings, adhesives, sealants, and elastomers.

Polymers made from gluten are transparent, flexible and completely biodegradable thermoplastics (Clarimval & Halleux, 2005). They are relatively impermeable to oxygen, (O<sub>2</sub>), and carbon dioxide, (CO<sub>2</sub>), but sensitive to moisture and may be found in water soluble food packaging applications.

### 11.4.3 Bioplastics synthesised from bio-derived monomers

In this category, polylactic acid (PLA) is one of the most commercially available and exploited bioplastics. In addition to Natureworks LLC<sup>®</sup>, the largest PLA manufacturer ([www.natureworkslc.com](http://www.natureworkslc.com)), many others such as the Purac and Sulzer partnership (Bioplastics Magazine, 2009b) are also producing PLA. In a more recent development, polyethylene, a non-biodegradable polymer has also been made from bio-ethanol fermented from sugar.

#### 11.4.3.1 *Poly(lactic acid (PLA)*

PLA – *Poly(lactic Acid or polylactide* – is an aliphatic polyester made mostly from starch/sugar-rich crops but it can also be derived from petrochemicals. The difference in terminology indicates simply the synthesis method chosen to produce PLA from lactic acid fermented from starch or sugars. There are three types of PLA (PLLA, PDLA and PDLA) because there are two stereoisomeric forms of lactic acid (laevo- or L-lactic acid and dextro- or D-lactic acids). The ratio and sequences of D- and L- units in PLAs have profound effects on their crystallinity, thermal and mechanical properties (Zhang & Sun, 2005).

PLA has high transparency and surface gloss together with other physico-chemical characteristics such as good chemical resistance to fats and oils. These enable the material to be an alternative to PET, HIPS, PVC, and cellulose in some packaging where high clarity is essential. For example, like PET, PLA is a clear material with similar aesthetics permitting a multitude of varied and complex container shapes and sizes. PLA can be processed by extrusion, thermoforming, injection- or blow-moulding, film blowing or stretching and fibre spinning to produce a large range of products in forms of film, sheet, fibre or moulded parts. PLA's most common applications are in areas such as fresh food packaging and short shelf life products that do not require sophisticated barriers. For example, the anti-fog properties of PLA are valued for the packaging of bread and other baked products that are packed warm. PLA packaging is available in a wide range of pack forms, including thermo-formed cups and trays, bi-axially oriented films, cast film, shrink labels and wrapping, foams and blow-moulded bottles. In addition to forming a flavour and aroma barrier comparable to PET, PLA readily accepts coatings, inks and adhesives and can be thermo-laminated to paper or paperboards. Other applications include PLA film used for the windows of sandwich cartons, PLA bottles for beverages and thermo-formed PLA trays for fresh produce, salads and coleslaw.

PLA is rigid, brittle and likely to deform at temperature in excess of its low glass transition temperature of  $\sim 55^{\circ}\text{C}$ . Considerable efforts have been made to improve the thermal and mechanical properties by controlling the L/D ratio or polymerising PLA by using specified catalysts, orientation of PLA chains by stretching at various ratios, degree of crystallisation and plasticisation (Martin & Averous, 2001; Zhang & Sun, 2005). Increasingly, PLA is often blended with other materials, such as nanoclay, starch or other bioplastics and celluloses, for cost reduction and/or modification of functionalities.

Until recently, PLA could not be used for hot-fill and gaseous drinks like beer and cola. However, development work is being conducted to address this. In 2007, Purac – a subsidiary of CSM (Netherlands, [www.purac.com](http://www.purac.com)) — announced its patented PLA polymers that withstand temperatures of at least  $175^{\circ}\text{C}$ . This new development enables its use in more widespread applications such as hot fill bottles, microwaveable trays, temperature resistant fibres, electronics and automotive parts. Purac's PLA technology is expected to stimulate the growth of the PLA market. Sizeable production volumes are anticipated from 2010.

The major supplier of PLA (Natureworks in the US, [www.natureworksllc.com](http://www.natureworksllc.com)) mainly uses genetically modified (GM) corn. Although PLA does not contain any genetic DNA, there is public concern in Europe over the use of GM sourced PLA. However, PLA can also be sourced from other products, such as sugar beet, tapioca and sugar cane, and 'GM-free' PLA is available at a premium.

Although PLA is compostable in industrial composting facilities, it has been shown not to be suitable for home composting (Song *et al.*, 2009).

#### 11.4.3.2 Polyglycolic acid (PGA)

PGA is produced by the ring opening of glycolide, a diester of glycolic acid that can be produced either from fermentation of starch or from petrochemicals. It is a rigid thermoplastic material with high crystallinity (46–50%), a glass transition ( $T_g$ ) temperature of 36°C and a melting temperature ( $T_m$ ) of 225°C. PGA can be processed by extrusion, injection and compression moulding. PGA is resistant to most organic solvents but highly sensitive to hydrolysis. The degradation product is glycolic acid, a natural metabolite. It has been used in medical applications such as drug release together with PLA or PLA/PGA copolymers (Clarimval & Halleux, 2005). As PGA has superior carbon dioxide (CO<sub>2</sub>) and oxygen (O<sub>2</sub>) barrier properties, it has now been produced commercially, for example, by Kureha in Japan ([www.kureha.co.jp/en/pdf/071218.pdf](http://www.kureha.co.jp/en/pdf/071218.pdf)) and used in multilayer packaging materials based on PLA or PET bottles for soft drinks, e.g. Krehalon UK Ltd. ([www.krehalonuk.co.uk/environment.php?id=12](http://www.krehalonuk.co.uk/environment.php?id=12)).

#### 11.4.3.3 Polyethylene from bio-ethanol (Bio-PE)

Polyethylene (PE) is currently the largest volume commodity plastic and, until recently, was only manufactured from petrochemicals. However, Braskem, a Brazilian thermoplastic resin manufacturer, has developed a 200 kt/annual capability to produce PE from the polymerisation of ethylene derived from ethanol by fermentation of sugar cane (Morschbacker, 2007). Although PE is non-compostable, the use of a carbon capturing renewable resource will lead to a near 'zero carbon' life cycle and the post-consumer PE can be recovered by existing Materials Reclamation Facilities (MRFs).

### 11.4.4 Biodegradable polymers from petrochemicals

This group of materials, consisting of *aliphatic polyesters*, *aromatic co-polyesters* and *polyvinyl alcohols (PVOH)*, are speciality polymers synthesised from petrochemical monomers and possess weak linkages that are vulnerable to enzymic attack leading to biodegradation of the polymer chains. As most of them are much more expensive than the common commodity polymers, they are rarely used alone for packaging applications and are often combined with starch, cellulose or as copolymers to produce compostable packaging materials.

#### 11.4.4.1 Aliphatic polyesters and derivatives

Poly(lactic acids (PLA), polyglycolic acid (PGA), polycaprolactone (PCL), polybutylene succinate (PBS) and polybutylene succinate adipate (PBSA) fall into this category. Synthesis of them has been described in detail (Jerome & Lecomte, 2005). PLA and PGA can both be derived from bio-based or petrochemical monomers as has been described earlier, and thus brief descriptions are given only about PCL, PBS and PBSA.

### *Polycaprolactone (PCL)*

PCL is prepared by ring-opening polymerisation of  $\epsilon$ -caprolactone. It is a semi-crystalline polymer with a low  $T_g$  of about  $-60^\circ\text{C}$  and  $T_m$  of  $50$ – $64^\circ\text{C}$ . Tone<sup>®</sup>, Union Carbide USA, ([www.ucarbide.com](http://www.ucarbide.com)) and CaPA<sup>®</sup>, Solvay Belgium, ([www.solvaypress.com](http://www.solvaypress.com)) supply PCL polymers. Its high ductility and low processing temperature has enabled it to be blended with starch, etc. in a range of starch blends including some of the grades in commercial use, such as Mater-Bi and Bioflex<sup>®</sup> (Nolan-ITU, 2002).

### *Polybutylene succinate (PBS) and Polybutylene succinate adipate (PBSA)*

PBS is a semi-crystalline polyester with 35–45% crystallinity,  $T_g$  of  $-32^\circ\text{C}$ ,  $T_m$  of  $114$ – $115^\circ\text{C}$  and similar properties to PET. PBSA is a PBS and adipate copolymer with crystallinity of 20–35%,  $T_g$  of  $-45^\circ\text{C}$ ,  $T_m$  of  $93$ – $95^\circ\text{C}$  and similar properties to that of LDPE (Clarimval & Halleux, 2005). These commercially available materials, e.g. Bionell<sup>®</sup>, Showa Hypolymer Japan, [www.sdk.co.jp](http://www.sdk.co.jp) and SkyGreen<sup>®</sup>, SK Polmers, Korea, [www.skchemicals.com](http://www.skchemicals.com), can be processed with conventional melt processing techniques. The blending of PBS with starch is a common approach to reduce materials cost (Ratto *et al.*, 1999).

### *Polyester amide (PEA)*

PEA is a modified aliphatic polyester obtained by polycondensation of butanediol with adipic acid and caprolactam, ([www.biodeg.net/bioplactic](http://www.biodeg.net/bioplactic)). An example of this polymer is BASF's BAK 1095.

#### 11.4.4.2 *Aromatic copolyesters*

Aromatic polyesters such as *polyethylene terephthalate* (PET) and *polybutylene terephthalate* (PBT) are formed by the polycondensation of aliphatic diols and aromatic dicarboxylic acids. The aromatic rings result in excellent resistance to chemical agents and to enzymic hydrolysis making them difficult to biodegrade. However, they can be modified by copolymerisation to introduce weak linkages and, thus, biodegradability. PBT or PET, for instance, can be modified with aliphatic dicarboxylic acid to form *polybutylene succinate terephthalate* (PBST) or, with reaction of butanediol with adipic and terephthalic acids, to produce *polybutyrate adipate terephthalate* (PBAT). *Polytetramethylene adipate terephthalate* (PTMAT) is made by the reaction of tetramethylene glycol with adipic and terephthalic acids (Clarimval & Halleux, 2005).

Examples of biodegradable copolyesters are some grades of BASF Ecoflex<sup>®</sup> and Easar Bio<sup>®</sup> (now sold to Novamont) while Biomax<sup>®</sup> (DuPont, [www2.dupont.com/Biomax](http://www2.dupont.com/Biomax)) is a modified PET.

#### 11.4.4.3 *Polyvinyl alcohol (PVOH) and poly(ethylene vinyl alcohol) (EVOH)*

PVOH and EVOH are two main water soluble polymers. PVOH can be produced by polymerisation of vinylacetate to polyvinylacetate (PVAC) and subsequent hydrolysis. The degree of hydrolysis signifies the extent of conversion from PVAC to PVOH. Partially hydrolysed PVOH has  $T_g$  of  $58^\circ\text{C}$  and  $T_m$  of  $180^\circ\text{C}$  and totally, hydrolysed PVOH has a higher  $T_g$  of  $85^\circ\text{C}$  and  $T_m$  of  $230^\circ\text{C}$ . Commercial PVOH include Elvanol<sup>®</sup> (DuPont, [www2.dupont.com/Elvanol](http://www2.dupont.com/Elvanol)) and Hi-Selon<sup>®</sup> (Nippon Gohsei, Japan, [www.nippon-gohsei.com/products/hiselon](http://www.nippon-gohsei.com/products/hiselon)). PVOHs

have been used in water soluble starch/PVOH blends of many commercial bioplastics including some Materbi<sup>®</sup> grades (Novamont, Italy, [www.materbi.com](http://www.materbi.com)) and Plantic<sup>®</sup> (Australia, [www.plantic.com.au](http://www.plantic.com.au)).

EVOH is also water soluble and used as an oxygen barrier in multilayer film packaging. In comparison with PVOH, its high cost is the main restriction for widespread bioplastic applications (Nolan-ITU, 2002).

#### 11.4.5 Polyesters directly produced from natural organisms

Some aliphatic polyesters can be synthesised by certain microbes (where they act as energy storage material in cells) and are produced commercially using bioengineering methods to accumulate and extract the polymers. They are collectively termed polyhydroxyalkanoates (PHAs), including polyhydroxybutyrate (PHB), polyhydroxyvalerate (PHV), polyhydroxyhexanoate (PHH) and their copolymers. These have been reviewed in detail by Chen (2005). Adjustments of  $T_g$ ,  $T_m$  and flexibility of the materials can be achieved by controlling the length of the aliphatic chains.

PHAs can be synthesised by various bacteria, e.g. *alcaligenes*, *eutrophus* and cyanobacteria. Many grades of PHA exist with different degrees of crystallinity and can be processed with conventional melt flow technologies. In this family, PHB, PHV and their copolymers are most common.

PHB has a  $T_g$  of 5°C and  $T_m$  of 180°C. The properties of PHB are similar to those of polystyrene but more rigid and brittle than polypropylene. Examples of commercially available PHB are some grades of Biomer<sup>®</sup> (Biomer, Germany, [www.biomer.de](http://www.biomer.de)).

Copolymers of PHB, PHV and PHH are more commonly produced to enhance biodegradability and processibility. Examples of such blends are Biopol<sup>®</sup> PHBV (Metabolix USA, [www.metabolix.com](http://www.metabolix.com)) and PHBH from some grades of Nodax<sup>®</sup> (Kaneka, Japan, [www.kaneka.com](http://www.kaneka.com)).

Most of the materials are biocompatible and bioresorbable, and hence have found medical applications, e.g. implants. Certain grades are for more general applications such as in packaging.

The crystallinity of PHAs can be manipulated to provide a blend of mechanical and barrier properties, in some cases matching the performance of engineered thermoplastics. The polymers will biodegrade either aerobically or anaerobically. Bio-degradation can occur in septic systems, commercial waste water treatment systems, composting environments or even in cold ocean waters. There is a wide range of applications from highly flexible films and fibres to thermoformed rigid packaging, including many single-use food service and liquid packaging applications. A major factor in the competition between PHAs and petrochemical-based polyesters is in production cost. The use of low-cost biomass raw materials, such as corn steeped liquor and molasses, has been suggested (Nolan-ITU, 2002). Clear versions of these materials are yet to be developed.

#### 11.4.6 Biocomposites

Biocomposites refer to composites made by the combination of two or more bioplastics for enhancement of:

- physical properties, e.g. gas/liquid barrier, optical properties, printability and heat sealing
- chemical properties, e.g. resistance to chemicals

- mechanical properties, e.g. strength, stiffness, ductility and heat deformation stability
- processibility, e.g. melt flow, melt strength and thermal degradation behaviours where inclusion of processing additives, e.g. plasticiser, compatibilisers, biodegradation enhancers, pigment and fillers etc., may not be sufficient (Irmak & Erbatur, 2008)

The common techniques to produce biocomposites with better performance include the following:

- forming copolymers
- blending of polymers
- lamination of multi-layer films
- natural fibre reinforcement of bioplastics
- nano-scale biocomposites

As the use of copolymers, polymer blends, laminations and natural fibre reinforcement have been described earlier, only the more recent developments in nano-biocomposites are briefly summarised here. Nano-biocomposites refer to biocomposites characterised by nano-scale second phases finely dispersed in the matrix at low concentration (typically 5–10 %wt), giving rise to a more extraordinary enhancement of properties, e.g. mechanical and barrier properties, than those in the usual blends.

The drivers behind the development are mainly to:

- improve barrier properties of monolayer packaging. A good barrier property is essential in many food packaging applications to reduce sorption, migration and transport of low molecular species (gases, water vapour and organic compounds) through the packaging for food safety and the extension of shelf life
- reduce property dependence on moisture content, characteristic of certain bioplastics, e.g. those based on proteins and polysaccharides
- enhance the thermal deformation stability of bioplastics with low  $T_g$ , e.g. those based on PCL and PLA
- enhance strength and stiffness and reduce material consumption and cost; bioplastics are typically more expensive than commodity polymers and lower costs can be achieved, e.g. by down-gauging of the nano-composites

Among various nano-biocomposites, those that have attracted most attention are the nano-clay biocomposites. When the layered structure of clays are fully disrupted and dispersed in the polymer matrix, the high modulus nano-layers act as a reinforcement phase to enhance strength, stiffness and heat deformation resistance. The increased tortuosity of the diffusion paths between the impermeable layers will also enhance the barrier property of the composites. Transparency of the polymer matrix can largely be retained as a result of low diffraction by the nano layers. A large number of bioplastics matrices, e.g. PLA, PHB, PHBV, PCL, starch and proteins, and layered inorganic agents, e.g. montmorillonite, kaolinite, bentonite, saponite and silicates with or without organic modifications, have been studied (Lagaron & Sanchez-Garcia, 2008; Dean & Yu, 2005), on protein-based nano-composites. (Commercial production of the materials had not been developed by 2009).

## 11.5 WASTE MANAGEMENT OPTIONS FOR BIOPLASTICS

The 'Waste Hierarchy' is a sequential listing of waste management options based on their relative environmental benefits and order of sustainability, with landfill viewed as the least attractive. It presents a framework to consider as to which option is preferable from an environmental perspective, as follows:

- *eliminate or minimise at source*: possible risk of hygiene issues and increased product damage
- *reuse*: is it possible to reuse the material thereby preserving the embodied energy?
- *recycle or compost*: reprocessing for reuse; home composting, in-vessel composting etc
- *recovery of value in some other way*, e.g. waste-to-energy
- *disposal*: the least favoured option to landfill

In the EU, the development of a waste management infrastructure is framed by legislation defined by the following:

- the Landfill Directive (99/31/EC as amended in 2003 & 2008) which aims at a stepwise reduction of the organic fraction in waste going to landfill
- the Directive on Packaging & Packaging Waste (2004/12/EC amending 94/62/EC), which sets the material limits for recovery and thermal utilisation of the packaging components

The impact of bioplastics, when entering the waste stream and handled by currently available options (recycling, incineration and landfill), is assessed briefly below. Since biodegradable plastics provide potential options for biological waste treatments as ways of recovering the materials and to produce useful products, such as compost and gas for energy, particular attention will be given to composting and anaerobic digestion (AD) of bioplastics.

### 11.5.1 Conventional waste management options

#### 11.5.1.1 Recycling

Sustainable recycling relies on a consistent supply of large quantities of good quality feedstock and a market for the recyclates (Hartmann & Rolim, 2002). Bioplastics at present, however, only represent less than 1% of the total annual plastic production (<http://www.european-bioplastics.org>). Although it is technically feasible to recycle bioplastics, e.g. PLA (Claesen, 2005), the lack of a continuous and reliable supply of bioplastics waste makes recycling economically unattractive. Furthermore, when entering the municipal waste stream, bioplastics may result in some complications for existing plastic recycling systems: starch or natural fibres reduce final materials performances (Scott, 1995) and (Hartmann & Rolim, 2002).

Considerable concerns have also been raised over the contamination of PET plastics bottle recycling by bioplastics. Further developments in technologies enabling segregation of bioplastics from conventional plastics in MRF systems are available but they are expensive given the low volumes of PLA in the waste stream. Technologies capable of capturing the characteristic chemical fingerprints of bioplastics, or the tracing of marker additives in bioplastics, are among those for exploration. Finally, for applications such as food packaging, multilayer lamination films/sheet of different biopolymers are often employed to enhance barrier properties, as in conventional plastics (Miller, 2005). However, such heterogeneous material compositions will

compromise recyclability of packaging manufacturing scrap and of post-consumer packaging wastes.

#### 11.5.1.2 *Waste-to-energy*

Energy recovery by incineration is regarded as a suitable option for all bioplastics, and it has been suggested that the renewable resources in bioplastics contribute to the production of *renewable energy* when incinerated ([www.european-bioplastics.org](http://www.european-bioplastics.org)). Natural cellulose fibre and starch have relatively lower gross calorific values (GCV) than coal but are similar to wood, and thus still have considerable value for incineration (Davis & Song, 2006). In addition, the production of fibre and starch materials consumes significantly less energy in the first place (Patel *et al.*, 2003), and thus contributes positively to the overall energy balance in the life cycle.

#### 11.5.1.3 *Landfill*

Contrary to a common misconception that bioplastic materials are good as they will ‘disappear’ when dumped in landfill sites, bioplastic wastes and other biodegradable materials, e.g. garden and kitchen wastes, in landfill sites can, under anaerobic conditions, generate methane, a greenhouse gas with 23 times the effect of carbon dioxide, CO<sub>2</sub> (Hudgins, 1999). The EU Landfill Directive (1999/31/EC as amended in 2003 & 2008), thus seeks to reduce the total amount of biodegradable municipal waste going to landfill.

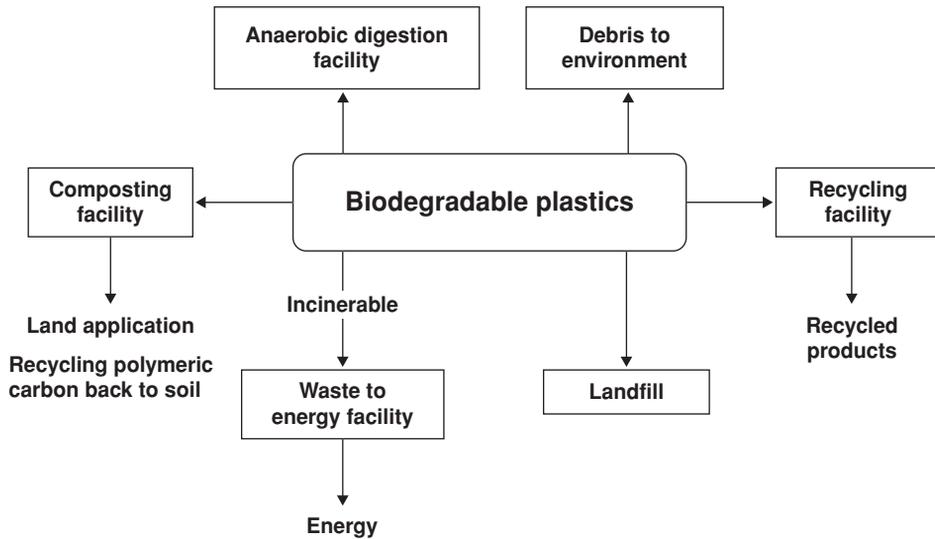
### 11.5.2 Biological waste treatments of bioplastics

A unique feature of bioplastics is that, unlike most conventional plastics, the post-use materials may be treated biologically, e.g. via aerobic composting (Song *et al.*, 2009), to generate carbon and nutrient rich compost as a soil improver or, via anaerobic digestion (AD) (Ramsay *et al.*, 1993; Mohee *et al.*, 2008), to generate methane for energy. However, being biodegradable does not have much inherent value if the bioplastics waste does not end up in a waste management system that utilises the biodegradability features. Fig. 11.4 illustrates the integration of biodegradable plastics with disposal infrastructures that utilise this biodegradable function of the plastic products (Song *et al.*, 2009).

The composting of bioplastics may be carried out with organic wastes either in industrial (or municipal) or home (or domestic/garden/backyard) composters. The biodegradability requirements, composting conditions and certifications are different and a bioplastic certified as ‘biodegradable’ or ‘compostable’ may compost well in an industrial composter at relatively higher temperatures but not as well as anticipated in a home composter. This has led to the establishing of different standards and certification systems to regulate the composting practices.

#### 11.5.2.1 *Industrial (municipal) composting*

Industrial composting refers to centralised composting facilities where large amounts of organic waste (referred to as biowaste), collected from diverse sources such as parks, household gardens and kitchens, is treated by aerobic biodegradation. Aeration is achieved by turning the waste at regular intervals (Wilde, 2007). Micro-organisms, e.g. bacteria and fungi, degrade the waste and convert it into new micro-organisms, humus, carbon dioxide, (CO<sub>2</sub>), and water. The degradation process is accompanied by heat release, which raises the temperature to 60–65°C for open



**Fig. 11.4** Integration of biodegradable plastics with disposal infrastructures (Song *et al.*, 2009).

windrow composters, or higher for in-vessel composters. This is known as the *thermophilic phase* of composting. It is of importance to ensure the destruction of thermosensitive human and plant pathogens, fly larvae, and weed seeds. Regulations by the US Environmental Protection Agency specify that to achieve a significant reduction of pathogens during composting the compost should be maintained at minimum operating conditions of 40°C for five days, with temperatures exceeding 55°C for at least four hours during this period (Song *et al.*, 2009).

Bioplastics satisfying the European EN13432 or American ASTM D6400 Standards are suitable for industrial composting. Bioplastic packaging enables food waste, e.g. from supermarket chains, to be composted without removing the packaging. The addition of bioplastics will also improve the carbon/nitrogen ratio of the biowaste reducing odour, e.g. ammonia.

The major threat is the potential adverse impact on the quality of the compost. Non-compostable plastics could be easily mistaken for compostable bioplastics and render the compost unsaleable. In addition to stringent certification of bioplastics and clear logos on biopackaging, effective public education and communication with regard to careful screening of plastics into organic waste at household level plays a vital role. Some composting systems might also need to be modified to accommodate bioplastic inclusion. For example, the location for screening of large pieces of material may need to be shifted downstream to allow for more complete fragmentation of the bioplastics.

There are important issues relating to the inclusion of bioplastics packaging in organic waste. These include public awareness of bioplastics packaging, labelling, separation and collection at household level and impacts on industrial composting of organic waste. These issues were assessed in a large-scale study in Kassel, Germany (Klauss, 2001). The purpose of this scheme was to introduce biodegradable packaging and manage its source separation by householders so that it could be collected with the green waste stream to produce compost. Surveys indicated that 82% households could clearly identify the bioplastics logo printed on packaging for plastic separation. Bioplastics packaging was included in green waste at a mass ratio of 1:99 and composted in industrial composters. The compost produced showed no differences in terms

of quality parameters compared to the compost comprised of solely green waste (Klauss & Bidlingmaier, 2004).

Household kitchen waste and, by association, compostable food packaging is classified under the EU Animal By-Products Regulation (ABPR) in a category that may either be composted or treated via anaerobic digestion, following strict requirements on handling, temperature and retention times. Green (botanical garden) waste incorporating such materials, therefore, must be composted in vessel composters in order to meet the requirements.

### 11.5.2.2 Home (or domestic/garden/backyard) composting

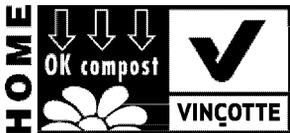
Home composting refers to composting at individual household level. In addition to kitchen and garden waste, home composting of bioplastics could divert waste from municipal collection systems and compliment industrial composting. It must be noted, however, that it is difficult to regulate home composting and anaerobic conditions, occurring in poorly managed systems, will result in the generation of methane. Moreover, home composting using compost bins or heaps are more variable and less optimised than industrial composting and the temperature achieved is rarely more than a few degrees Celsius ( $^{\circ}\text{C}$ ) above ambient temperature (Song *et al.*, 2009). This is far below the thermophilic temperature ( $55\text{--}65^{\circ}\text{C}$ ) required for both suitable degradation of certain materials and to achieve sanitisation.

Under home composting conditions, certain bioplastics certified for industrial composting, e.g. the ‘OK compost’ scheme in Table 11.1, may not biodegrade sufficiently, and this has led to the establishment of a standard specifically for home composting. For instance, the ‘OK Compost Home’ standard, which repeats the EN13432 test protocol at ambient temperature, has

**Table 11.1** Comparison of standards for industrial and home composting (Song *et al.* 2009).

	<b>Industrial composting (EN13432)</b>	<b>Home composting (Vinçotte certification)</b>
Biodegradation	Test at $58^{\circ}\text{C}$ in 180 days Biodegradation min. 90%	Test at $20\text{--}30^{\circ}\text{C}$ in 365 days Biodegradation min. 90%
Disintegration	Test at $58^{\circ}\text{C}$ in 90 days Sieve 2 mm mesh Disintegration $> 90\%$ Max 10% of dry weight allowed to be retained by 2 mm sieve	Test at $20\text{--}30^{\circ}\text{C}$ in 180 days Sieve 2 mm mesh Disintegration $> 90\%$ Max 10% of dry weight allowed to be retained by 2 mm sieve
Certification	Din Certco/OK Compost	OK Home





The seedling logo and the OK Home Compost logo illustrated in the Table are shown by courtesy, respectively, of the European Bioplastics e. V. and Vinçotte.

been established by AIB-VINÇOTTE in Brussels ([www.aib-vincotte.com](http://www.aib-vincotte.com)). Some bioplastics, particularly those used as bags and pots for horticulture or waste collection bags, have been certified by the 'OK Compost Home' scheme (<http://www.aib-vincotte.com/data>). This distinction is important, and it is vital that clear guidance is communicated to the public who may otherwise assume that any products labeled as 'biodegradable', 'compostable', or 'eco-' under the numerous certification systems can be put into their home composters.

Song *et al.* (2009), characterised the extent of biodegradation when a range of biodegradable or potentially biodegradable packaging materials were treated under simulated home composting conditions typical of the autumn/winter period in the United Kingdom. It was to establish whether potentially biodegradable packaging materials would show appropriate levels of biodegradation when home composted together with garden waste under non-thermophilic conditions, which is a regime where mesophilic micro-organisms dominate. Temperature in the composts was found to range from 5 to 18°C over a 180 days period, less favourable for biodegradation than the 20–30°C specified in the 'OK Compost Home' standard. It was demonstrated that several biodegradable packaging materials, predominantly based on high levels of starch and plant fibre/starch composite, can be processed in home composting systems and yield compost materials suitable for plant growth. This capability will enable such materials to be disposed of in well-run home composting systems. However, the work also demonstrated that a number of packaging materials that typically biodegrade well in industrial, thermophilic high-temperature composting systems, such as PLA and some starch/polyester complexes, failed to biodegrade adequately in a home composting environment that operates at low temperature, in mesophilic environments.

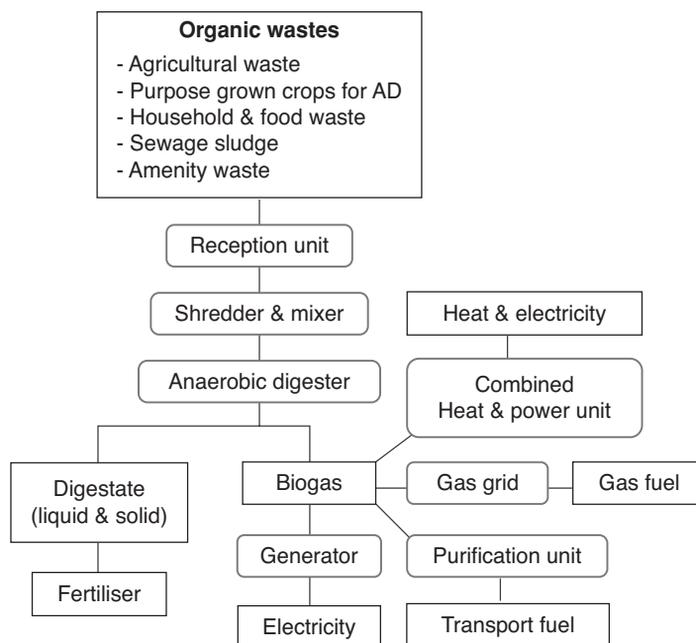
At a practical level, these results suggest that it is vital to clearly distinguish biodegradable packaging materials that can be expected to biodegrade under ambient, mesophilic conditions from those that biodegrade under a thermophilic (55–65°C) regime of a composting process typically found in industrial composting systems. Labelling schemes and consumer education and information should support such a distinction.

### 11.5.2.3 Anaerobic digestion

Anaerobic Digestion (AD) is the process where biowaste is converted into useful products, such as biogas and digestate, by micro-organisms in the absence of air following the schematic flow diagram shown in Fig. 11.5 ([www.biogas-info.co.uk](http://www.biogas-info.co.uk)). A broad range of biowaste from agricultural waste and sewage sludge to household and food waste may be treated by the AD process. After necessary particle size reduction and mixing, the biowaste is digested in a sealed tank by naturally occurring micro-organisms, releasing ~60% methane, (CH<sub>4</sub>), and ~40% carbon dioxide, (CO<sub>2</sub>). The biogas can be used to provide heat and power, or to produce purified bio-methane as a road fuel. The material left over at the end of the process, digestate, is rich in nutrients such as those containing nitrogen and potassium, and it can thus be used as a fertiliser and soil conditioner.

The combined benefits of renewable energy from biowaste and the utilisation of the digestate as a soil improver make AD a very attractive option in biological waste management. It can help to reduce fossil fuel use and greenhouse gas emissions. As in composting, it also diverts biowaste from landfill.

AD is not a new technology having been used for many years in the treatment of sewage effluent. A large number, over 23 million, of very small scale, less than 10 m<sup>3</sup>, AD facilities have been used to generate biogas as a supplementary fuel for heating/cooking and fertiliser by



**Fig. 11.5** Flow diagram of AD process. (Courtesy of the National Non-Food Crop Centre, (NNFCC, 2010), see [www.biogas-info.co.uk](http://www.biogas-info.co.uk).)

rural farm households in China and India. The potential generation of renewable energy for heat and power on much larger scales has received increasing interest and over 4300 on-farm and centralised AD plans have been established in recent years in European countries, (Anderson report, 2008).

In addition to the usual biowaste shown in Fig. 11.5, plastics packaging materials are most likely to enter the AD feedstock streams with household organic waste or food waste. As with composting, bioplastic packaging materials require careful control prior to AD treatment. Some starch-based packaging digests fully in AD conditions. However, as (ligno)cellulosic materials are not digested in anaerobic conditions, woody biomass, pulp-based packaging and bio-composites with high plant fibre content should not enter the AD feedstock. Several biodegradable plastics also require oxygen to breakdown, and thus are not suitable in AD. This area is worthy of more detailed study and appropriate standards, certification and labelling systems must be in place before bioplastics are widely accepted into the AD feedstock.

### 11.5.3 Summary

Together with other conventional plastics, bioplastics can be combusted in well-managed incinerators for energy recovery. While the gross calorific values (GCVs) of these materials are somewhat lower than many convention plastics, they are increasingly produced from renewable resources and so contribute positively to the generation of renewable energy.

Recycling of post-consumer bioplastics remains a major challenge due to the relatively low volume, the diversity of their compositions and property deterioration due to biodegradation or

partial biodegradation in the waste stream. Bioplastics entering the plastic waste stream may also contaminate conventional plastic recyclates.

Post-use biodegradable bioplastics are most suitable for biological waste treatment through industrial and/or domestic composting and, potentially, in anaerobic digestion (AD) systems. They should, ideally, be separated at household level from non-biodegradable materials and collected with organic waste, including food waste. In doing so, bioplastics suitable for industrial composting should be clearly distinguished from those suitable for home composting by certification and labelling. This distinction needs to be communicated effectively to the wider public.

## **11.6 BIOPLASTICS – CHALLENGES FOR A GROWING MARKET**

Although bioplastics packaging presently represents relatively small niche markets, significant growth potential has been demonstrated over the past decade spurred on by the fast-rising market demand for low carbon products and packaging. This is linked to benefits assigned to the use of renewable (bio)resources, increasing public awareness of – and sensitivity to – the environmental impacts of packaging and associated legislation. Also, bioplastics are expected to become priced more as commodity materials when critical mass is achieved, driven by a combination of forces including performance and cost improvements. To date, the costs of bioplastics are generally higher than their traditional plastic counterparts and, so far, cost has been one of the major factors constraining more widespread adoption. However, market growth is expected to continue particularly as the general upward trend in the price of oil is likely to resume with global economic recovery impacting on the price of conventional plastics. Factors influencing the market growth of bioplastics also include the following:

- low capacity – producers are unable to meet commercial demands in some applications
- uncertain advantages from a carbon perspective when compared with fossil-based plastics that are being recycled
- long-established supply network and food production systems designed for petroleum-based plastics
- ethical issues relating to the use of intensive agricultural practices used for the growth of non-food crops
- genetically modified (GM) feedstock is a key issue with European consumers
- possible shift to thermal rather than organic recovery techniques
- capital investment and the cost of production of bioplastics remain prohibitive in some circumstances
- consumer understanding and perception is developing but demand for premium and ‘organic’ ranges could reduce in periods of economic recession

The challenges posed include the following:

- communication: Labelling, product identification and consumer perception
- separation of biodegradable bioplastics at source or, co-mingled disposal, collection and sorting
- demonstrating the advantages of bioplastics from a carbon perspective

## 11.7 CONCLUSION

In the short to medium term, bioplastics will need to establish niche roles in high value premium and 'organic' ranges, together with a clear utility and obvious post-use routes. Whether they become mainstream alternatives to the majority of other plastic products in the long term remains to be seen. In all likelihood, bioplastics will be used as complementary products to the more common and flexible materials available.

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