Introduction

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At the start of the third millennium the world population was approximately six billion, which is expected to rise to ten billion by the middle of the twenty-first century. The exponential increase in population increases the demand on food, energy, water, resources and chemicals, and effects a corresponding increase in environmental pollution and a depletion of finite resources (e.g. fossil fuels). Since the 1930s, research and development into synthetic chemical products has afforded a significant improvement in the quality of life and availability of products for consumption. Not least being synthetic polymers, specifically fibres, for apparel and furnishing applications. Wallace Carothers and DuPont developed the first synthetic polyamide, nylon, in 1935; Whinfield, Dickson, Birtwhistle and Ritchie advanced the early research of Carothers, creating the first polyester fibre called Terylene (based on polyethylene terephthalate) in 1941 manufactured by Imperial Chemical Industries; DuPont followed this up with the invention of Dacron in 1946. Other synthetic fibres were also developed, including polyurethane (Bayer, 1937), acrylic (DuPont, 1944), polypropylene and high density polyethylene (both Banks and Hogan, 1951).

The main problems with synthetic polymers are that they are non-degradable and non-renewable. Since their invention, the use of these synthetic fibres has increased oil consumption significantly, and this continues today; arguably, polyester now is the most used of all fibres, taking over from cotton. Oil and petroleum are non-renewable (non-sustainable) resources and at the current rate of consumption, these fossil fuels are only expected to last for another 50–60 years; the current petroleum consumption rate is estimated to be 100,000 times the natural generation rate.[1] The Energy Information Administration projects that world conventional oil production will peak somewhere between 2021 and 2112, depending on the annual production growth rate (0–3%) and resource estimates (2248–3896 billion barrels). A maximum production growth rate (3% per year) combined with a low resource estimate (2248 billion barrels) gives a peak production year of 2021. For the expected (mean–resource) USGS case (3003 billion barrels) the peak will be somewhere between 2030 and 2075. This means that the raw material for fibres will change.

An even more important problem with the use of fossil energy is the huge translocation of carbon from the ground into the atmosphere accompanied by emissions of sulphur and nitrogen oxides as well as all kinds of hydrocarbons and heavy metals. Fossil fuels are also the dominant global source of anthropogenic greenhouse gases (GHG), rising concentrations of which are widely understood to drive global warming;[2] a growing majority of the scientific community believes this will lead to an unstable and unpredictable climate. Global warming can lead to more frequent and more extreme weather events such as floods, droughts, heatwaves, wind-storms, ice-storms, hurricanes and cyclones. Other negative effects are an increase in air pollution; increase in water- and food-borne diseases; the arrival of diseases like malaria, dengue fever and yellow fever; an increased number of wildfires; the loss of land by sea level rising; the forced migrations of people, plants and animals that can result in a serious reduction in the number of species; drop in prosperity and even starvation. Even climate change sceptics have expressed support for increased efforts to better understand the issues. More cautious business leaders increasingly view fossil-fuel-related emissions and global climate change as a key risk parameter, with strong potential to adversely impact long-range business planning goals and objectives.

Of even more concern is the ability of polymeric fibres to remain unchanged in the environment as such polymers do not degrade very readily, which has exacerbated the already existing ecological and environmental problems of waste building; the volume in waste disposal and landfill is very high. Landfills are decreasing in number, making less space available to discard waste. In the last few years the Republic of Ireland declared that they no longer had any space for landfill, imposing large taxes on the use and disposal of polymers. Landfill space in the UK is decreasing and in the US alone, the number of landfills dropped from 8000 to 2314 between 1988 and 1998.[1] Many governments, in response, have established laws to encourage recycling;[3] some governments have enforced stricter 'take-back' rules requiring manufacturers to take back packaging and products at the end of their life.

Biodegradable fibres

A material is defined as 'biodegradable' if it is able to be broken down into simpler substances (elements and compounds) by naturally occurring decomposers – essentially, anything that can be ingested by an organism without causing that organism harm. It is also defined that it must be non-toxic and able to be decomposed in a relatively short period even on a human time scale.[4] Albertsson and Karlsson[5] defined the biodegradation of a polymeric material as 'an event which takes place through the action of enzymes and/or chemical decomposition associated with living organisms (bacteria, fungi, etc.) and their secretion products'. Biodegradable polymers can be classified[6] into three main categories:

1. Natural polysaccharides and biopolymers;
   - e.g. cellulose (Chapters 2, 4, 5 and 12), alginates (Chapter 3), wool, silk (Chapter 8), chitin (Chapter 12), soya bean protein (Chapter 13).
2. Synthetic polymers, particularly aliphatic polyesters;
   - e.g. poly(lactic acid) (Chapter 6), poly(ε-caprolactone) (Chapter 7).
3. Polyesters produced by microorganisms;
   - e.g. poly(hydroxyalkanoate)s (Chapter 7).

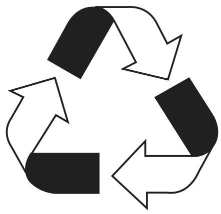
Biodegradable polymers and the fibres that can be produced from them are very attractive in offering a possible solution to waste-disposal problems, but these polymers tend to have a high price associated with them (Table I.1), hence applications of these polymers need to be found and taken on by manufacturers in order to consume sufficiently large quantities of these materials and drive the price down so that they can compete economically in the market.

Table I.1 Cost comparison of traditional and biodegradable polymers[7]

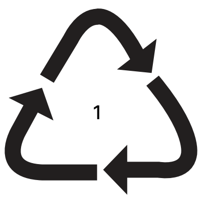
	Material	Average cost $/kg^{-1}
Traditional polymers	poly(propylene)	0.73
	high density poly(ethylene)	0.82
	poly(ethylene terephthalate)	1.15
Biodegradable polymers	poly(lactic acid)	3.30–6.60
	poly(hydroxyalkanoate)s	8.80–13.90

One of the most important factors in developing new biodegradable fibres that can compete economically is the public perception of what a biodegradable polymer is (or should be); demand for such products can be driven by the public and the media. 'Biodegradable' chemistry is generally perceived by the public to be good for the environment (although that statement alone could be seen as a paradox, the term 'chemistry' often being associated with 'dirty' processes). Some industries use this to their advantage, but what is purported to be 'green' is often not so in reality. The paper industry claimed that paper packaging should be used as an alternative to plastic because paper was 'biodegradable' and plastic was not, without having any scientific evidence to support these claims; in actual fact, in a well-engineered landfill environment neither paper nor plastic is biodegradable. Polymer producers developed the first generation of 'degradable' polymers in the 1980s, which consisted of polyolefin polymers with starch additives that would cause fragmentation of the composite into polymer pieces in a biodegradable environment. However, in 1990 a class-action lawsuit forced producers to remove the degradable claim. The US Federal Trade Commission has since created guidelines[8] for environmental marketing claims related to degradability, biodegradability, photodegradability, compostability and recyclability.

Recyclability is often confused by the public with biodegradability, the terms often being regarded as interchangeable. Obviously this is not the case, as recyclability refers to retrieving useful materials from waste via either mechanical or chemical breakdown. Recyclability of materials, however, is made publicly obvious through labelling techniques, in a way that biodegradability is not. The universal recycling symbol (Fig. I.1) means that the product is both recyclable and made of recycled materials. Manufacturers also use the symbol shown in Fig. I.2, developed by the Society of the Plastics Industry, to indicate the type of plastic used for the packaging; SPI code numbers range from 1 to 7.



I.1 Universal recycling symbol.



I.2 SPI symbol indicating source material for possible recycling: (1) poly(ethylene terephthalate); (2) high density poly(ethylene); (3) poly(vinyl chloride); (4) low density poly(ethylene); (5) poly(propylene); (6) poly(styrene); (7) other.

Recycling of polymers is on the increase and should be encouraged, but the process of both material and chemical recycling consumes a significant amount of energy, and, even if very efficient, could not cope with all polymers used. It is therefore very easy to understand the necessity for biodegradable polymeric fibres, which can be recycled by microorganisms. While in some ways biodegradable polymers and plastics recycling complement each other, there are concerns that widespread use of biodegradable polymers could be detrimental to recycling. The main concern is that the contamination of recycled polymers with biodegradable polymers could adversely affect the properties of recycled polymers. This is becoming a common concern for many newly developed polymers, biodegradable or not.

Disposal of biodegradable polymers is most appropriately carried out by the public through a composting mechanism, but this system requires an infrastructure, including collection systems and composting facilities. Germany has invested in compost infrastructure and more than 60% of all German households have been issued organic waste bins, whose contents are collected for composting. In 2001–2002 a successful pilot study was undertaken in Kassel, Germany to demonstrate the use of biodegradable packaging in connection with composting. The UK's first certification scheme for compostable packaging was launched by the Composting Association[9] in 2003. The scheme enables certification to the DIN V 54900, BS EN 13432 and ASTM D 6400 standards. In order to achieve certification materials, intermediates and additives are exhaustively tested in four different areas:

1. Chemical test (test for heavy metals).
2. Complete biodegradation.
3. Disintegration under compost conditions.
4. Ecological test (plant toxicity).

In addition to ensuring compostability, certification enables biologically degradable products to be identified by way of clear labelling. The compostability mark (Fig. I.3) serves to inform both waste consumers and disposers and the product must bear the inscription 'compostable' as well as the registration number assigned to it during the certification process.

I.3 Composting Association compostability mark.

Second-generation biodegradable polymers were commercially introduced around 1990 and are represented by the starch-based products offered by Novamont (Mater-Bi™) and by several families of polyesters. One of these polyesters, poly(ε-caprolactone), has been commercially available for more than twenty years; other biodegradable polyesters, which have been commercialized very recently, include poly(lactic acid) and other aliphatic polyesters. As a result of plant investments made by Cargill-Dow LLC (now NatureWorks LLC) and others, biodegradable polyesters should become more affordable very soon.

Just as with most other polymers, processability is an important parameter to commercial success for biodegradable polymers. For example, some grades of starch-based polymers can be processed on standard low-density poly(ethylene) extrusion equipment for making blown or cast film. Other grades can be extruded on existing equipment with minor die modifications to make loose-fill foam. Poly(lactic acid) can be processed in ways similar to processing of polyolefins and can be extruded with modifications. Performance properties are also important parameters to commercial success.

Sustainable fibres

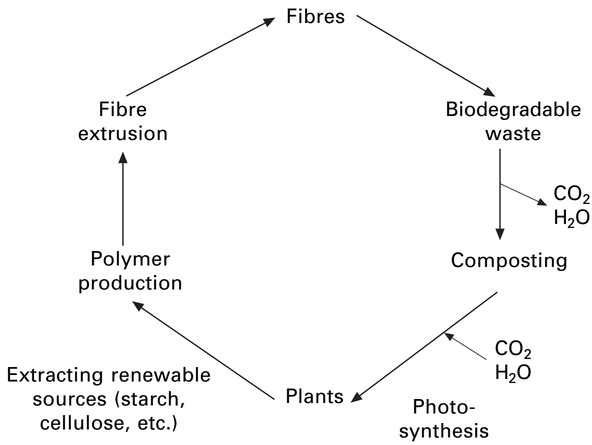
Arguably more important than biodegradability is the concept of 'sustainability'. By definition, sustainable living is taking no more potentially renewable resources from the natural world than can be replenished naturally and not overloading the capacity of the environment to cleanse and renew itself by natural processes.[4] Resources are sustainable if they cannot be used up; for instance, oil resources are gradually decreasing whereas the wind can be harnessed to produce energy continuously.

In terms of fibres, a sustainable fibre is one that ideally involves completely renewable chemicals[10] in its production and non-fossil-fuel-derived energy in the production processes. Renewable sources of polymeric materials offer an answer to maintaining sustainable development of economically and ecologically attractive technology. Vink[11] set out a number of factors that the ideal sustainable material should meet; it should:

- provide an equivalent function to the product it replaces, and perform as well as or better than the existing product;
- be available at a competitive or lower price;
- have a minimum environmental footprint for all the processes involved, including those up- and down-stream;
- be manufactured from renewable resources;
- use only ingredients that are safe to both humans and the environment;
- not have any negative impact on food supply or water.

These criteria reflect a strong empathy with the need to address the environmental aspects, and Vink demonstrated the positive benefits that poly(lactic acid) could achieve, both in terms of the manufacturing process, as well as the waste management disposal options at the end of a product's useful life.

The most important concept in terms of a truly 'green' material (in terms of this book, a fibre) is the concept of a fully green life cycle of the product. This embraces innovations in the development of materials from biopolymers and other renewable resources; the preservation of fossil-based raw materials; the reduction of fossil fuels used in energy production for fibre processing; the reduction in the volume of waste; compostability in the natural cycle; complete biological degradability; protection of the climate through the reduction of carbon dioxide released; and the reduction and elimination of hazards and environmentally detrimental chemistry at any point in the life cycle.[12] An idealised life cycle for a green fibre is given in Fig. I.4.



I.4 Life cycle of compostable, biodegradable fibres.

The key measurement tool to assess the environmental sustainability of a product is Life Cycle Assessment (LCA). Life cycle inventory analysis accounts for all inputs and outputs for a particular product and is typically practiced on a cradle-to-grave basis. A key benefit of LCA is the opportunity to benchmark performance against competitor products and processes in the marketplace, both to justify performance claims and to identify operations appropriate for performance improvement efforts.

Recent developments in biodegradable polymers

This book focuses on polymers and their fibres defined and detailed in Section 1.2. However, new biodegradable polymers are appearing frequently due to the demand and interest for this technology. Although these polymers have no specific fibre application at press they should be examined in future research and development to afford new biodegradable fibre opportunities and applications.[13]

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