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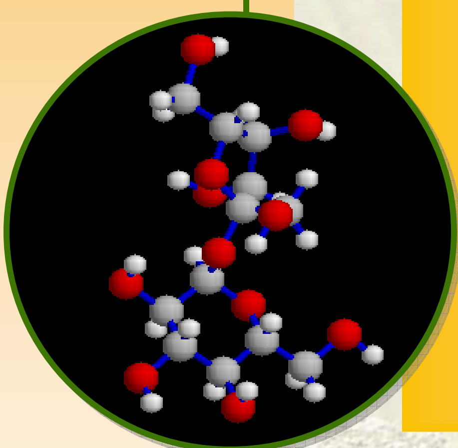

The Landscape for Biopolymers in Packaging

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Summary

Packaging is a potentially important market for biopolymers. The global packaging industry is worth about £300bn and the UK industry over £9bn. Every person in the UK consumes 160kg of packaging each year of which 25kg is plastic. The packaging industry is under considerable regulatory and public pressure, and there is the potential for significant substitution of petrochemical polymers with biopolymers and bio-derived polymers.

This report describes the context and background for the application of biopolymers in packaging. The landscape in which biopolymers must find their niche.

The report is intended to provide a robust platform or the development of a technology roadmap for the use of biopolymers in packaging.

There are three distinct types of packaging in the supply chain:

- Primary packaging - the packaging directly handled by the end user
- Secondary packaging - packaging that groups individual units together for transportation, display or for multipacks sold to the end user.
- Tertiary packaging - pallets, trays, cartons and wrap that are used to collate together the secondary packs for ease of transport and handling.

Primary packaging is the biggest waste problem. It is disposed of through the domestic waste channel, is dispersed, often contaminated and hard to recycle cost-effectively.

There are powerful trends and drivers in the packaging sector leading to an increase in packaging use and equally powerful forces pushing for a reduction in packaging use. The tension between these forces is driving the industry direction. Biopolymers must fit with these industry imperatives if they are to be successful.

- Drivers for more packaging:
  - Ageing population and smaller households
  - Greater wealth, more impulse consumption and a desire for convenience
  - Longer and more complex supply chains
  - Desire for fewer preservatives and more ‘natural’ food
  - Improvements in packaging functionality

- Drivers for less packaging:
  - Packaging and distribution costs
  - Environmental concerns and packaging legislation
  - Public pressure to reduce packaging volumes
  - Drive towards ‘sustainable’ packaging
  - Technical developments that reduce the amount of packaging required to do a job

These drivers are translated into a different wants and needs for each party in the supply chain. For biopolymers the important point is that biodegradability, compostability, renewable feedstocks and biopolymers do not feature in the lists of needs and wants.

Environmental performance and benefits are not enough to create a market for biopolymers. They must also be cost-effective, fit for purpose and ideally provide unique benefits in use.

The packaging industry is responding to these pressures with a number of initiatives. Biopolymers will need to demonstrate that they are adding value to these industry approaches.

- Many companies are developing sustainable packaging strategies focused on minimising packaging, reusing and recycling, and using renewable raw materials and renewable energy where possible.
- At the same time packaging is being designed using eco-design principles. Reducing the use of hazardous materials, minimising resource consumption, using recycled and renewable materials and designing for re-use and recycling. The goal is to reduce overall life-cycle impacts whilst maintaining or improving value for money.
- A very significant response is engineering packaging to be more weight and cost effective. As a result high performance packaging materials are increasingly composites rather than single polymers. Biopolymers will therefore be combined with petrochemical polymers with implications for composting and recycling.
- Re-use and recycling of secondary and tertiary packaging is increasing. Supermarkets are successfully recycling >80% of the plastic packaging collected in store.

Options for end of life disposal are important in deciding when and where biopolymers can add value. The waste hierarchy views waste avoidance and re-use as the best strategies. Recycling, incineration with energy recovery and disposal to landfill are considered progressively less attractive approaches. The major options available for recycling and disposal are:

- Mechanical recycling – reuse the plastic in a lower grade application. OK for manufacturing scrap and secondary and tertiary packaging as waste streams are clean. Difficult for primary packaging because of separation costs. Biopolymers will not be present in large volumes in the short term and just add complexity.
- Chemical recycling – break the plastic down into monomers or other chemical building blocks and re-use these to produce new polymer. Pilot plants have been built, but the commercial viability is uncertain. Will work with biopolymers.
- Composting – biological treatment of biodegradable waste. Ideal for biodegradable biopolymers. However, not all biopolymers are biodegradable and the need to separate plastics into types is a formidable obstacle.
- Incineration with energy recovery – widely used in Europe, and can handle both petrochemical and bio-derived polymers. Massive public opposition in the UK led by NGOs and local groups concerned about health risks.
- Landfill – the least favoured option. Particularly bad for biodegradable waste as anaerobic digestion releases methane a much more powerful greenhouse gas than CO_2.

Primary biopolymer packaging waste will be very difficult to handle. Separation costs make recycling difficult. Composting is only possible if the waste can be reliably separated from non-biodegradable waste. Further, biodegradable polymers are likely to be combined with non-biodegradable polymers in complex engineered systems.

Apart from certain niche applications, biodegradability will not be the feature of biopolymers that leads to reduced environmental impact. It will be the use of renewable raw materials to replace petrochemical feedstocks.

We need to develop incineration with energy recovery in a way that meets the objectives of public policy and the needs of public opinion. Failure to do so blocks an important route to completing the look for biopolymers and gaining the maximum economic benefit from petrochemical polymers.

There are four different types of technologies for producing polymers from biological systems:

- Direct production of a useful biopolymer as a natural part of the functioning of the biological system – eg cellulose and starch
- Modifying the metabolism of a living system to generate a useful biopolymer – eg polyhydroxyalkanoates
- Making monomers from bio-feedstocks that can be conventionally polymerised – eg polylactic acid
- Breaking down biomass into synthesis gas – a mixture of CO and H_2 that chemical plants can convert into building blocks for polymers.

This means that bio-derived materials will be used to feed two separate industries – the biopolymer industry and the conventional chemical industry. By creating bio-derived base chemicals and building blocks we can provide conventional polymers using renewable raw materials, as well as new materials that are genuine biopolymers.

The biopolymers that are commercially available today are:

- Cellulose fibres and films
- Thermoplastic starch and starch polymer blends
- Polylactic acid (PLA)

Excluding cellulose, capacity is expected to grow from 220 kT in 2003 to 760 kT – 1560 kT by 2010.

The next generation of materials will be seen in the timeframe from 2010 – 2020. Developments will include:

- Improved technical performance for starch opening up new applications and volume growth due to lower prices from improved processing
- PLA costs fall as industry drives down the learning curve. PLA may achieve price parity with petrochemical polymers by 2020. PLA made from lignocellulose feedstock will become commercially viable
- First generation of polyhydroxyalkanoates (PHA) will become commercially viable
- Other bio-monomers develop including 1,3-propanediol, 1,4-butanediol and succinic acid. Several new polymers wholly or partially constructed from bio-monomers emerge
- US reaches its target of 10% basic chemical building blocks arising from plant derived renewables by 2020.

The longer term, beyond 2020, is very difficult to predict. However, expected developments include:

- PLA becomes a fully mature commodity polymer selected for price/performance
- PHA breaks through to mainstream or fails
- Bacterial cellulose cost drops low enough to use for commodity applications
- A full range of bio-based monomers and building blocks develops. ‘Conventional’ polymers available made entirely from renewable feedstocks
- Oil production is in steep decline as we pass the Hubbert peak. Large scale conversion of plant biomass to bioethanol and chemical building blocks through pyrolysis and gasification.

Looking at the market drivers and needs, and the development of the technology, a number of unresolved issues, gaps in capability and opportunities can be identified.

In developing a plan for the successful exploitation of biopolymers in packaging these are likely to be some of the key considerations:

Issues

- The sustainability benefits of biopolymers arise from the fact that they are made from renewable raw materials, not that they are biodegradable
- Public opinion is in a fragile state. People are supportive of the concepts of recycling and biodegradability, but suspicious about the claims being made
- Labelling biopolymer packaging as compostable is a problem in the absence of the necessary separation and composting facilities
- ‘Biodegradable’ packaging made from petrochemicals increase confusion; in particular ‘oxo’-degradable plastics that do not meet compostability standards.
- Only about 7% of the world's oil is converted into plastics. The impact of biopolymers can be over-hyped.
- Complex ‘engineered’ packaging will combine biopolymers with conventional materials. How are the benefits to be communicated?
- When biopolymers meet the price and performance requirements of the packaging converters, volumes will climb very rapidly. Supply chains need to prepare for success.
- Weight based recycling targets focus attention on denser glass and paper, and away from plastic packaging
- Incineration with energy recovery should be a key part of managing packaging waste, yet it is scarcely discussed in the UK
- The European focus is on minimisation and recycling – not renewables.

Gaps

- We need drop-in substitutes for existing materials
- More grades of biopolymers are required with different functionalities to allow manufacturers to completely redesign the packaging
- Biopolymers are not yet addressing in the key supply chain
- We need to increase the range of applications where biopolymers can compete on price/performance
- Packaging is a high-volume application of plastics. We need manufacturers who can provide users with security of supply

- Biopolymers need to develop unique properties so that they can compete on a technical as well as an environmental basis
- We need reliable data on performance in use of biopolymers
- We need a clear consensus on life-cycle impact of biopolymers
- There is a need for a strategy for the use of plant biomass to match the US 2020 vision.

Opportunities

- the NNFCC could establish itself as an authoritative and independent source of information on the use of biopolymers in packaging
- Exploit interest in sustainable packaging with biopolymers at the right price and performance
- Over 40% of current packaging is manufactured from a renewable biopolymer, cellulose. We can learn from this example
- Develop the niche opportunities for biodegradable plastics first
- Develop applications knowledge for biopolymers
- Link small scale developers of biopolymer materials with large scale materials companies to create large production capacities.
- New barrier properties are needed in packaging materials. Identifying and optimise novel barrier properties in biopolymers
- Drive down the price/learning curve for biopolymers to open up new opportunities
- Create a non-GM PLA for applications in Europe.
- Improve the visual properties of starch based polymers
- Create complex three-dimensional shapes to replace the foam blocks used to protect shock sensitive products.
- Support the development of technologies for producing bio-monomers and syngas from UK sourced biomass.
- Exploit the rich source of feedstock for bio-monomers in UK wheat. We have excellent wheat agronomy and a substantial surplus.
- Use sustainable procurement initiatives to increase market uptake for products from renewable raw materials.
- Build biopolymers into eco-design thinking
- With biopolymers you gain the benefits of the renewable feedstock for all end of life disposal options apart from landfill. Communicate these benefits
- Communicate benefits of ‘partial’ biopolymers involving both bio- and petro-chemical components
- Support the development of a home composting standard and label for biopolymers.
- Ensure waste management technologies do not accidentally exclude biopolymers from consideration.

1. Introduction

1.1. Report Purpose

This report is part of an ongoing project to develop a technology roadmap for the application of biopolymers in the packaging industry.

The global packaging industry is worth about £300 billion, and the UK industry is worth over £9 billion.

Every person in the UK consumes 160 kg of packaging each year, of which 25 kg is plastic. This represents a large industry, a significant consumer of petrochemical feedstocks, and a major problem of waste management.

Biopolymers offer the possibility of reducing the reliance on petrochemical feedstocks, reducing energy consumption and greenhouse gas production, and offering alternative disposal routes at end of life.

However, with the exception of cellulose fibres (paper and board), biopolymers have a negligible market share in the packaging sector. To grow this share, we need to understand the market needs, the capabilities of current and future biopolymers, and the steps that need to be taken to exploit the available opportunities.

The report reviews:

- trends and drivers in the packaging industry
- identified market needs
- current activities in the packaging supply chain to address these needs
- existing and emerging biopolymer technologies
- suitability of these technologies to address market needs
- technology gaps and opportunities

The report presents the context and background for the application of biopolymers in packaging. The landscape in which biopolymers must find their niche.

The report is intended to assist the NNFCC in developing a deeper understanding of the emerging biopolymer packaging markets, and to provide a robust platform for the development of a technology roadmap for the use of biopolymers in UK packaging.

1.2. Report Scope

In this report biopolymers cover any industrially useful polymeric material produced by any available technology from renewable biological systems or biomass.

This report does not cover degradable or biodegradable polymers made exclusively from non-renewable raw materials.

Packaging includes everything from primary packaging, which is handled directly by the end user, to tertiary packaging used to assemble and protect goods in the distribution chain.

This report does not cover edible coatings made from biopolymers used in the food industry (1)

Although cellulose is clearly a biopolymer, the use of paper and board in packaging is only covered peripherally in this report. Paper and board are the most significant packaging materials in the UK both by volume and value. The paper and board packaging sectors are well established, have their own dynamic, and are not facing the same technology issues and gaps as other biopolymers.

Packaging is an interesting application for biopolymers for several reasons:

- packaging accounts for almost half of the world's production of plastics and therefore represents a high volume potential market
- society is demanding more packaging, and more sophisticated packaging, whilst being increasingly concerned about environmental impact
- packaging uses a very large range of materials, and so provides many different price/performance niches where biopolymers can find a market

1.3. Technology Roadmap Process

This report is intended to provide background and context to the development of a technology roadmap for the application of biopolymers in packaging.

Technology roadmapping is a widely used methodology for creating a conversation between current and future market needs, and available and developing technologies (2, 3).

A conventional roadmap describes the possible routes between two geographic locations. It sets out the alternatives and their implications. Once a route has been chosen, the specific steps required to reach the final destination are clear. If the change has to be made during the journey, either because the destination has changed, or because the facts on the ground at different to what was originally believed, it is not necessary to go back to the starting point. The roadmap enables you to link to alternative routes from whatever point you have reached.

A technology roadmap provides similar support to decision-making. It makes explicit the alternative routes to meeting a specific market need, and helps people to understand the cost, duration and difficulty of any developments required. A technology roadmap also provides a framework for discussion between different stakeholders, organisations and functions. It supports a collaborative decision-making process and promotes faster and more realistic decisions about priority and investment.

Unlike a geographic roadmap, a technology roadmap has a strong concept of time built into it. An identified market need may have to be satisfied by a specific point in time. Either to avoid losing market share to a competitor, or to meet a regulatory deadline. Available technologies will rarely meet the market need without additional development. The roadmap makes explicit the time taken from where we stand today with our current technologies to finally delivering the product or service to the market.

When starting a technology roadmap in project, there is an identified market, and some available technologies. The market is being affected by all sorts of external trends and drivers that create new or additional market needs. At the same time the science base is bubbling up all sorts of new technologies that might or might not be relevant to those market needs. The challenge is to link the market needs to the technologies (Figure 1.1)

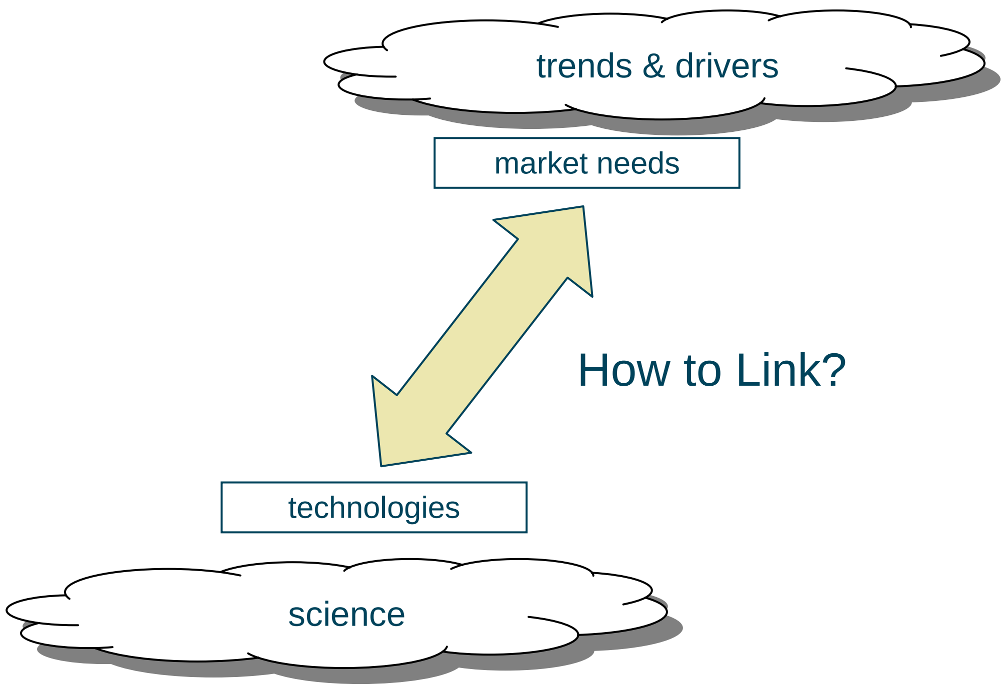


Figure 1.1 Technology roadmapping – linking market needs to technologies

To make the link between market needs and technologies, we identify the functionality is required to meet the market needs, the products which can provide that functionality, and the technologies which can deliver those products (figure 1.2).

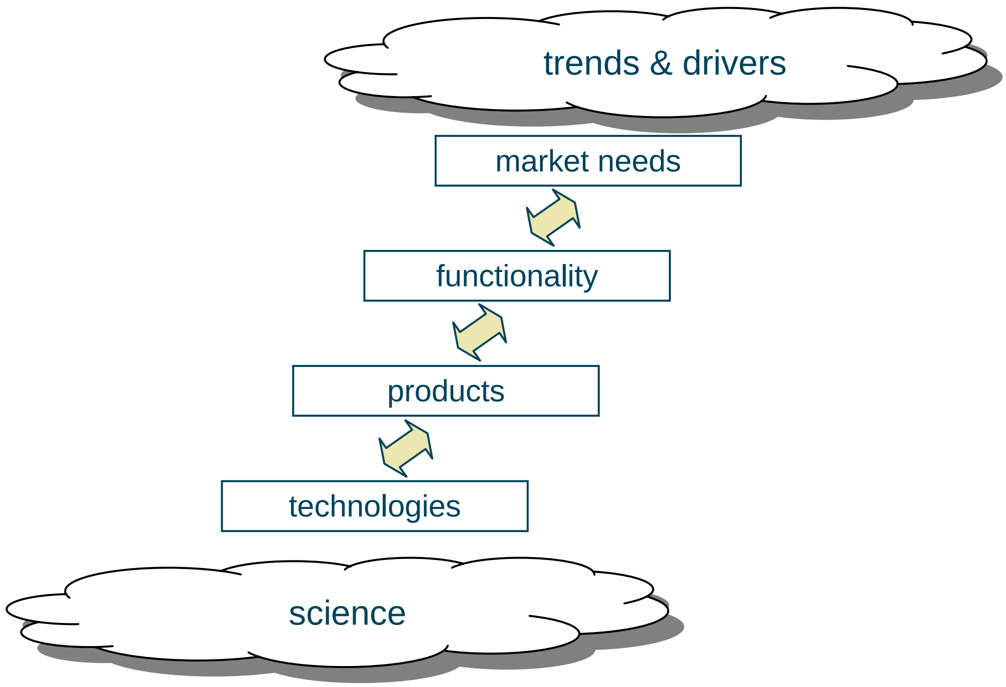


Figure 1.2 technology roadmapping – filling in the gaps

There are five key steps to developing a roadmap:

1. Understand the market context
    - what are the business and market drivers;
    - what are the functionality and performance requirements;
    - where are the uncertainties?

2. Identify product or service features that would meet the market needs
    - possible product concepts;
    - features and benefits;
    - where are the gaps?

3. Possible technology routes to features
    - what technologies are available;
    - what technologies are being developed;
    - where are the gaps and how could they be filled?

4. Map the links and dependencies
    - what must happen to meet the market needs?

5. Identify actions that would deliver to the market
    - specific programme plans
    - actions to fill gaps or manage uncertainty.

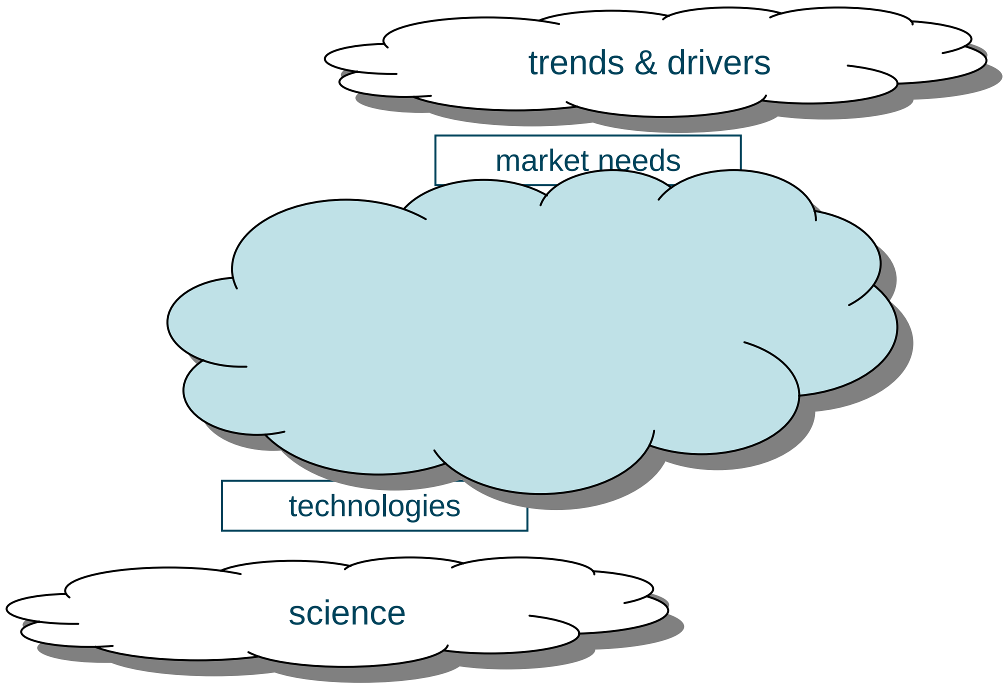


Figure 1.3 parts of the technology roadmap covered in this report

This report is not intended to be a completed the technology roadmap, only to provide context and background. It therefore focuses on the market, what are the trends and drivers and consequent market needs, and the technologies, what is available to us now, and what do we expect to be available in the future? The gap between market needs and technologies will be filled in at a later stage in the project (Figure 1.3).

1.4. Methodology

This report was compiled from two key sources of information. Published reports, presentations and public web sites (see section 10) provided the bulk of the background. This was supplemented by face-to-face and telephone interviews with a number of industry participants and stakeholders (see section 10.3 Interview Sources). We would like to acknowledge the contribution of these experts who generously gave their time to the creation of this report.

2. The Packaging Industry

Key points

- Packaging has several purposes including: product protection, communication, presentation, security, improving usability and providing for safe handling and use.
- Primary packaging is directly handled by the end user. Secondary and tertiary packaging is used for multi-packs and in transportation and handling. Primary packaging is the major waste problem.
- UK consumes about 9.5 million tonnes per annum – 161 kg per person.
- 70%-80% of packaging in the UK is in the consumer supply chain. About 1/3 for food and 2/3 for non-food applications.
- Just under half of packaging is paper and board, and about one third plastic.
- The packaging industry accounts for about half the polymers produced worldwide.
- In the packaging supply chain retailers have the strongest position, and converters the weakest. Converters produce packaging materials from bulk polymers and supply the packers who assemble the final product.

2.1. What is Packaging For?

Packaging has a number of important functions:

- **Protection**
  One of the primary functionalities of packaging is to contain and protect the product through the supply chain from manufacturing to the point of use by the consumer. It must protect the product from:
  - pressure
  - being dropped
  - shock and vibration
  - puncture
  - water or chemical damage
  - temperature and humidity variations

  In the specific case of pharmaceutical and food products protection may also required from:
  - microbial contamination
  - insect or other animal attack

- moisture and other gases or vapours
- other chemical or biological contamination
- light (where the product photo-degrades)

- **Communication**
  The packaging can provide a communication route to the consumer, providing information about the product, its use and disposal. It can also provide key information in the supply chain through bar codes, part numbers etc.

- **Presentation**
  Through the packaging design, the packaging plays an important role in presenting the product to the consumer. Packaging communicates the brand proposition, and is key to positioning the product for the consumer.

- **Security**
  Packaging can help provide product assurance to the consumer.
  - Tamper evident packaging is used for high-value or potentially dangerous products such as pharmaceuticals to demonstrate to the customer that they are receiving the product in its intended state.
  - Security holograms on software, CDs and DVDs demonstrate that the product is genuine.

  Consumers will typically reject any product where the packaging is visibly damaged; assuming that damage to the packaging could indicate damage or degradation to the product inside.

- **Usability**
  Packaging should enhance product usability by providing easy opening and easy dispensing.

  "If it takes more than 5 seconds to open a sandwich container, the consumer will decide that there is something wrong with the sandwich"

  In a survey *Yours* magazine has identified a trend they call "wrap rage" among the over 50's struggling with product packaging. 71% of the respondents said they had been physically injured trying to open food packaging.

  However, good design can also make the product easier to use, for example metered dose inhalers for drugs and 2-part epoxy syringes that measure out the correct ratios of resin to hardener.

- **Safe use and handling**
  Packaging can protect the user from hazardous materials, and promote safe handling. In industry solvents can be shipped in 'safe containers' that connect directly to the equipment where it is used to create a sealed system so workers are never exposed to the solvents and release to the environment is controlled.

Similarly the use of blister packs for drug tablets and capsules improve dispensing and reduce the occurrence of accidental overdoses.

2.2. Types of Packaging

Within the supply chain three different types of packaging are recognised:

- **Primary packaging**
  The packaging directly handled by the end user

- **Secondary packaging**
  Packaging that groups individual units together for transportation, display or for multipacks sold to the end user.

- **Tertiary packaging**
  Pallets, trays, cartons and wrap that are used to collate together the secondary packs for ease of transport and handling.

The bulk of domestic packaging waste is primary packaging. This must be disposed of through doorstep collections, and is the hardest to recycle. It is dispersed, contaminated and a mix of materials. The majority of secondary and tertiary packaging remains within the supply chain. Here we are dealing with large, clean, homogenous streams, and it is much easier to organise re-use and recycling. Significant progress has been made in managing this type of packaging waste (4).

2.3. UK Packaging Industry Facts

The packaging industry in the UK is a large, but slowly declining, sector of the economy. Over the period 1997 – 2002 the value of packaging manufactured in the UK declined from £9.4 bn to £8.7bn (5). Whilst sales of UK produced packaging have declined, imports have risen by more than 25% in the same period.

In 2001 the value of packaging produced in the UK was £9.2 bn; representing 3% of a world market of £280 bn and 11% of a European market of £77.6 bn (6). This represented 5% of the UK manufacturing economy, employing 93,000 people in 2500 businesses.
In 2000 the UK consumed approximately 9.5 million tonnes of packaging, equivalent to 161 kg per person (6).

About 70% - 80% of packaging in the UK is used in the consumer supply chain, with about 1/3 for food packing and 2/3 for non-food.

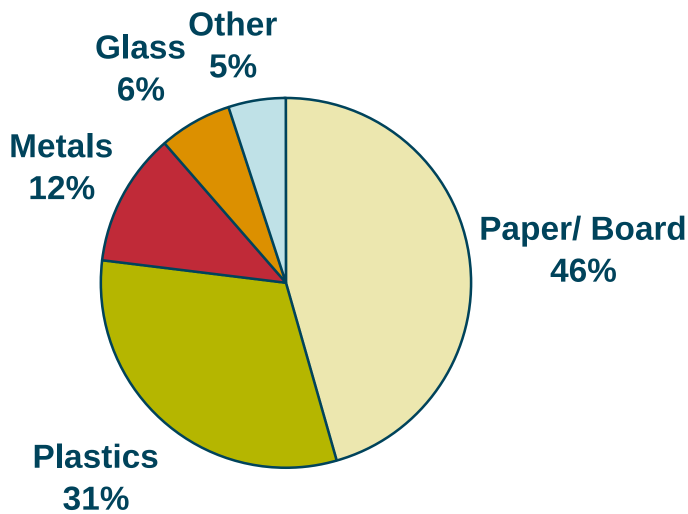


Figure 2.1 Distribution by value of materials in the UK packaging market

The split of the UK market by material is shown in Figure2.1. Just under half of packaging is paper and board with plastics now representing 31% by value of the market (6). The market share of paper/board and plastics are growing at the expense of other materials.

The paper and board packaging sector continues to be the most important because of ease of use, cost, light weight, strength, printability and ease of recycling. The sector is expected to continue to grow supported by increasing environmental pressures and costs.

Packaging is the largest single use for plastics, accounting for about half of polymers produced worldwide. The vast majority of plastics used in packaging are commodity thermoplastics, including polypropylene, polyethylene, PET, polystyrene and PVC. Other polymers such as polyamides and ethylene vinyl alcohol may be added to provide a barrier layer or other functionality.

The plastics sector has been growing at a slower rate than paper/board, partly due to the industry’s success in using less material to achieve the same packaging outcome. The sector will continue to grow both in value and volume and will continue to substitute for other materials.

Rigid plastics will continue to replace glass, metal and paper/board packaging. Flexible films will continue to replace cartonboard containers, and through new formats such as pouches will also replace metal and glass containers.

Plastics packaging is one of the most innovative sectors of the industry. The number of different polymers and composite materials that can be used, together with the ability to engineer packaging shapes and properties across a wide range, provides more opportunity for packaging innovation compared to other materials. Two examples are microwavable and oven stable trays for ready meals, and stand-up pouches for ambient stable food products.

2.4. The Plastic Packaging Supply Chain

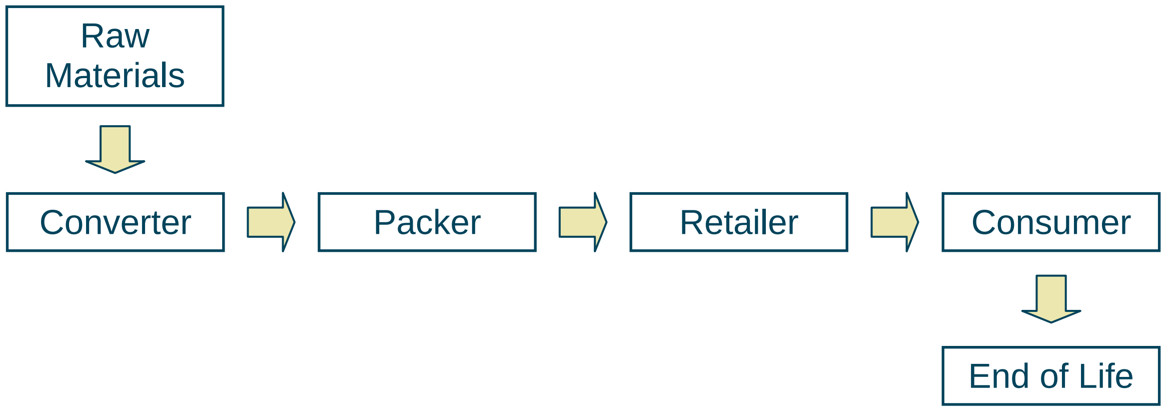


Figure 2.2 Basic packaging supply-chain

The basic packaging supply chain is illustrated in Figure 2.2. Depending on the application, there may be integration between different functions in the chain or further sub-division. The basic roles are:

- **Raw material supplier**
  The raw material supplier provides the polymers to be converted into the packaging. Biopolymer producers would be raw material suppliers to the packaging supply chain. Polymers may be provided in a variety of forms from simple polymer pellets, to complex laminated films.

- **Converter**
  The converter produces packaging materials ready to use by the packer. Converters produce a very wide range of products from single and multi-layer films for form-fill seal operations, to blow moulded bottles, injection moulded containers and closures and thermoformed tubs, pots and trays.

- **Packer**
  The packer assembles the final product in packed form ready for distribution or use. The packer may be the manufacturer of the product, or a separate contract packer.

- **Retailer**
  The retailer displays, sells, and increasingly delivers the product to the consumer.

- **Consumer**
  The consumer is the end user for the product. For the majority of packaging this will be an individual purchasing goods from a retail outlet.

- **End of life disposal**
  End of life disposal is handled by a complex of commercial organisations and local government bodies providing for reuse, recycling, composting and landfill as appropriate. The topic of routes for disposal at end of life is dealt with in detail in section 5.

A key player in the whole chain is the brand owner. The brand owner is deeply concerned with delivering a good consumer experience, and packaging plays a vital role in that experience. Brand owners may be both manufacturers and packers; assembling the final product form in an integrated operation. This was the traditional approach of the major fast moving consumer goods (FMCG) companies such as Kraft, Unilever, P&G, and Masterfoods etc. Increasingly both the product manufacture and the packing may be outsourced to contract providers. In the UK major retailers, such as the big supermarkets, are also brand owners. These distributors' own brands (DOB's) have always been both manufactured and packed by contact suppliers.

Within the supply chain in the UK the retailers hold the strongest position through their economic strength, their control of the route to the consumer and their role as brand owners.

In a recent study of the competitiveness of the UK packaging industry PIRA claims that the converters have the weakest position squeezed between the giant raw material suppliers, the retailers and the brand owners.

Each participant in the supply chain has their own set of pressures and needs that will be discussed in section 4.

2.4.1. Raw material production

The Raw Materials box in figure 2.2 can be expanded out to provide more detail on the supply chain from primary production to polymers as shown in figure 2.3

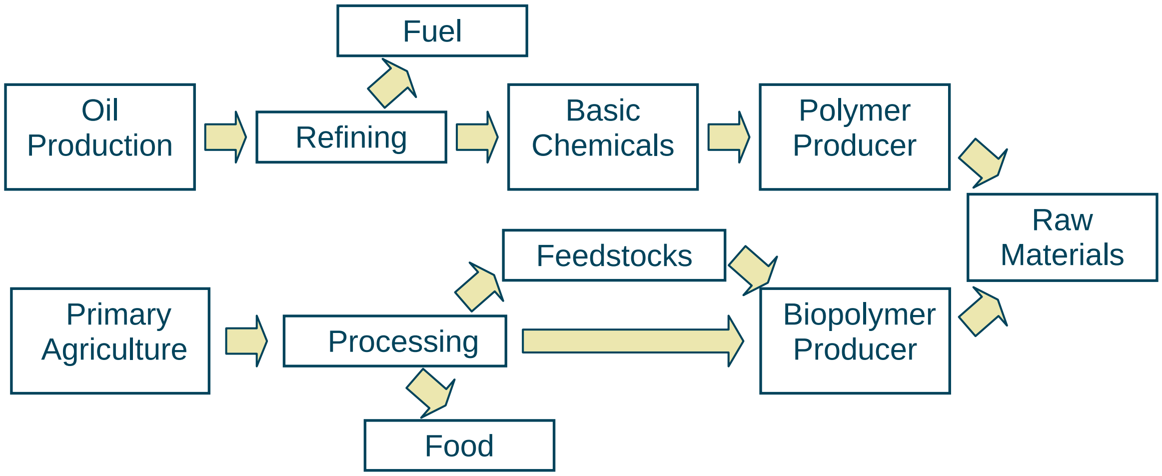


Figure 2.3 Production of raw materials

In the conventional petrochemical route extracted oil is first refined to produce fuel and a range of chemical feedstocks. This are then processed to further basic and platform chemicals including monomers for polymer production. Some companies are integrated, stretching all the way from oil production to polymers (eg BP). Others participate in only part of the supply chain.

The supply chain to biopolymers is less well developed, but there are obvious similarities. The output from primary agriculture is processed predominantly for human and animal nutrition. Co-products and spare food grade material can be processed directly into a biopolymer (eg starch), or can be converted into an industrial feedstock before production of the biopolymer. At present no producer is fully integrated from agriculture to biopolymer. However, Cargill is an example of a company that is integrated from processing agricultural products to production of biopolymers.

3. Trends and Drivers

Key points

- Packaging industry trends and drivers have been classified according to the STEEP model (Social, Technological, Economic, Environmental and Political).
- Some important drivers tend to increase the use of packaging; others to reduce it.
- Drivers for more packaging:
    - Ageing population and smaller households
    - Greater wealth, more impulse consumption and a desire for convenience
    - Longer and more complex supply chains
    - Desire for fewer preservatives and more ‘natural’ food
    - Improvements in packaging functionality
- Drivers for less packaging:
    - Packaging and distribution costs
    - Environmental concerns and packaging legislation
    - Public pressure to reduce packaging volumes
    - Drive towards ‘sustainable’ packaging
    - Technical developments that reduce the amount of packaging required to do a job

The trends and drivers for the packing market have been derived from public reports (6-12) and from the interviews with various stakeholders (see section 1.4 Methodology)

There are several different ways of classifying trends and drivers. In this report the ‘STEEP’ model has been used. STEEP stands for:

- **S**ocial
- **T**echnological
- **E**conomic
- **E**nvironmental
- **P**olitical

Social factors relate to the society and the social systems we live in. It includes demographics, lifestyle aspirations and choices, patterns of work and leisure, mobility and migration, and requirements for security, shelter and food.

Technological factors relate to the way that broad technological development changes the consumer and industrial environment. It includes changes in the way we can manipulate materials, delivery systems, packaging, transportation, communication, information systems and new business models.

Economic factors relate to the impact of the financial systems on a global, national, corporate and personal level. Access to finance, management of risk, and exploitation of differing cost structures across the globe.

Environmental factors relate to the physical environment in which we live. It includes resource consumption, waste generation and disposal, end of life disposal, environmental and health impacts and risks.

Political factors relate to the systems that govern us at the global, national and local levels. It includes policy, regulation and legislation, and the political processes that drive them.

For each of the five factors we have identified trends and drivers with the greatest impact on the manufacture and use of packaging.

3.1. Social

Demographics

Low birth rate and declining mortality are leading to an ageing population.

In the longer term there will be significant economic migration to Europe as birth-rates here continue to fall.

Ageing and wealthy consumers will demand products tailored to their specific needs; including smaller pack sizes, easier to open and close packaging, and improved labelling.

The average size of the household is falling as more people live alone. By 2002, nearly a third of UK households consisted of a single person.

At the same time as the population is ageing, children are becoming increasingly influential in retail purchase decisions.

High participation in the workforce increases the importance of convenience in all products.

Lifestyle

In the UK we work longer hours than the rest of the EU, and spend as much as possible of our free time on activities we enjoy. We are increasingly "time poor" and demand convenience and immediate gratification.

We spend less time cooking. Many people spend less than 15 minutes on preparing the main meal, and we consume more ready meals and spend more time and money eating out.

We resent time spent on "chores" and use many labour saving devices to preserve our time.

We live more of our lives on the move. Meals and sport and leisure activities are not a fixed part of a daily and weekly timetable, but are fitted in whenever suits us.

We are becoming more health-conscious, investing more time in sport and exercise, and seeking out healthier food.

We want fewer preservatives and other ‘chemicals’ in our food.

We like to be treated as individuals with specific tastes and needs. Mass customisation and the designer label are spreading throughout our lives.

We use our increasing wealth to pamper ourselves, investing in a wide range of special treats.

We are changing from a ‘needs’ based to a ‘wants’ based economy.

Public attitudes

The public has two views of packaging. It demands that the packaging be there to protect the product and provide the required consumer experience. At the same time, as soon as the packaging has been removed from the product it becomes a problem.

A 2004 survey by *Yours* magazine found that 97% of older consumers thought that manufacturers used too much packaging, 99% felt the packaging was getting harder to use, 71% had injured themselves trying to open packaging, and 70% had had to abandon a product because they could not get into it.

Currently, the public consider packaging to be the manufacturer’s or retailer’s problem not theirs. This affects the effort they are prepared to expend to support recycling.

The public also distinguish between "good" packaging and "bad" packaging. Good packaging can be easily recycled, and includes papers/board, glass and metal. Bad packaging cannot be easily recycled, creates a litter problem, and is largely plastic.

In the medium term, as public education continues and doorstep recycling schemes increase in sophistication we can expect a much greater public commitment to recycling.

The public have a very positive attitude to products that are biodegradable.

The public like the idea of sustainability and sustainable packaging, but are not clear what it means.

In the short term consumers will demand products that are more environmentally friendly whilst still delivering high performance. In the medium term they will demand ‘risk-free’ products.

In the medium term rejection of GM technology in the EU may limit availability of commercially viable biopolymers (for example Cargill PLA is not acceptable in some retail applications because of the GM Maize that is used).

In the long term public resistance to intensive agriculture and changes in the countryside may limit the availability of bio-derived feedstocks for the plastics industry.

Public health and safety concerns are currently very different in different countries. In the medium to long-term we can expect more common views to emerge at a regional and finally global level.

In the medium term public pressure will demand ‘responsible manufacturing’ that is not solely profit-driven.

Wealth

Rising wealth in the developed world has increased leisure and fuelled demand for non-essential consumer goods. This has driven demand for advanced and functional packaging to support the lifestyle.

In the short and medium term this will continue, sustaining the demand for novelty and improved functionality across all consumer goods.

In the long term, the whole world will aspire to Western standards of living, continuing to drive innovation.

Social cohesion

Concern for the stability of the rural economy increases in Europe as reform of the Common Agricultural Policy continues. Governments support attempts to diversify farmers away from food production.

3.2. Technological

Household technology

To save time and effort and to enrich our lives, we are investing in increasing amounts and sophistication of household technologies. Washing machines, fridges, freezers, microwaves, dishwashers have all changed the products we buy and how they are packed.

Our desire to make household chores invisible will lead to increased development of, and investment in, household automation. This will shift packaging towards more single use formats, and intelligent multiuse systems. Packaging will become increasingly able to exchange information with household appliances (think of modern inkjet cartridges).

Dematerialisation of some products will continue. Sales of legally downloaded music now exceed CD sales. DVDs will follow.

Communications technology will continue to decouple workers from physical workplaces. This will lead to supply systems that can deliver small quantities of whatever is needed to a precise place at a precise time.

In the longer term, rapid prototyping technology will evolve into custom manufacturing technology that can fabricate complex objects in the home. Small high value objects (including electronics) will be made at the point of use, and will not require shipping.

Supply chain

As manufacturing and agriculture globalise, supply chains are becoming longer and longer. Packaging will be required that can protect products through these long supply lines and minimise the cost.

"Efficient Consumer Response" initiatives (www.ecrnet.org) are transforming supply chains by making them more resource efficient, collaborative and information rich. Packaging will change to support ECR.

Increasing internet purchasing, home delivery and mass customisation will mean more of the supply chain consisting of individual packages targeted at a single consumer.

Supply chains will make increasing use of intelligent packaging starting with RFID tags and leading to packages that play an active role in heir delivery.

New materials	Packaging materials are likely to become more ‘engineered’. Packaging is already likely to be a composite of many different materials. This will increase with new laminates, composites and surface treatments evolving to add more functionality.
	There will also be a trend to use more recycled materials in manufacturing, and in the long term we may also ‘mine’ waste dumps for raw materials.
	Renewable raw materials will gradually emerge from their current niches to become mainstream feedstocks. In the short term this will be in high-value low-volume applications. In the longer term substitution will extend to feedstocks for the commodity sector.
Advanced packaging	Functional packaging will continue to develop to provide additional value in the supply chain and to the consumer.
	New types of packaging will be developed for the controlled atmospheres required to ship perishable products through a long supply chain.
	New surface treatments and printing technologies will allow more effective communication with packaging.
	There is an increasing demand for tamper-evident packaging.
	Security packaging will be able to assure the authenticity and history of the package. Starting with holograms and other security printing devices and leading to RFID tags and finally complete secure chips that can trace the package all the way back to original manufacture.
	In the longer term flexible and printable computer systems will enable much greater functionality in packaging and the development of intelligent packaging.
	Intelligent packaging will be able to interact directly with users. Possible uses range from advising customers on the right foodstuffs for their diet, or using a DNA chip to match products to customer’s genotype. Imagine IKEA style flat-pack furniture where the package advises you on assembly.
	The same developments will be important in delivering efficient supply chains. Every package a node on the network.

3.3. Economic

Globalisation	Globalisation means dramatically extended supply chains. Packaging will need to provide protection and ease of handling. Globalisation will also extend to packaging materials. Commodity materials will increasingly be sourced outside the EU as more manufacturing for the chemical and chemical using industries moves to more economically advantageous areas. In the long term, development of efficient manufacture on a small scale, and pressures to reduce the environmental impact of global transportation, could lead to a regeneration of manufacturing in the UK based on localised production.
Added Value	The boundary between pack and product will become increasingly blurred as manufacturers seek to add value. This will also address the consumers concerns about excess packaging. A tray for a single use product such as a ready meal is a problem because it is immediately disposed of. A shampoo bottle is less of problem is it fulfils an important role in dispensing. An inkjet cartridge has completely fused product and container. Brand owners will seek innovative added value packaging off all sorts to differentiate their products in the market. Innovative packaging will offer greater emotional kick, more convenience, better product experience and improved value for money.
Changing business models	Forced by legislation, accounting processes will change to internalise more of the total whole life costs of a product or service. In the medium to long term this will drive the adoption of greener products and processes.
Demands for 'responsible' manufacturing	Both industrial customers and consumers are demanding ever-higher standards from manufacturers. Already many high profile consumer goods manufacturers require that their suppliers comply with various national and international standards of environmental and sustainable performance (ISO 14000, Forest Stewardship, Marine Stewardship, Global Reporting Initiative, ILO standards on child-labour etc). In the medium term buyers will only work with suppliers with excellent green and sustainability records, and suppliers will only work with buyers with similarly high standards

3.4. Environmental

Climate change

Concern about climate change is growing. This will drive a growing interest in low energy and low carbon economies.

Industry will be pressed to reduce energy consumption in manufacturing and the supply chain.

In the long term the threat of global warming will be a powerful driver for the adoption of more sustainable models for consumption and the use of renewable raw materials. However, some scenarios for climate change lead to dramatically reduced agricultural productivity in the northern countries and this will affect the availability of alternative feedstocks for biopolymers.

Resource efficiency

Social and public policy drivers are already leading to a focus on the efficiency of resource use. We will need an improvement in eco-efficiency of at least factor-10 to sustain our society.

In the short term this will lead to demands for greater effects from less material. It will also lead to a continued focus on energy consumption in manufacture, use and disposal of products.

Over the medium to long term, non-renewable resources will gradually be replaced with renewable or recycled raw materials. We are currently “burning through the fossil record at 20 million years per year” (13).

In the longer term biological systems will become increasingly important, as sources of raw materials, manufacturing systems and products.

Current waste streams will become a valuable source of raw materials.

Water is a resource under particular stress around the world. Manufacturing process and products will make progressively lower demands on fresh, clean water.

Recycling

The need to convert society from a ‘use and dispose’ model to more closed systems will lead to more focus on recycling. The various EU end-of-life disposal directives are examples.

Packaging is a particular focus for recycling.

In the medium term methods for chemically recycling plastics will develop to complement the existing mechanical recycling methods.

Design for recycling will become normal. Industries will develop to manage recycling and fully exploit recycled materials.

Ultimately manufacturers will be forced to take responsibility for the entire life-cycle of their products.

.*Waste Disposal*

Drives to reduce material going into landfill will affect packaging materials and practice.

There will be continued pressure to develop biodegradable and compostable packaging materials.

Packaging manufacturers and users will aim for ‘zero to landfill’ in the medium term.

In the medium to long term, publicly acceptable methods for energy recovery from waste will develop.

Sustainability

Governments will use sustainable procurement initiatives to drive more recycling of packaging and packaging made from renewable raw materials.

Public opinion will increasingly support sustainability although there will continue to be lack of clarity about what sustainability is and implies.

Corporate sustainability reporting is becoming mainstream, and this trend will accelerate. Disclosure rules will force corporate attention on to the triple bottom line.

In the medium to long term there will be a drive for sustainable packaging within a sustainable society.

3.5. Political

Legislation

Concerned by the impact of packaging on waste and the environment the EU has identified packaging as a priority waste stream and piloted the concept of producer responsibility in the sector.

Public pressure also encourages politicians to act on visible waste – i.e. litter in public spaces.

Legislative pressure on packaging waste is expected to increase.

There are two main areas of legislation that impact on the packaging industry and the use of packaging:

- Environmental
- Health and safety

In the UK environmental legislation includes:

- Producer Responsibility Obligations
- Climate Change Levy
- Pollution Prevention and Control Regulations
- Aggregates Levy
- Landfill tax

Environmental legislation in process includes:

- REACH (chemicals)
- Integrated Product Policy

There is also an EU Thematic strategy on waste prevention and recycling. [For further details see ref 6 and http://europa.eu.int/comm/environment/index_en.htm]

These regulations all act to reinforce the waste hierarchy, encouraging industry to reduce packaging, reuse, recycle and only finally dispose as waste as a last resort.

Health and Safety Legislation includes Food Contact Legislation and Dangerous Goods Legislation.

These regulations provide barriers to new entrant materials and companies.

Globalisation of standards

Existing employment, environmental and health and safety legislation varies significantly from country to country. As a result production of many goods can move to a location with significant reduction in production costs.

In the short term this will lead to production moving to areas with a more favourable regulatory environment. WTO rules will then allow the products to be sold in the most attractive markets.

In the medium to long term, public demand around the world will lead to convergence of standards. The driver to move production to more favourable regulatory regimes will vanish.

The 'knowledge economy'

Current focus in the UK and the West generally on the 'knowledge economy' leads to acceptance of a declining manufacturing sector.

In the medium to long term, successful investment by the UK government in skills will allow industry to achieve the levels of innovation required to create a successful, sustainable economy with a radically smaller manufacturing component.

3.6. Balance of Drivers in the Short Term

In the short term there are forces driving greater use of packaging and forces driving less use of packaging. How the market evolves will depend on the balance between these forces (Figure 3.1).

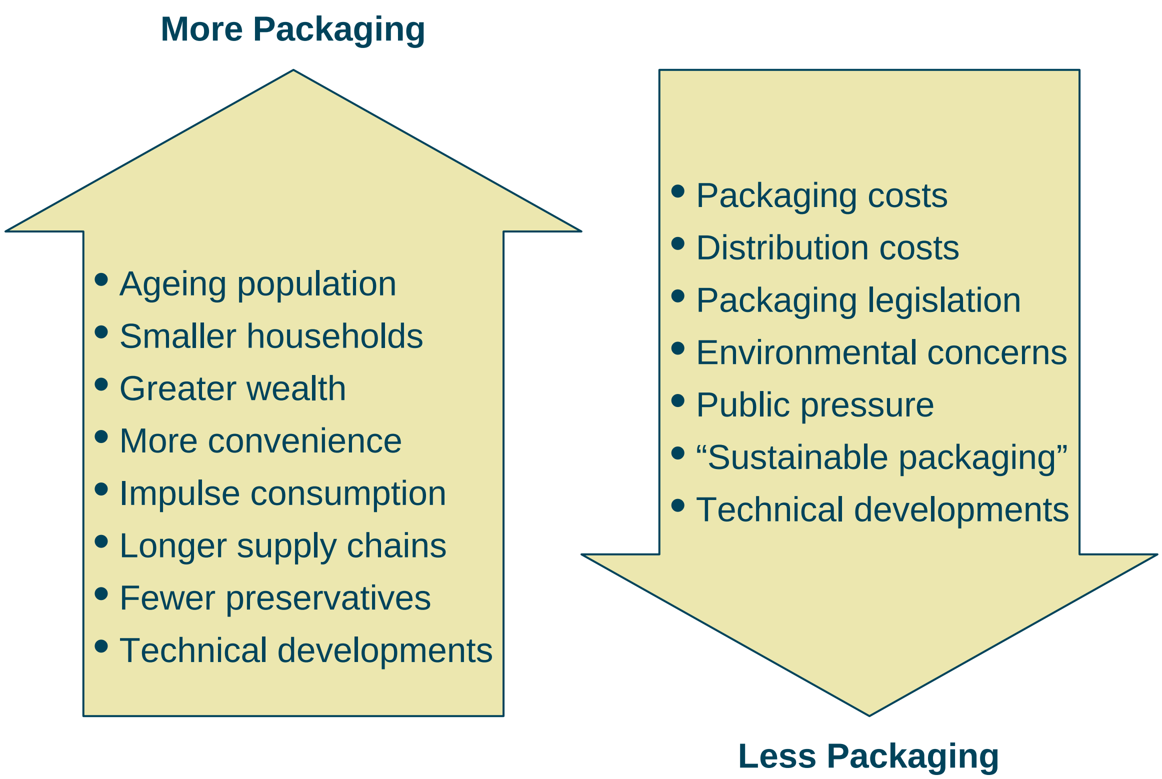


Figure 3.1 Balance of drivers for more or less packaging

4. Needs and Wants

Key points

- Each member of the supply chain has a different set of needs and wants.
- Biodegradability, compostability, renewable feedstocks and biopolymers do not feature in the lists of needs and wants.
- Environmental performance and benefits are not enough to create a market for biopolymers. They must also be cost-effective, fit for purpose and ideally provide unique benefits in use.

The drivers described in section 3 are expressed as needs and wants by the different participants in the packaging supply chain. The brand owner is placed between the retailer and the manufacturer/packer as the brand owner can be either, or can stand outside the supply chain (for example Microsoft in the case of the X-Box. All design, manufacturing and distribution are handled by third parties). Sections 4.2 and 4.4 refer to a retailer or packer who is not acting as a brand owner.

4.1. Consumer

- Packaging that ensures and assures quality, and safety of product
- Highly functional packaging
- Easy to open, close, use
- Packaging that makes life easy
- Safe
- Exotic perishable goods delivered fresh
- Packaging that is fun and engaging
- Recyclable, biodegradable and sustainable
- Packaging that vanishes immediately it is no longer needed
- Minimum packaging
- Packaging that avoids litter
- Packaging that does not damage the environment

4.2. Retailer

- Reduce in-store costs
- Optimise transit packaging (secondary and tertiary)
- Easy management of in-store waste
- Fit with home shopping services
- Support retailer brand positioning
- Reduce supply chain costs and losses
- Low cost compliance with regulation
- Lower weight
- Environmentally friendly (meeting cost and performance criteria)

4.3. Brand Owner

- Project the brand image
- Preserve brand values
- Differentiate brand
- Assure quality
- Anti-counterfeit packaging
- Tamper-proof, tamper evident packaging
- Support multiple distribution channels
- Add consumer value
- Reduce supply chain cost and losses
- Offer innovation
- Ease outsourcing
- Zero to landfill

4.4. Packer

- Lower weight
- Lower cost
- Fit for purpose
- High quality
- High strength
- Suitable barrier properties
- Compatibility with packing lines/manufacturing processes
- Differentiated package formats for customers
- Anti-counterfeit packaging
- Tamper-proof, tamper evident packaging
- Complies with regulation (eg food contact)

4.5. Converter

- Lower weight
- Lower cost
- Fit for purpose
- High quality
- High strength
- Suitable barrier properties

- Compatibility with packing lines/manufacturing processes
- Differentiated package formats for customers
- Ability to claim superior environmental performance

The interesting feature in these lists is that although there is considerable overlap of the wants and needs between the groups, few of them explicitly mention biodegradability, compostability, renewable raw materials or biopolymers.

In order to succeed, biopolymers must fulfil a broader range of requirements. Environmental performance and benefits are not on their own enough to create a market for biopolymers. Biopolymers must also be cost effective and fit for purpose, and ideally provide some unique benefits in use.

5. End of Life Disposal

Key points

- The average UK family buys 4,300 items a year weighing 2,800 kg and consuming 258 GJ in production, distribution and use.
- All packaging for these goods weighs 190 kg and consumes 7.1 GJ – less than 3% of the total energy.
- The UK ‘domestic dustbin’ contains 16 million tonnes including 0.9 million tonnes of plastic.
- Public opinion is that recycling and avoiding litter has the greatest impact on the environment. The reality this has the smallest impact. Using fewer goods and reducing energy consumption have the greatest impact.
- A simple message has been communicated to the general public – *“recycling good – landfill and incineration bad”*
- Options for recycling and disposal:
    - Mechanical recycling – reuse the plastic in a lower grade application. OK for manufacturing scrap and secondary and tertiary packaging as waste streams are clean. Difficult for primary packaging because of separation costs. Biopolymers just add complexity.
    - Chemical recycling – break the plastic down into monomers or other chemical building blocks and re-use. Commercial viability uncertain. Will work with biopolymers.
    - Composting – biological treatment of biodegradable waste. Ideal for biodegradable biopolymers. However, not all biopolymers are biodegradable and the need to separate plastics into types is a formidable obstacle.
    - Incineration with energy recovery – widely used in Europe, and can handle both petrochemical and bio-derived polymers. Massive public opposition in the UK led by NGOs and local groups concerned about health risks.
    - Landfill – the least favoured option. Particularly bad for biodegradable waste as anaerobic digestion releases methane a much more powerful greenhouse gas than CO_2.

End of life disposal is a key step in the life cycle of packaging. Decisions about which route is followed at the end of life has a large impact on the overall life-cycle impact of all plastics including biopolymers (25). In addition there is a great deal of focus on the topic of waste disposal, recycling and landfill in public policy at an EU, national and local level. It is important in thinking about the use of biopolymers in packaging that the fate of the packaging at end of life is fully considered. The development of the waste treatment industry will have as much influence on the use of biopolymers as any other factor.

5.1. Environmental Impact of Packaging

The basic information in this section is largely taken from the report “Towards Greener Households: products, packaging and energy” commissioned from Dr Jan Kooijman for INCPEN (14) together with other resources.

Packaging, and particularly plastic packaging, is a very visible problem. Although only a small part of the UK domestic waste stream by weight, its low density and long life brings it to the front of the public’s mind, and has encouraged politicians and regulators to make it apriority waste stream. However, we need to understand the true scale of the problem, not just the apparent scale.

The average family buys 4,300 items a year, split as shown in Figure 5.1

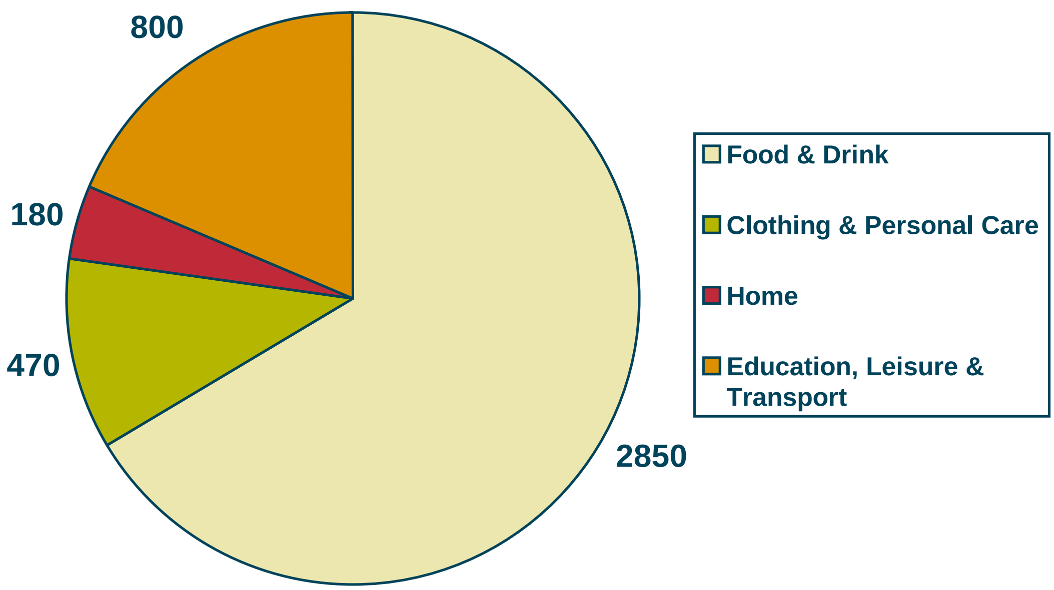


Figure 5.1 items purchased by an average family in a year.

These items weight 2,800 kg/year and cost 110 GJ/year to produce (Figure 5.2)

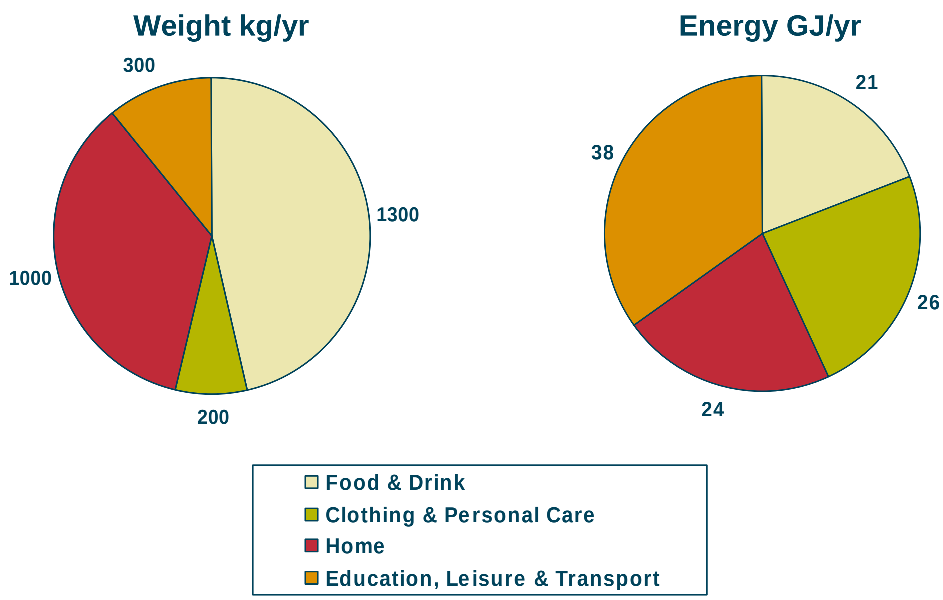


Figure 5.2 Weight and energy used to produce items purchased by an average family

These goods require packaging. The total weight of all primary, secondary and tertiary packaging is 190 kg/year and the energy consumption 7.1 GJ/year (Figure 5.3).

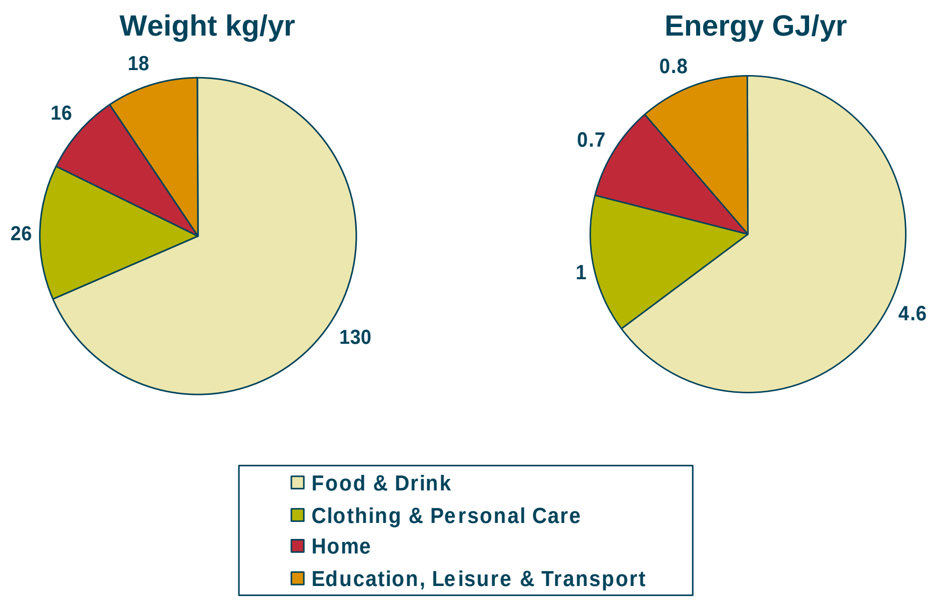


Figure 5.3 Weight and energy used in packaging items purchased by an average family

Figure 5.4 includes the energy used in distribution and retailing, and in use of the products at home.

Taking energy as a proxy for overall environmental impact, it is clear that the production and use of goods in the home dominates the total impact. Packaging has a relatively small overall impact.

For the same reason, the differences between packaging types are insignificant in the overall environmental impact of the product.

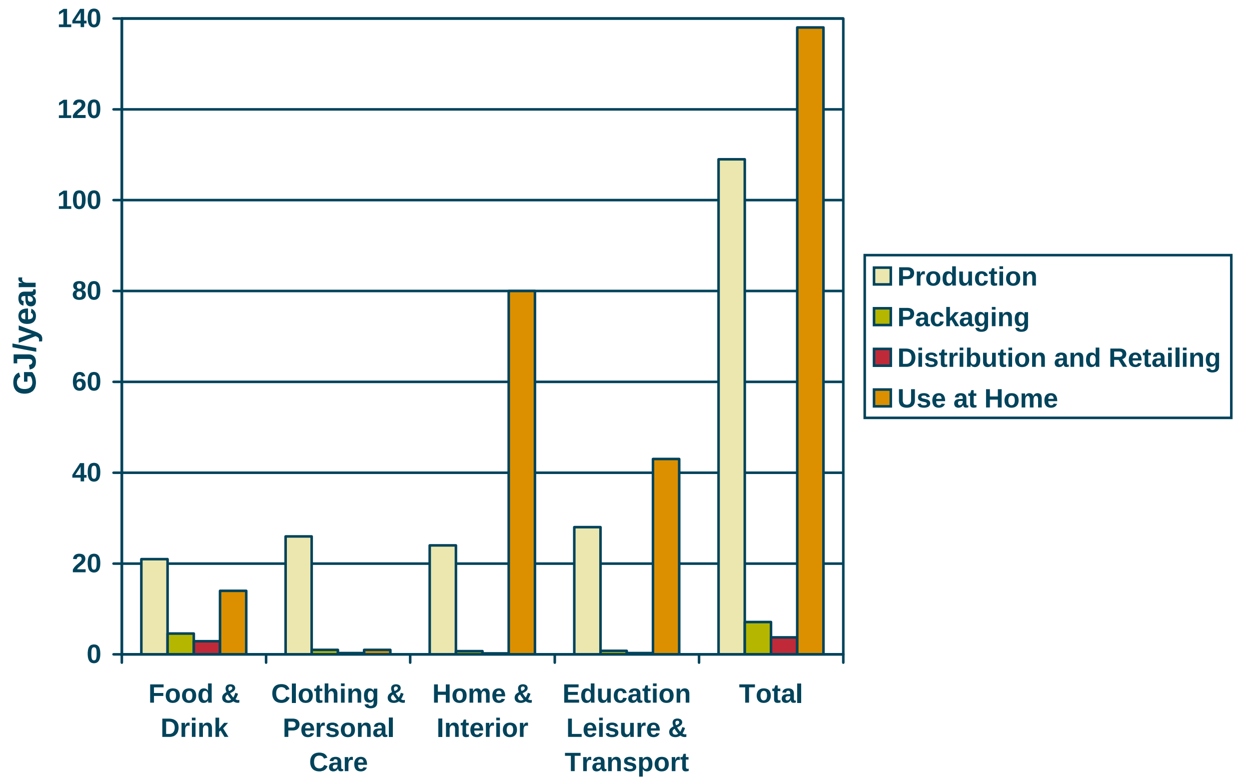


Figure 5.4 Energy consumption for average household purchases

The total UK ‘domestic dustbin’ is 16 million tonnes of waste. Of this a maximum of 4 is packaging, with plastics accounting for 0.9 million tonnes (Figure 5.5). Plastics accounts for about 20% of packaging, but protects about 53% of goods.

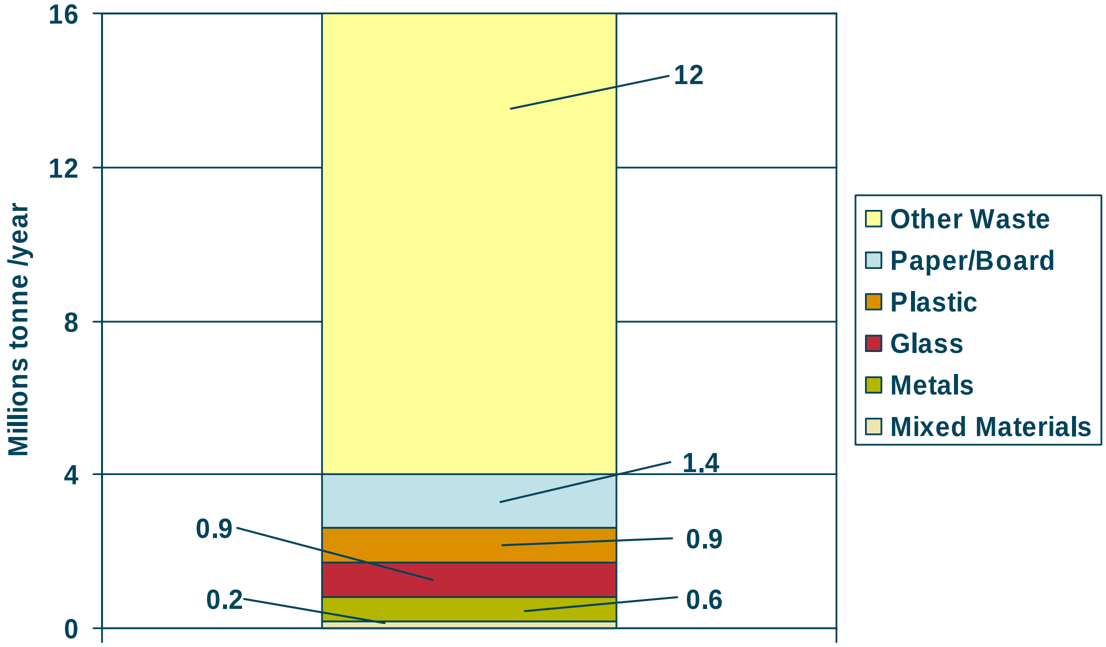


Figure 5.5 Contents of the national domestic dustbin

Plastic packaging is therefore a small part of the domestic waste stream, but delivers considerable value by protecting a significant proportion of all the goods we buy.

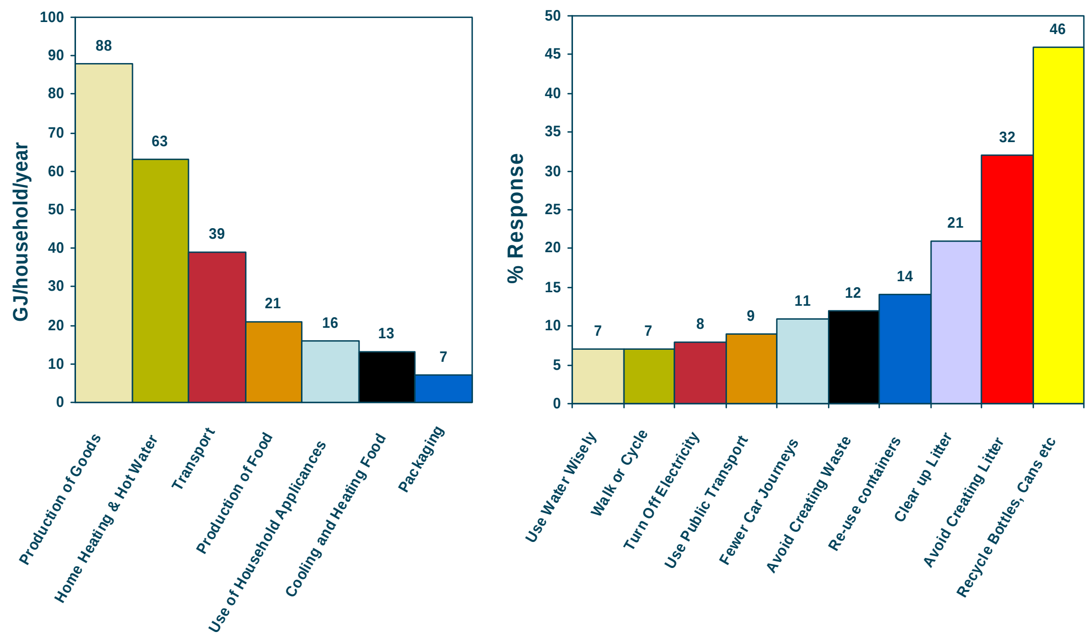


Figure 5.6 Comparing household environmental energy use with perceptions of what people can do to improve the environment

The way in which consumers perceive their environmental impact does not fit with reality. Figure 5.6 compares the average household's environmental impact in GJ per household per year, with the responses to the 1999 MORI General Public Survey that asked the question "what kinds of things can people do to help protect and improve the environment?" In terms of impact the public's view of what is important is wildly inaccurate.

5.2. The Waste Hierarchy

Thinking about how to handle waste in the UK has been dominated by the concept of the waste hierarchy. Figure 5.7 shows the hierarchy from the government's "Waste Not, Want Not" strategy document (15).

The idea behind the hierarchy is that the closer to the top of the pyramid you are, the more sustainable your waste management. So avoiding the generation of waste is the best option, and landfill the worst option.

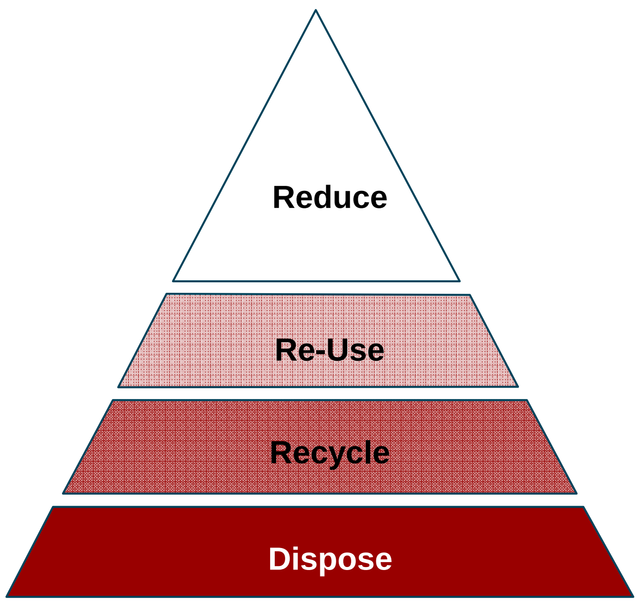


Figure 5.7 The waste hierarchy

The hierarchy can also be expanded to show some of the options in detail (Figure 5.8). The waste hierarchy is meant to be a tool for thinking and communicating, not to represent an absolute statement of environmental value. From the point of view of the overall impact of a product through its life-cycle, it is not always true that packaging waste should be minimised. Not if it increases losses in the supply chain. Similarly, whilst incineration or landfill are not the preferred options for the end of life disposal of packaging, there may be significant environmental impacts from transportation and energy input that increase the impact of recycling to the point where it is no longer viable.

Figure 5.8 Expanded waste hierarchy

However, there is a problem that some groups take the hierarchy as a prescription not as guidance to be matched to circumstances. To convince the general public it helps to have a simple message that can be boiled down to a few key statements; such as:

"Recycling good – landfill and incineration bad"

Whether or not this statement is true in any particular set of circumstances, it is easy to grasp and tends to trump the rather more complex scientific arguments. There is a real risk that these simplistic views will act against the adoption of biopolymers for packaging.

The main options in the recycle and dispose parts of the waste hierarchy will be compared in the sections 5.2.1 – 5.2.5 as they impact on the use of biopolymers.

5.2.1. Mechanical recycling

Mechanical recycling refers to processes involving the melting, shredding and/or granulation of waste plastic. This is the easiest recycling process. For successful recycling the waste plastic needs to be cleaned and sorted into type. It is most successful with homogenous waste streams such as manufacturing scrap, or tertiary and secondary packaging waste collected from stores.

It is hard to apply effectively to post consumer waste apart from some special cases such as PET bottles, which are easily identified and separated by the consumer for doorstep collection.

Existing landfill reduction targets are weight based. This discourages local authorities from making efforts to recycle low density, complex and dispersed plastic packaging (4). If the recycling of biopolymers requires any increase in complexity of doorstep collection, it is unlikely that local authorities will provide the necessary infrastructure.

At the moment most sorting for mechanical recycling is done manually, although a wide range of automatic methods are rapidly developing.

Once the polymer has been separated for recycling it can either be re-used for the same type of application, or downgraded to a less demanding application. An example of an outlet for low grade mixed recycled plastic is the production of recycled plastic lumber (RPL) for applications like garden furniture or decking.

High purity recycled plastic can be used in quality sensitive applications including food contact. In co-extrusion, a core of recycled plastic is faced on both sides with a thin layer of virgin plastic to provide a good visual appearance for the consumer and to protect the contents of the package from any contamination. 5% of plastic bottles in the UK are made this way (envirowise).

The problem for biopolymers is that they will represent another plastic that must be separated from the others in order to provide high quality recycled material. This will only be cost-effective if there is sufficient volume, and as market entrants, it is unlikely that there will be significant amounts of biopolymer in post consumer waste in the medium term.

Recyclers will resist additional plastics that increase the complexity of their operations. This may represent a further barrier to acceptance of biopolymers in the short term.

Manufacturing scrap and secondary and tertiary packaging waste from the supply chain are the best sources for clean, homogenous scrap in the short term.

Strengths	Weaknesses
▪ High purity recyclate ▪ Simple process ▪ Value of polymer synthesis preserved ▪ Outlets for downgraded product ▪ Techniques for using recycled plastic in demanding applications	▪ Hard to apply to post consumer waste ▪ Capital and labour intensive ▪ Requires clean, homogenous waste streams
Opportunities	**Threats**
▪ Recycle from manufacturing scrap ▪ Recycle from secondary and tertiary packaging in supply chain	▪ Biopolymers may be seen as a contaminant to more established materials

5.2.2. Chemical recycling

Chemical or feedstock recycling describes a range of plastic recovery techniques that break down polymers into their constituent monomers or other fragments. These can be used to create new polymer or diverted to other uses in the chemical industry (40).

A wide range of techniques are being actively pursued including oxidation, gasification, thermal degradation, catalytic cracking and hydrocracking. A wide range of reactor types have also been investigated including fixed and fluidised beds, screw feeds and thermal risers. None have yet proved commercially viable.

The big advantage of chemical recycling is that it could accept more variable feedstock composition and would be more tolerant to contaminants than mechanical recycling. However, the approach is capital intensive and requires a large unit to be cost-effective. This means a large waste stream which needs to be transported to the plant.

Pilot plants have been successfully demonstrated by BP at Grangemouth and BASF at Ludwigshafen among others. A key issue for economic viability is the reliable sourcing of sufficient waste of a suitable quality and cost. Work continues on developing chemical recycling of polymers in many universities and companies. However, no viable business model has yet been developed.

This could be a good option for recycling materials made from bio-derived monomers using conventional polymerisation as you could recover the monomer. However, it is unlikely to be attractive for biopolymers made directly in living systems.

Strengths	Weaknesses
▪ Produces a feedstock that can be used to create virgin polymer ▪ Relies on well established chemical engineering ▪ Will tolerate greater feedstock variability ▪ More tolerant to contaminants	▪ Capital intensive ▪ Needs a large plant to be cost effective ▪ Large scale chemical engineering needed – complex process. ▪ Never proven at full scale ▪ Only appropriate for some biopolymers
Opportunities	**Threats**
▪ Could handle post-consumer waste ▪ Could handle multi-material ‘engineered’ packaging ▪ Integrate biopolymers with general polymer waste stream	▪ Energy and transportation costs mean that process will never be viable ▪ Viable plants cannot handle enough feedstock variability to tackle post consumer waste

5.2.3. Composting

Composting is a potentially interesting route for disposal for biopolymers, as some commercially available biopolymers are intrinsically biodegradable, and many can be rendered biodegradable by appropriate design and treatment. In a composting process, the biopolymers returned to the biosphere as carbon dioxide and as carbon compounds retained in the compost for use as a soil improver or growing medium.

Information about composting can be gained from the website of the Composting Association (www.compost.org.uk).

There are four types of composting recognised:

- aerobic windrow composting - where the waste is composted in heaps in the open air
- in-vessel aerobic composting - the same as open composting but in a closed vessel
- anaerobic digestion - biological breakdown in the absence of oxygen
- mechanical biological treatment (MBT) -residual waste is mechanically separated, and the non-recoverable fraction sent to an enclosed in-vessel composting system. This is not to produce saleable compost, but reduces the weight and stabilises the residue. The final material can be safely landfilled.

The vast majority of composting carried out in the UK is done in the open through aerobic windrow composting (16).

80% of the waste processed by composting in the UK in 2002 was green waste (mostly garden and horticultural waste) (16). 6% was food wastes, 3% of mixed kitchen and garden waste and 11% a mixture of other organic materials including forestry waste, sewage sludge and paper/board. 86% of household waste was collected from civic amenity sites, with the remainder collected at the kerbside.

The strategy is to significantly increase waste disposal via composting; both through home composting and industrial composting. This will significantly reduce the amount of material going to landfill, and by providing a commercial product for horticulture and agriculture contributes to recycling targets.

However, there are a number of problems to be overcome. In order to increase the contribution of composting to waste management in the UK, it is necessary to significantly increase the proportion of household biodegradable waste which is treated. The Animal By-Products Order requires that any organic waste that may contain meat must be composted in an enclosed environment and reach defined temperatures for a defined minimum period of time. The resulting compost can also not be used on pasture land for grazing animals (17). At the moment, the UK has few composting operations of the required type.

A dramatic increase in composting also implies a dramatic increase in the amount of compost coming onto the market. The intention is that the compost should be seen as a high value material which can be used as an input to horticulture and agriculture. However, there is already some evidence that the market is out of balance, and it may not be possible to sell sufficient quantities of compost at the required price to make composting economically viable.

Biodegradable polymers can be mixed in with compostable waste, and an international standard exists to certify material as compostable (BS EN 13432:2000). Any material that meets this standard will be completely degraded at the elevated temperatures in a closed vessel composting system. It is not clear whether sufficiently rapid degradation would occur in open windrow composting.

The IBAW (www.ibaw.org) has developed a range of labels to certify that products and packaging meet the standards and are compostable. Compostable packaging would need to be separated from other packaging material and collected separately at the kerbside for processing. This requires education of the public and of the local authorities. In the early days, there may not be sufficient compost or packaging in the supply chain to make this a realistic option.

compostable compostable compostable

An extensive experiment was carried out at Kassel in Germany on the recovery and treatment of biodegradable polymer packaging (18). Biodegradable packaging was provided to all retailers in the experimental area, and this was clearly labelled as compostable for collection at the kerbside. In general the experiment showed that compostable packaging could be handled through the waste stream, but misclassification of waste by the consumer was a major problem. In particular, packaging coming from outside the experimental area caused problems. This suggests that very careful source separation would be required until people were familiar with the process of separating out compostable packaging, and the percentage of compostable packaging in the waste stream became high enough.

A further problem with compostable packaging which meets the standards is that it is unlikely to degrade quickly under home composting conditions. A number of retailers have already commented that they would be very reluctant to label packaging as compostable unless it could be dumped into the domestic compost heap and be eliminated in a reasonable period of time.

Manufacturers need to reduce the quantity of packaging whilst increasing the strength and performance is encouraging the production of more complex engineered packaging products. These are usually made out of a number of separate polymers, so that even if biodegradable polymers did become more widely used in packaging in their final form they will probably be mixed polymers and would not meet the composting standards.

There will be niche applications for compost or packaging from biopolymers. For example, compostable bin bags for holding green waste, or cutlery and food containers used in a closed environment such as a theme park or sports stadium.

Apart from niche applications of primary packaging, there will be opportunities to use secondary and tertiary packaging collected in the supply chain, but in this case recycling would be a better option.

Strengths	**Weaknesses**
▪ Dramatically reduces landfill ▪ Can cope with any biodegradable material ▪ Produces a commercial product ▪ Low energy input ▪ Returns carbon from biopolymers to the biosphere	▪ Requires careful separation of waste streams ▪ Cannot handle ‘engineered’ packaging that includes non-biodegradable polymers ▪ Treatment of kitchen waste requires new closed vessel composting
Opportunities	**Threats**
▪ Niches applications where composting can be guaranteed ▪ Major switch to compostable packaging	▪ Inadequate market for the compost ▪ Retailers won’t label materials that will not compost at home ▪ Misclassification problem raises costs

5.2.4. Incineration with energy recovery

Incineration with energy recovery is one of the most contentious parts of the waste hierarchy.

On the surface it is an extremely attractive option. For waste materials which cannot be cost effectively recycled, incineration offers the chance to recover the energy contained within them and to dramatically reduce the residual waste which must be disposed of to landfill or other outlets such as construction.

For petrochemical plastic packaging you can make the argument that the fossil carbon has already had one high value use, and is now being used again as a fuel. For about 90% of the world's oil production this would have been its main use anyway. The pathway from oil well to energy production via useful polymers increases the value which is extracted from this non-renewable resource. It is a more eco-efficient option than simply burning the oil directly.

For biopolymers, incineration with energy recovery is a good outcome. The carbon is returned to the atmosphere and the biosphere from which it was recently extracted, and energy is being produced by burning a renewable feedstock.

However, the public and many environmental campaigners are very suspicious of incineration. There has been a history of problems with toxic emissions from incineration plants that the industry and government have tried to down play. Although the design and operating standards for plants have improved dramatically, the public is not convinced. Environmental campaigners such as Greenpeace mount strong and successful campaigns against the whole idea of incineration (www.greenpeace.org.uk), and have commissioned a number of reports and white papers showing how we can avoid the need for incineration (17,19).

Incineration plants are usually not visually appealing, and have failed to contribute positively to the communities where they are located. As one interviewee commented:

"If you have a big chimney with stuff coming out of the top, it just doesn't look environmentally friendly"

The government and the industry have totally failed to counter the issues raised by the environmentalists and the concerns of the public. They have not made of the positive case about the safety of incineration, and its contribution to renewable energy supplies.

Despite the arguments of many that incineration with energy recovery must be a key part of our waste management strategy, there is a very good chance the public opinion will block this indefinitely.

In other European countries, including Germany, the case for incineration with energy recovery has been made successfully, and many plants are in operation today. The UK needs to learn from this success.

One potential route would be to make incineration of bio-based polymers eligible for Renewable Obligation Certificates (ROCs). This would make bio-based polymers an attractive source of energy. However, it would require separation of the bio-based polymers from petrochemical based, and has been noted this will be difficult to achieve in the short term.

Strengths	**Weaknesses**
▪ Handles all waste with a high carbon content ▪ Recovers energy from original fossil feedstock ▪ Carbon from biopolymers returned to the biosphere ▪ Efficient use of resources	▪ Capital intensive ▪ Pollution risk if poorly designed or operated ▪ Public suspicion fuelled by campaigns ▪ Swings in energy price could threaten viability
Opportunities	**Threats**
▪ Biopolymers contribute to renewable energy	▪ Public opinion blocks incineration

5.2.5. Landfill

Landfill is the least favoured option in the waste hierarchy. It is explicit government policy to reduce the quantity of waste which ultimately ends up in landfill.

At the moment, there is no prospect of completely eliminating landfill. There are waste streams that remain commercially uneconomic to recycle or reuse; although many campaigners hope that it will be possible ultimately to achieve zero waste systems that will leave nothing left to landfill (19).

Landfill is attractive because it is extremely simple and cheap. No separation, cleaning or treatment is necessary. However, there has been increasing focus on the amount of toxic materials present in domestic refuse and their implication for the environment and health if they leach out of the landfill site. Across Europe we are also running out of suitable sites for landfill, and it is clearly not a sustainable option in the long-term.

Landfill represents a particular problem for biodegradable materials, including some biopolymers. If anaerobic conditions develop in the landfill methane will be produced. Methane is a much more powerful greenhouse gas than CO_2.

New designs for landfill sites are being trialled that will allow complete recovery of the methane for energy production (20), but methanogenesis remains a problem.

<table>
<tr><td>Strengths
Simple
Low cost
Can handle almost all waste
No complex sorting or treatment</td><td>Weaknesses
Few suitable sites
Wastes resources
Produces methane
Toxic materials leach into surroundings.</td></tr>
<tr><td>Opportunities</td><td>Threats</td></tr>
</table>

6. Industry Actions

Key points

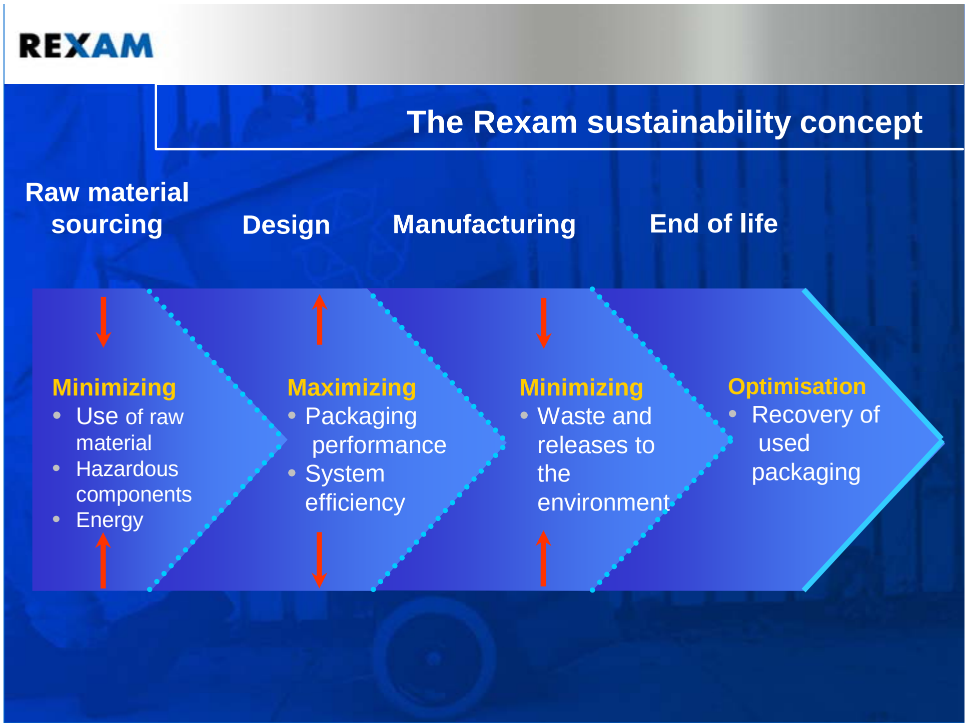
- Companies involved in the packaging supply chain are responding to public and regulatory pressure with a number of initiatives.
- Many companies are developing sustainable packaging strategies focused on minimising packaging, reusing and recycling, and using renewable raw materials and renewable energy where possible.
- Using eco-design principles – designing to reduce overall life-cycle impacts whilst maintaining or improving value for money.
- Engineering packaging to be more weight and cost effective. A result is that high performance packaging materials are increasingly composites rather than single polymers. Biopolymers will therefore be combined with petrochemical polymers with implications for composting and recycling.
- Re-use and recycling of secondary and tertiary packaging is increasing. Supermarkets are successfully recycling >80% of their plastic packaging.

Industry has responded to public concerns about packaging waste, and the pressures of regulation, with a range of initiatives. There is a lot of momentum behind these initiatives, particularly from the big players. They are setting the direction for the future of packaging, and biopolymers will need to fit in with these directions if they are to succeed.

6.1. Sustainable Packaging Strategies

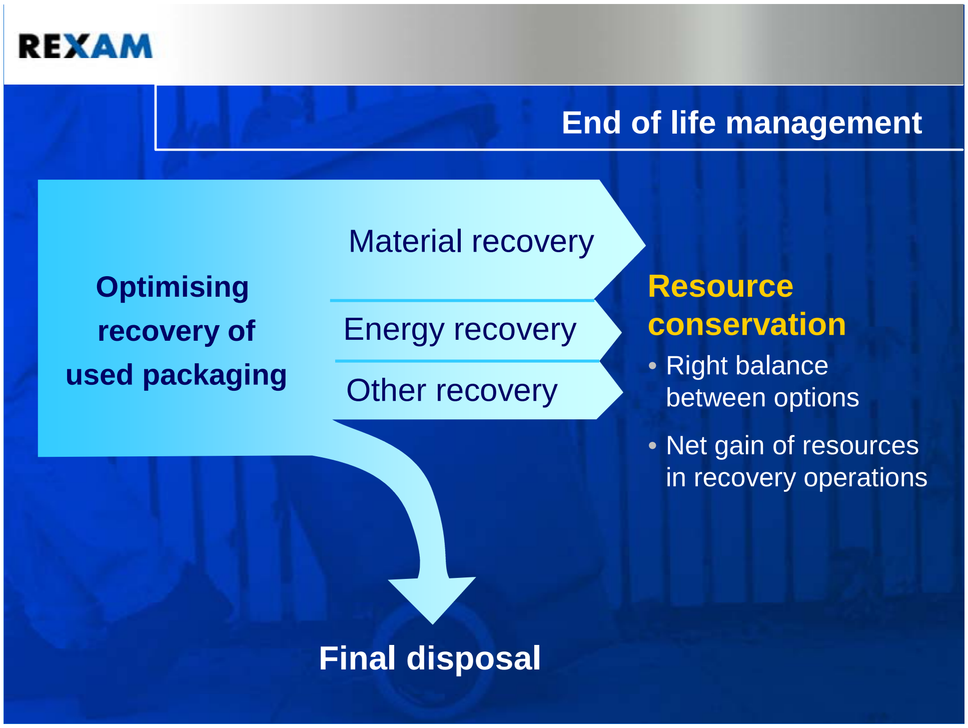
Many companies are developing sustainable packaging strategies. These are very important as they show the way in which major players in the packaging supply chain are responding to the pressure from society.

Rexam is on of the top five producers of consumer packaging with sales in 2003 of £3.2bn (21). The following are two slides from a presentation given by Anders Linde, Director of External Environmental Affairs at a conference “Packaging our Futures” in March 2004 (10).



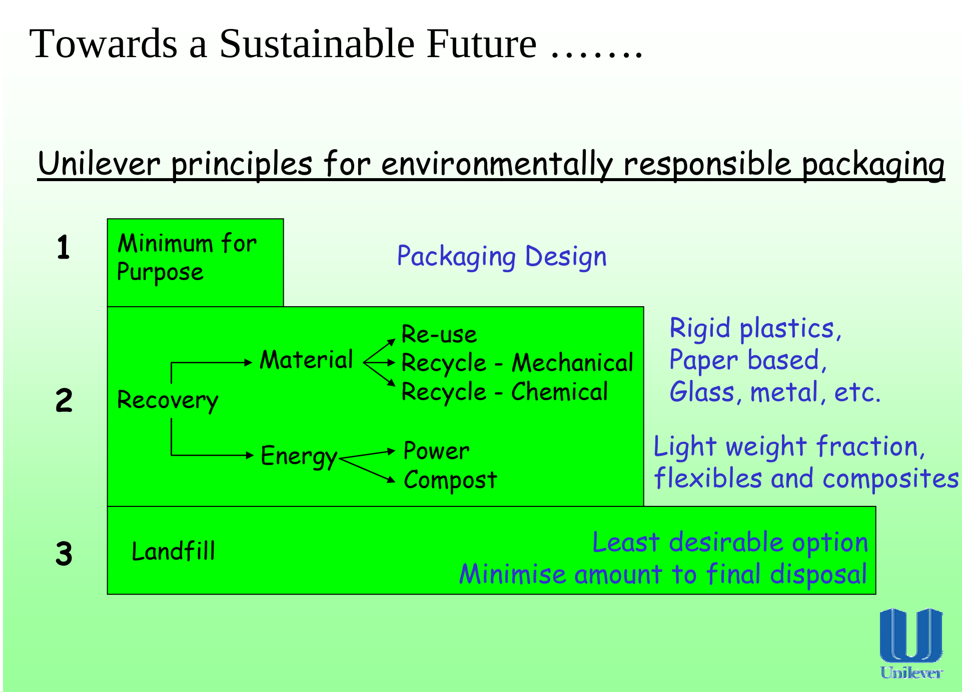
The first slide shows the Rexam sustainability concept. It maps closely to the waste hierarchy and focuses on minimising inputs and wastes, whilst maximising the efficiency and performance of the packaging and recovery of used packaging.

The second slide focuses on optimising the recovery of used packaging. Again it shows a hierarchy that closely matches the waste hierarchy with material recovery at the top and final disposal (landfill) at the bottom.



Although it does not explicitly mention biopolymers or renewable raw materials, it is clear that they would be compatible with this approach. However, they would need to deliver the required price/performance ratio.

At the same conference Harry Jongeneelen of Unilever gave a presentation on Unilever's vision of a sustainable packaging future (9)



This is focused around the same principles of minimising the amount of packaging needed to provide the required performance in the supply chain and for the consumer, recovering packaging at end of life according to the waste hierarchy, and disposing the absolute minimum to landfill.

The presentation also provides specific details of where Unilever is trying to go with plastic packaging (see box).

Unilever Sustainable Plastic Packaging Vision

Short to medium term

- Maximise use of recycled plastics by retaining material at highest level as long as possible
- Recover the energy when not commercially viable to recycle
- Promote bio-based plastics to begin to address the global warming issue
- Zero to landfill

Issues:

- Ability to change status quo severely limited
  - ~7% of oil is used for production of plastics
  - <50% of plastics are used for packaging

Conclusion:

- Rate limiting step will be adoption of "green energy"
  - In the interim energy recovery remains the only responsible alternative

Long term

- Move to Bio-based Plastics
- CO2 neutral
- Use of "green energy" to produce plastic packaging
- Zero to landfill

Issues:

- Appropriate use of agricultural land and water
- Still need to balance micro waste products

Three points are interesting in this plan:

- An explicit move to biopolymers
- A focus on the importance of green energy in the total mix
- A goal of zero to landfill

Other companies have similar strategies (eg Boots http://www.boots-plc.com//environment/news/)

6.2. Eco-design

A second key theme in company responses to packaging issues is the concept of eco-design (22, 23). This is defined as:

> "the incorporation of environmental considerations into product and packaging design so as to reduce overall life-cycle impacts whilst maintaining or improving value for money"
>
> (22)

A recent publication from the government programme Envirowise provides guidance on eco-design of packaging.

The key ideas are:

- Reduce the use of hazardous materials
  - heavy metals
  - solvents in inks
  - coatings and adhesives
  - paper bleaching chemicals
- Design for resource minimisation
  - reducing production losses
  - eliminating packaging
  - reducing void space and fillers
  - lightweighting and downsizing
  - reducing energy use
  - improving transportation efficiency
- Designing for renewable and recycled materials
- Design for re-use
  - different types of re-use
  - durability and weight
  - use and handling
  - cleaning and refurbishment
- Designing for recycle and composting
  - use single materials and compatible polymers
  - minimise contamination
  - make contamination easier to remove
  - improve biodegradability
- Design for final disposal

Although mention is made of the use of renewable materials, limited advice is given on what is available or how it should be specified. More focus is given to how to include recycled materials. Similarly the section on improving biodegradability mentions BS EN 13432:2000, but only gives paper and board as an example. Biopolymers are mentioned on one page of a 70 page document. Much of the focus is on designing for resource minimisation.

This is consistent with the focus reported by packaging converters, packers and retailers/brand owners. Reduction of the amount of packaging (particularly primary packaging) carries high value in the waste hierarchy. In addition it saves costs in materials and transport, and is the response by the industry most likely to provide an immediate business return. This ‘lightweighting’ or ‘downgauging’ of packaging leads directly to the next industry action which is improving packaging effectiveness.

6.3. Improving Packaging Effectiveness

The packaging supply chain is being pulled in two directions. Waste hierarchy thinking requires minimisation of packaging, whereas the extending of the supply chain requires more protection for the product.

This has led to increasingly sophisticated ‘engineered’ packaging to provide the required, strength and performance for the packaging at lower weight per kg of product.

This is important because product losses in the supply chain also bring environmental impacts. A study by Erlov *et al* in 2000 (24) demonstrated that for a given material with given properties, there is an optimum weight and design of packaging that gives adequate performance with lowest weight. Both above and below this optimum packaging weight, environmental impacts increase. So it is vital to provide sufficient protection.

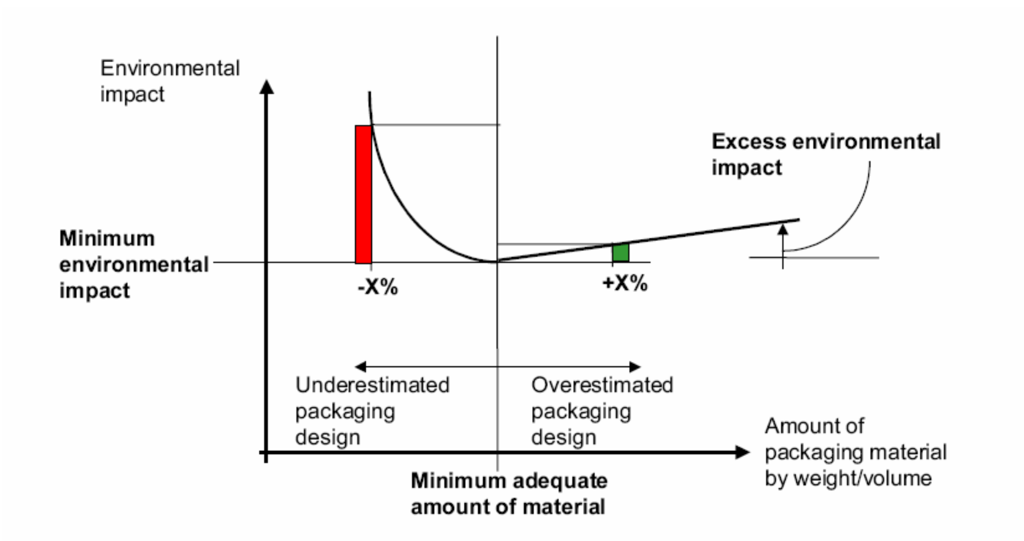


Figure 6.1 Optimum packaging weight (from 24)

In balancing these conflicting needs, a great deal of innovation has occurred over the years both in design of packaging and materials. A practical outcome of this is that for many types of consumer packaging single materials are no longer used for packaging. Multiple materials are used to provide the protection, minimum weight and consumer satisfaction. Films used for food packaging may consist of four different layers. The film may be used in a ready meal to close a tray made of another polymer. Cardboard drinks cartons have an inner layer of polyethylene film to protect ensure low moisture permeability and to allow high-speed through-liquid sealing. If long-life liquid products are packed they have an additional layer of aluminium foil, and to provide a better user experience the package may have a complex closure and pouring spout. The same processes are found in all kinds of consumer packaging.

As a result, post consumer packaging waste is likely to be a complex mixture of polymers. Low density and very difficult to recycle.

Biopolymers will find themselves operating in this market. There will be niches where single biopolymers can be used, but if they are used in mainstream packaging, they are likely to find themselves in combination with other polymers. For the foreseeable future this means petrochemical polymers. Depending on the preferred routes for end-of life disposal that emerge in the UK this will make biopolymers more or less attractive.

6.4. Re-use and Recycling of Secondary and Tertiary Packaging

The key problem in the management of packaging waste is primary packaging as this must be collected from the consumer.

Many companies have therefore focused attention on secondary and tertiary packaging where they have more control.

Tertiary packaging is increasingly designed for re-use. All the major supermarkets are using re-usable crates as much as possible. Stronger than conventional packaging the extra weight is repaid by the high number of return trips they can make. Much fresh produce is not only transported in plastic crates, it is also displayed in the supermarket in the same crates.

The increase in internet shopping and home deliveries from supermarkets increases the use of re-usable crates. As Europe's largest on-line retailer, Tesco pays great attention to the opportunities for re-usable crates.

It is not only in food. Marks and Spencers have re-used plastic clothes hangers for many years, and high-street cleaners have adopted the same trend. Xerox has increased the strength of the packaging for its copiers to allow it to be used many times. Since Xerox install and maintain their office sized copiers, they can ensure the packaging is properly reused.

Where the tertiary packaging is not directly re-usable (for example where deliveries are made to smaller stores and returning the packaging is difficult), stores find it easy to collect the waste packaging for recycling. It comes in a small number of grades, is a clean waste stream and is available in relatively large volumes.

Secondary packaging retained at the store can also be easily recycled. In 2003 Tesco recycled 79.8% (186kT) of its cardboard waste and 85.4% of its plastic (15kT) (4).

7. Life Cycle Analysis of Biopolymers

Key points

- Despite many LCA studies there is no consensus view on the relative impact of biopolymers compared to petrochemical polymers.
- The view that biopolymers ‘must’ have a lower impact is simplistic.
- Evidence available suggests that biopolymers have significant energy and greenhouse gas savings compared to benchmark commodity petrochemical polymers. However, the disposal route has a major impact on whether these savings are realised. Any conversion of carbon to methane in composting or landfill reduces the savings.

A large number of LCA studies have been carried out on biopolymers. Many have compared biopolymers with conventional polymers. However, because of differences in procedure, intention and boundary assumptions, there is no consensus view of how biopolymers compare across their lifecycle with petrochemical polymers.

There is a tendency to assume that biopolymers ‘must’ have a better environmental profile than petrochemical based polymers, but this is not necessarily true. The energy and fuel inputs to agriculture, and the relatively dispersed and low density nature of agricultural feedstocks, must be taken into account. Only a full life-cycle analysis can identify and quantify whether the potential benefits are realised in a practical supply chain.

Murphy and Bartle (25) recently conducted a meta-study of over 100 papers on the LCA of biopolymers. They used statistical methods to aggregate the results from the different studies and to generate a consensus view of the key outcomes. They concluded:

- On a cradle to gate basis (ie the polymer manufacturing process) biopolymers showed significant energy and greenhouse gas savings compared to LDPE or LLDPE.

Biopolymer	Energy savings (MJ/kg)	GHG savings kgCO_2 eq/kg polymer
Thermoplastic starch (TPS)	51	3.7
TPS + 60% polycaprolactone	24	1.2
Polylactic acid (PLA)	19	1.0

- The route for end of life disposal plays a large role in whether the benefits of the renewable raw material are captured across the lifecycle. Composting with full conversion of the carbon to CO_2 provides the best results. As methane is a much stronger greenhouse gas than CO_2 (28-33 times stronger), any conversion of carbon to methane loses some of the cradle to gate benefits. Methane generation can occur in poorly maintained composting systems or in landfill.

- More LCA data on biopolymers in different end of life scenarios is required.

Despite the many studies which have been carried out we are not able today to evaluate the environmental impact across the lifecycle of the practical choices we make about selection of materials and method of management.

In a contentious area where people are looking for good reasons to switch to biopolymers it will continue to be a weakness that we cannot substantiate the claims being made about the environmental benefits with reliable scientific data.

8. Biopolymer Technologies

Key points

- There are four routes to polymers from biological systems:
  - Direct production of biopolymer – eg cellulose and starch
  - Controlling plant metabolism – eg polyhydroxyalkanoates
  - Monomers from plants – eg lactic acid or 1,3-propanediol
  - Thermally break down biomass into synthesis gas ($CO + H_2$) and synthesis polymers conventionally.
- Two different industries will develop; production of biopolymers, and the production of feedstocks for the conventional chemical industry using renewable raw materials.
- Commercially available biopolymers:
  - Cellulose fibres and films
  - Thermoplastic starch and starch polymer blends
  - Polylactic acid (PLA)
  - Excluding cellulose, capacity is expected to grow from 220 kT to 760 – 1560 kT
- Next generation 2010 - 2020:
  - Improved technical performance for starch and volume growth
  - PLA costs fall. May achieve price parity with petrochemical polymers by 2020. PLA made from lignocellulose feedstock
  - First generation polyhydroxyalkanoates (PHA) commercially viable
  - Other bio-monomers develop including 1,3-propanediol, 1,4-butaiediol and succinic acid. Several new polymers wholly or partially constructed from bio-monomers emerge
  - US reaches target of 10% basic chemical building blocks arising from plant derived renewables.
- Longer term 2020 - :
  - PLA a fully mature commodity polymer
  - PHA breaks through to mainstream or fails
  - Bacterial cellulose available for commodity applications
  - Full range of bio-based monomers and building blocks. ‘Conventional’ polymers available from renewable feedstocks
  - Oil production in steep decline
  - Large scale conversion of plant biomass to bioethanol and chemical building blocks through pyrolysis and gasification.

8.1. Routes to Biopolymers

There are four conceptually different approaches to obtaining useful polymers from biological systems:

- Direct production of a useful biopolymer as a natural part of the functioning of the biological system
- Modifying the metabolism of a living system to generate a useful biopolymer
- Making monomers from bio-feedstocks that can be conventionally polymerised
- Breaking down biomass into synthesis gas – a mixture of CO and H_2 that chemical plants can convert into building blocks for polymers.

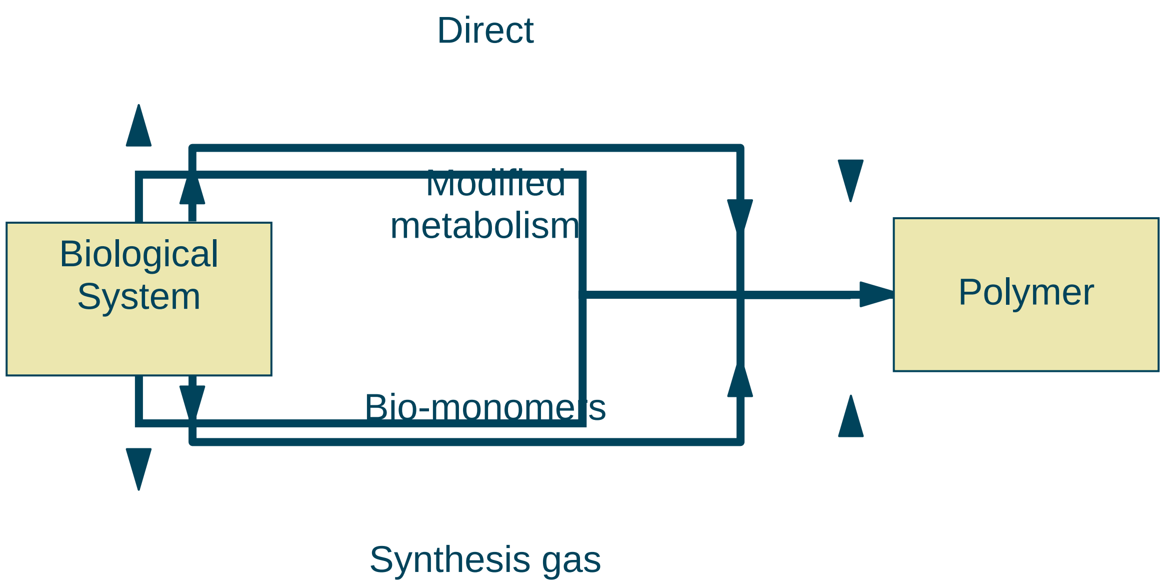


Figure 8.1 Routes to biopolymers

8.1.1. Direct Production

This route involves natural biopolymers directly extracted from biomass and used as is, or after chemical modification.

The two key families of biopolymers with potential for commercial polymers are polysaccharides and proteins. The other biopolymer family of DNA and RNA are not available in high concentrations in living systems, and do not have identified properties to make them attractive for conversion to commercial polymers.

Proteins

Proteins such as casein, gluten, keratin, whey proteins, zein and collagen have found application in edible coatings (1), and have a range of interesting barrier properties. However, protein based plastics are generally very sensitive to relative humidity giving them a limited range of use in conventional packaging. The current focus is in protective coatings of foodstuffs and in situations where an edible wrap brings additional user benefits. Casein is used in adhesives for labelling.

Polysaccharides
The main polysaccharides of industrial interest have been cellulose, starch, gums and chitin/chitosan. All are produced by polymerising sugars.

Cellulose is the most abundant natural polymer on earth. It is a linear polymer of glucose units. With a regular structure and many hydroxyl groups it tends to form strongly hydrogen bonded crystalline microfibrils and fibres, familiar as the fibres in wood and paper.

Cellulose fibres are the basis of the most abundant biopolymer packaging material; paper/board. This accounts of over 40% of packaging and is widely and effectively recycled. Although water sensitive itself it is easy to coat with a water repellent layer for use in moist conditions or in contact with liquids.

Paper/board demonstrates that with sufficient development of products and investment in the supply chain a biopolymer can compete directly on price and performance with petrochemical polymers.

Cellulose can also be converted into a film by dissolving it in a caustic solvent and regenerating the cellulose with an acid bath. This process developed at the end of the 19th Century was the basis of a range of products from rayon fibres for textiles to films such as Cellophane. Cellulose film is still widely used as a packaging material offering excellent optical properties. Because of a melting temperature above the degradation temperature it cannot be heat-sealed and is a poor moisture and gas barrier. To overcome these limitations it is often coated with another polymer.

A variety of cellulose derivatives can be used to make films, but are too expensive for widespread use. The main exception is cellulose acetate and variants which is used in food and other packaging.

Most cellulose fibre is obtained at low cost from woody plants. However, this source is contaminated with hemicelluloses (such as xylan, glucomannan and xyloglucan) and lignin, a complex cross-linking phenolic polymer that provides structural rigidity to woody plants. These materials must be removed and disposed of if not required (a major problem in the paper industry). An alternative source of high purity cellulose is fungal or microbial cellulose. Species of *Acetobater* ‘spin’ cellulose from pores directly into the growth medium and extremely high purity cellulose can be harvested. However, these cellulose sources cannot yet compete on price for commodity applications with chemically treated wood-pulp.

The second most abundant natural biopolymer is chitin (poly-β-1,4-D-*N*-acetylglucosamine). This is found in the exoskeletons of invertebrates and is available from crab, prawn, shrimp and lobster shells from commercial fisheries. Chitosan is a partially de-acylated form of chitin with different properties. Chitosan forms films with good gas barrier properties and could be used as a coating on other polymers. A biodegradable laminate made of chitosan-cellulose with polycaprolactone has been demonstrated for use in controlled atmosphere packaging of fresh produce (1).

Starch is the storage polysaccharide of cereals, tubers and legumes. It is a widely available as a renewable raw material for industrial applications and is used for plastics, adhesives, rheology modifiers and texturants.

Starch comes in two forms: amylose - a linear polymer of glucose units, and amylopectin - a branched form. Natural starches contain different ratios of these two materials conferring different properties.

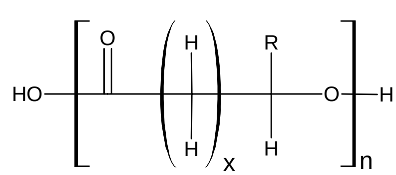
Starch on its own is too brittle for use as a packaging material. It is processed by a combination of thermal treatment, mechanical working, derivatization and blending with biodegradable plasticizers to produce a thermoplastic starch (TPS). This can then be blended with a more hydrophobic polymer to produce a material that can be used for injection moulding and film blowing. Starch is the major source of thermoplastic biopolymers today and is discussed further in section 8.2.

Finally there are gums such as guar and carrageenan. These are also long chain polysaccharides, but the chain length is shorter and they form gels. They are used as thickeners and rheology modifiers, particularly in the food industry. There has been relatively little interest in them as packaging materials as the other polysaccharides offer better starting materials.

8.1.2. Taking Control of Plant Metabolism

Another route to biopolymers is to take an organism that does produce a biopolymer and to modify its natural metabolism to produce material more suitable to industrial needs.

The prototype materials here are the polyhydroxyalkanoates (PHAs). PHAs are aliphatic polyesters produced directly by a micro-organism as an energy store. The PHA accumulates as granules within the cytoplasm and can be produced in conventional industrial fermentation processes (26). PHAs are polymerised from R-(-)-3-hydroxyalkanoic acid monomers. The generic formula is:



For current development PHAs x=1 and R may be up to 16 or more carbons. When R=methyl the product is poly(3-hydroxybutyrate), and when ethyl the product is poly(3-hydroxyvalerate) the two most common materials. A wide variety of co-polymers can be produced with a range of properties. The nature of the monomers depends on the bacterial strain and the carbon source used for the fermentation.

Although PHAs are produced naturally as an energy store, full scale production requires improved metabolic efficiency product recovery. Bacteria are being modified both by classic mutagenesis and by genetic engineering. In order to further improve yields and reduce costs, there have been several programmes to engineer the required genes into crop plants.

At the moment, PHAs are getting all the attention and are the most likely candidates for wide scale commercialisation. Other biopolymers that might follow the same route of modifying the metabolism to achieve commercial production include bacterial cellulose and possibly some of the bacterially produced gelling agents such as xanthan, schleroglucan and gellan could be modified to provide interesting properties.

Given the capabilities of modern biotechnology, it is probable that a very wide range of interesting biopolymers will ultimately be made using this route. However, at present the relatively high cost of biotechnology products and the concerns about GM technology in Europe is likely to keep this technology in the background.

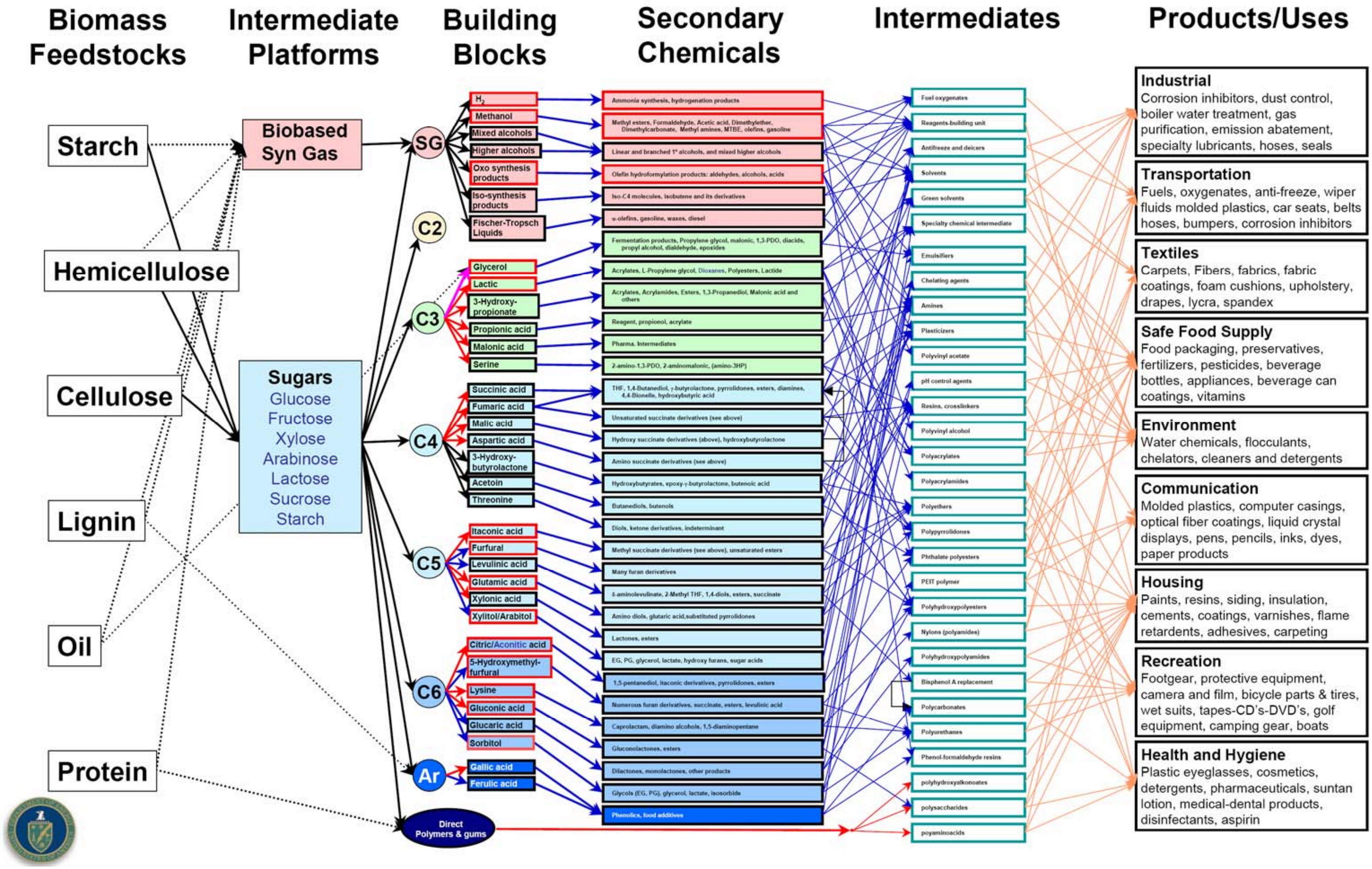


Figure 8.2 Biomass feedstocks for the chemical industry (from 27)

8.1.3. Monomers from Plants

Figure 8.2 comes from a US Department of Energy Report on value added chemical from biomass (27) and combines information on the last two routes to biopolymers.

The first of these takes biomass from plants and converts it directly or indirectly into monomers that can be conventionally polymerised into renewable polymers.

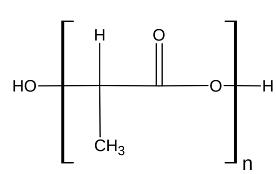
A well established example of this is to take unsaturated fatty acids from plant oils and dimerise them at the double bonds. This gives a long chain di-acid that can be used as one of the monomers for a polyamide. The dimer acid can be reduced to a dimer diol and used in polyesters and polyurethanes. By epoxidising the double bond and ring-opening with a polyhydric alcohol, a polyol can also be produced.

A single renewable feedstock can be converted into many different monomers, which can in turn be converted to a wide range of polymers.

Figure 8 .2 shows how the same thing can be achieved with plant polysaccharides. By degrading the polysaccharides we can release the sugars. These in turn provide a range of C2 to C6 fragments that can be converted into an even wider range of chemical intermediates. This ‘sugar’ route gives us access to a very large number of functional building blocks well known in the chemical industry. Many of these can be used as building blocks for polymers.

In order to simplify the chart, the report only lists the 30 chemical building blocks that it believes represent the best commercial opportunities. The diagram shows no products from the C2 fragments despite the obvious opportunities for producing acetic acid and anhydride, ethanol, glycine, oxalic acid and ethylene glycol. These are seen as already commodity products and therefore less attractive

The obvious current example is the production of poly-lactic acid (PLA). Starch is converted to sugar by enzymatic or acid hydrolysis and the sugar fermented to produce lactic acid. The lactic acid can then be polymerised by two different routes to produce a range of high molecular weight polymers.



Other useful bio-based monomers can be produced. 1,3-propanediol (PDO), 1,4-butanediol (BDO), succinic acid, adipic acid and caprolactam have all been investigated.

Bio-monomers can be polymerised with other bio-monomers or with petrochemical monomers. We can imagine a very wide range of polyesters, polyamides and polyurethanes being made from bio-monomers. Ultimately a significant quantity of routinely used commercial polymers could be made partially or wholly from renewable feedstocks.

Another concept starts from the bioethanol, which will be produced from biomass in large volumes and at low cost to meet the needs for renewable liquid road fuel. Ethanol can be dehydrated to ethylene, which is a well known and well understood feedstock for the chemical industry and specifically for the manufacture of polyethylene. Catalysts are available for this process and it is practised in Brazil to reduce oil imports. What the economics of such a process would be on a global scale is not clear, but the combination of biological and chemical synthesis will provide access to many product areas of the current chemical industry starting from renewable raw materials.

8.1.4. Production of Synthesis Gas

An even more dramatic use of biomass is to thermally break it right down to C1 fragments. Specifically to the mix of CO and H_2 known as synthesis gas or syngas. Synthesis gas has been the mainstay of the chemical industry since its roots in the industrial revolution. With the appropriate reactors and catalysts, synthesis gas can be made into a huge variety of chemicals, and with processes such as Fischer-Tropsch synthesis and Oxo-synthesis, chemical entities can be grown into larger and more complex structures.

Synthesis gas can not only be used with chemical catalysis. It is possible to anaerobically ferment synthesis gas into ethanol using bacteria such as *Clostridium ljungdahlii.* Again chemical and biological processes combine.

Synthesis gas can be a viable route to monomers and polymers.

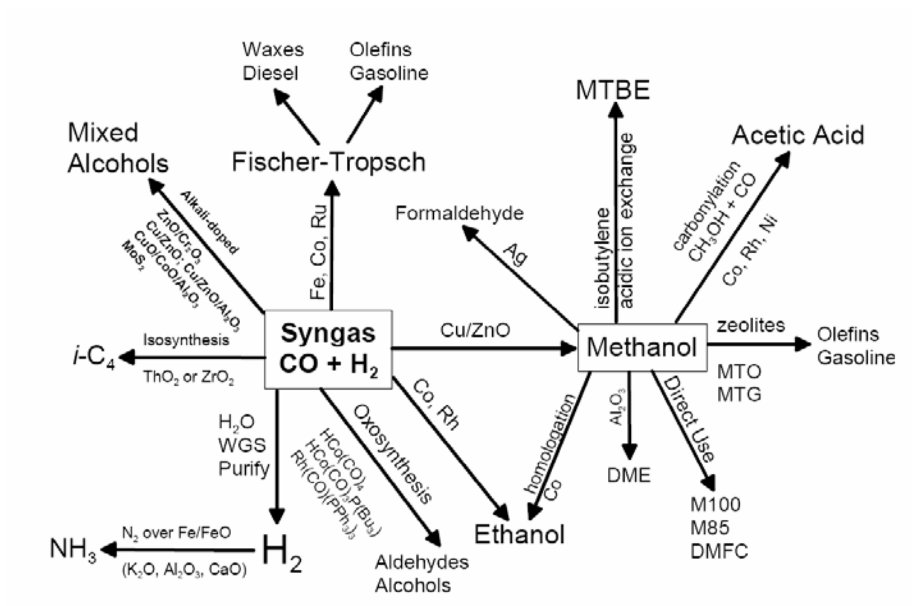


Figure 8.3 Chemicals from synthesis gas (from 28)

Synthesis gas can be produced from almost any source of hydrocarbon including biomass. If biomass is heated with only about 1/3 the amount of oxygen needed for efficient combustion, it converts to synthesis gas. If no oxygen is provided, it pyrolyses instead of gasifying to yield an oily material that can be used as a fuel.

This technology has been well developed over the last two decades, and many different sizes and designs of gasification units have been tested as pilot plants and as full scale commercial operations. Particular attention has been given to this technology in the US as part of their energy security programme (28-30).

Since synthesis gas can be made from any source of hydrocarbon the choice is dictated by availability and economics. At present the most cost effective source is orphan natural gas (gas reserves that have no economically accessible markets because of their remote or hard to access location). Natural gas is cheap and clean and is already being converted via synthesis gas and Fischer-Tropsch synthesis to diesel fuel that can be used in the local markets or more easily transported to distant markets.

A lot of the existing gasification plants were designed to produce synthesis gas for power generation, and since this is a low value use, the economic viability of these systems has not been certain. However, as fossil hydrocarbon reserves become depleted, and biomass-derived synthesis gas is used for higher value materials, the economic balance will shift towards the use of biomass as a feedstock.

One intriguing idea is that instead of incinerating waste (including waste packaging); it could be converted into synthesis gas and used to make new chemicals and polymers. Unfortunately, at present our technology is not up to this idea. Waste gasification experiments have shown that to get high quality synthesis gas, you must adjust operating conditions continuously to match a varying feedstock. This proved hard to do. Further the optimum size for a gasification plant feeding a conventional chemical synthesis plant, rather than a co-generation power plant, would be very large. This would mean a large supply area, and lots of waste transportation to a central location. The other routes for waste disposal may have a better overall environmental impact. Bio-based synthesis gas is probably going to be generated from relatively homogenous streams of agricultural waste or energy crops.

8.2. Current Biopolymers

A large and comprehensive report "Techno-economic Feasibility of Large-scale Production of Bio-based Polymers in Europe" has recently been prepared by Utrecht University and the Fraunhofer Institute for Systems and Innovation Research for the European Commission (26). Much of the data for the remainder of section 8 has been gathered from this report, validated by interviews and some other views of the developing market (31 and websites mentioned in text).

Only three types of polymers are in commercial use today:

- Cellulose films (including acetate, butyrate and propionate)
- Thermoplastic starches
- Polylactic acid

Of these, starch based polymers dominate the market. In 2002 about 30,000 tonnes were produced, accounting for 75%-80% of the total market in biopolymers (26). 75% of starch based polymers were used for packaging.

8.2.1. Cellulose

Originally developed at the end of the 19th century, cellulosic films dominated plastic film packaging until the 1950s when polyolefins took over. Cellulosic films now occupy niche applications. Cellulose film has excellent strength and optical properties, but is moisture sensitive. It is usually combined with another polymer layer to improve the gas and moisture barrier properties.

Cellulosic films are mature products with a relatively high price (~€3/kg (26)), and costs are unlikely to fall without a significant breakthrough in manufacturing. Cellulose based polymers are still quite widely used for injection moulding parts such as handles, toothbrushes and spectacle frames.

Manufacturers producing cellulose based polymer films for packaging include:

▪ Eastman	Tenite®	www.eastman.com
▪ Mazzuchelli1849	Bioceta®	www.mazzucchelli1849.it
▪ Innovia Films	Natureflex®	www.films.ucb-group.com

Of these only Natureflex is actively positioned as a biopolymer with sustainability benefits. It is certified compostable and has found a number of applications including wrapping organic fruit and vegetables in Sainsbury's.

Cellulose based films compete with several other biopolymers including PLA. With dramatic progress in the costs of these newer biopolymers, cellulose based films will struggle to capture a significantly greater proportion of the film market in the short term.

8.2.2. Starch

Starch polymers can be made from a wide range of starch sources including corn, wheat, potato, tapioca and rice. Corn is the major source with significant activities in potato and wheat in Europe. There are three routes to prepare starch for use as a biopolymer:

- Pure starch – as extracted
- Modified starch – some of the hydroxyl groups are modified enzymatically or chemically. This can change starch properties; for example, increasing the water resistance of the final polymer.
- Partially fermented starch – an approach used with potato waste slurry from the food industry (Rodenburg)

After separation starch is extruded at a sufficient temperature and mechanical energy input to break down the crystalline structure. This produces thermoplastic starch. At the same time polymers and other additives are blended in to modify the properties.

Blending with different polymers provides a range of commercially useful products. Adding poly(vinyl alcohol) produces a water soluble polymer useful as a biodegradable loosefill. Poly(caprolactone) limits moisture sensitivity, boosts melt strength, and helps plasticize the starch.

Current manufacturers of starch based polymers include:

▪ Novamont	Mater-Bi®	www.materbi.com
▪ Rodenburg	Solanyl®	www.biopolymers.nl
▪ Potatopak		www.potatopak.org
▪ Greenlight	GreenFill® EcoFlo® ECO_2® EcoBloc®	www.greenlightproducts.co.uk
▪ Biotec	BioPlast®	www.biotec.de
▪ BIOP	BIOPar®	www.biopag.de
▪ American Excelsior[1]	Eco-Flow®	www.amerexcel.com
▪ Japan Corn Starch[2]	EverCorn®	www.japan-cornstarch.com

Current products include:

- loosefill and other void-filling systems (Greenlight and American Excelsior) as a replacement for expanded polystyrene (EPS)
- films and bags (Novamont, Biotec and BIOP)
- pots and trays (Rodenburg, Novamont and Potatopak)
- nets (Novamont)

[1] American Excelsior are packaging converters. The source of their starch polymer is not known. National Starch and Chemical Company used to supply American Excelsior with their Eco-Foam material, but they have stopped advertising it.
[2] It is not known whether this is a commercial product.

Starch polymers can substitute for EPS for loosefill, blocks and trays, and for polyolefin films, particularly low density and high density polyethylene (LDPE and HDPE), and polypropylene.

As well as simple film, airbags and bubble wrap are now becoming available (32 and Greenlight).

Starch based polymers have poor resistance to oil and solvents, are sensitive to moisture and have a high permeability to water vapour. Although reasonably transparent, the visual appearance is not good. As a result, applications are focused around void-fill, pots and trays, and carrier bags (Sainsbury's use a carrier bag made from Tapioca starch). Improvement in any of these properties would open up a bigger market.

Costs for blended starch polymers in 2003 ranged from €1.50/kg for injection moulding foams up to €4.50/kg for high quality films. At the same time prices for bulk polyolefins were below €1/kg and polypropylene film at €1.50 - €2.50/kg. Reducing the costs of starch polymers will increase market penetration.

The cost of starch in Europe is twice that in the US (26). However, the raw starch cost is not the main driver of final price. Currently the processing of starch into the polymer is the dominant cost component. There is therefore plenty of scope to improve manufacturing processes and cut polymer cost.

8.2.3. Polylactic Acid

The final biopolymer available commercially today is poly(lactic acid) (PLA).

The lactic acid monomer for PLA is obtained by fermentation from sugars obtained from a wide variety of agricultural sources, typically co-products of food preparation. Hydrolysis of lignocellulosic waste will in future be a significant source of carbon for lactic acid fermentation.

Different polymerisation routes (ring-opening polymerisation or poly-condensation), degrees of polymerisation, different stereochemistry, and co-polymerisation produce several PLA families with different properties (33, 34).

Current manufacturers of PLA include:

▪ Cargill[3]	NatureWorks®	www.natureworksllc.com
▪ Hycail	Hycail®	www.hycail.com
▪ Biomer[4]	Biomer®	www.biomer.de
▪ Toyota[5]	Eco-Plastic	www.toyota.co.jp

In addition to these producers of PLA, there are many converters who produce packaging materials, for example Treofan in Europe (www.trespaphan.com).

[3] In January 2005, Cargill agreed to buy out the Dow Chemicals interest in the 50/50 joint venture Cargill-Dow created in 1997 to commercialise PLA.
[4] Small-scale production.
[5] Internal consumption for automobile parts. Used as a composite with kenaf fibre.

See also the NatureWorks website for lists of converters (www.natureworksllc.com).

PLA has successfully been used in commercial packaging (31); both for films and rigid structures. Italian supermarket IPER uses PLA to pack bread, fresh fruits, vegetables, pasta, salads, ham, sliced salami and cheese. Hinged containers can be produced for products such as sandwiches and fresh salads (see for example BrenMar products www.brenmarco.com). Drinks bottles can also be made out of PLA, and Biota Spring Water in Colorado has replaced PET bottles with PLA (www.biotaspringwater.com).

PLA has a unique collection of properties that make it an interesting packaging material even discounting its renewablility (33):

- High modulus – packages can be made 30% - 40% thinner than polystyrene
- Fold, crease and twist retention
- Grease barrier
- Unique aroma and flavour barrier properties
- Water and gas permeability similar to PET
- Printable without surface treatment
- Biodegradable and compostable

As with other biopolymers, PLA can be combined with other polymers to extend the range of properties.

PLA can be converted from bulk polymer to packaging materials using slightly modified thermoplastic processing equipment. Techniques include thermoforming, injection moulding, blow-moulding, extrusion and film extrusion. From a processing point of view PLA is a drop in replacement for other polymers.

PLA will be able to technically substitute to some extent for polypropylene, polyamides, PS, PET, LD-PE and HD-PE (26, 33).

A significant problem with the use of PLA in Europe, and in particular the UK, is that the Cargill material is made from corn sourced in Nebraska where the majority of the corn grown is GM. Cargill PLA cannot be certified GM free, and this is enough to prevent a number of major retailers from considering PLA at present. Having taken strong and public positions about guaranteeing no GM products in their stores, in response to consumer pressure, they cannot take the risk of using PLA.

Hycail's planned developments of European sources of PLA that can be guaranteed GM free should overcome this problem (33).

Recycling of PLA has now been demonstrated in an experiment that reprocessed PLA four times at temperatures up to 240C (33). Where recycling is feasible, we can be confident that the PLA will retain its properties through the loop.

The price of PLA is currently around €2/kg whilst the materials it competes with range from €0.75 - €1.50/kg (26, 33). However, in terms of cost to deliver a specific functionality, there are applications where it can compete. Packaging users have commented that it is price competitive with amorphous PET, with micro porous PP for bakery and with crystal PS for sandwich boxes and salad containers.

The cost of PLA is dominated by the cost of the lactic acid. Development of large integrated plants, possibly using the bio-refinery concept, could drive prices down towards €1.20-€1.30/kg (26, 33).

8.2.4. Global capacity

The PRO-BIP study has estimated the global production capacity for biopolymers out to 2010 (26). In 2010, the market will still be dominated by cellulose polymers, starch polymers and PLA:

Polymer	**Global Capacity kT**
Cellulose	Unknown (estimated > 4,000)
Starch	200-300
PLA	530 -1,150
Others	30-100
Total Biopolymer (-cellulose)	**760-1,560**
Petrochemical polymers	260,000

Total capacity in 2003 was estimated to be ~220 kT excluding cellulose polymers with starch showing a 4x growth and PLA an 8x growth at the high end of the estimates.

8.2.5. UK feedstocks

Does the UK have the feedstocks to participate in the development of the biopolymer market?

In principle, yes.

Between now and 2010, feedstocks will continue to be starches and sugars. In the longer term lignocellulosic routes will become technically and economically viable, and the attention will shift from starch and sugar to plant biomass as a feedstock for biopolymers.

Starch is used both to make starch polymers and as a feedstock for lactic acid production for PLA. Starch is available in the UK principally from cereal crops. The main global source of starch for industrial uses is maize and the UK imported 531kT of maize in 2002 (59% of industrial starch feedstock) (35). Yet wheat in particular grows extremely well in the UK. Taking account of the yields and the value of the other products from the crop, in 2003 the net UK cost of starch from wheat was ~£30/tonne and from maize ~£70/tonne (35).

There is no raw material reason why the UK could not develop a biopolymer industry based on UK sourced starch.

Sugars are not a sensible feedstock for industrial production of biopolymers in the EU because of the distorting effects of CAP subsidy regimes and the planned changes to those regimes. Production costs in the UK are far above world open market prices for refined sugar.

In the longer term biomass will become an important feedstock. In the UK this is likely to be bound up with the development of biomass for renewable energy and biomass as a source for bioethanol for liquid road fuel. These applications will be much larger than biopolymers and will define the development of the UK biomass industry.

8.3. Next Generation

Looking out to 2010 – 2020, how do we expect technologies for the development of biopolymers to develop?

8.3.1. Current technologies

There will continue to be developments in technologies for the established biopolymers.

Cellulose polymers
In the short term no change in properties or cost structure of current cellulose polymers are predicted.

Developments will continue with bacterial cellulose, but it will not yet have reached commodity prices and will be reserved for medical and other high value applications.

Starch Polymers
Starch based polymers continue to grow in volume. Processing costs will fall, and rising costs of petrochemical feedstocks will make it increasingly attractive.

Spurred on by the rising market, R&D investment will overcome some of the limitations of current starch polymers. In particular, the current petrochemical polymers used to blend with starch will be replaced by polymers from renewable feedstocks.

Towards the end of the period, biotechnology may provide new types of starch with properties tailored for biopolymer production.

Developments in blending and converting starch polymers will overcome performance limitations such as moisture sensitivity and transparency whilst preserving the biodegradability and compostability of the existing starch polymers.

PLA
Costs for PLA will continue to drive down as the industry accelerates along the learning curve. NatureWorks plans to have 3 plants operational by 2010 with a combined capacity of 300kT.

PLA will start to be made from lignocellulosic feedstocks and renewable energy. This will further reduce costs and improve the environmental footprint. Integrated biorefineries producing renewable energy, liquid fuel, biopolymers and high value specialties will start to appear.

Petrochemical polymers will continue to fall in price, but at a slower rate as the manufacturing curve flattens out and oil prices rise. By 2020 some scenarios show PLA and other bio-polyesters approaching price parity (26).

We will continue to learn how to produce PLA with attractive properties and how to exploit these properties in commercial products. A powerful applications knowledge base will develop that will rival that for the established petrochemical polymers.

8.3.2. Polyhydroxyalkanoates

After 2010 we should see the first generation of polyhydroxyalkanoates (PHA) becoming commercially viable.

PHA producers already active in 2005:

▪ P&G/Kaneka	Nodax®	www.nodax.com
▪ Metabolix	Biopol®	www.metabolix.com
▪ Biomer	Biomer®	www.biomer.de

Currently PHA is being produced by microbial fermentation. The exact type of PHA can be controlled by the carbon source supplied and the exact strain of bacterium.

Production of commodity materials by fermentation has always required a great deal of optimisation. Getting the product produced at economically viable concentrations and then separating it from the biomass and the fermentation broth are significant challenges. Experiments during the 1950s and 1970s failed to achieve commercial viability (26), and viability has yet to be definitively demonstrated in 2005. The presumption is that with perseverance a cost effective route can be developed.

At the moment carbon sources account for up to 50% of the cost of PHA. Use of GM organisms and lower cost feedstocks will reduce price.

As part of that challenge Metabolix is currently trying to express PHAs in crops to allow production through conventional agriculture. Metabolix and BP's Innovene subsidiary are collaborating to transfer the genes for PHA production into switchgrass which can then be grown both for PHA and as an energy crop.

PHAs can be produced with a range of properties from stiff materials suitable for injection moulding and melt spun fibres through to soft/elastic materials suitable for adhesives and elastomeric gloves (26, 36).

PHAs have some advantages over existing biopolymers. In particular they are water insoluble and relatively resistant to hydrolytic degradation, but completely digested in a hot alkaline solution to CO_2 and water (36).

P&G see the main applications of Nodax in alloys or blends with other biopolymers. In this way they can reduce the price and gain control over properties such as disintegration rate, ductility/modulus, clarity and processing conditions.

Two key candidates for polymer blends are PLA and thermoplastic starch. P&G see the synergies as (36):

- Nodax – PLA Blends
    - PLA and Nodax improve each resin's processing
    - Nodax improves PLA ductility
    - PLA improves Nodax tensile strength
    - Nodax improves PLA degradation
    - Nodax improves PLA high-temperature hydrolytic stability
    - Nodax improve PLA barrier properties
    - Nodax provides heat sealability

- Nodax – TPS Blends
    - Nodax lower melt temperature prevents starch degradation during processing
    - Nodax improves starch stability
    - Nodax reduces noise and improves clarity
    - Nodax improves barrier properties
    - Starch allows tailoring of disintegration/degradation profile

8.3.3. Other bio-monomers

During this period of 2010-2020, several polymers wholly or partially constructed from bio-monomers should achieve commercial viability.

The most advanced material is bio-derived 1,3-propanediol (PDO). This is the key monomer for the production of poly(trimethylene terephthalate) (PTT) used to make Dupont's Serona® fibres. PTT was originally developed with a petrochemical PDO made by hydration of acrolein. Later a process was developed with Genecor to produce bio-PDO. Dextrose from wet-milled starch is converted by a genetically engineered *E. coli* directly to 1,3-propanediol. The PDO is separated from the fermenter broth and passed to a conventional polymerisation process and combined with either dimethyl terephthalate or pure terephthalic acid. Dupont and Tate & Lyle have recently announced a joint venture that will produce bio-PDO at a plant in Loudon Tennessee during 2006. The announcement claims that Serona based on bio-PDO will be available by the end of 2006.

This type of development is fundamentally different to the biopolymers described so far. In this case the final product is by definition a direct replacement of the existing polymer; it is exactly the same product. Therefore all of the technical

know-how in working with the polymer already exists. Its markets are known and providing any additional costs are not excessive, market take up should be faster than for biopolymers which represent genuinely new additions to the ranks of commercial polymers.
Once bio-PDO is commercially available, it could be used in a number of other part bio-based part petrochemical polymers. For example, being used as a chain extender in polyurethanes (26).

Other bio-monomers will follow. MBI International is working on the commercialisation of a fermentation route to succinic acid (37). This is a C4 di-acid that can be used to make poly(butylene succinate) (PBS) an established commercial polymer. It can also be used in polyamides. The succinic acid can be further converted to 1,4-butanediol which is used in making PBS and poly(butylene terephthalate) (PBT) another established commercial polymer.

PBS could be the first 'conventional' commercial polymer to be synthesised entirely from renewable feedstocks.

Succinic acid is in fact a good example of a platform chemical that can be converted by chemical or biotechnological processes into a whole range of useful building blocks. The start of this cascade is illustrated in Figure 8.4 from MBI International (37). See also Figure 8.2 and (27).

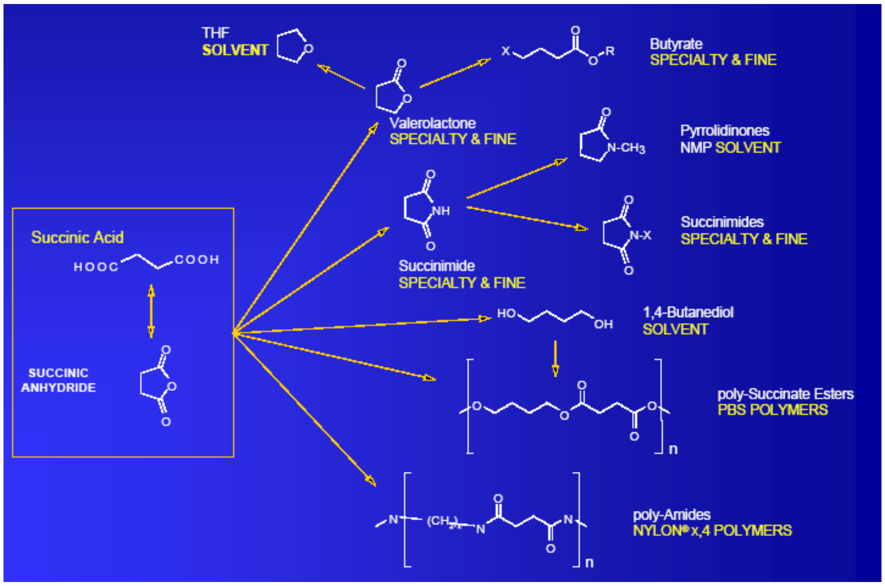


Figure 8.4 Opportunities from fermentation produced succinic acid (from ref 37)

Other bio-monomers for which fermentation pathways have been demonstrated on at leas the lab scale are caprolactam and adipic acid for polyamides.

Polyurethanes are a very versatile range of polymers that already make extensive use of bio-monomers in the form of plant oils converted into di-acids or polyols. Bio-derived di-acids and polyols will also find application in these materials.

The development of bio-derived platform chemicals will be a key part of the next 10-15 years, as they support not only bio-monomers, but a complete range of building blocks for the chemical industry. This has been a focus of US thinking for some years, and their roadmap for plant based renewable resources for 2020 (38) describes a plan:

> *"…to achieve at least 10% of basic chemical building blocks arising from plant-derived renewables by 2020, with development concepts in place by then to achieve a further increase to 50% by 2050."*

Achievement of this plan will provide a seamless link from agricultural products and biomass, through biotechnology and the chemical industry, to consumer products.

8.4. Longer Range Options

> *"Prediction is difficult.*
> *Especially of the future!"*
>
> *Neils Bohr*

In the longer term, detailed predictions become of less and less use. Beyond 2020 it is hard to say what will happen to specific polymer families.

PLA will become a fully mature polymer; selected simply because of its price and performance.

PHAs will have succeeded and become mainstream materials, or will have failed again as they have done so often since the 1950s.

Bacterial cellulose will have come down in price and will no longer be restricted to high value applications. Whether it will have properties that compete in the packaging market we cannot tell.

The other bio-based monomers will be in full production, and 'conventional' polymers will be available from renewable feedstocks.

GM may have become totally accepted, allowing first high value pharmaceuticals and specialties and then commodity materials to be grown in plants. Alternatively, the resistance of many consumers may prove fatal.

Impacts of global warming, population growth and environmental degradation may have changed our willingness or ability to divert agricultural production to industrial use.

One thing that we can be pretty sure about is that the oil will be running out. Exactly when the so-called Hubbert Peak occurs is a matter for debate, but the consensus amongst the petroleum experts is that it is out there, and not very far away (www.hubbertpeak.com).

As we look out beyond 2020, we are imagining a very different world. A recent report commissioned by the US government looked at the expected decline in oil production as the available reserves become depleted (39). The most likely production curve for the total extractable reserves peaks in 2016 (Figure 8.5).

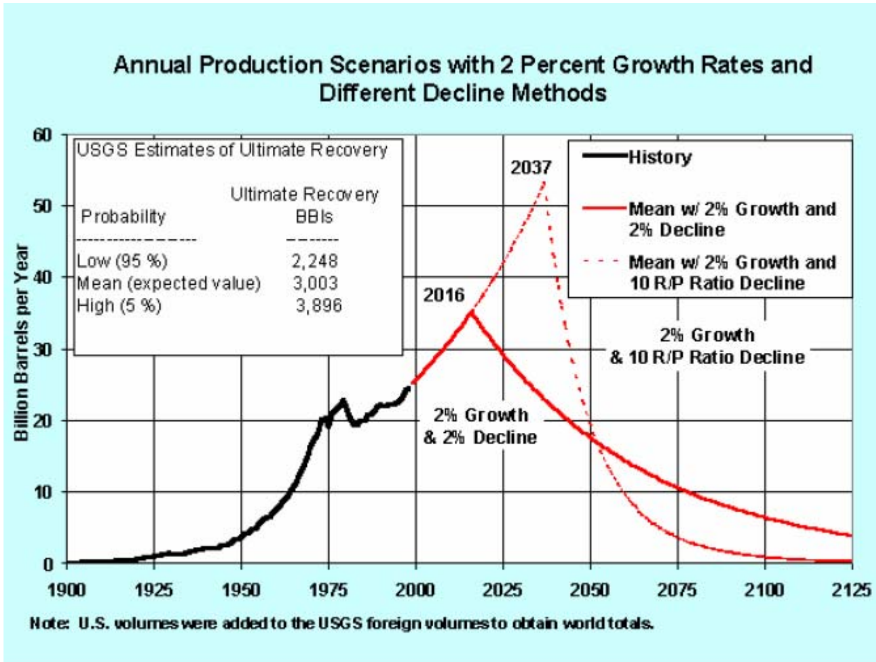


Figure 8.5 Oil production scenarios (from ref 39)

As the demand is expected to grow beyond the peak of production, substitutes must be found. Natural gas production will follow a similar path to petroleum. Clean coal technology will probably be developed for electricity production but will not impact the need for liquid transport fuels. The report asserts that alternative non-fossil fuel sources will require 10-20 years of sustained development effort to make them available on a global scale.

Amongst these substitute technologies are large scale bioethanol and biomass conversion by pyrolyses or gasification to synthesis gas (section 8.1.4). Exactly how those technologies will evolve is very difficult to assess. But we can be confident that the need for energy sources will drive the production of chemical building blocks from plant biomass that will in turn provide bio-derived building blocks for conversion into all the manufactured materials that we will use.

No matter which of the four routes described in Section 8.1 proves to be the most successful, out beyond 2020 the polymers that we use to build our societies will ultimately be derived from the biosphere and will form a closed loop with that biosphere.

9. Issues, Gaps and Opportunities

From the evidence presented in this report, it is possible to identify a number of:

- Issues around the current and potential use of biopolymers in packaging that stakeholders need to be aware of.
- Specific gaps in our knowledge or capabilities that need to be bridged.
- Opportunities for development of the market for biopolymers in packaging.

9.1. Issues

Renewable *not* biodegradable
The sustainability benefits of biopolymers arise from the fact that they are made from renewable raw materials, not from the fact that they are biodegradable.

Need for independent evidence
The complexity of the packaging life cycle, and the impacts of different choices made about materials, supply chains and end of life disposal allow many different views of the best way towards more sustainable packaging. Various alternatives are loudly championed by different interest groups with claim and counterclaim. We need an independent and authoritative view of the alternatives

Fragility of public opinion
Public opinion is in a fragile state. People are generally supportive of the concepts of recycling and biodegradability, but suspicious about the claims being made by manufacturers and retailers. Media stories about the international trade in plastic waste give the impression that recycling is not working, and could easily turn the public against it. There is a risk that the public will give up on the whole idea of eco-friendly and sustainable packaging.

Labelling packaging as compostable
Labelling biopolymer packaging as compostable raises a number of issues. The necessary doorstep collection and separation facilities for industrial composting are not yet in place. Packaging that meets the standard for compostability cannot be reliably home composted. For many people providing packaged goods to the end consumer this is enough reason to avoid labelling altogether.

‘Biodegradable’ plastics from petrochemicals
‘Biodegradable’ packaging made from petrochemicals increase confusion. In particular ‘oxo’-degradable plastics that do not meet compostability standards. These materials do disappear over time, improving the litter problem, but make little contribution to sustainability. The public, retailers and brand owners are becoming increasingly confused and concerned.

Overestimating the impact of biopolymers
If you include the energy used to make conventional plastics, then only about 7% of the world's oil is converted into plastics. Most of the remaining 93% goes into heating, transport and energy production. Biopolymers will not make much impact on the consumption of oil and gas. The idea can be over-hyped.

Complex ‘engineered’ packaging
To respond to market drivers for increased performance and lower weight, the packaging industry is turning increasingly to highly ‘engineered’ materials. From multilayered films to sophisticated closures and dispensers, these solutions involve the use of multiple polymers. This increases the difficulty in recycling these materials, and means that where biopolymers are used, they are likely to be used in combination with petrochemical polymers for the foreseeable future. Can the benefits of using biopolymers in these multicomponent products be communicated to the stakeholders?

Preparing for success
When biopolymers meet the price and performance requirements of the packaging converters, volumes will climb very rapidly. Large companies need to be involved in supplying the market.

Weight based recycling targets
The waste recycling targets for local authorities are weight based. This focuses attention on denser glass and paper, and away from plastic packaging. The incentives for recycling of plastic primary packaging are too weak.

Incineration as a key part of waste management
The vast majority of commentators believed that incineration with energy recovery will play a key part in the disposal of packaging waste in the foreseeable future. However, there is strong public opposition to incineration in the UK.

European focus on minimisation and recycling – not renewables
In Europe there is a focus on the plastics in the waste stream. The goals are minimisation and recycling, and insufficient attention is given by all parts of the supply chain to the potential role of biopolymers.

9.2. Gaps

Drop-in substitutes
Many biopolymers are intended to be substitutes for existing materials used in packaging. As far as possible a substitute needs to be a direct drop-in replacement for the existing material if it is going to be successful. Unless there are very large commercial benefits to be had, users do not want to spend time and money, rebuilding or replacing packaging manufacturing or filling lines. More work needs to be done to create grades of biopolymers that are direct substitutes.

Limited range of properties
The range of biopolymers which is commercially available at the moment is very small. More commercial grades of biopolymers are required with different functionalities to allow manufacturers to completely redesign the packaging using biopolymers. The full benefit of the sustainability positioning is only obtained when all of the packaging for a product can be made from renewable raw materials.

Meeting real user needs
Biopolymers are not yet addressing in the key supply chain needs identified in section 4.

Price/performance gap
Price/performance is always an issue. There are currently a limited number of cases where biopolymers can compete directly with conventional polymers on the basis of cost per unit of functionality. We need to increase the range of applications where biopolymers can compete.

Production scale
Packaging is a high-volume application of plastics. The strategy of many in the biopolymer field is to target applications where the technical requirements are not too high. These are typically applications where commodity polymers are used in very large volumes. Not only does the price have to be right, but the biopolymer manufacturers need to be able to achieve the production scale necessary to assure the buyers of continuity of supply. This can be done (cf Cargill and Novamont) but requires time and resources.

Unique properties
In selecting a polymer for a particular packaging application, a manufacturer will be thinking about the specific characteristics of candidate materials. At the moment, biopolymers have relatively few unique properties that marked them out from other polymers. Biopolymers need to develop those unique properties so that they can compete on a technical as well as an environmental basis.

Performance data in use
Insufficient work has been done on the properties of biopolymers for use in the packaging sector. If you are trying to persuade a user to switch from their existing material to a new material, you are asking them to take a risk. You must be able to provide them with excellent data on the performance of that material in a specific application if you want them to take that risk. Even for the existing commercial biopolymers not enough has yet been done. For the next generation of biopolymers that work has barely started.

Lack of clear consensus on life-cycle impact
There is a perceived gap in life cycle analysis of plastics in packaging in general. Despite the many studies which have been carried out, those involved in the packaging supply chain feel a great deal of uncertainty about what the environmental impacts are for different options for managing supply chain and end of life disposal. This lack of consensus leaves them vulnerable to attack by stakeholders favouring a particular type of solution, and makes them conservative and risk averse.

Strategy for the use of plant biomass
In the longer term the use of plant biomass as a renewable feedstock for the chemical production of polymers is a real opportunity. However, at present, there is no clear UK strategy for the use of plant biomass as a chemical feedstock. This is in contrast to the US, where it is at the heart of much of their 2020 vision for fuel and for the chemical industry (38).

9.3. Opportunities

Creating an independent source of reliable information
There is an opportunity for the NNFCC to establish itself as an authoritative and independent source of information on the use of biopolymers in packaging. This will require co-operation with other expertise centres including packaging industry groups.

Exploit interest in sustainable packaging
There is a strong appetite for more sustainable packaging, particularly amongst brand owners and retailers. If biopolymers can meet the price performance requirements, there is a market.

Learn from paper and board
Over 40% of current packaging is manufactured from a renewable biopolymer, cellulose. The fact that paper and board can compete on price/performance with all other packaging materials illustrates what can be done when there is time to optimise manufacturing and develop applications knowledge. What has been achieved with paper and board can be achieved with other biopolymers.

Develop the niches for biodegradable plastics
There are niche opportunities for biodegradable biopolymers in applications where disposal via composting can be assured. For example, in the production of plastic bags for storing green waste for doorstep collection, or in producing biodegradable cutlery and containers for closed environments such as theme parks, sports stadia etc.

Develop applications knowledge
Developing the market for biopolymers is not only about creating new biopolymers and producing them at a reasonable cost; it is also about learning how to use them. Most established polymers have many years of application research behind them. This needs to be duplicated for the biopolymers.

Build alliances
Success in the packaging materials sector requires scale. There is an opportunity to link small scale developers of biopolymer materials with large scale materials companies with the size and resource to create large production capacities.

Novel barrier properties
New barrier properties are needed in packaging materials. Identifying and optimising barrier properties in biopolymers will open up new applications.

Moving along the price/learning curve
PLA is already cost competitive for some applications on the basis of cost per unit functionality. This has been achieved quite early in the life cycle of the material. Further work on PLA costs will undoubtedly open up additional market applications. The same approach needs to be taken for all biopolymers.

GM free PLA for Europe
At the moment, almost all commercially available PLA is made from a GM containing feedstock. There is an opportunity to create non-GM PLA for applications in Europe.

Improved visuals for starch
One of the problems with existing packaging based on thermoplastic starch is poor visual appearance. Improvements in the visual appearance of starch materials would open up additional markets.

3D foamed starch
Foamed thermoplastic starch has already demonstrated that it can substitute for loose fill packaging material. The next opportunity is to create complex three-dimensional shapes to replace the foam blocks used to protect shock sensitive products.

Bio-monomers and syngas from biomass
Support the development of technologies for producing bio-monomers and syngas from UK sourced biomass.

UK opportunity in wheat starch
The UK has a rich source of feedstock for bio-monomers in wheat. We have excellent wheat agronomy and a substantial surplus. There is an opportunity to grow the production of biopolymers in the UK by linking agricultural producers to biopolymer producers in an integrated supply chain.

Use sustainable procurement initiatives
Sustainable procurement initiatives have proved successful in increasing market uptake for a variety of products from renewable raw materials. We should seek to make sure packaging is included in sustainable procurement schemes, and that biopolymer packaging is properly evaluated.

Building biopolymers into eco-design thinking
Ensure that plastics from renewable raw materials are built into eco-design thinking and documentation.

Sell benefits of renewable feedstocks
One of the advantages of biopolymers is that you gain the benefits of the renewable feedstock for all end of life disposal options apart from landfill. Communicating these benefits will help develop the market.

Communicate benefits of ‘partial’ biopolymers
In the medium term bio-monomers will be combined with petrochemical monomers to produce existing and new materials. The sustainability benefits of these need to be quantified and communicated to packaging users and the public. It is important that they are seen to contribute to a lower environmental footprint, and not seen as ‘greenwash’.

Home composting
Support the development of a home composting standard and label for biopolymers.

Ensure waste management technologies do not exclude biopolymers
As pressure continues to be applied to recycle plastic waste and prevent it going into incineration and landfill, new technologies for waste treatment and recycling will be developed. We must ensure that biopolymers are not accidentally excluded by new waste management strategies.

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10.3. Stakeholders Interviewed

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▪ Jane Bickerstaffe	INCPEN
▪ Chris Claesen	Hycail
▪ Derek Davies	Co-Operative Retail
▪ Richard Hands	Tetrapak
▪ Harald Kaeb	IBAW
▪ Nick Morley	Oakdene Hollins
▪ Graham Rice	BP
▪ Helen Roberts	Marks and Spencers
▪ Tony Ryan	Sheffield University
▪ Warren Smith	NNFCC
▪ Florian Sommer	Forum for the Future
▪ Tony Taylor	Unilever
▪ Jeremy Tomkinson	NNFCC

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