UN environment

# Exploring the potential for adopting alternative materials to reduce marine plastic litter

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# Glossary

### Organisations and miscellaneous terms

| Acronym/term | Definition |
|---|---|
| ALDFG | Abandoned, Lost or otherwise Discarded Fishing Gear |
| Biodegradable | Biologically-mediated process involving the complete or partial converted to water, $CO_2$/methane, energy and new biomass by microorganisms (bacteria and fungi). |
| Compostable-domestic | Capable of being biodegraded at low to moderate temperatures, typically found in a domestic compost system |
| Compostable-industrial | Capable of being biodegraded at elevated temperatures under specific conditions and time scales |
| DECOIN | Organisation for the Defence and Ecological Conservation of Intaq, Equador |
| EI | Environmental Impact Index |
| ESI | Ecological Sustainability Index |
| EU | European Union |
| FAO | Food and Agriculture Organisation of the United Nations |
| GESAMP | Joint Group of Experts on Scientific Aspects of Marine Environmental Protection |
| IUPAC | International Union of Pure & Applied Chemistry |
| LCA | Life Cycle Analysis |
| NOAA | National Oceanic and Atmospheric Administration |
| PEF | Product Environmental Footprint |
| SDG | Sustainable Development Goals |
| SWOT | Analysis of Strengths, Weaknesses, Opportunities and Threats |
| UNDP | United Nations Development Programme |
| UNEA | United Nations Environment Assembly |
| UNEP | United Nations Environment Programme |

### Naturally-occurring polymers and materials

| Material | Composition, derivation or process |
|---|---|
| Abaca/Manila hemp | Cellulose, lignin & pectin from the inedible Banana *(Musa textiliis)* |
| Alginate/alginic acid | Polysaccharide (copolymer of mannuronate and guluronate ) derived from Brown seaweed *(Phaeophyceae)* |
| Alpaca wool | Keratin fibre from the alpaca |
| Angora wool | Keratin fibre from Angora rabbit |
| Araca | Araca palm *(Araca catechu)*, grown for the 'betel' nut |
| Bagasse | Waste fibrous material from agricultural production |
| Bamboo | Moso bamboo *(Phyllostachys edulis)* is most widely used species |
| Casein | Protein fibre in milk |
| Cashmere | Keratin fibre from Cashmere goats |

| | |
|---|---|
| Cellulose | Naturally-occurring polysaccharide in plant cells |
| Chitin | Naturally-occurring polyester in fungal cell walls and the exoskeleton of crustacea (e.g. shrimps) |
| Coir | Cellulose and lignin fibre from coconut outer shell |
| Cotton | Cellulose fibre from the cotton plant (*Gossypium sp.)* |
| Cutin | Waxy biopolyester in plant cuticles |
| Flax/linen | Cellulose fibre from the flax/linseed plant *(Linum usitatissimum)* |
| Fibroin | Protein fibre forming silk |
| Gluten | Protein composite found in the endosperm of cereal crops, having viscoelastic properties |
| Hemp | Cellulose fibre from the hemp plant *(Cannabis sativa)* |
| Jute | Cellulose and lignin fibres from the plant *Corchorus sp.* |
| Keratin | Protein fibre forming wool |
| Kenaf | Fibres obtained from the stems a species of the hibiscus *(Hibiscus cannabinus)* |
| Kraft paper | Paper manufactured using the kraft process, removing lignin and maintaining long cellulose fibres for greater strength |
| Lignin | Naturally-occurring polymer used to form cell walls in wood and bark |
| Maize | Species of large grain plant, also known as corn *(Zea mays)* |
| Phyllosilicate | Clay minerals with plate-like structure |
| Piña | Cellulose and lignin fibre from Pineapple leaf *(Ananas comosus)* |
| Piñatex™ | Fabric made from pineapple leaves |
| QMilch™ | Casein fibre from soured cow's milk |
| Retting | Process of extracting fibres from hemp, flax and coir by soaking in water and physical extraction |
| Seagrass | Marine species of flowering plant (angiosperms) |
| Sheep's wool | Keratin fibre |
| Silk | Fibroin fibre from the silk moth *(Bombyx mori)* |
| Sisal | Fibres obtained from a species of Agave *(Agave sislana)* |
| Staple fibre | A fibre of a defined length (natural or cut to length synthetic fibre) |
| Zein | Maize protein |

**Synthetic and semi-synthetic polymers and associated chemicals**

| Short form | Composition/full name/function |
|---|---|
| ABS | Acrylonitrile butadiene styrene resin |
| Cellophane | Semi-synthetic cellulose-based film |
| Cellulose acetate | Semi-synthetic cellulose-based fibre or film |
| BPA | Bisphenol A |
| Composite | A material composed of two or more polymers or other substances |
| EP | Epoxy resin (thermoset) |
| EPS | Expanded polystyrene |
| Ingeo™ | Fibre composed of PLA |
| Monomer | The 'building blocks' making up a polymer |

| | |
|---|---|
| PA | Nylon, Polyamide 4, 6, 11, 66 |
| PAN | Polyacrylonitrile, acrylic |
| PBDE | Polybrominated diphenyl ethers – flame retardants |
| PBS | Poly *(butylene succinate)* |
| PBSA | Polybutylene succinate-co-butylene adipate |
| PBT | Polybutylene terephthalate |
| PCBs | Polychlorinated biphenols |
| PCL | Polycaprolactone |
| PE | Polyethylene |
| PE-LD | Polyethylene low density |
| PE-LLD | Polyethylene linear low density |
| PE-HD | Polyethylene high density |
| PES | Polyester |
| PET | Polyethylene terephthalate |
| PHA | Polyhydroxylkanoates |
| Phthalate | Plasticiser |
| PLA | Poly (lactic acid) |
| PMMA | Poly (methyl) methacrylate |
| PP | Polypropylene |
| PS | Polystyrene |
| PTFE | Polytetrafluroethylene |
| PU (PUR) | Polyurethane |
| PVA | Polyvinyl alcohol |
| PVC | Polyvinyl chloride |
| Rayon | Semi-synthetic cellulose-based fibre |
| Spandex | Polyether-polyurea |
| TPS | Thermoplastic starch |
| Viscose | The most common form of rayon |

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Marine plastic debris on beach
Photo Credit: Shutterstock/

# Executive summary

The ocean has become a repository for an increasing quantity of plastics and microplastics. This has been matched, in recent years, by growing awareness of the social, economic and environmental impacts that this phenomenon is causing. There is widespread recognition that urgent action is required to reduce the leakage of plastics to the ocean, but that there is no simple solution. It is clear that the traditional linear production, use and disposal model for conventional plastics is not sustainable and results in unacceptable harm. This requires the development and implementation of more closed-loop, or circular, production models. But there is scope for assessing whether there are alternative solutions that minimise the use of conventional plastics for applications in which they are not essential.

The purpose of this study was to assess the potential of replacing conventional plastics with alternative materials in certain applications, as part of a wider strategy of reducing marine plastic litter and microplastics. The target audience is governments and businesses. This may appear a daunting task, given the ubiquity of plastics in our daily lives, described in Chapter 2, so it seemed sensible to identify certain categories of plastics that may prove more amenable to reduction or replacement. Following an assessment of the most common items reported in field surveys (Chapter 3), it was decided to focus part of the study on 'single-use' plastic waste from single-use packaging and consumer products intended for short-term use, such as food and drink containers, given the preponderance of these categories in surveys of ocean plastics, especially in shoreline debris. Another common feature of microplastics identified in surveys of biota, sediments and seawater is the abundance of micro-fibres. Micro-fibres on shorelines, especially near urban centres, consist mostly of textile fibres and this provided a second focus for the study.

Three main categories of alternative materials were considered: natural fibres (Chapter 4), biomass-based, compostable, synthetic biopolymers (Chapter 5) and re-usable durable non-plastic materials (Chapter 6). Each of the chapters considers the potential options available and then presents a series of illustrative case studies. Twenty-five case studies are presented in total. Natural fibres derived from both plants and animals were considered and their uses were illustrated in a series of case studies. This included fibres with a long history of use as well as more novel applications. The latter includes the use of fungal mycelium with biomass waste to 'grow' structures and protective packaging for delicate goods. The three main categories of compostable biopolymers considered were thermoplastic starch, poly(lactic acid) (PLA) and polyhydroxylkanoates (PHA). These can all be synthesised from waste biomass but need to be used in closed-loop systems to ensure: i) they are kept separate from recycled plastic waste streams; and, ii) they do not enter the ocean, where PLA and PHA will behave like conventional plastics and fail to degrade. One case study is presented that illustrates the use of PLA for food packaging and food canteen items in the University of Cambridge in the UK. The case studies illustrating the re-use of materials focussed on stainless steel food containers and 'up-cycling' used bamboo chopsticks and waste textiles in the clothing sector.

The following chapter (Chapter 7) places the potential use of alternative materials in the context of the UN Sustainable Development Goals and the cradle-to-cradle philosophy, including carbon-neutral, zero waste options. A specific example was described of the application of green design principles to the packaging sector. Life Cycle Analysis is a useful tool to assess the potential social, economic and environmental consequences of using different materials. All LCAs depend on making a number of assumptions about which factors to include and the weighting given to each of these as well as the value assigned. Some factors, such as energy use, are relatively easy to quantify whereas others, such as end-of life fate, are much more problematic to describe. Unfortunately, most published LCAs comparing plastics with alternative materials only consider the cradle-to-factory gate phases of the production cycle. Leaving out the end-of-life phase, and possible beneficial uses of the 'waste', means that such analyses are grossly misleading. There is a clear need for environmental economists to work with agronomists, material scientists, environmental scientists and others, to devise more realistic and reliable techniques for whole life cycle analysis assessment. Chapter 8 presents a series of suggested next steps. These encompass the need for an incremental and multi-stakeholder approach, with due attention paid to the challenges and opportunities presented in different social, economic and environmental contexts. The potential for taking forward some of the examples presented in the report is explored, including a summary of the technical and financial requirements of the various schemes, and their potential for scaling up.

This report aims to provide representative examples of some of the many alternative materials that are either available commercially, or are in development. It is intended to encourage entrepreneurs, 'start-ups' and established businesses - as well as researchers in the fields of materials science, engineering, agronomy and related fields – to explore more effective and sustainable products and practices. The overall aim should be to reduce society's dependence on the unnecessary use of plastics, especially from fossil-fuel sources. Potential solutions will need to take account of regional and local differences in the social, economic and environmental circumstances. It is important to foresee and eliminate unintended consequences; for example, putting at risk food security or affordability by using staple food crops such as cassava for non-food uses. Life Cycle Assessments are a key tool to test the sustainability of different options, but they must be sufficiently broadly based to include all the relevant factors, including how the alternative materials will behave in the environment and the degree to which different options can be scaled up. To encourage greater take up, avoid confusion and minimise misuse, it is important for regulators to ensure that the labelling of products is clear, accurate, comprehensive and understandable by users.

# 1. Background

## 1.1 Marine litter as a global issue

Plastics[1] are regarded by many as an essential part of our lives, in the 21st Century. Since their widespread introduction in the mid-1950s, the production and development of plastics has expanded dramatically, the number of applications has grown substantially, with plastics being utilised in construction, food and water provision, clothing, medicine, transport, electronics and household goods. Undoubtedly plastics have brought about a great many societal benefits, with greatest per capita use occurring in developed or large emerging economies (Figure 1.1). Unfortunately the pace of adoption has not been matched by an appreciation of the social, economic and environmental damage being caused by improper disposal of unwanted or end-of-life plastics. Perhaps as a consequence, these costs have rarely been included in assessments of the 'sustainability' of plastics production and use. We have paid insufficient attention to preventing the unnecessary use and inappropriate disposal of unwanted and end-of life plastics, with the inevitable results that we now find plastic litter on every continent, in some of the most remote regions, and throughout the ocean.

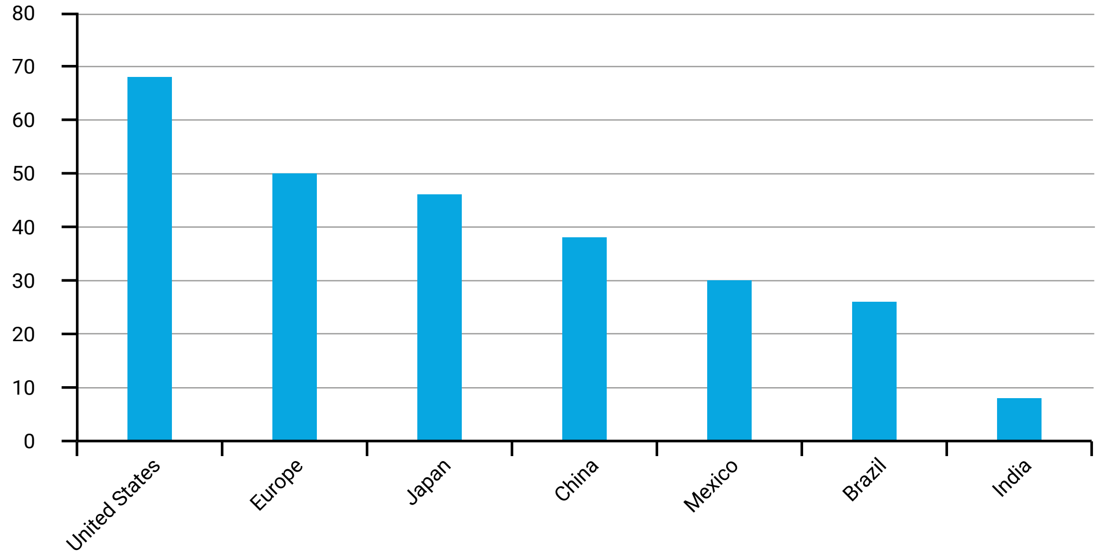

**Figure 1.1** Per capita use (kg) of plastics by region in 2014; data source https://www.statista.com[2]

Fortunately it is becoming much more widely recognised that plastic debris in the ocean represents a very significant form of pollution, with demonstrable social, economic and environmental impacts (United Nations Environment Programme 2016). It is not a new problem. Reports in the scientific literature about the occurrence and possible impact of plastics in the ocean started to emerge in 1960s and 1970s. But there was a failure to embrace the magnitude of the issue, by society in general and in part by the wider scientific community. Other forms of contamination such as heavy metals, biocides and radionuclides tended to receive more attention. 'Business as usual' continued, with land- and sea-based commercial sectors, as well as and the general public, treating the ocean as a convenient repository for waste plastics, and many other unwanted pollutants. It was not until the mid-2000s that the problem started to emerge and attract the attention of the scientific and wider community, by which time enormous quantities of plastics had entered the ocean.

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[1] Plastic is defined here as a synthetic polymer with thermo-plastic or thermo-set properties, which may be synthesized from hydrocarbon or biomass raw materials (UNEP 2016).

[2] https://www.statista.com/statistics/270312/consumption-of-plastic-materials-per-capita-since-1980

Geyer *et al.* (2017) have estimated that 8,300 million tonnes of virgin plastics have been generated to date, of which 6,300 tonnes of plastic waste has been generated, as of 2015. Of this, they estimate 9% has been recycled, 12% incinerated and 79% accumulated in landfill or the natural environment. We do not know, with certainty, the total quantity of plastics currently residing in the ocean, nor the annual incremental increase from land- and sea-based sources. What has been possible is to use proxy evidence of plastics production, use and disposal to provide estimates of what may have entered the ocean. This can be compared with estimates of what is there by combining data from sampling programmes with the results of ocean circulation models. Estimates have been made of the total production of plastics globally, and the quantities that are recycled or sent to landfill. Estimates have also been made of the quantities of plastic that may be entering the ocean as a result of inadequate land-based waste management, for example 4.8 – 12.7 million tonnes in 2010 (Jambeck *et al.* 2014). These types of study are extremely helpful in indicating the scale and geographical distribution of the problem. For example, the analysis by Jambeck *et al.* (2015), based on figures of waste generation by country from the World Bank, suggested that the leakage of waste plastic was greatest from a relatively small number of large developing economies, due to inadequate solid waste generation rather than higher per capita use.

Unfortunately, even these quite sophisticated investigations have not been able to take account of all significant marine litter sources.  Not included are direct inputs from maritime activities such as sea-based sources from shipping, fisheries and aquaculture and shipping, as well as plastics from shoreline or coastal water activities, such as beach tourism and recreational boating and fishing. Without these sources we cannot estimate the total annual inputs to the ocean. In addition, we are largely ignorant of the quantities of plastics and microplastics residing on the seabed. Despite these caveats, we can state, with a high degree of confidence, that there is too much plastic in the ocean, that it causes unwanted social, economic and environmental impacts, and that too much continues to enter each year. Consequently, an intervention is essential (United Nations Environment Programme  2016).

## 1.2 The Response

The response to tackling the issue of marine plastics and microplastics in the ocean has been focused largely around identifying 'leakage' points in the current plastic-based economy. Leakage of plastics into the environment can come at every stage of the production, manufacturing, distribution, use and disposal pathway. A common approach has been to identify these points and then intervene by designing measures to reduce or eliminate the source(s). These issues were described in some detail the report 'Marine plastic debris and microplastics – global lessons and research to inspire action and guide policy change', which was presented at UNEA-2 in May 2016 (United Nations Environment Programme 2016). This approach can be viewed as fitting into a broader strategy of adopting a more circular, or closed-loop, production cycle. This is reflected in a number of Marine Litter Action Plans developed in recent years, both at an intergovernmental (e.g. G7 countries, G20 countries, EU) and national (e.g. Indonesia) level. In general the Action Plans include involvement by local government and municipalities, the private sector – encouraging the adoption of more sustainable practices in industrial and commercial practices and business models -  and pressure from civil society.

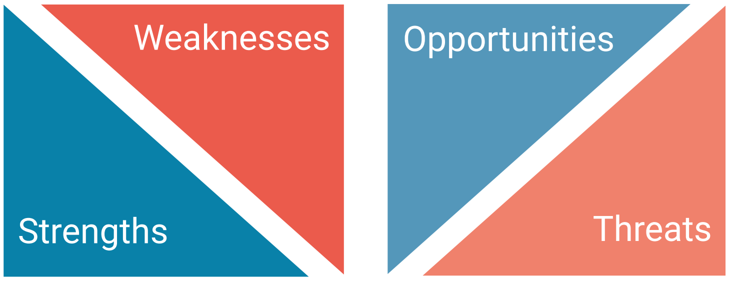
Rather less attention, at an inter-governmental level, has been paid to the potential of reducing our use of plastics altogether by exploring the wider adoption of alternative naturally available materials, particularly for short-life applications such as packaging, as well as textiles. The widespread adoption of plastics in many aspects of modern living, for reasons of cost and convenience, has proceeded without due regard to the significant social and environmental costs. This trend may lead us to ignore society's historic dependence on plants and animals for non-food use, such as clothing, shelter, textiles and food storage, over millennia.

There are many applications for which synthetic plastics provide an essential role, particularly in the medical field. But, there are applications for which plastics are not essential, and where natural materials and existing or emerging technologies may have an important part to play to wean society off an overly dependent relationship with traditional plastics. To make a significant difference, such materials will need to meet the demands of applications where they are replacing plastics. It is essential that progress is accelerated on developing and implementing a more sustainable use of resources, both for plastics and non-plastics.

## 1.3 Purpose and content of the report

This report presents a range of alternative approaches and materials that have the potential for reducing our use of plastics for a range of common applications. All alternative approaches have one thing in common with conventional polymers; they can be characterised in terms of their Strengths, Weaknesses, the Opportunities they present and the Threats (SWOT) that may be associated with their adoption. This can be neatly summarised in a SWOT analysis table (Table 1.1), and this is used as a unifying thread through the report.

Table 1.1 Presentation of a SWOT analysis



Chapter 2 describes society's current relationship with plastics and microplastics, and is intended to provide context to the following chapters. It acknowledges the great benefits that have been gained from the widespread adoption of plastics, but also identifies the unintended but significant social, economic and environmental impacts that have been experienced. We cannot rid the oceans of plastics simply by seeking alternative materials, but we can identify which types of litter occur most commonly on shorelines and in the ocean (Chapter 3), to help focus where change may have the greatest impact. The three following chapters provide examples of the use of naturally-occurring materials (Chapter 4); newer-generation biomass-based and compostable polymers (Chapter 5); and, re-usable durable objects (Chapter 6). The emphasis is on consumer products, especially for packaging applications, as these represent a major use of traditional plastics and the prime categories contributing to marine litter. The United Nations 2030 Agenda, and the Sustainable Development Goals (SDGs), provide a key framework for integrating efforts to reduce ocean plastics and microplastics with wider effects to improve human welfare and encourage more sustainable practices. Within the 2030 Agenda it is important to consider the wider social and economic context of developing different approaches, as well as the environmental consequences in the production, use and post-use phases. These issues are discussed in Chapter 7. Options for further developing options for reducing our dependence on plastic packaging and other short-lived wastes are explored in Chapter 8. The report concludes with a series of conclusions and recommendations for action.

## The #CleanSeas Campaign

UN Environment launched #CleanSeas in February 2017, with the aim of engaging governments, the general public, civil society and the private sector in the fight against marine plastic litter. So far, 43 countries have joined the campaign, and more than 80 000 people worldwide have pledged to take action to reduce their own plastic footprints.

Going forward, we will address the root-cause of marine litter by targeting the production and consumption of non-recoverable and single-use plastic. To do this effectively, we need citizens to be aware, engaged and active in addressing the problem in their own lives and beyond. We are giving a platform to hundreds of local organizations who are already doing important work on marine litter to highlight their efforts. We also need to be informed about what alternatives to plastic exist, and this report is an important contribution in that regard.

By connecting individuals, civil society groups, industry and governments, UN Environment aims to transform habits, practices, standards and policies around the globe to dramatically reduce marine litter and the harm it causes. It is time to turn the tide on plastic!

http://www.cleanseas.org/

UN Environment launch of the Clean Seas campaign in Bali, Indonesia.
Photo Credit: UN Environment/Shawn Heinrichs

# 2. Our relationship with plastic

## 2.1 Criteria for adopting plastics

The widespread adoption of plastics, from the 1950s onwards, has brought about very significant benefits for society. These benefits have rapidly been extended to most communities across the globe, and include:

1. Improved human health – medical applications
2. Improved food security – reducing food wastage from field to market, and from market to the consumer
3. Improved efficiency of resource use – e.g. lower energy and water consumption
4. Lower costs of products to the consumer (the cost excludes the external costs to society and the environment)
5. Novel applications where there are no equivalent non-plastic alternatives

The benefits of conventional synthetic polymers, together with some of the disadvantages, are summarised in a SWOT analysis (Table 2.1).

**Table 2.1 SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of conventional synthetic polymers.**

| | |
|---|---|
| S1. Improved human health outcomes from medical applications<br>S2. Packaging reduces food wastage from field to market and market to consumer<br>S3. Lower water and energy consumption in production<br>S4. Novel applications where there are no equivalents<br>S5. Lower fuel consumption in aviation and vehicular transport<br>S6. Packaging reduces damage to goods during transport<br>S7. Convenience to consumers, including for 'take-away' or 'fast-food' applications | W1. Utilises fossil fuels and is not carbon neutral<br>W2. Risk to human health during production due to exposure to chemicals, including endocrine-disrupting chemicals<br>W3. Risk to human health, social and economic well-being and the environment during use and end-of-life phases<br>W4. Very limited biodegradation in the environment, especially in the ocean, leading to rapid accumulation<br>W5. Waste management solutions are grossly inadequate in most countries<br>W6. Circular production patterns are rarely implemented |
| O1. Development of new polymers and composites for diverse applications<br>O2. Redesign of products to allow lower material use, product re-use and improved recycling potential, in a circular or closed-loop production cycle<br>O3. Utilisation of intrinsically lower risk chemicals in production and as additives to maintain performance | T1. Continuing accumulation of plastics and microplastics in the environment<br>T2. Long term consequences for human reproductive and developmental health<br>T3. Long term consequences for social and economic well-being due to impact of plastic waste |

One of the main drivers of this approach has been convenience. It can seem easier to use plastics for some applications. Another characteristic has been a reluctance to deal with plastics once the product is no longer required – the end-of-life phase. Unfortunately, convenience is often accompanied by another characteristic, the emergence of 'single-use' plastics. This is exemplified by the emergence of the ubiquitous thin-film shopping bag, which are used globally in enormous quantities (Figure 2.1). This is one area that has witnessed a number of initiatives to reduce or curtail use, including the use of fees and outright bans, providing a clear incentive to introduce alternative materials. Another example is the extensive use of plastic micro-beads in personal care products such as toothpaste and skin cleaning scrubs. Their inclusion is unnecessary. Prior to their introduction many products were produced containing a natural equivalent, such as ground nut kernels, wood fibres, mica flakes or pumice. The replacement of plastic micro-beads by such materials will not detract from the performance of the product, whether it is to clean or to provide sparkle[3].

**Figure 2.1** **The 'Bagmonster', pictured at the SDG14 Oceans Conference in New York, June 2017 UNHQ, illustrating the number of bags an individual shopper might use in a year ©Peter Kershaw**

Single-use food containers are not a uniquely modern phenomenon. Many communities in South Asia, Southeast Asia, Africa and South America have a long tradition of the sustainable use of the leaves from several species of plant to wrap, cook or serve food. Examples include the leaves of the Sal *(Shorea robusta)*, Banyan *(Ficus benghalensis)* and banana or plantain *(Musa sp.)*. There has been a decline in popularity in some regions following the introduction of plastic products[4].

The adoption of single-use, short-lived products is seen at its most extreme in the 'fast food' economy, in which plastic food and drink containers, lids, cutlery, stirrers and straws are used extensively, only to become waste sometimes just a few minutes later (see section 2.4.2). It is also seen in our use of plastics for the protection of goods in transit, and for the presentation of goods to the consumer, both edible and non-edible. It seems reasonable to ask whether all such uses are fully justified. The question could be framed as: 'is the adoption of plastics for this application useful, justified and appropriate; or useful, convenient but inappropriate?' The quest to find alternatives to plastics is probably best directed towards applications where the answer to this question is (b).

**Is the adoption of plastics for this application:**
**a) useful, justified and appropriate?**
**or**
**b) useful, convenient but inappropriate?**

Most attention in the development of applications for plastics has focussed on the part of the plastics economy that starts with the raw material and ends either at the factory gate or upon delivery to the retail outlet or customer. Most Life Cycle Analysis (LCAs) of plastics production are confined in a similar way (Chapter 7). This excludes the downstream costs of plastics use, exemplified by an almost complete absence of the social and environmental costs of plastics use in such assessments. The relatively recent upsurge in public and political interest in marine plastic litter has highlighted this

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[3] https://www.lushusa.com/Stories-Article?cid=article_all-that-glitters
[4] https://timesofindia.indiatimes.com/city/ranchi/Sal-leaf-dishes-make-way-for-plastic-ones/articleshow/13128420.cms?referral=PM

dis-connect between two competing social demands – for plastics in their myriad forms and for an environment free from plastic waste.

The proposition presented in this report is that the wider adoption on non-plastic alternative materials will allow the functions provided presently by plastics to be met at lower social and environmental cost. Before examining the potential of this approach it is necessary to look at some key aspects of the current plastics economy and society's utilisation of this broad range of materials.

## 2.2 Conventional plastics

### 2.2.1 Synthetic thermoplastic and thermoset polymers

In the present context the term 'plastic' refers to a group of synthetic polymers, composed of repeating chains of carbon-based units. The source of carbon can be from fossil fuels or biomass. There are two main groups of plastic: thermoplastics, capable of being deformed by heating; and thermoset, which cannot be re-moulded (Figure 2.2). In volume terms, the market in conventional plastics is dominated by four classes of polymer, synthesised primarily from fossil fuel sources: polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP) and polyvinyl chloride (PVC). However, there are many other plastics produced, and many new formulations based on combinations of existing polymers. Some of the most important polymers are listed in table 2.2, together with their typical applications.

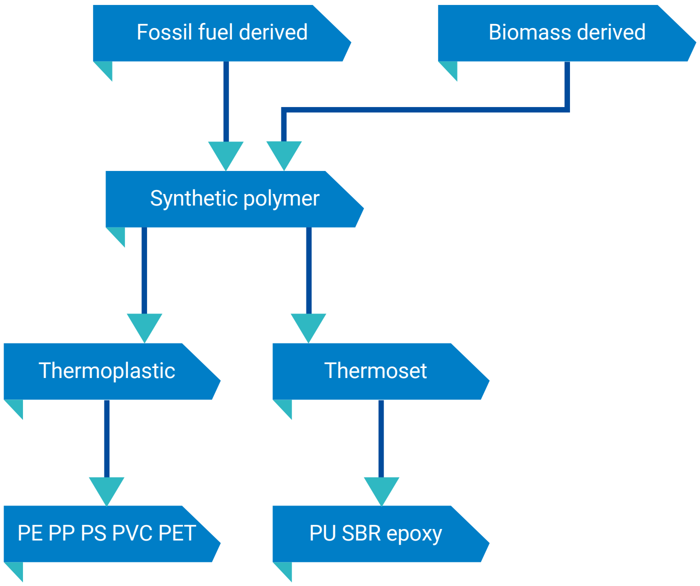

**Figure 2.2** Production of conventional synthetic plastics from fossil fuel and biomass sources (adapted from Joint Group of Experts on Scientific Aspects of Marine Environmental Protection 2015)

**Table 2.2** Typical applications by polymer, excluding fibres (adapted from Plastics Europe 2016)

| Polymer | | Typical applications |
|---|---|---|
| Acrylonitrile butadiene styrene resin | ABS | High impact parts in automobiles |
| Polybutylene terephthalate | PBT | Optical fibres |
| Polycarbonate | PC | Substitute glass in greenhouses, roofing sheets, spectacles |
| Polyethylene – low and linear low density | PE-LD<br>PE-LLD | Bags, trays, containers, agricultural film, food packaging film |
| Polyethylene – high and medium density | PE-HD<br>PE-MD | Toys, milk bottles, shampoo bottles, pipes, household goods |
| Polyethylene terephthalate | PET | Bottles for water and other drinks, dispensing containers for cleaning fluids |
| Poly(methyl) methacrylate | PMMA | Touch screens for electronic goods |
| Polypropylene | PP | Food packaging, snack/sweet wrappers, microwave-proof containers, automotive parts, bank notes |
| Polystyrene | PS | Spectacle frames, cutlery, plates and cups |
| Expanded polystyrene | EPS | Packaging, insulated food packaging, building insulation, buoyancy |
| Polytetrafluoroethylene | PTFE | Telecommunication cables |
| Polyurethane | PUR | Building insulation, insulation for fridges/freezers, foam mattresses |
| Polyvinyl chloride | PVC | Window frames, floor and wall coverings, cable insulation, |
| Other thermoset and thermoplastics | | Epoxy resins, surgical devices, seals, coatings and many other diverse uses |

European plastics demand is dominated by the packaging (40%) and construction (20%) sectors, with appreciable quantities used in the automotive (9%), electrical and electronics (6%) and agricultural sectors (3%) (Figure 2.3, Plastics Europe 2016).

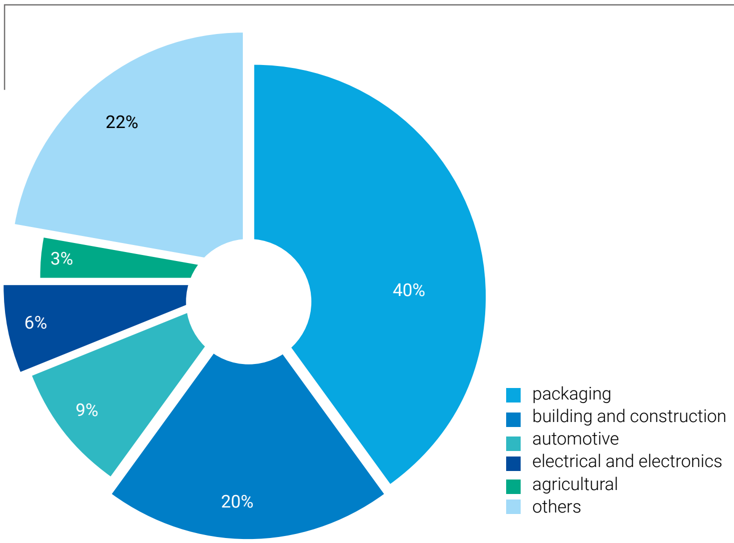

**Figure 2.3** European demand for plastics (thermoplastics and polyurethanes) by market sector in 2015 (Plastics Europe 2016)

### 2.2.2 Synthetic fibres

Synthetic polymers are widely used for the production of fibres, particularly for use in textiles and rope. Here the market is dominated by polyester (PES) and PET, which is a particular form of polyester, but there are several others that are used for more specialist applications, including: polyacrylonitrile (acrylic, PAN), polyamide (nylon, PA), polypropylene (PP) and polyether-polyurea co-polymer (Spandex) (Table 2.3, Figure 2.4). Most synthetic fibres are made from fossil-fuel sources, although a large proportion of PET fibres are made from recycled PET bottles. Fabrics are frequently manufactured using combinations of synthetic polymers and natural fibres.

Table 2.3 Synthetic polymer fibres and their applications

| Polymer | | Typical applications |
|---|---|---|
| Polyacrylonitrile | PAN | Thermal clothing, fire-resistant fabrics, carpets, protective clothing, hair extensions, faux fur |
| Polyamide (aliphatic) | PA | Nylon PA6, PA 66 – clothing, other textiles, rope, fishing line |
| Polyamide (aromatic) | PA | Body armour, racing sails, bicycle tyres, rope e.g. Kevlar™ |
| Polyester | PES | Clothing, other textiles |
| Polyethylene terephthalate (polyester) | PET | Outdoor clothing, other textiles |
| Polypropylene | PP | Thermal clothing, sleeping bag filler |
| Polyether-polyurea | Spandex | Sportswear, swimwear, under-garments e.g. Elastane, Lycra™ |

The market in synthetic fibres is dominated by polyester (Figure 2.4), and production has increased substantially compared with cotton (Figure 2.5).

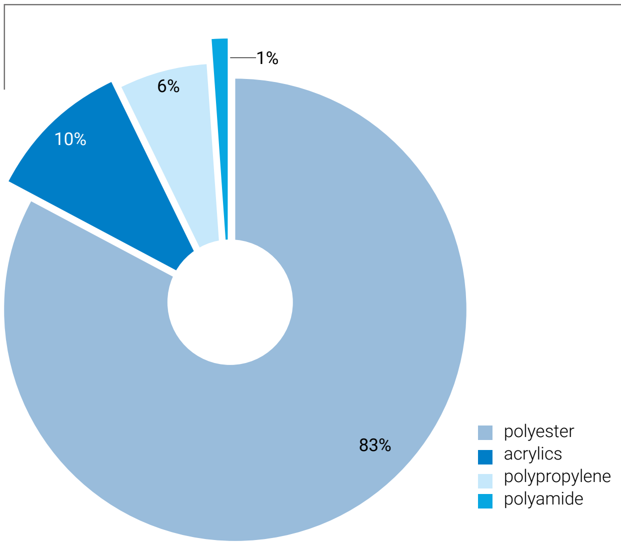

Figure 2.4 Synthetic staple fibre production, 2014 (The Fiber Year Consulting 2015).

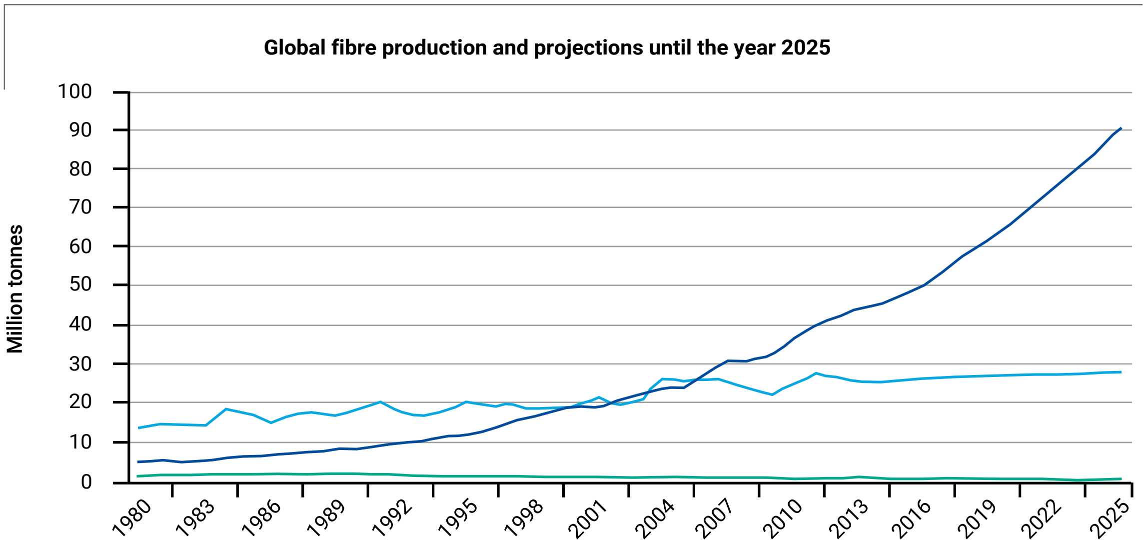

**Figure 2.5** Global fibre production (million tonnes) of polyester, cotton and wool, to 2025; reproduced from Lusher *et al.* 2017; data source Tecnon OrbiChem.

Natural and synthetic fibres occur in two forms. Staple fibre is characterised as a fibre of a particular length, either occurring naturally (wool, cotton) or cut to length (synthetics). Filament fibres are produced in near continuous form and may occur naturally (e.g. silk) or be synthesised and left uncut.

Fibre production represents about 15% of total synthetic polymer production (Figure 2.6, based on Lusher *et al.* 2017). Most production of synthetic fibres is occurs in Asia (80%), followed by 11% Europe (11%), the Americas (7%) and the rest of world (2%).

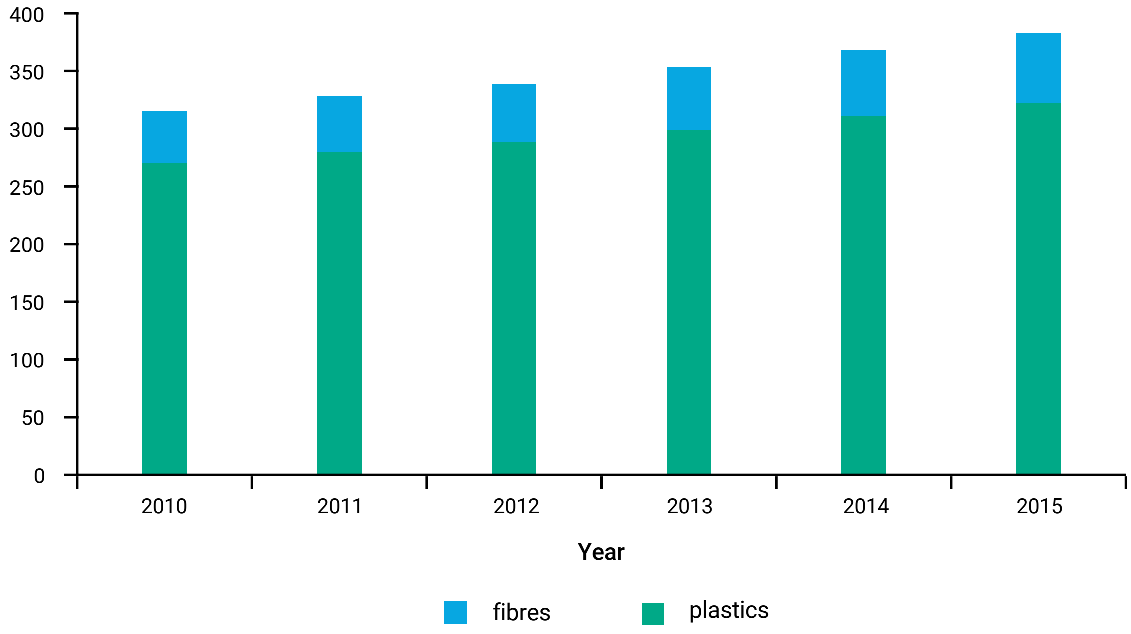

**Figure 2.6** Global production of plastics (thermoplastics, thermosets, polyurethanes, adhesives, coatings and sealants) and synthetic fibres (PA, PE, PP, PUR, PET, acrylic and PES fibres); from data compiled by Lusher *et al.* 2017.

### 2.2.3 Human health aspects

The introduction and widespread adoption of plastics in so many aspects of our lives has brought about enormous benefits. Unfortunately, there have been many unwanted consequences resulting in impacts on human society and the environment, including due to chemical hazards associated with plastics production (Lithner *et al.* 2011). This has led to some significant impacts on human health, particularly for those people who have experienced occupational exposure during plastics manufacture. Well documented examples include the increased incidence of certain cancers amongst workers exposed to styrene monomer in the reinforced plastics industry (Ruder *et al.* 2016, Christensen *et al.* 2017); and a number of conditions in workers exposed to vinyl chloride monomer (VCM) such as genotoxicity, liver cancer and neurological dysfunction, collectively called VCM disease (Wang *et al.* 2011). A summary of hazard rankings for selected polymers is presented in Table 2.4.

**Table 2.4 Ranking of selected polymers based on the hazard classification component monomers, based on Lithner *et al.* (2011), which should be consulted for more comprehensive hazard rankings and explanation of the methods used. The hazard score for some polymers will vary depending on the plasticiser used (e.g. PVC) or the incorporation of another monomer (e.g. PAN)**

| Polymer | Monomer(s) | Hazard level | Hazard score |
|---|---|---|---|
| Polyurethane (PUR) | Propylene oxide, ethylene oxide | V | 13,844 |
| Polyacrylonitrile (PAN) | Acrylamide | V | 11,521 |
| Polyvinyl chloride (PVC) - plasticised | Vinyl chloride | V | 10.551 |
| Acrylonitrile–butadiene–styrene (ABS) terpolymer | Styrene, acyonitrile | V | 6,552 |
| Epoxy resin DGEBPA) | Bisphenol A | V | 4,226 |
| Polycarbonate (PC) | Bisphenol A, phosgene | IV | 1,177 |
| Polymethyl methacrylate (PMMA) | Methyl methacrylate | IV | 1,021 |
| Polyamide 6 (PA) (nylon 6) | ε-caproamide | II | 50 |
| Expanded polystyrene (EPS) | Styrene | II | 44 |
| Polystyrene (PS) | Styrene | II | 30 |
| High-density polyethylene (HDPE) | Ethylene | II | 11 |
| Linear-low-density polyethylene (LDPE) | Ethylene | II | 11 |
| Linear-low-density polyethylene (LLDPE) | Ethylene | II | 10 |
| Polyethylene terephthalate (PET) | Dimethyl terephthalate, ethylene glycol | II | 4 |
| PP | Propylene | I | 1 |
| PVAc | Vinyl acetate | I | 1 |

Applications of single-use plastics in medicine include disposable syringes, intravenous bags, dialysis tubing and surgical gloves, with great benefits to patients and workers. However, even within the healthcare sector concerns have been raised about the resultant exposure to endocrine disrupting chemicals characteristics of certain polymers and products (North and Halden 2013).

The association of endocrine disorders with a range of environmental stressors has been reviewed by Maqbool *et al.* (2016). Chemicals with endocrine disrupting (EDCs) properties include a range of pesticides, additives in plastics (Table 2.5) and Persistent Organic Pollutants (POPS) such as PCBs. In-vitro studies have demonstrated very significant impacts due to exposure to EDCs (Yang *et al.* 2011). Epidemiological evidence has been reported of the link between endocrine-disrupting chemicals and the incidence of breast cancer (Brophy *et al.* 2012), diabetes (Velmurugan *et al.* 2017), metabolic syndrome (Halden 2010), cardiovascular and reproductive health (Mariana *et al.* 2016). Foetal brain development is influenced by the maternal endocrine system. Exposure to certain phthalates in late pregnancy has been linked to a range of neurobehavioural problems in boys (Kobrosly et al.2014) and abnormal sexual maturation, including low sperm quality (Bergman *et al.* 2013). The ubiquity of EDCs in the home provides a ready source for potential low-level but persistent exposure, which may occur via a variety of routes including ingestion and inhalation. Establishing more reliable dose-response data requires further research, including exposure in the womb and during early life stages, when the risk may be greatest (Koch and Calafat 2009, Meeker *et al.* 2009). A useful literature review on plastics, gender and the environment has been compiled by Lynn *et al.* (2016)[5].

**Table 2.5** **Examples of common plastic additives, associated functions, potential effect and status under the Stockholm Convention**

| Additive | Function | Effect | Listing under Stockholm Convention[a] |
|---|---|---|---|
| Phthalates | Plasticiser used to soften plastics, especially PVC | Endocrine disruptor | |
| Nonylphenol | Antioxidant and plasticiser | Endocrine disruptor | |
| Bisphenol A (BPA) | Antioxidant and plasticiser (PP, PE, PVC) | Oestrogen mimic | |
| Brominated flame retardants (BFR) | Reduce flammability | Endocrine disruptor | |
| hexabromobiphenyl | Reduce flammability | Endocrine disruptor | Elimination |
| hexabromocyclododecane | Reduce flammability | Endocrine disruptor | Elimination[b] |
| commercial penta, octa and decabromodiphenyl ether | Reduce flammability | Endocrine disruptor | Elimination |
| Short-chain chlorinated paraffins (SCCP) | Plasticiser, reduce flammability | Carcinogenic | Elimination |
| Pentadecafluorooctanoic acid (PFOA) | Surfactant in production of fluropolymers and as water and stain protection on textiles | Carcinogenic | Under consideration |

[a] as of October 2017; [b] special exemption for the production and use of HBCD in EPS for buildings

Greatest exposure from ECDs may be expected to occur in occupational settings, where exposure may be prolonged over many years. This appears to be the case for workers in the automotive plastics industry, for example by exposure to mists and vapours during injection moulding (Brophy *et al.* 2012). Female workers in this industry, who account for approximately 28% of the workforce in North America, reported abnormally high occurrences of breast cancer and reproductive disorders. Overall, women in this sector had a three-fold increase in the risk of developing breast cancer compared to the control group, according to one Canadian study, with the risk increasing to five-fold in pre-menopausal women (Brophy *et al.* 2012).

This phenomenon is not limited to the plastics industry. Higher incidences of breast cancer have been observed in female workers in the agricultural sector following exposure to pesticides. One difficulty in proving that these and similar endocrine disorders are related to occupational or environmental exposure is the lack of adequate epidemiological studies. The same is true when looking at the incidence and causes of development abnormalities, where exposure may have occurred in the womb or during early life stages (Halden 2010, Kobrosly *et al.* 2014).

A concise but comprehensive consensus statement on the impact of endocrine disruption, based on the published scientific literature, has been compiled by Bergman *et al.* (2013). This provides a summary

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[5] http://www.wecf.eu/english/publications/2017/Gender-and-Plastics.php

of major UN report produced jointly in 2013 by the United Nations Environment Programme and the World Health Organisation (Berman *et al.* eds. 2013). A further complicating factor is that the workplace may represent the source of a number of additional toxic and carcinogenic compounds (Fenga 2016). Separating the contribution of these various environmental stressors may be challenging. However, it is clear that the substantial increase in endocrine-related disorders, and the potential contribution of plastics, requires urgent attention.

> **Female workers in the automotive plastics industry in Canada have a three-fold increased risk of developing breast cancer due to exposure to endocrine disrupting chemicals.**
>
> **Brophy et al.2012**

Concern about the impact of plastics on human health extends to the end-of-use phase. Recycling is often heralded as the most important aspect of preventing plastics from ‘leaking’ into the environment and promoting a more closed-loop plastic production cycle (see section 2.5 on the plastics economy). Unfortunately workers employed in the commercial recycling sector can be exposed to damaging levels of a number of compounds. There is a well-developed import-export trade in waste plastic, with much of the waste from Europe and North America (the regions with the greatest per capita use) ending up in India, China and West Africa, where working conditions and compliance with regulation may be poor (United Nations Environment Programme 2016). For example, a study amongst workers engaged in the recycling of plastic e-waste in China demonstrated that exposure to VOCs, during the recycling of PS, PA, ABS and PVC, resulted in a significant increase in the lifetime risk of developing cancer (He *et al.* 2015).

One major area of uncertainty remains the risk to health from exposure to nano-sized plastic particles. Most research on nano materials has focussed in the behaviour of nano-metals, such as nano-gold, and it is unclear to what extent the results are relevant to nano-plastics due to differences in the surface properties (Bouwmeester *et al.* 2015). Wick *et al.* (2010) reported that nano-sized particles of polystyrene (PS) up to 240 nm in diameter were able to cross the human placental barrier. The study used a perfusion technique on placentas retrieved at full term. However, a later study demonstrated that the placenta perfusion model was subject to significant artefacts, including migration of the fluorescent dye across cell membranes, which raises uncertainties on the validity of the conclusions in the original study (Grafmueller *et al.* 2016). This is an area of research requiring much greater attention. .

The point of raising these concerns is not to vilify plastics in general, but to illustrate that our use of plastics comes with certain risks to human health. Some of these risks are associated with plastics manufacture and others with use or the end-of-life stage. These risks need to be more widely recognised by manufactures, regulators and users. This will allow the risks to be better quantified and more effective steps adopted to minimise them, with stakeholders acting in partnership (Thompson *et al.* 2009). Equivalent risks to human health from EDCs occur in other sectors, such as agriculture. Any initiatives to substitute conventional plastics with alternative materials need to take such risks into account, for example from the use of biocides or the inclusion of additive chemicals to enhance the properties of the finished goods (e.g. dyes, flame retardants, water-proofing surfaces). Otherwise there is the potential for one set of risks to be replaced by a different but still unwanted set of new risks.

### 2.2.4 Degradation of synthetic polymers in the environment

Almost all conventional polymers share one common feature: they are very durable. Weathering, cracking, weakening and fragmentation will occur in the terrestrial environment, given suitable conditions of high temperature, oxygen availability and exposure to UV irradiation. However, further degradation and eventual conversion to simple molecules of methane, carbon dioxide and water by the process of biodegradation is extremely slow, and this sequence appears to be delayed almost indefinitely in the marine environment (United Nations Environment Programme 2015, Joint Group of Experts on Scientific Aspects of Marine Environmental Protection 2016). A table of definitions of degradation, biodegradation and compostable is provided in Table 2.6. The inclusion of metal-based additives to accelerate the fragmentation of plastic PE films, to produce 'oxo-degradable' plastics merely increases the rate of production of microplastics, and does not reduce the quantity of the polymer in the environment. In addition, the inclusion of such polymers in waste streams can compromise the quality of recycled plastics (Department for Environment, Food and Rural Affairs 2010) 'Oxo-degradable' plastics should not be considered an 'environmentally-friendly' alternative to conventional plastic films (International Biodegradable Polymers Association & Working Groups 2005, European Bioplastics 2015, United Nations Environment Programme 2015).

**Table 2.6 Definitions of degradation, biodegradation and compostable**

| Term | Definition |
|---|---|
| Degradation | The partial or complete breakdown of a polymer due to some combination of UV radiation, oxygen attack, biological attack and temperature. This implies alteration of the properties, such as discolouration, surface cracking, and fragmentation |
| Biodegradation | Biologically-mediated process involving the complete or partial converted to water, $CO_2$/methane, energy and new biomass by microorganisms (bacteria and fungi). |
| Compostable – industrial (C-i) | Capable of being biodegraded at elevated temperatures under specified conditions and time scales, usually only encountered in an industrial composter (standards apply) |
| Compostable – domestic (C-d) | Capable of being biodegraded at low to moderate temperatures, typically found in a domestic compost system |

Some polymers synthesised from fossil fuels have been reported to have show biodegrading properties, but the extent and rate of degradation is critically dependent on the conditions that the material is subject to. In some cases, the claim of 'biodegradability' may not be matched by the environmental conditions in which the material is used.

## 2.3 Semi-synthetic biomass-based fibres and films

### 2.3.1 Materials, biomass sources and uses

Semi-synthetic fibres and films are produced from biomass, principally cellulose. Cellulose is the most abundant organic polymer on the planet. It is a relatively 'stiff' polysaccharide with an important structural role in supporting plant cell walls. The source of cellulose can include agricultural waste, wood chips, or crops grown specifically for use as a raw material, such as bamboo, in particular the fast-growing moso bamboo *(Phyllostachys edulis)*, native to China. The term semi-synthetic is used because the raw product is transformed using a variety of chemical processes. The main materials produced include vulcanised rubber, rayon fibres, cellophane™ and cellulose acetate fibres and films (Figure 2.7). These all require chemically-intensive processing to extract and separate the cellulose (Blanc 2016). Fibres and films are produced by extrusion through spinnerets or slits.

There are several forms of rayon, which differ in the source of cellulose or the chemistry of the production methods (Table 2.7). The viscose method dates from the late 19th century, and became the most common production method. Wood pulp is dissolved with aqueous sodium hydroxide and carbon disulphide, producing a viscous solution, resulting in the labelling of the fibres and fabrics as Viscose. The method allows the inclusion of lignin in addition to cellulose in the raw material, making wood a convenient source. This is extruded through spinnerets to produce rayon fibres.

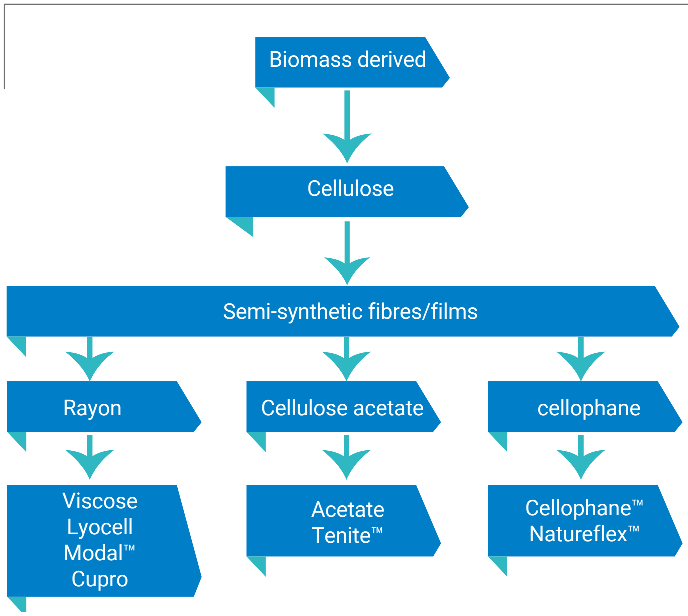

**Figure 2.7** Production of semi-synthetic fibres and films from biomass sources

The form of rayon known as Lyocell (originally developed as Tencel®) involves the dissolution of wood chips using either the sulphite process (sulphurous acid) or the sulphate (kraft) process, to produce a pulp from which most of the lignin and hemicellulose has been removed. The pulp is then dissolved in N-methylmorpholine N-oxide, filtered and passed through spinnerets to produce Lyocell fibre. Modal® is made from beech wood, and is one of several forms of rayon currently produced by Austrian company Lenzing using the viscose method, but in a closed-loop chemical process (Shen *et al.* 2010).

Cupro is a form of rayon made from cellulose derived from cotton linter, ultra-fine fibres that adhere to the seeds after the initial separation with a cotton gin. The cellulose is dissolved in a solution of ammonia and copper oxide (cuproammonium process). It is often used as a substitute for silk in fashion garments.

Cellophane, the thin transparent film, is made with cellulose from a variety of sources, using the viscose process, with glycerin added to increase flexibility. It was invented in 1900, and is still produced commercially. It is marketed as a 'breathable' film for the packaging of cheese and bread, and can be used as an ovenproof wrapping for cooking food. Cellophane is often marketed as 'biodegradable', but should more correctly be labelled as compostable. The rate of microbial degradation can be inhibited by the use of polymer coatings which are commonly applied to improve the barrier resistance and to extend shelf life (Benyathiar *et al.* 2015). Unintentionally, the polymer coating may inhibit the subsequent degradation of the products.

Cellulose acetate is produced from purified cellulose, usually from wood pulp or cotton. It is reacted with acetic acid and acetic anhydride before being dissolved in acetone. Cellulose acetate fibres are created by extrusion as filaments through spinnerets. The solvent is evaporated in warm air via dry spinning, producing the acetate fibres. It is sometimes combined with other polymers to improve performance (e.g. flexibility, durability) but this may affect end-of life behaviour and waste treatment. It is used to manufacture photographic film and textiles, but perhaps is most familiar as the main ingredient of cigarette filters.

**Table 2.7** Semi-synthetic fibres and films: types, biomass source, manufacturing process and common uses

| Product | Common biomass source | Chemical process | Uses |
|---|---|---|---|
| **Rayon** | | | |
| Viscose | Bamboo, cotton, hemp, wood pulp | Sodium hydroxide and hydrogen disulphide | Clothing fabrics |
| Lyocell (formerly Tencel®) | Oak & birch trees | Sulphurous acid or sulphate (kraft) process, followed by dissolution in N-methylmorpholine N-oxide | Clothing fabrics |
| Modal® | Beech wood | Sodium hydroxide and hydrogen disulphide | |
| (closed-loop in Lensing factory, Austria) | Clothing fabrics | | |
| Cupro | Cotton linter | Cuproammonium (ammonia and copper oxide) | Clothing fabrics |
| **Other materials** | | | |
| Cellophane | Cotton, hemp, wood pulp | Sodium hydroxide and hydrogen disulphide | Packaging, food contact packaging, adhesive tape |
| Natureflex™ (Cellophane) | Cotton, hemp, wood pulp | Sodium hydroxide and hydrogen disulphide | Packaging, food contact packaging |
| Cellulose acetate | Cotton, wood pulp | Acetic acid, acetic anhydride, sulphuric acid, acetone | Photographic film, clothing fabrics, cigarette filters |

## 2.3.2 Human health aspects

The marketing of viscose is often couched in terms of advertising its 'green credentials', on the basis that the raw material is from a renewable resource. This reputation may be enhanced if the source of the cellulose is waste organic matter or bamboo, a fast growing crop that requires relatively little additional fertiliser or pesticide use. However, the use of carbon disulphide represents a substantial health risk to unprotected workers. There appears to have been scant regard for occupational health and the health of residents living close to manufacturing facilities, throughout most of the history of viscose production (Blanc 2016).

> **The production of viscose using carbon disulphide continues to have significant health impacts for the workforce and local inhabitants, especially in parts of Asia.**
>
> **Blanc 2016**

Although improvements to workers' welfare started to be introduced in the last decades of the 20th century in North America and Western Europe, there is continuing concern about occupational health for workers in some parts of the world, especially in Asia. In some countries the use of closed-loop chemical processing systems is less common, and the chain of custody may be more difficult to establish (Blanc 2016). This needs to be accounted for when conducting comparative Life Cycle Analyses of different types of synthetic, semi-synthetic and natural materials (Chapter 7).

### 2.3.3 Behaviour of rayon fibres, cellophane and cellulose nitrate in the environment

The behaviour of semi-synthetic fibres and films in the environment has received less attention than that of conventional synthetic polymers, particularly in the marine environment. However, some observations can be made from the results of monitoring activities (Chapter 3). The widespread occurrence of rayon fibres and cellulose acetate cigarette filters in the ocean implies a limited degree of degradation, even if the rate has not been quantified (Table 2.8).

**Table 2.8** Semi-synthetic polymers with a qualitative assessment of biodegradable and composting properties (based on reported observations, where available, otherwise estimated): domestic composting C-d, industrial composting C-i, biodegradable B; degradation rate: high H, medium M or low L; qualitative sustainability indicator: blue high, medium purple, low red).

| Material | Polymer | Terrestrial | | | Aquatic |
|---|---|---|---|---|---|
| | | **C-d** | **C-i** | **B** | **B** |
| Viscose fibres | Rayon | L | H | L | L |
| Lyocell fibres | Rayon | L | H | L | L |
| Modal fibres | Rayon | L | H | L | L |
| Cellophane | Cellophane | L | H | L | L |
| Cellulose acetate | Cellulose acetate | L | H | L | L |

The relative benefits and disadvantages of semi-synthetic cellulose-based fibres and films are summarised in a SWOT analysis in Table 2.9.

**Table 2.9** SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of semi-synthetic cellulose-based fibres and films as a substitute for conventional synthetic polymers.

| | |
|---|---|
| S1. Utilises renewable natural resources<br>S2. Sources of cellulose are readily available in most developing and developed countries,<br>S3. Can be composted in an industrial facility or decomposed by anaerobic digestion at end-of-life<br>S4. Lost-cost substitute for natural fibres<br>S5. Can be used for food contact | W1. Risk to human health during production due to exposure to harmful chemicals<br>W2. Biocides and artificial fertiliser may be used on commercial crops, resulting in risks to human health and the environment<br>W3. Substitution for conventional polymers limited by intrinsic properties of the material<br>W4. Fibres and films may remain in the aquatic environment for several years before degrading, posing a risk to social well-being and the environment |
| O1. Expanded utilisation of renewable natural resources | T1. Loss of habitat and biodiversity<br>T2. Intensification of production will drive greater use of biocides and artificial fertiliser, and hence increased risks to human health and the environment<br>T3. Use of agricultural land for non-food use may drive up prices and impact food security |

## 2.4 Microplastics

'Microplastic' is a term that has been adopted within the past decade to describe pieces of synthetic polymer of 5mm diameter or less (Joint Group of Experts on Scientific Aspects of Marine Environmental Protection 2015). This definition is rather arbitrary but is sufficient to designate a class of plastics that tend to exhibit different behaviours from larger items of plastic. A further division is often made to distinguish 'primary' and 'secondary' microplastics, according to their origin. 'Primary' microplastics are those that are purposefully manufactured to a particular size or shape to fulfil a specific purpose. These include plastic resin pellets used to transport the initial plastic resin between production facilities; powders used for the injection moulding of manufactured goods; abrasive powders used for industrial applications (e.g. hull cleaning); and, micro-beads used in some domestic cleaning and personal care products (e.g. toothpaste, facial scrubs). 'Secondary' microplastics represent fragments, flakes or fibres, that originated from a larger item, either before entry into the environment or afterwards. The principal sources and composition of secondary microplastics are summarised in Table 2.10.

One of the main areas of concern is the potential harm caused by the ingestion of microplastics by marine organisms, both to the organism and potentially to human consumers of seafood (Lusher *et al.* 2017). Interaction with microplastics could cause direct physical damage or indirect damage through an inflammatory response to an ingested particle. Alternatively, there may be a satiation effect where the organism feels full, but the 'food' lacks nutrition and cannot be readily digested. In addition, there is the potential for harm due to the leaching of chemicals from within the polymer. There are three possible sources of chemical contamination:

i. monomers, or building blocks, making up the polymer – some are intrinsically hazardous but the degree of hazard varies substantially (Table 2.4);
ii. additive chemicals included to adjust the properties and performance of the polymer, for example: UV resistance, flexibility, flame retardation and colour (Table 2.5) – in many cases these chemicals are not strongly bound within the plastic matrix so will tend to leach into the surrounding environment (some additives are subject to review and regulation under the Stockholm and Rotterdam Conventions[6]);
iii. absorbed contaminants – many persistent organic pollutants already present in the environment (e.g. PCBs, PBDEs, DDT) are preferentially absorbed by plastics, with the potential for being desorbed into an organism after ingestion, in the different chemistry of an animal's gut (Joint Group of Experts on Scientific Aspects of Marine Environmental Protection 2016).

**Table 2.10 Characteristics of secondary microplastics: common polymers, typical applications and potential for microplastic generation by shape category.**

| Polymer | Typical applications | Potential for secondary microplastic generation during use |
|---|---|---|
| PAN | Acrylic fibres, clothing, yacht sails, fire-resistant textiles | Fibres from washing, wear and tear |
| PUR | Foam insulation, carpet underlay, sports clothing | Fibres and fragments from wear and tear |
| PC | Drinking vessels | Flakes and fragments due to damage |
| PA (nylon 6) | Textiles (clothing, carpets) | Fibres due to washing and wear and tear |
| PS | Disposable food and drink containers and cutlery | Fragments and flakes due to wear and tear and damage |
| EPS | Construction insulation, fresh food storage (e.g. fish), 'takeaway' containers, flotation devices | Fragments and flakes due to wear and tear, damage during installation and removal |

Contd...

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[6] http://www.brsmeas.org/

**Table 2.10** Characteristics of secondary microplastics: common polymers, typical applications and potential for microplastic generation by shape category.

| | | |
|---|---|---|
| HDPE | Drinks bottles, bottle caps, piping, storage containers | Fragments and flakes due to wear and tear |
| **Polymer** | **Typical applications** | **Potential for secondary microplastic generation during use** |
| LDPE | Plastic bags, food wrap, food and drink cartons, snap-on lids | Flakes due to wear and tear |
| LLDPE | Plastic bags, food wrap, food and drink cartons, flexible tubing | Flakes due to wear and tear |
| PP | Potable plumbing, textiles (clothing, carpets), rope, sanitary products, sutures | Fibres due to washing, wear and tear |
| PVAc | Paper coating, adhesives, sanitary products, water-soluble bags | Flakes (short-lived) |
| PET | Drink bottles, clothing | Fibres from washing, fibres and flakes from wear and tear |
| PLA[a] | Food and drink containers | Fragments and flakes due to wear and tear |

[a] PLA is a biomass-based biopolymer, see Chapter 5

## 2.5 The plastics economy

### 2.5.1 Introducing the 3 Rs

There is a widespread recognition that the current use of resources to manufacture conventional plastics is inefficient, and that end-of-life solutions for unwanted plastics are wholly inadequate; i.e. the current plastics economy is unsustainable. This has led to the promotion of a great number of initiatives to promote improved stewardship under what is often described as the 3 Rs principle: Reduce, Re-use and Recycle (Figure 2.8). It is possible to introduce further elaborations on this theme, for example to include re-design, refuse (to use) and replace, creating the 6 Rs (United Nations Environment Programme 2016). However, the 3 Rs is a more familiar and widely accepted term, especially in East Asia where the number three has special significance and the term is being incorporated into national and regional marine litter action plans. Opportunities to replace conventional plastics with alternative materials will be considered in more detail in Chapters 4, 5 and 6.

Two factors that are frequently cited as inhibiting the wider application of the 3 Rs principle are cost and scale. It can appear more expensive to re-use or recycle plastics than to generate new plastics from fossil fuel-based resources. Critically, the social, economic and environmental costs of the damage caused by waste plastic in the environment are rarely taken into account. This will be examined further in Chapter 7, together with a comparison of the relative costs of alternative materials.

Plastics recycling can be an effective solution to reducing the leakage of plastics into the environment. However, there are a number of factors that can reduce the effectiveness of this approach. For example, some single-use drinks bottles can be difficult to recycle because design considerations have been market-led (e.g. use of several polymers and colours) rather than concerned with improving the end-of-life waste management of the product (Harrabin 2017). Single-use coffee cups and packets for food snacks are often composed of mixed materials, with limited options for recycling. The contamination of food packaging by residual food waste may also limit the recycling potential. In addition, the Stockholm Convention does not permit the recycling of plastics containing POPs (under Article 6), although penta-BDE and octa-BDE will be allowed until 2030 provided the Secretariat is notified. A report presented at the 8th Conference of the Parties (COP 8) revealed that BDEs had been found in a range of articles that were not subject to flammability requirements, including children's toys. It was concluded that this had arisen inadvertently from the use of recycled plastic containing BDEs.

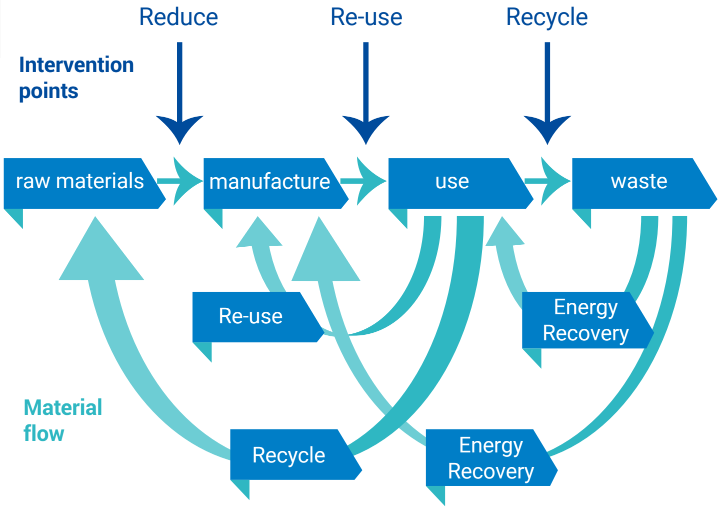


**Figure 2.8** Closing the loop within the plastic economy, showing options for re-using, recycling and recovering energy, within the globally-understood 3 Rs principle of Reduce, Re-use and Recover (adapted from United Nations Environment Programme 2016).

Figure 2.9 Clothing label illustrating the source of PET fibres, from recycled bottles, ©Peter Kershaw

Recycling can also lead to unintended consequences. PET drinks bottles are readily recycled, but about 80% of recycled PET is used for fibre production rather than producing new PET bottles (Figure 2.9). Fibres are readily lost from fabrics during wear and washing, and this represents a significant source of microplastics to the environment (Chapter 3).

Some polymers, such as EPS, are inherently difficult to recycle. Inevitably the best option will be collection for energy regeneration, with landfill the second best, but with great scope for waste generation and littering in areas of use such as construction, durable goods protection and food packaging. As packaging forms such an important component of the plastics economy it is worth considering in more detail.

### 2.5.2 Plastic packaging and the throw-away catering industry

Packaging can help to minimise food waste from harvesting to market, preserve food in storage and ensure food is delivered to the consumer in a safe and edible condition. When used appropriately, packaging confers enormous benefits to society, whether manufactured from plastics or more natural materials. Unfortunately, the use of food packaging can be problematic for a number of reasons: the type of material may be inappropriate; the design of the packaging may make re-use or recycling difficult; or, the use of packaging may be excessive or unnecessary. This third point is explored in this section.

Food packaging composed of conventional polymers is used widely in the catering industry, particularly for take-away and 'fast-food' outlets. There is great scope for littering and rather limited scope for waste collection, separation and recycling, even where the consumers are constrained in some way, for example within the security zone of an airport (Figure 2.10).

Unfortunately, there is a tendency for the use of plastic packaging and implements to become the norm, even when it would be quite feasible to offer an alternative, such as in institutional settings such as hospitals, commercial premises and government or IGO buildings (Figure 2.11).

**Figure 2.10** A selection of food for consumption, but only a single option for purchase – in plastic packaging; JFK airport New York, June 2017 ©Peter Kershaw.

**Figure 2.11** The short life of a plastic lunch container, plastic cutlery, plastic drinks bottle and plastic cup: International Institutional staff canteen, June 2017 © Peter Kershaw.

In the case of the institutional canteen, plastics, aluminium and glass are allocated one waste bin, paper and cardboard a second bin, with everything else allocated the third bin for 'general trash'. There is no separate bin for food waste. As Figure 2.11 reveals, users of the canteen are not very efficient at sorting their waste. Food-contaminated packaging makes recycling conventional plastics more problematic, and may lead to a higher proportion going to landfill or diverted to energy recovery (Figure 2.12). The useful life of the packaging, in this example, is approximately 15 - 20 minutes.

The use of plastic may be presented as a novel alternative to a traditional application, where the implied benefit is of questionable value. An example is the introduction of the plastic teabag, individually wrapped in plastic film, replacing the traditional natural fibre bag which is usually presented either separately in a small paper wrapper or in bulk in a cardboard box (Figure 2.13). This appears to be a case of unnecessary and wasteful 'innovation' to improve the marketability of an everyday product. Unfortunately, there are many other examples, including plastic straws, cotton bud sticks, toothpicks and lolly sticks for icecream and other sweets. Options for reducing the use of conventional plastics in food packaging, and reducing the overall impact of food packaging in the marine environment will be considered in later Chapters.

**Figure 2.13** A wasteful breakfast - a plastic mesh teabag, presented in a plastic wrapper, Bremen Germany, May 2017, ©Peter Kershaw.

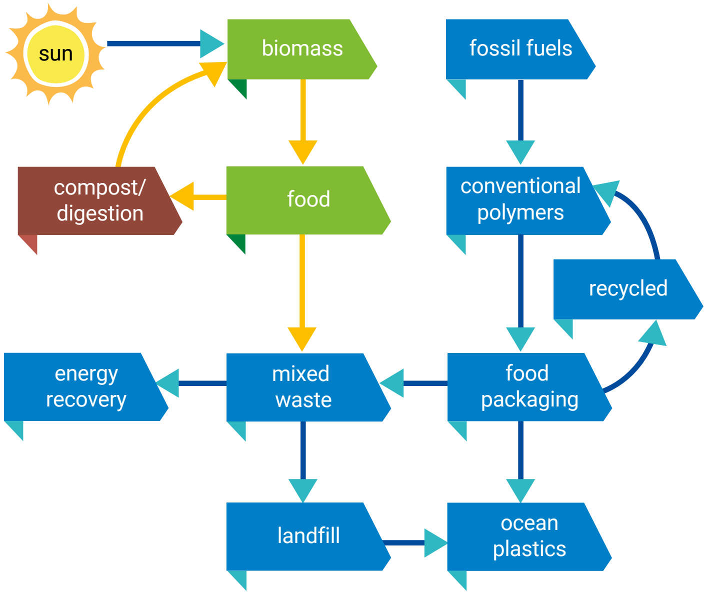


Figure 2.12 Simplified schematic of the production and fate of food packaging made from conventional plastics (original by P J Kershaw).

## 2.5.3 Plastic packaging and durable goods

Many durable goods need to be protected during transit. Not to do so would result in unnecessary damage and be a waste of resources. However, there is great scope for reducing the impact of such packaging on the environment in the selection of the packaging design and materials used.

Expanded polystyrene (EPS) is commonly used as pre-formed protective moulds around electronic goods, and as loose fill (Figure 2.14). Much of this material is consigned to landfill as recycling EPS is difficult and few facilities exist, even in the most developed economies. The very nature of the polymer means that a proportion of waste EPS it is very likely to leak to the environment, enter waterways and reach the ocean. This source is compounded by the extensive use of EPS in construction (insulation sheets), for food packing (e.g. fresh or frozen fish) and for take-away/street food, as well as its widespread use in aquaculture in Asia. Each of these sources will require different approaches, but there are alternative materials available which need to be considered.

Figure 2.14 Loose fill used to protect goods in transit, made from EPS, ©Peter Kershaw.

Another common style of packaging is the use of preformed clear plastic ‘blister pack’ covers, often used with card backing, to display a wide range of goods, such as: toothbrushes, tools, toys and household goods (Figure 2.15). It is not always obvious that the quantity of packaging used is needed to protect the item, rather than increase the visibility and marketing potential of the goods.

Figure 2.15 Plastic 'blister pack' covers – necessary protection or marketing ploy? ©Peter Kershaw.

## 2.6 Final thoughts

Society will continue to use plastics for many good, justifiable reasons. But we need to be aware of the environmental, social and economic damage that plastics can cause, especially at the end-of-life stage due to our inadequate response. Members of society interact with plastics in different ways and this needs to be recognised when targeting education and intervention. For example, as women tend to make most of the spending decisions in a household context, especially around food purchases, it is logical to target women in outreach programmes about the impact of food packaging. Similarly, personal care products containing plastic micro-beads, such as body scrubs, are used most commonly by women, so it makes sense to target outreach campaigns to illustrate their impact in the marine environment.

It is instructive to review what might be described as the 'main culprits' when it comes to marine plastic litter (Chapter 3), before considering whether and how we should re-assess our use of conventional synthetic and semi-synthetic polymers. This reassessment might include improved implementation of the 3Rs, but it is important to consider whether there are alternative approaches and materials which reduce our dependence on plastics overall. A number of options to substitute conventional synthetic polymers with alternative materials are presented in Chapter 4, 5 and 6, together with illustrative case studies.

# 3. Marine plastics and microplastics – the main culprits

## 3.1 The leakage of plastics to the ocean

The leakage of plastics and microplastics to the ocean has been the subject of several high profile publications in the scientific literature (Ericksen *et al.* 2014, Jambeck *et al.* 2015, Lebreton *et al.* 2017) and global assessments (Joint Group of Experts on Scientific Aspects of Marine Environmental Protection 2015, 2016, United Nations Environment Programme 2016). The sources of marine plastics and microplastics are highly diverse, from land- and sea-based activities, and the reasons why leakage occurs often complex. The quantities of plastics and microplastics in the ocean are unknown, although attempts have been made to quantify certain categories of litter, such as floating plastics, by combining observations with ocean circulation modelling (Eriksen *et al.* 2014, van Sebille *et al.* 2015). In addition, methods to estimate the contribution of some of the major sources (e.g. mismanaged solid waste) and entry points (e.g. riverine inputs, Figure 3.1) are becoming more sophisticated, and provide a good basis for targeting reduction measures (Jambeck *et al.* 2015, Lebreton *et al.* 2017).

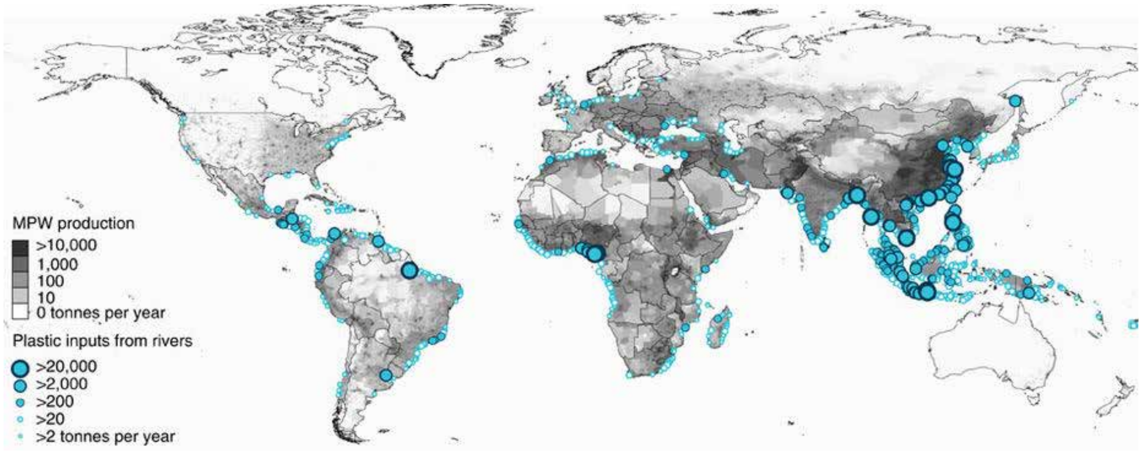


**Figure 3.1** Estimated annual mass (tonnes) of plastic entering the oceans via rivers. River contributions are derived from individual watershed characteristics such as: population density (inhabitants km-2); per capita mismanaged plastic waste (MPW) production (kg d-1) and monthly averaged run-off (mm d-1). The model is calibrated against river plastic concentration measurements from Europe, Asia, North and South America (reproduced from Lebreton *et al.* 2017 under a Creative Commons Attribution 4.0 International License).

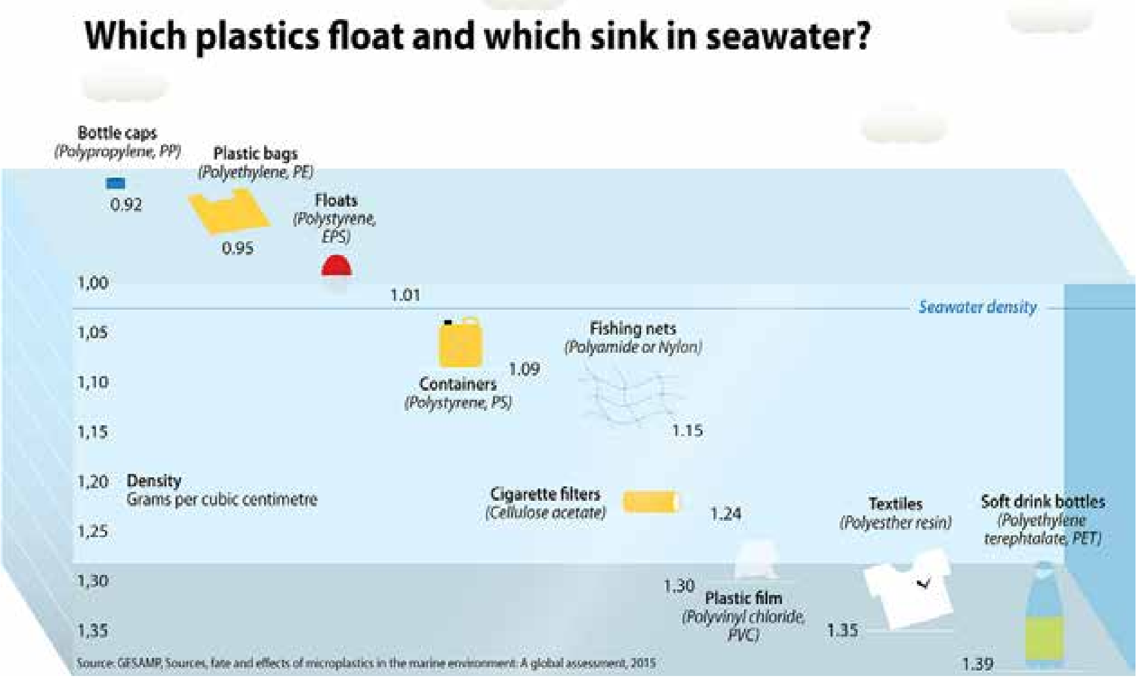
Observations from official monitoring programmes, scientific research cruises, citizen science initiatives and coastal clean-ups are providing an improved understanding on the composition and distribution of plastics and microplastics in the environment, on shorelines, in the water column, on the seabed and associated with biota (entangled or ingested). Unfortunately, differences in the methods and protocols used in separate monitoring surveys can create difficulties in the compilation and interpretation of the results, despite the emergence of guidelines to encourage a more consistent approach (Cheshire *et al.* 2009).

**A lack of harmonisation in sampling design and monitoring methods limits the reliable comparison of survey results**

In the present context, quantifying the distribution of difference categories and sources of litter - including identifying accumulation ‘hotspots’ and mapping the extent or scale of particular features - can help to target where intervention using alternative materials might be most effective. One caveat to this approach is that there is a general lack of consistency in the methods adopted by those responsible for organising the monitoring programmes or other initiatives. The extent to which this limits reliable comparisons to be made between survey results was graphically highlighted by a comparison of results of surveys of the coastline of the USA, made by NOAA and the Ocean Conservancy (International Coastal Clean-up) (section 3.2, United States National Oceanic and Atmospheric Administration in press).

**Table 3.1** Common synthetic and semi-synthetic polymers and applications, together with their tendency to float or sink in the aquatic environment, based on density difference without additional floatation, such as a fishing float (modified from Joint Group of Experts on Scientific Aspects of Marine Environmental Protection 2016).

| Polymer | Common applications | Density | Behaviour |
|---|---|---|---|
| Polyethylene | Plastic bags, storage containers, | 0.91–0.95 | Float |
| Polypropylene | Rope, bottle caps, gear, strapping | 0.90–0.92 | Float |
| *Pure* water | | 1.00 | |
| Polystyrene (expanded) | Cool boxes, floats, cups | 0.96 –1.05 | Float |
| *Average seawater* | | 1.025 | |
| Polystyrene | Utensils, containers | 1.04–1.09 | Sink |
| Polyamide or Nylon | Fishing nets, rope | 1.13–1.15 | Sink |
| Polyacrylonitrile (acrylic) | Textiles | 1.18 | Sink |
| Polyvinyl chloride | Film, pipe, containers | 1.16–1.30 | Sink |
| Cellulose Acetate | Cigarette filters | 1.22–1.24 | Sink |
| Poly(ethylene terephthalate) | Bottles, strapping | 1.34–1.39 | Sink |
| Polyester resin + glass fibre | Textiles, boats | >1.35 | Sink |
| Rayon | Textiles, sanitary products | 1.50 | Sink |



Source: GESAMP, Sources, fate and effects of microplastics in the marine environment: A global assessment, 2015

**Figure 3.2** Schematic of which synthetic polymers tend to float and which tend to sink in the ocean; image from GRID-Arendal (2016).

Having a better understanding of what ocean plastic litter is composed of, and where it comes from, can help to target where substituting plastics with alternative materials may be most effective, at reducing overall levels of marine plastics.

## 3.2 Plastic litter on shorelines and beaches

Ocean plastic litter is most readily observed on shorelines. Regular beach monitoring surveys and coastal clean-ups have provided growing evidence of the categories of litter most often encountered. Despite methodological differences it has been possible to discern some general patterns, and some striking regional differences (Figures 3.3, 3.4, 3.5). The latter can be a reflection of the relative importance of land-based and maritime sectors, the adequacy of infrastructure and waste management controls, and even cultural or demographic variations (United Nations Environment Programme 2016).

This report is not intended to provide a comprehensive overview of marine litter distribution, but some examples are presented to illustrate the types of materials and variations in relative quantities that have been reported. For example, one study compared the quantity and composition of shoreline litter adjacent to four urban centres in Europe: Constanta (Black Sea), Barcelona (Mediterranean Sea), Riga (Baltic Sea) and Oostende (North Sea) (Arcadis 2014). The study used similar sampling and recording protocols at all four sites, and developed a methodology to allocate each item to its probable source. Litter was allocated to two categories: i) single-use consumer plastics; or, ii) non-consumer plastics and other materials. This revealed clear differences in the total quantity of litter items at each site (Figure 3.3). The proportion of single-use consumer plastic was relatively constant at three sites (54-59%) but significantly lower at Oostende, where maritime sources were dominant.

The proportion of different types of single-use plastics varied between sites, which is reflected in the allocation of items to probable source (Figure 3.4). Two sites had significant quantities of sewage-related waste, with large numbers of plastic sticks used for cosmetic cotton buds. This reflects inadequate wastewater infrastructure as well as cultural habits in using lavatories for solid waste disposal. Recreational use was associated with high levels of disposable plastic packaging (bottles, bags, food wrappers) and cigarette stubs.

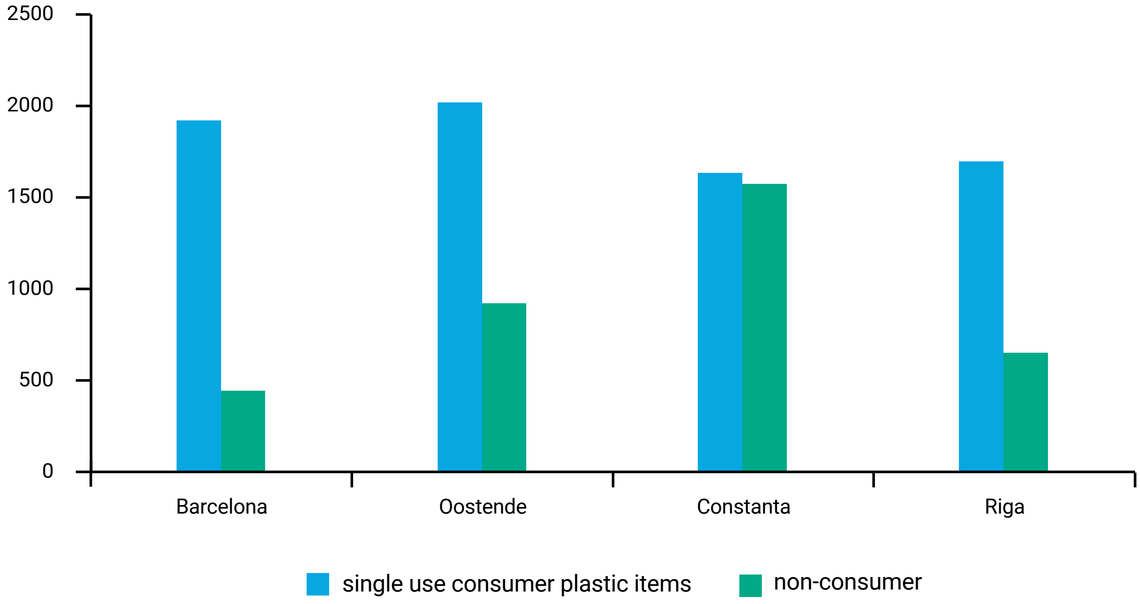


**Figure 3.3** Arcadis 4 seas study proportion of single-use consumer items

National surveys conducted in the UK and China (Figure 3.5 (a) and (b)) using similar methodologies (Hong ed. 2017) reveal the preponderance of plastic fragments as the most significant category. In China there is a much greater proportion of EPS fragments, which is thought to be due to the extensive use of EPS buoys in aquaculture. This was also seen in a more limited survey in Vietnam (Figure 3.4 (c)). All three surveys recorded variable quantities of consumer packaging waste. In contrast, the protocol used in the annual coastal clean-up organised by the Ocean Conservancy (Ocean Conservancy 2017) results in the under-reporting of plastic fragments. Consequently this category does not appear in the list of the top ten most common items (Figure 3.5 (d)). This apparent emphasis on recording single-use consumer items is due to differences in the methodology used, and illustrates why caution is needed when interpreting survey data (United States National Oceanic and Atmospheric Administration in press).

## 3.3 Seabed litter

Seabed surveys of litter are harder and more expensive to conduct, often involving sophisticated camera systems, or diving surveys in shallow waters. The latter often reveal large quantities of plastic litter, including consumer items such as plastic bags and bottles. In regions close to continental margins, such as off the Mediterranean coast of France and the Monterey Canyon off California, large quantities of consumer plastics, including PET bottles, were observed using camera surveys (Galgani *et al.* 1995; Schlining *et al.* 2013). Here, plastic debris originating from rivers, shorelines and recreational users

Floating plastic debris
Photo Credit: Shutterstock

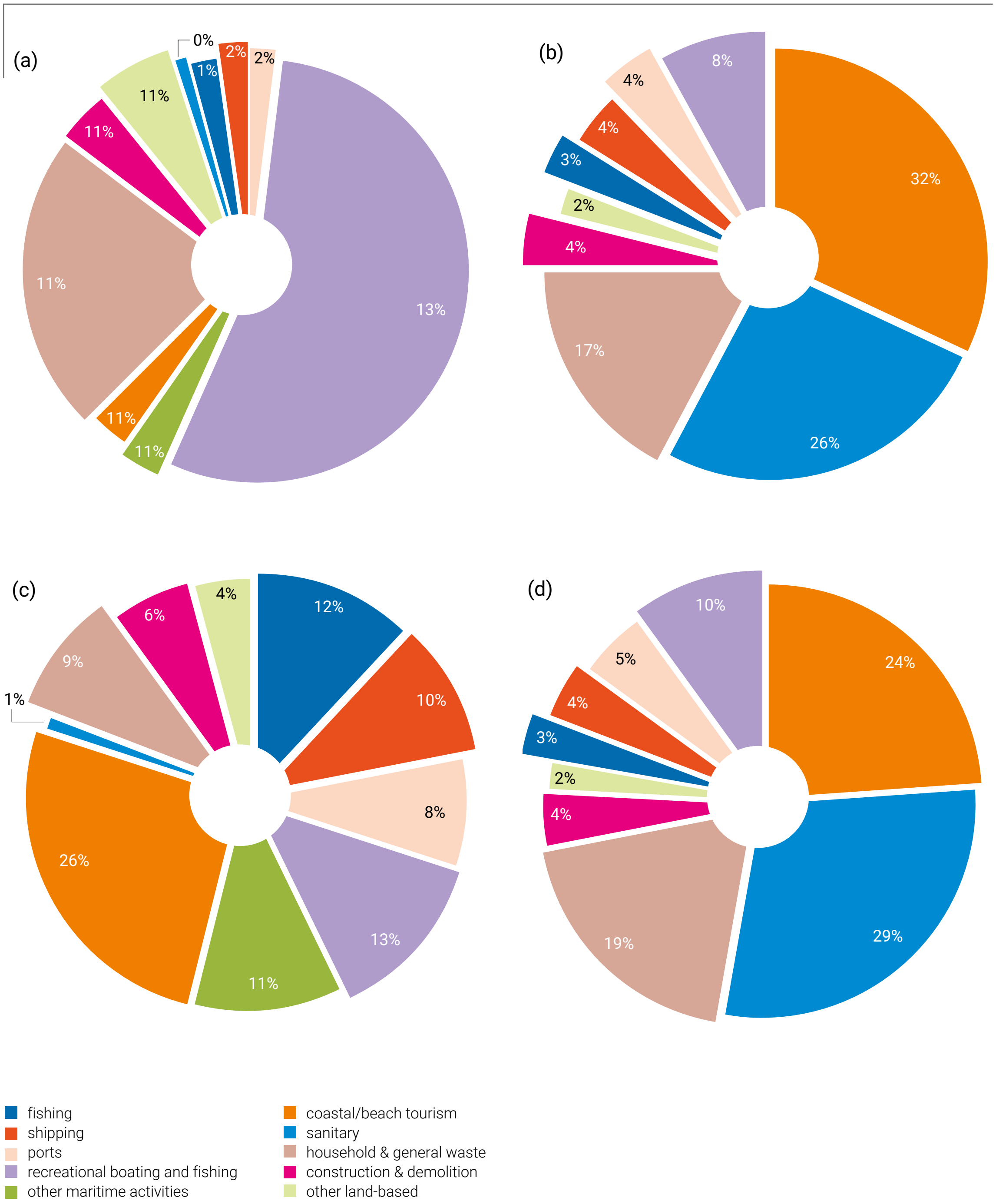


**Figure 3.4** Compilation of shoreline litter monitoring at four European sites near urban areas, indicating the probable source: (a) Constanta, Black Sea; (b) Barcelona, Mediterranean Sea; (c) Oostende, North Sea; and, (d) Riga, Baltic Sea; (adapted from Arcadis 2012).

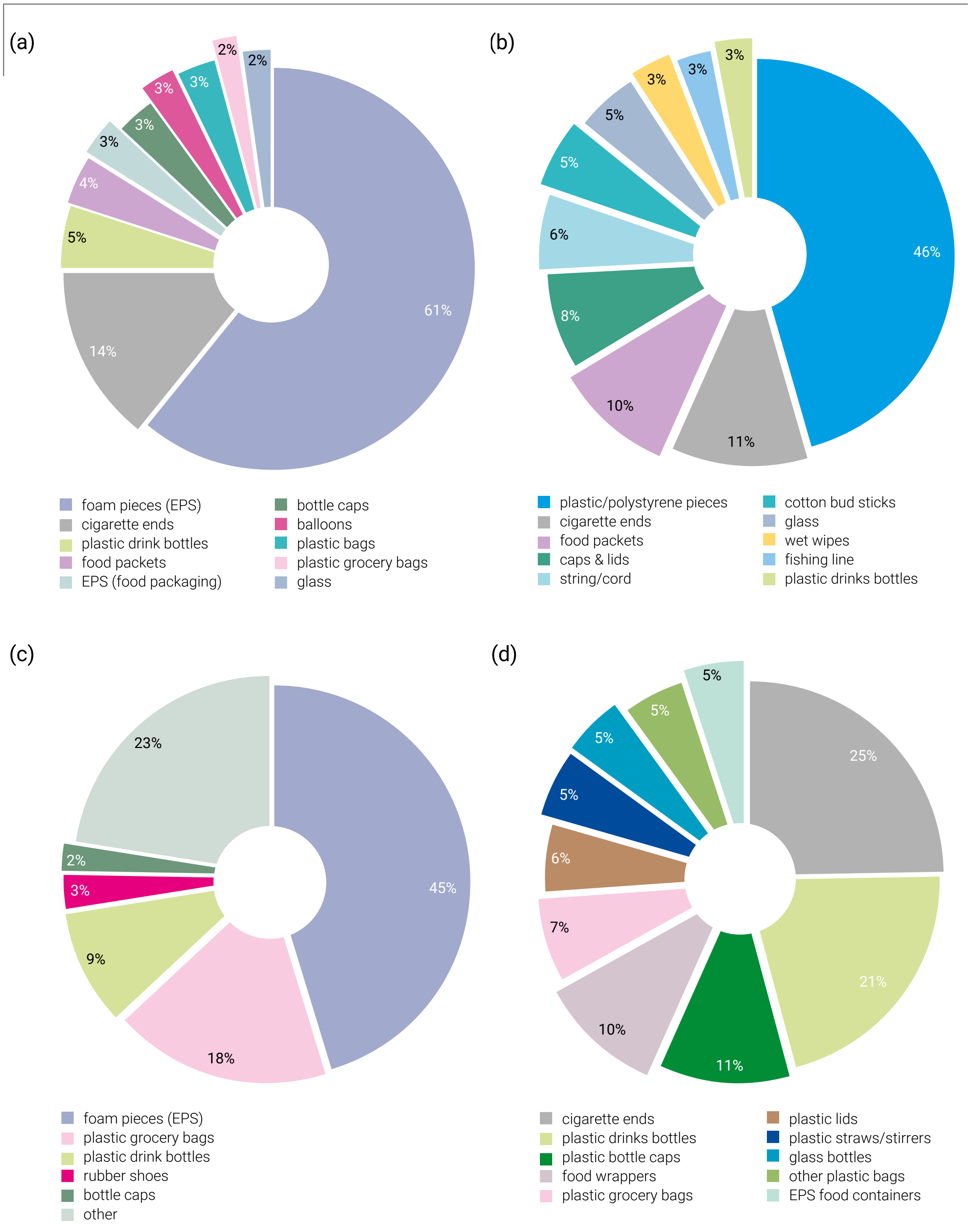


**Figure 3.5** Composition of shoreline debris: (a): national survey in China September 2016 (304 km, 41 tonnes) (Hong ed. 2017); (b) national survey in the UK 2016 (Marine Conservation Society 2017); (c) clean-up of the Ha Long Bay UNESCO World Heritage Site, Vietnam, 2016-2017 (2.2 km, 1.6 tonnes) (Hong ed. 2017); and, (d) International Coastal Clean-up 2016 (Ocean Conservancy 2017).

cascades down submarine canyons to deep waters (e.g. 2000 m). Camera surveys have also revealed the presence of fishing-related plastic debris in areas on the continental shelf, slope and seamounts frequented by fishing vessels (Pham et al 2014; United Nations Environment Programme 2016). The recording of litter collected during fisheries management bottom-trawl surveys can provide a rich source of data (United Nations Environment Programme 2016). The total amount and regional distribution of seabed litter is hard to quantify. However, it is clear that in some regions, such as submarine canyons off narrow continental shelves, a high proportion of single-use consumer plastic items can accumulate.

## 3.4 Micro-fibres in the ocean

A great deal of interest has been generated by the recognition that microplastics are widespread in the marine environment, and that they may act as vectors for the transfer of chemical contaminants through the food chain. This is partly driven by concerns for food safety, although a recent comprehensive assessment concluded that the risk to human health from seafood consumption, due to chemical exposure to absorbed and additive chemicals is low (Lusher *et al.* 2017). However, it is only relatively recently that attention has started to focus in more detail on the physical and chemical characteristics of different categories of microplastics. This revealed the presence of micro-fibres composed of a number of common polymers. Recent studies have reported that these occur extensively in the marine environment, in seabed sediments and biota (Browne *et al.* 2011, Lusher *et al.* 2013, Woodall *et al.* 2014, Remy *et al.* 2015). The main sources appear to be textiles and ropes/nets, with synthetic and semi-synthetic fibres recorded.

Browne *et al.* (2011) first reported the presence of fibres in shoreline sediments, claiming that higher abundances occurred near urban areas, close to wastewater discharge points. In contrast, Nel and Froneman (2015) and Nel *et al.* (2017) found no evidence that the distribution of fibres along the coastline of southern Africa was influenced by the population density. The authors suggested that regional hydrodynamic conditions were more important.

Browne *et al.* (2011) suggested that the washing of fabrics was a significant source of synthetic fibres. Napper and Thompson (2016) examined the loss of fibres during clothes washing using three types of fabric: polyester, polyester-cotton mix and acrylic. They also tested different washing treatments, which were found to influence the quantity released. Fewer fibres were shed for polyester-cotton fabrics than polyester or acrylic. It was estimated that over 700,000 fibres of acrylic could be released in a single 6kg load.

However, fibres are not restricted to the near shore. Woodall *et al.* (2014) revealed the presence of fibres in deep ocean sediments in the North-east Atlantic, Mediterranean and Southern Indian Ocean, reporting that fibres were preferentially being deposited on the seabed whereas flakes were relatively more numerous in surface waters. Lusher et al (2013) found that fibres were common in the gut contents of fish sampled from the English Channel. The polymer composition does vary, reflecting the probable source (Figure 3.6). Acrylic, viscose, PET and polyester fibres are associated with textiles, whereas polyamide, polypropylene, polyethylene and polystyrene have more mixed sources (Table 2.6). It should be noted that the accurate identification of fibre polymer types is challenging. Rayon and cotton fibres show similar FTIR profiles and can only be distinguished by detailed inspection of the form of the fibre. This may lead to the over-reporting of rayon fibres when cotton fibres are present in the sample[7].

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[6] http://www.brsmeas.org/

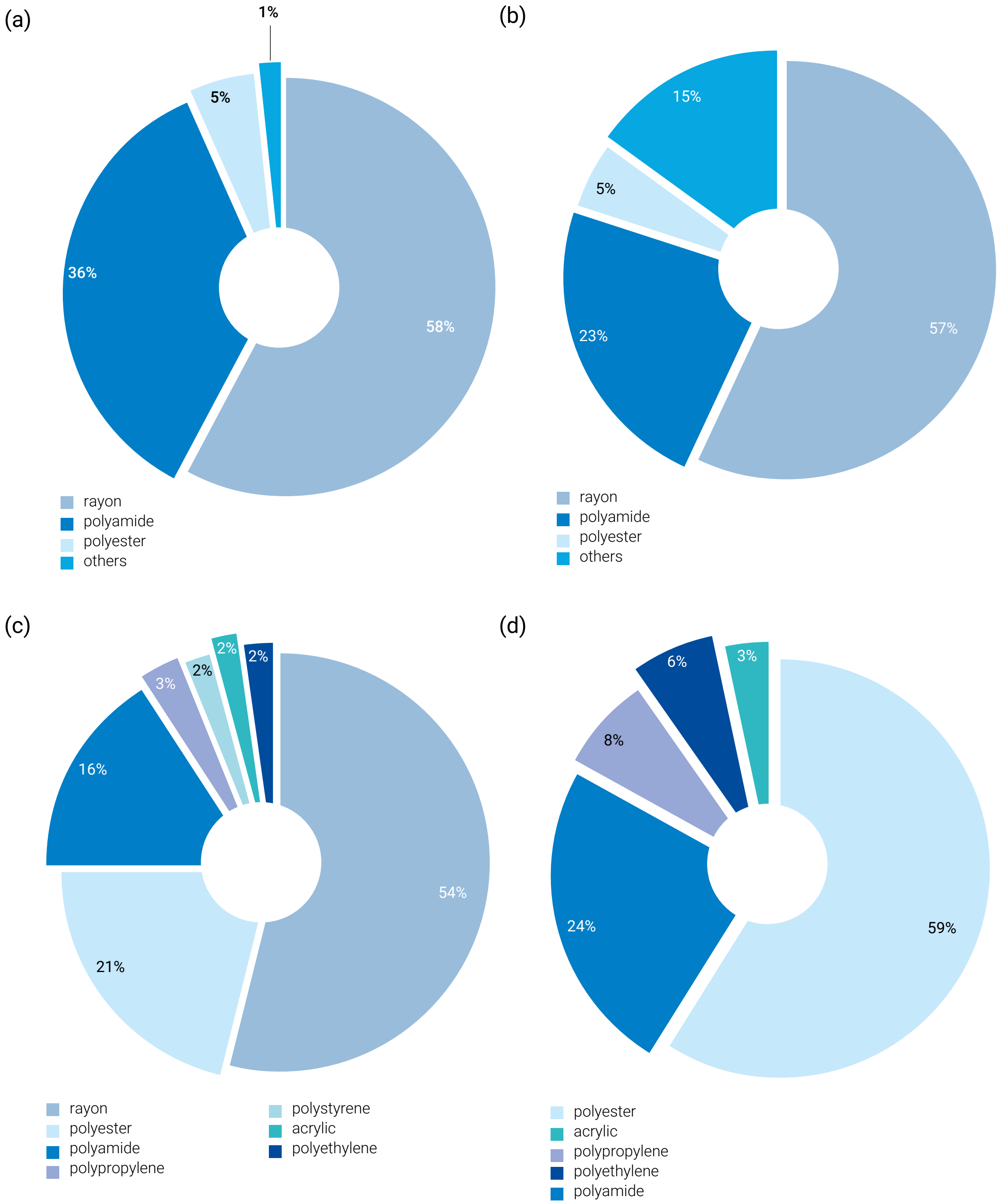

**Figure 3.6** Composition of microfibers sampled in different compartments of the marine environment, compiled from published sources: (a) fish guts from the English Channel (Lusher *et al.*2013); (b) deep sea sediments in the North and North-Eastern Atlantic, Mediterranean Sea and South-Western Indian Ocean - 'other' includes polyamide and acetate (Woodall *et al.* 2014); (c) Arctic sea ice (Obbard *et al.* 2014); and (d) shoreline sediments near urban areas worldwide, excluding rayon fibres (Browne *et al.* 2011).

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7 Conclusion of the PICES S2 Topic Session on microplastics, 28 September, 2017 Annual Science Conference, Vladivostok, Russian Federation; www.pices.int

# 4. Alternative materials - natural polymers/ materials

## 4.1 Natural polymers and organic materials

Our early human ancestors used natural materials for covering and shelter in order to survive. The materials used, whether derived from plants or animals, reflected their local availability, which in turn reflected the geography and climate of the region. With time humans, while still hunting and gathering, started to domesticate livestock, grow crops and develop trade. So the global trade in natural organic materials began. Natural organic materials are composed of polymers, chains of identical molecules. For the purposes of this report the main polymers to consider are lignin, cellulose and cutin, a natural polyester, in plant-derived materials, and chitin and protein fibres in animal-derived materials (Table 4.1).

**Table 4.1 Polymers and their occurrence in nature**

| Polymer | Natural occurrence | Common uses |
|---|---|---|
| Lignin | Cell walls of plants | Construction, fuel, newsprint |
| Cellulose | Cell walls of plants and many algae | Clothing, paper, cardboard/paperboard (Kraft paper), raw material for biopolymers |
| Cutin | Plant cuticles | Raw material for biopolymers |
| Chitin | Cell walls of fungi<br>Exoskeleton of crustacean and insects | Mycelium-based packaging, conversion to chitosan |
| Protein fibre (e.g. fibroin, keratin, casein) | Silk, wool, milk | Clothing |

One of the principle differences between synthetic or semi-synthetic and natural polymers is that the latter biodegrade very rapidly when not being maintained by a living organism. This is why the preservation of ancient fabrics or other organic artefacts, or human corpses, is so rare. It is why we are not buried under enormous quantities of dead plants and animals. Most of these materials will biodegrade relatively rapidly in the ocean, although a large-diameter ship's hawser made of coir will take longer to disappear than a thin piece of coir string.

In the enthusiasm to embrace synthetic and semi-synthetic polymers, the availability, utility, social and economic benefits of natural fibres have received less attention. In response the UNGA passed a resolution in 2006 (A/RES/61/189) declaring 2009 to be the International Year of Natural Fibres. The resolution noted:

> **'…… the diverse range of natural fibres produced in many countries provides an important source of income for farmers, and thus can play an important role in contributing to food security and in eradicating poverty and hence in contributing to the achievement of the Millennium Development Goals'**
>
> **extract from: 2006 UN Resolution A/RES/61/189**

FAO was requested to facilitate the observance of the Year, in collaboration with others. FAO, in collaboration with the Common Fund For Commodities[8], organised a 'Symposium on Natural Fibres' in October 2008. The proceedings of the Symposium provide a rich source of information on the topic

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[8] Common Fund for Commodities – an autonomous intergovernmental financial institution established within the framework of the United Nations, http://common-fund.org/

(Food and Agriculture Organization of the United Nations 2009). FAO has also published a study on unlocking the commercial potential of natural fibres, including their use as composites with conventional polymers in the automotive industry (Food and Agriculture Organization of the United Nations 2012).

## 4.2 Plant-based polymers

### 4.2.1 Types, uses and production

A wide variety of natural materials are utilised to meet many of society's needs. Figure 4.1 indicates examples of commercially important plants grouped by the source of the fibre together with a non-exhaustive list of common examples.

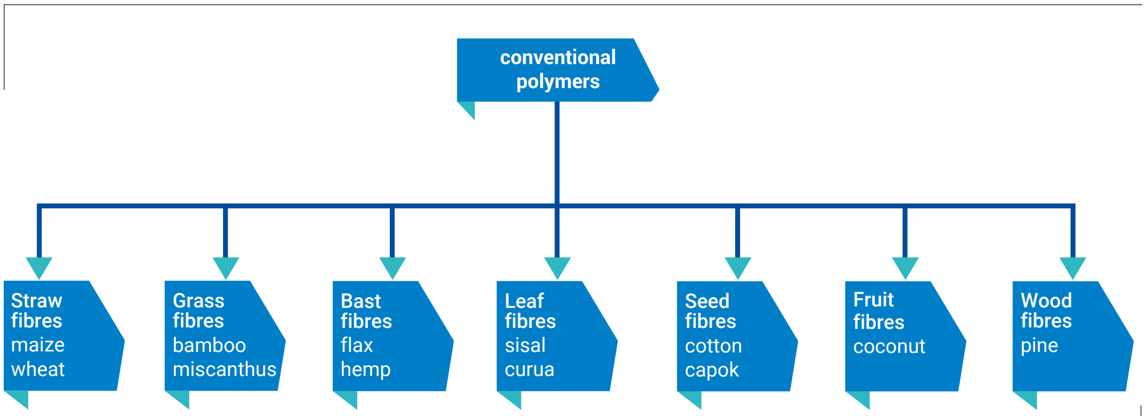

**Figure 4.1** Main categories of plant fibres with examples (adapted from Suddell 2009)

The production of plant fibres for textiles is dominated by cotton (85%), followed by jute and related plants (Figure 4.2). Cotton is of major importance for the manufacture of clothing, bedding, furnishing fabrics, bags and many other uses. Table 4.2 lists a variety of common plant materials, the component polymer(s), plant source and examples of common uses. The table also provides a qualitative estimate of the degradation properties under a variety of terrestrial and aquatic conditions. Generally, degradation rates will be higher under warmer conditions. The main countries of origin are indicated in Table 4.3, together with global production in 2004 (Suddell 2009).

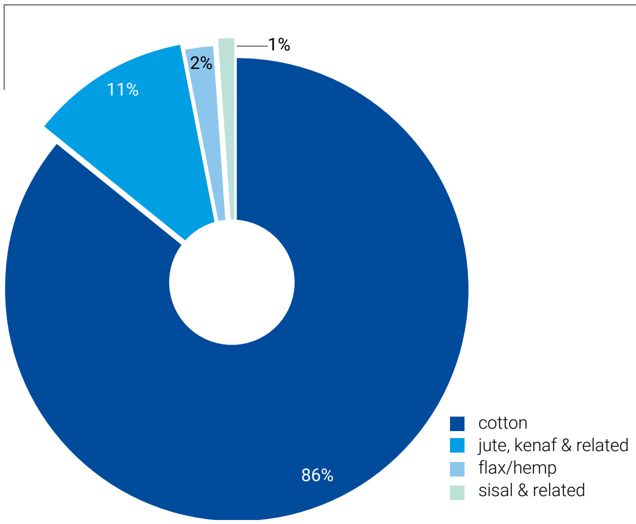

**Figure 4.2** Global use of natural fibres by major group in 2008, excluding use of straw, grass and wood fibres (adapted from Rashka and Carus 2012)

**Table 4.2** **Plant-based materials, polymer(s), plant source and common uses, together with biodegradable and composting properties (based on reported observations, where available, otherwise estimated): domestic composting C-d, industrial composting C-i, biodegradable B; degradation rate: high H, medium M or low L; qualitative sustainability indicator: blue high, medium purple, low red).**

| Material | Polymer | Common biomass source | Examples of common uses | Terrestrial | | | Aquatic |
|---|---|---|---|---|---|---|---|
| | | | | C-d | C-i | B | B |
| Cotton | Cellulose | Cotton plant *(Gossypium sp.)* | Clothing, other fabrics | H | H | H | H |
| Hemp | Cellulose | Hemp *(Cannabis sativa)* | Clothing, other fabrics | H | H | H | H |
| Flax/Linen | Cellulose | Flax/linseed *(Linum usitatissimum)* | Clothing, other fabrics | H | H | H | H |
| Jute | Cellulose & lignin | *(Corchorus sp.)* | Sacks, carpets, clothing, rope, other fabrics | H | H | H | H |
| Coir fibre | Cellulose & lignin | Coconut (outer shell) | Mats, brushes, sacking, rope, fishing nets | H | H | H | M |
| Ramie | Cellulose | China grass *(Boehmeria nivea)* | Clothing, other fabrics, industrial sewing thread, | H | H | H | H |
| Abaca/Manila hemp | Cellulose, lignin & pectin | Banana *(Musa textiliis*, inedible) | Tea bags, banknotes, matting, rope | H | H | H | H |
| Piña | Cellulose & lignin | Pineapple leaf *(Ananas comosus)* | Clothing, other fabrics | H | H | H | H |
| Sisal | | *(Agave sislana)* | Textiles, bags, rope, twine | H | H | H | H |

Table 4.3 Commercially important natural fibres: data 2004 from Suddell (2009), 2014* from FAOSTAT[9], 2014^ from Food and Agricultural Organisation (2015), 2015 from Food and Agricultural Organisation (2016) ; a value for 2013/14, [b] value for 2014/15 (adapted from Suddell 2009)

| Fibre | Main countries | Origin | Global production in ('000 tonnes) | | |
|---|---|---|---|---|---|
| | | | 2004 | 2014 | 2015 |
| Wood | Various (>10,000 species) | Stem | 1,750,000 | | |
| Bamboo | China (>1250 species) | Stem | 10,000 | | |
| Jute | India, Bangladesh | Stem | 2,861 | 3,393*<br>2,860^a | 2,563 b |
| Kenaf | India, China | Stem | 970 | 252^a | 230 |
| Coir | India, Vietnam, Sri Lanka | Fruit | 931 | 1,131*<br>1,064^ | 1,024 |
| Flax | China, Europe | Stem | 830 | 320* | |
| Sisal | Brazil, Tanzania, Kenya | Leaf | 378 | 248*<br>253^ | 247 |
| Ramie | China | Stem | 249 | 113* | |
| Hemp | China, Europe | Stem | 214 | | |
| Abaca | Philippines, Ecuador | Stem | 98 | 77^ | 78 |
| Agave | Columbia, Cuba, Mexico | Leaf | 56 | 41* | |

It is clear that plant-based materials have provided for many of society's domestic needs for millennia. There is evidence that cotton has been used to make fabrics since 7-8,000 years BP. This raises the question as to why synthetic and semi-synthetic polymers were adopted in preference, and whether this trend can be reversed, without causing unintended negative impacts. This becomes especially pertinent when society has to react quickly to political decisions such as the introduction of bans on thin-film synthetic shopping bags (Table 4.4).

Table 4.4 SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of utilising plant materials as a substitute for conventional synthetic polymers.

| | |
|---|---|
| S1. Utilises renewable natural resources<br>S2. Potential to be carbon neutral<br>S3. Provides social and economic opportunities in rural areas for vulnerable groups in society<br>S4. Can be composted in a domestic or industrial facility or decomposed by anaerobic digestion at end-of-life<br>S5. Biodegradable in the environment | W1. Biocides and artificial fertiliser may be used on commercial crops, resulting in risks to human health and the environment<br>W2. Limited availability may inhibit development of wider markets<br>W3. Substitution for conventional polymers limited by intrinsic properties of the material<br>W4. Supply chains to market may be poorly developed |
| O1. Expanded utilisation of renewable natural resources<br>O2. Development of social and economic independence in rural area<br>O3. Substitution for single-use consumer products such as shopping bags | T1. Loss of habitat and biodiversity<br>T2. Intensification of production will drive greater use of biocides and artificial fertiliser, and hence increased risks to human health and the environment<br>T3. Use of agricultural land for non-food use may drive up prices and impact food security |

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[9] http://www.fao.org/faostat/en/#data

The degree of processing required from harvesting to use varies greatly, depending on the nature of the plant and the intended use. Timber and bamboo for construction may need quite limited preparation, whilst the production of paper requires a much higher input of water, energy and chemical processing. Some plant leaves can be used directly, for example, to make woven baskets and containers or as a 'plate' or food wrapper. Sometimes more complex processing is needed to produce useful fibres for making into textiles. Each type of plant will require different processes and treatments. The soft seed cover or boll of the cotton plant is readily collected and spun into a yarn before being woven into fabric. For most other plants more robust treatment is required to extract the fibres. Sisal fibres are extracted from the leaves by the process of mechanical decortication. The fibres of hemp, flax and coir are extracted by a combination of mechanical crushing and a process known as retting. Bundles of the raw material are submerged in water, causing the stalks to swell and allowing partial bacterial decay. If poorly managed it can result in significant contamination of ponds and rivers, including fish kills.

Plant materials are also used extensively for the production of semi-synthetic rayon fibres, cellulose acetate and cellophane (section 2.3) and for the production of biomass-based biopolymers (Chapter 5). Both purposely grown and waste agricultural material can be used.

### 4.2.2 Production of paper

Figure 4.3 Cardboard packaging for protecting goods in postal transit ©Peter Kershaw

Paper is produced from cellulose, with wood pulp being the most common modern source. There are many different grades of paper, determined by the length of the cellulose fibres, the chemical treatments applied, the use of additives such as chalk, and the proportion of lignin that is retained. Newsprint is made from logs that have been mechanically ground, producing short fibres and a higher proportion of lignin, making the finished product weaker and liable to yellowing.

The material variously known as cardboard or paperboard, used extensively for packaging, is also called sack kraft paper, named after the kraft pulping process that removes lignin effectively. It is much stronger and has greater tear resistance than standard paper made using other pulping processes, due to the lack of lignin and longer cellulose fibres. The raw material is softwood timber, although bamboo and kenaf can also be used. Kraft paper has been used for many decades to provide inexpensive and effective packaging, including thin-walled paper bags and durable corrugated composite sheet boxes (Figure 4.3).

### 4.2.3 Other uses of plants

Bamboo is a type of grass, consisting of about 1250 species of bamboo with a widespread distribution across Asia, Africa, Australasia and the Americas. Greatest densities occur in tropical and warm temperate latitudes. It is a highly versatile material with a very long history of being used as a construction material, as well as a wide variety of other products such as chopsticks, baskets, wall coverings, window blinds and as a foodstuff. One of the best-known species is the Moso bamboo *(Phyllostachys edulis)*, which occurs in China, Taiwan and Japan. It can grow up to 28m in height and is cultivated in plantations in China. Bamboo fibres are extracted by crushing and retting and can be woven in textiles. This is a quite different process than that used to produce 'bamboo rayon', in which bamboo is used as a source of cellulose (Chapter 5).

Various species of woody plants are used for applications as diverse as providing structural timbers for buildings to protecting artisan cheese (Figure 4.4).

Seagrasses form an important shallow water marine habitat, providing nutrition, sanctuary and spawning sites for many species of fish, as well as acting as a stabiliser on soft sediment bottoms.  Unlike seaweed, seagrasses are classified as flowering plants. A limited number of applications have been identified, and one is described below.

Figure 4.4 Wooden cartons to protect artisan cheese and butter ©Peter Kershaw

Fallen palm leaves have been used to create plates and bowls by a simple process of pressing in moulds. The leaves of the pinapple *(Ananas comosus)* are used to produce Piña fibres, composed of cellulose and lignin. It used to manufacture clothing and other fabrics and is a by-product of commercial pineapple cultivation (Kannojiya *et al.* 2013. Case studies describing the processes involved and the products produced are presented below.

## 4.3 Animal-based polymers

The fibres obtained from animal sources are all forms of protein. Wool and hair are composed of keratin and silk from fibroin. Casein is contained in milk and is the basis for fibres made from soured cow's milk. Table 4.5 list common materials, the animal source and example of common uses, together with a qualitative assessment of degradation behaviour in the environment. Sheep have been bred to be adaptable to a wide range of climates and terrain, and the importance of the wool trade dates back centuries. For example, it was the basis for much of the wealth generation in England in Medieval times, with the modest sized city of Norwich once only second to London in importance.  Sheep's wool was used for underwear, breeches, dresses, coats/cloaks, hats, gloves, scarves and jumpers, and was particularly important for protection and warmth in colder climates. All these uses are still evident, although at a lower relative volume following the introduction of cotton and synthetic fabrics. Improved breeding and production techniques has allowed the development of new applications, such as base

Table 4.5 Examples of animal-based materials, polymer(s), animal source and common uses, together with a qualitative indication of biodegradable and composting properties (based on reported observations, where available, otherwise estimated): domestic composting C-d, industrial composting C-i, biodegradable B; degradation rate: high H, medium M or low L; qualitative sustainability indicator: blue high, medium purple, low red).

| Material | Polymer | Common biomass source | Examples of common uses | Terrestrial | | | Aquatic |
|---|---|---|---|---|---|---|---|
| | | | | C-d | C-i | B | B |
| Sheep's wool | Keratin | Sheep (e.g. Merino) | Knitwear, carpets<br>Other fabrics | H | H | H | H |
| Mohair | Keratin | Angora goat | Clothing other fabrics & carpets | H | H | H | H |
| Angora wool | Keratin | Angora rabbit | knitwear | H | H | H | H |
| Alpaca wool | Keratin | Alpaca | Clothing, other fabrics | H | H | H | H |
| Cashmere wool | Keratin | Cashmere goats | Clothing, other fabrics | H | H | H | H |
| Silk | Fibroin | Silk moth *(Bombyx mori)* | Clothing, other fabrics | H | H | H | H |
| QMilch™ | Casein | Cow's milk (soured) | Clothing, other fabrics | H | H | H | H |

layers for outdoor sports made with soft Merino wool. Other sources of wool, such as cashmere and mohair, have tended to be used for higher end, more expensive clothing, outside the regions of origin. In New Zealand, possum fur is used in combination with wool to produce a sought after material. Silk is produced by the silk moth *(Bombyx mori)*, and is hugely important in many parts of Asia.

## 4.4 Additional organic polymers

### 4.4.1 Fungi-based polymers

Fungi are members of a group of organisms, formerly referred to as a kingdom, that utilise chitin as in their cell walls. They do not photosynthesise, unlike plants, but depend on the absorption of dissolved nutrients, like animals (Ballen and Greene 2017). The group includes mushrooms, molds and yeasts. Fungi have long been used by society as a direct source of food, for fermentation and for various pharmaceutical and industrial purposes. The reason for considering fungi in this chapter is the recent development of using fungal mycelium to produce relatively robust structures when inoculated in a suitable growing medium, such as agricultural plant waste. Examples of applications, for packaging and insulation, are given later in this chapter.

### 4.4.2 Algae-based polymers

Brown seaweeds *(Phaeophyceae)* are ubiquitous on many shorelines and coastal waters in temperate latitudes, providing a continuing source of alginate, or alginic acid. Alginic acid is a polysaccharide, a copolymer of mannuronate and guluronate, and has been used for a wide variety of applications, include food and pharmaceuticals. New developments include packaging applications for dry goods, pastes and fluids, and examples are provided in this chapter.

## 4.2 Case studies

### Rationale for the selection of case studies

The case studies have been selected to illustrate a wide range of applications or initiatives, on a wide variety of scales. Some are suitable for adoption by individuals. Others are most effectively implemented on a much larger corporate basis. All have the goal of increasing the more sustainable use of resources. The intention is to provide examples to show what is possible, and to inspire others to follow. Three of the examples were winners of Circular Design awards in the 2017 Ellen McArthur Foundation Innovation Prize, part of the New Plastics Economy initiative[10].

### Case study 1 – One Million Women

One Million Women[11] was founded by Natalie Isaacs, a former business leader in the cosmetics industry based in Australia. Natalie became disillusioned with our current patterns of living and realised that over-consumption was having a significant impact on the planet. The focus of the movement on women was in recognition that, on average, women are estimated to make 85% of household purchasing decisions. It follows that if one million women make better choices then it should lead to real change, and the greater the adoption of this approach then the greater the progress towards a more sustainable future.

The movement promotes a number of campaigns. One of these is called ‘Leave it on the shelf’. It is targeted at the excess use of food packaging when it is not required to protect the items, either from damage or getting soiled (e.g. bananas sold in a polyethylene bag). Shoppers are encouraged to ‘sign the pledge’ and refuse to purchase over-packaged items. The pledge and number of signatories is being

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[10] https://newplasticseconomy.org/innovation-prize

[11] https://www.1millionwomen.com.au/

sent to the CEOs of major supermarket chains in 13 countries on five continents. Natalie argues, based on her commercial experience, that manufacturers and retailers will respond to changes in customer behaviour. In a recent interview she made two important points: be passionate about the issue, and live it; and, changing the way we live is hard but it is also empowering[12].

> **‘Be passionate about the issue, and live it**
> **Even the smallest actions in your personal life can and will make a difference.**
>
> **Changing the way we live is hard - but it is also empowering**
> **Start with one thing then another. It’s challenging, but will soon become a habit and second nature’.**
>
> **Natalie Isaacs**

## Case study 2 – Products from fungal mycelium

Several initiatives have explored the potential of using fungal mycelium to create structures, using waste vegetable material as a source of nutrition. Mycelium is the vegetative part of a fungus, consisting of branching ‘threads’ that can form dense mats. Once dry, the mycelium-infused material has useful properties that can be exploited for several applications.

### Mycofoam™

Mycofoam™ was developed by Ecovative[13], a company based in New York, which developed from a concept explored in 2006 by the two-co-founders, whilst still at college. It is intended as a compostable alternative to EPS for a number of packaging applications. The raw material is cellulose/lignin fibre from agricultural waste that is inoculated with a strain of fungus. Mycelia generated by the fungus permeate the organic waste, which acts as an energy source, and ‘glue’ the fibres together during an incubation

Figure 4.5 Production of Mycofoam™ from agricultural waste, showing the raw material, inoculation by a fungal strain, incubation and pressing. The example shows protective corner mounts, replacing the use of EPS; images courtesy of Ecovative.

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[12] https://womensagenda.com.au/latest/eds-blog/cosmetics-entrepreneur-climate-warrior-meet-natalie-isaacs/
[13] https://ecovativedesign.com/about

period. This can be pressed into a variety of shapes, such as protective caps to fit onto the corners of cartoons and flat panels (Figure 4,5). These have been used by a number of companies for shipping high value goods, including Dell Computers.

Further developments include Mycoboard™, whose production uses particular types of fibre, such as hard and soft wood chips, flax and rape/canola depending on the intended use. It is used as a core in engineered wood applications such as chair backs and doors, as well as wall tiles. Clearly there is scope for extending this approach much more widely, to wherever there is a regular and dependable source of waste organic material.

## Grown structures

In addition, fungal mycelium can be used to 'grow' structures. This is the idea of Aleksi Vesaluoma, of the Mandin Collective, based in London,. The aim is to make use of waste materials such as cardboard to produce something that is an elegant combination of function and form. In its simplest form, waste cardboard is inoculated with oyster mushroom mycelium and packed into tubes formed of cotton bandage. This 'mushroom sausage' is bent into the desired shape and left to grow in a greenhouse for 2 – 4 weeks. Once growth is complete the structure is dried and becomes quite robust (Figure 4.6). Potential applications include structures for fairs and festivals and other 'pop-up' events. The external fruiting bodies provide a source of gourmet oyster mushrooms, and the whole structure can be composted after use.

**Figure 4.6** **Grown structures created using waste cardboard, cotton bandage and inoculation with oyster mushroom mycelium – practical and edible; images courtesy of the Mandin Collective.**

## Case study 3 – Dell Computers

Dell Technologies represents a major international manufacturer and provider of information systems, desktop and laptop computers, monitors and a range of peripheral devices. This involves the shipping of a very large number of 'units', both small and large, with an equivalent volume of protective packaging. Dell has a declared vision to achieve a '100% waste-free' solution to their use of packaging, and currently report having achieved 94%[14]. The concept fits into the overall corporate responsibility programme, described in the annual updates of their 2020 Legacy of Good Plan (Dell 2017). The approach is to make modest incremental improvements, with minimal disruption to existing production patterns. The selection of suitable materials is the first critical step, with the aim to utilise waste materials where possible, or materials from sustainable sources. Attention to packaging design can reduce the quantity of material required and allow tighter packing of boxed goods, with lower energy use in transportation.

Dell has acted partly in response to customers reporting difficulty in disposing of EPS packaging, commonly used for IT equipment. The approach has used a variety of materials, including wheat straw, cardboard, and bamboo, with sufficient flexibility to accommodate changes in material availability, competition with other sectors and price. Some EPS is still used but alternatives are being sought, such as the use of mycelium-based protective corner moulds for boxed goods (see Mycofoam case study). The ultimate aim is for all packaging to be suitable for home composting or household collection.

## Case study 4 – Personal care cleaning products

Plastic has taken over as the norm for many products used in the home, directly or indirectly, to keep our selves and our homes clean. However, their use is not inevitable and some examples are provided here of alternative materials and approaches. These include toothbrushes with bamboo handles, a nailbrush made of wood and natural fibre bristle, and wooden tooth picks (Figure 4.7). Another novel example is a bar of shampoo that is supplied in a cardboard box rather than the usual liquid version in a plastic bottle[15].

**Figure 4.7** A selection of personal care products in which the use of plastic has been reduced or eliminated: a toothbrush with a bamboo handle marketed in a cardboard box, wooden toothpicks and a nailbrush made with wood and natural bristle; ©Peter Kershaw.

Some cosmetics are manufactured to meet a demand for 'glitter' makeup, and micro-flakes of plastic are sometimes used. As an alternative, some manufacturers use flakes of the rock-forming natural mineral mica (a layered aluminosilicate mineral), or flakes of a 'synthetic mica' synthesised at high temperature with the addition of fluorine. These will act no differently from natural rock dust in the environment.

## Case study 5 – Turtle bags™ - partnerships with workers' collectiveness in Bangladesh and Ecuador

Turtle bags™ was set up by an entrepreneur based in the UK, working in partnership with three workers collectives in Bangladesh and Ecuador. The company promotes the sustainable production of natural fibres and manufacture of bags made from jute, seagrass and sisal.

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[14] This case study was based on a telephone interview with Stephen M. Roberts of Dell Corporation; see also: http://www.techpageone.co.uk/business-uk-en/dells-legacy-good-benefits-people-planet/

[15] http://www.friendlysoap.co.uk/friendly/

Jute production is one of the oldest cottage industries in the Tangail region of Bangladesh (Figure 4.8). Jute is harvested locally and made into bags both TARANGO[16], a Women's Empowerment Programme NGO. This programme provides training, support, employment and financial independence for vulnerable women in by rural and urban areas. The project has certification through the World Fair Trade Organisation (WFTO), helping to develop markets overseas. The bags have featured in the fashion magazine Vogue.

Figure 4.8 Harvesting jute in Bangladesh, image courtesy of the Tarango Project.

Baskets made from seagrass and jute, with a cotton lining, are made in southern Bangladesh. The baskets have won a sustainability award for incorporating seagrass into the design. In this example seagrass is harvested sustainably, providing a long-term income stream and ensuring the seagrass beds are maintained and protected. This helps to stabilise coastal areas that are vulnerable to flooding, and provides an additional economic argument to counter other developments that might damage the habitat.

A women's collective, living in Intaq Valley in the cloud forest of Ecuador, use sisal to make bags. The sisal is produced from locally grown native agave plants. The collective is part of DECOIN[17] (Organisation for the Defence and Ecological Conservation of Intaq). DECOIN has been active for over 20 years, providing support to communities to resist mining interests, helping to conserve over 12,000 hectares of biodiversity and encourage alternative livelihoods for 38 communities. DECOIN was one of eight organisations, out of over 800 nominations, awarded the 2017 UNDP Equator Prize[18]. The Equator Prize is an initiative to promote nature-based local solutions for sustainable development.

Figure 4.9 Bamboo straws, produced by Bali-boo in partnership with a family business in Bali Indonesia; images courtesy of Bali-boo.

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[16] http://www.tarango-bd.org/about-us-2/

[17] http://www.decoin.org

[18] http://www.undp.org/content/undp/en/home/presscenter/pressreleases/2017/06/29/equator-prize-2017-winners-announced-highlighting-outstanding-nature-based-solutions-for-local-sustainable-development.html

## Case study 6 – Bali-boo bamboo straws

Plastic drinking straws can be considered one of the best examples of the unnecessary manufacture of single-use plastics. They are not needed (apart from medical necessity) but remain surprisingly popular, even amongst adults. Paper straws were used quite satisfactorily prior to the invention of the plastic variety. A more recent development has been the introduction of bamboo straws. They have the added advantage of being re-usable and, if discarded, will degrade in the environment. Bamboo straws only require boiling and steaming to sanitise them, so the process does not create unwanted chemical waste. Bali-boo is a small company based on Bali in Indonesia, set up by two wandering European entrepreneurs, Frédéric Kreder and Diego Morodo,  who arrived in Bali and decided they wanted to do something to stem the flow of single-use plastic to the ocean, which was all too evident. They developed a partnership with a family in central Bali who harvest locally grown bamboo, providing training and a steady income stream which is about four-times the commercial rate (Figure 4.9). The company brings marketing expertise and innovation, such as the laser labelling of products for hotel chains, has expanded distribution well outside the region, and is developing other bamboo-based products.

## Case study 7 – Plates and bowls made from leaves

Many communities have traditionally used plant leaves as plates for presenting and consuming food. For example, it has been customary to use leaves from the sal or shala tree *(Shorea robusta)*, which occurs extensively in northern and central India. However, a trend has been reported of decreasing use as plastic plates have become more widespread[19]. Against this background there have been attempts to widen the appeal of leaf plates to new markets, and two such initiatives are reported here.

### Banana leaves

Leaf Republic GmbH[20]  is a Munich-based start-up, initiated in 2013, with a self-proclaimed quest to ‘disrupt the packaging industry’. Pedram Zolgadri, the co-founder and CEO, started to research possible alternatives to the widespread use of conventional polymers for packaging, in an effort to reduce the

**Figure 4.10 Plates made from dried, stitched plant leaves; image courtesy of Leaf Republic GmbH.**

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[19] https://timesofindia.indiatimes.com/city/ranchi/Sal-leaf-dishes-make-way-for-plastic-ones/articleshow/13128420.cms
[20] http://leaf-republic.com/

negative impact of plastics on society and the environment. Travelling to India, Pedram observed the traditional use of Patraveli plates for daily consumption of food. Patraveli plates are made from the leaves of local plants, including the Banyan tree. Leaf Republic works with subsidiaries in India who employ experienced local women in rural areas to harvest leaves from the forest. The leaves are stitched together to make round discs, using a natural thread, before being dried. In Germany the leaf 'patches' are pressed with a layer of paper between, into a variety of shapes (Figure 4.10). The cuttings from this process are used for packaging. Future plans include using the waste for pulp production.

### Araca palm

Manufacturing disposable plates from discarded palm leaves was the inspiration of Sandra Adar, Director of Little Cherry, a UK business set up to provide a range of catering products made from compostable materials[21]. The leaves come from the areca palm *(Araca catechu)*, which grows in much of tropical Asia, the tropical Pacific and parts of east Africa. The areca nut, also called the betel nut, is chewed as a stimulant, a practice that is widespread throughout the growing region. It is sometimes chewed with betel leaf *(Piper betle)*. Unfortunately, significant health problems are associated with the practice.

**Figure 4.11 Plates and bowls produced from the leaves of the areca palm (Araca catechu); photographs courtesy of Little Cherry.**

Little Cherry has formed a partnership with communities in rural areas of India, bringing an additional source of revenue and local autonomy. Each areca palm sheds about 8 to 10 leaves each year, as part of its natural life cycle. This provides the raw material for producing the disposable plates. The leaves are gathered from the ground and soaked in water before rinsing. The leaf sheaths are left to dry in closed chambers, before being pressed in heated moulds. Production takes place in communities close to the source of the leaves, reducing transport costs. Attention is paid to minimise the environmental impacts of the packaging used, which has resulted in a 20% increase in the number of items that be carried in a shipping container. Production waste is composted at the point of origin. The plates and bowls are suitable for wet and oily foods (Figure 4.11). After use, the plates can be disposed of by home

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[21] https://www.littlecherry.co.uk/

composting or can be included in food waste. The company also market compostable 'clam-shell' food containers made from pressed compressed wheat straw pulp and a range of plates and other catering items made from bamboo.

## Case study 8 – Products from peel

Enormous quantities of fruit and vegetable peel are generated everyday. For example, it has been estimated that more than 16 million tonnes of orange peel are produced year on a global scale. Peel is used for animal feed but can also be used on a smaller scale in cosmetic products and for pest control. In this case example, orange peel is collected from commercial juice sellers. It is dried and ground, then mixed with a homemade organic glue, and resulting paste is pressed into moulds and left to set (Figure 4.12). It is the work of Aleksi Vesaluoma and Richard Sullivan of the Mandin Collective, a design team based in London. Other peels with the same potential include: beetroot, carrot, lychee, mandarin, lemon, honeymelon, kiwi, mango, lime, potato, banana and avocado.

Figure 4.12 Manufacturing household objects from discarded orange and lemon peel; images courtesy of the Mandin Collective.

This is an example of a local initiative, operating at a small scale, but illustrates a model of utilising what otherwise might be regarded as food waste. As such the model has scope for much wider application.

## Case study 9 – From waste milk to high fashion: QMilch fabric

QMilch fabric is the creation of German entrepreneur Anke Domaske, a former microbiology student. The fabric is manufactured from casein fibres, extracted from raw sour-milk from cows (Figure 4.13). The idea for using casein emerged in the 1930s, but the process required a fairly complex process and chemical treatment. Domaske's aim was to simplify the process with a minimum of intervention. The unused raw milk cannot be traded, under current German legislation, leading to the annual disposal of 2 million tonnes of milk. The company Qmilch GmbH was formed in 2011 and is engaged on further development of biopolymers manufactured from milk proteins.

This particular example of using unwanted food production may have limited application, but it serves to illustrate the potential of utilising raw materials from a variety of potentially over-looked sources.

Figure 4.13 The production cycle of Qmilch fabric, from source to finished product; central image entrepreneur and company founder Anke Domaske; Holstein Freisian cow ©Liz Lund, all other images courtesy of QMilch, model in red dress Britta Pathe ©Anna-Marina Fuhr.

## Case study 10 – Piñatex™ 'leather' from pineapple leaves

Piñatex™ is manufactured by the London-based company Ananas Anam, using the leaves from commercial pineapple cultivation in the Philippines (Figure 4.14). Piñatex™ can be used as a substitute for leather, and applications include the manufacture of shoes, bags and furnishings. The collection and processing of the pineapple leaves provides an additional source of income for the farmers. The long Piña fibres are extracted by a process involving the mechanical removal of the outer layers of the leaf (decorticating), followed by de-gumming.

The waste biomass from this process can be used as a natural fertiliser or to produce biogas. The fabric is bonded together without weaving. It can be recycled after use and the whole process has the potential of being operated in a closed loop system (Figure 4.16).

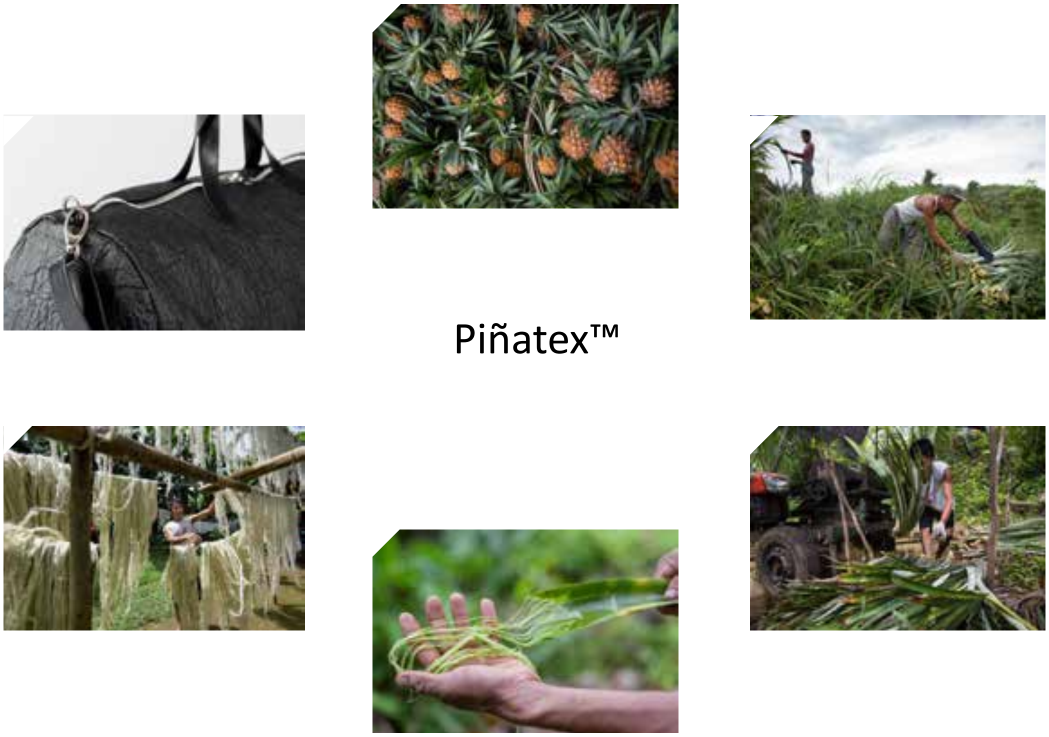
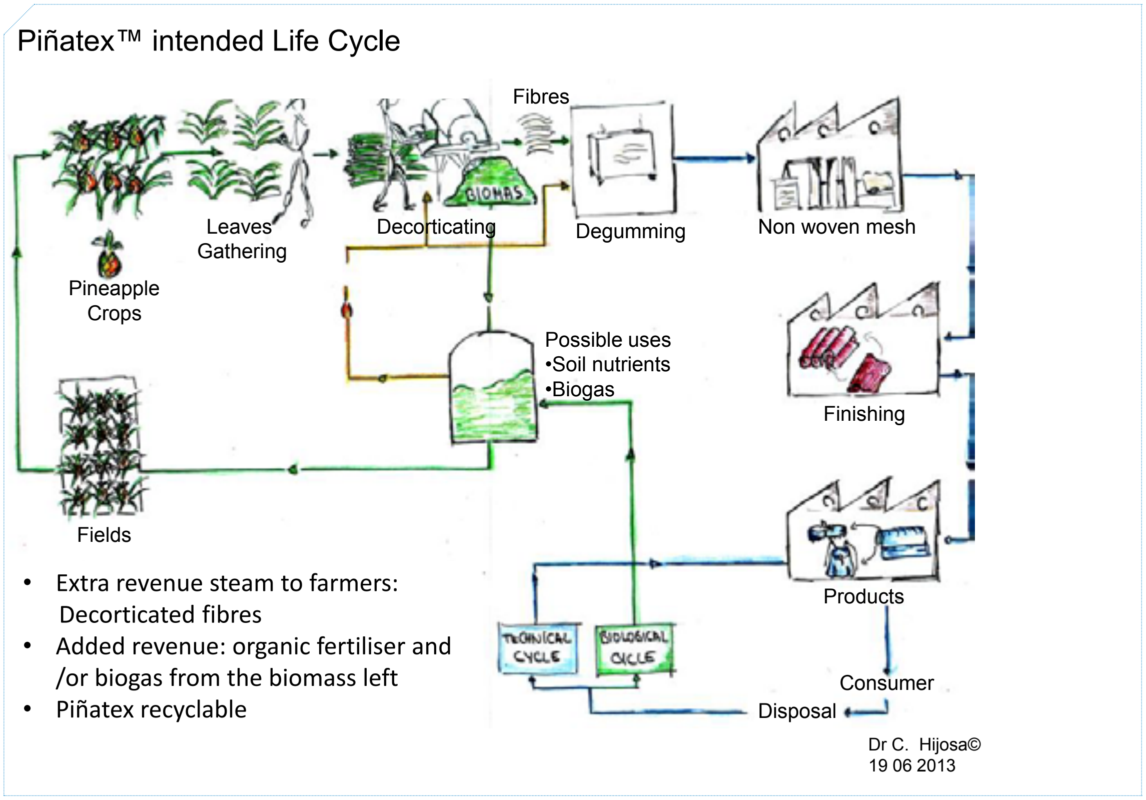


Figure 4.14 Production of Piñatex™ fibres and products, from harvested pineapple leaves (images courtesy of Claire Mueller, Ananas Anam).


Piñatex™ intended Life Cycle

- Extra revenue steam to farmers: Decorticated fibres
- Added revenue: organic fertiliser and /or biogas from the biomass left
- Piñatex recyclable

Figure 4.15 The intended life cycle of Piñatex™ as proposed by the manufacturer (image courtesy of Ananas Anam).

## Case study 11 – Responding to the Kenya plastic bag ban

Kenya introduced a nationwide plastic bag ban in August 2017, in response to a growing problem with littering and underdeveloped waste management infrastructure. At the time of the ban, the Kenya Environment Minister was quoted as saying: *'Plastic bags now constitute the biggest challenge to solid waste management in Kenya. This has become our environmental nightmare that we must defeat by all means.'*[22] The response has been to encourage the greater use of traditional materials, such as sisal, papyrus, paper and baobab (Figure 4.16), as well trigger the development of innovative potential solutions.

**Figure 4.16 Shopping bags made from papyrus and baobab fibres ©Peter Kershaw**

The forestry industry in Kenya has relied on single-use plastic bags to grow seedlings. With the advent of the ban an alternative was urgently needed. This provided the incentive for Diana Ndungi, an agriculture teacher at a girls' high school, to seek a solution, turning to sisal and banana and enlisting the help of some enthusiastic pupils.[23] The pupils of the Thika Girls' Karibaribi high school now produce woven sisal containers to grow saplings (Figure 4.17) . As the bags are biodegradable they can be left in the soil. The school takes inspiration from the late environmental campaigner and Nobel Laureate Wangari Maathai, a founder of the Green Belt Movement in Kenya, set up to protect and restore the country's forests.

## Case study 12 – Creating business opportunities from invasive water hyacinth

In some circumstances the utilisation of natural materials can provide both an economic opportunity and a solution to an unwelcome problem. The water hyacinth *(Eichhornia crassipes)* is native to the Amazon basin but has spread to many tropical and sub-tropical parts of South and North America, sub-Saharan Africa, South and South East Asia and Australia. It grows rapidly in favourable conditions, causing a hindrance to navigation, loss of fisheries, blocking of water intakes and irrigation systems, flooding (by blocking drainage ditches) proliferation of disease such as schistosomiasis (bilharzia) and increased water loss by transpiration (Patel 2012).

A number of innovative solutions have been devised in an attempt to both control the spread of this unwanted weed and make use of it as a raw material. Uses include: remediation of wastewater; production of briquettes for fuel (Munjeri *et al.* 2016), as an alternative to collecting wood, and the production of paper; as a limited life geotextile in construction, with superior properties to some alternatives such as coir and sisal (Bordoloi *et al.* 2016); as a feedstock for bio-refining (Santibanez-Aguilar *et al.* 2013); for the production of household goods and artefacts using the dried woven plant stems; and, for paper production (Calvert 1998).

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[22] http://www.bbc.co.uk/news/world-africa-41069853
[23] http://www.nyikasilika.org/innovation-bio-degradable-seedling-bag-beatpollution/
[24] http://www.rainharvest.co.za/2011/03/kenyan-villagers-turn-invasive-water-hyacinth-into-moneymaker/

**Figure 4.17** Teacher Diana Ndungi and pupils from the Thika Girls' Karibaribi school, weaving containers from sisal as a replacement for plastic bags, for use in the forestry industry; image of single pot courtesy of Thika Girls' Karibaribi, other images ©Peter Kershaw.

Examples of the utilisation of water hyacinth as a source of hard-wearing fibre can be found in many countries, including Indonesia, India, the Philippines, Kenya[24] and Nigeria. Mitimeth is a social enterprise operating around Lagos and in the delta region of Nigeria, founded by Achenyo Idachaba, formerly a computer scientist based in the USA[25]. The knowledge and skills needed to utilise water hyacinth are based on traditional methods of weaving, applied to this underutilised raw material by means of developing partnerships and running workshops in the local rural community[26]. The plant stems are air dried and woven into ropes that are used to create a wide variety of mats, bags and other containers (Figure 4.18). The waste from manufacturing is combined with cow dung and fed into a bio-digester for energy generation.

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[25] https://www.mitimeth.com/

[26] http://www.rainharvest.co.za/2016/01/using-water-hyacinth-seaweed-to-create-everyday-household-products/

**Figure 4.18** Household items made from dried water hyacinth fibres: ladies handbag made from loom-woven water hyacinth fibres and leather, place mats and floor-standing lampshade; images courtesy of Achenyo Idachaba of Mitimeth.

Other initiatives, in Bangladesh[27] India, Indonesia, Kenya and the Philippines, have examined the potential to use water hyacinth to produce paper and paper products, with the potential to reduce the demand for conventional plastic products as well as for traditional paper pulp, easing the pressure on over-utilised timber stocks, in addition to dealing with a serious social and environmental problem (Calvert 1998). One project in Kenya is receiving support from the National Environment Management Authority. Cosmos Githinji Karari, the entrepreneur behind the venture, is experimental with mixing the water hyacinth with other fibres, such as papyrus, to adjust the properties of the finished product, and uses waste materials to produce ingenious designs (Figure 4.19).

**Figure 4.19** Carrier bags, cards and envelopes made from dried water hyacinth fibres harvested from Lake Victoria, Kenya, with decorations made from scrap materials. ©Peter Kershaw

## Case study 13 – Compostable coffee cups

The global demand for coffee is huge and growing, and much of it is dispersed in single-use containers, either entirely made of plastic of with a plastic component, such as a waterproof membrane. Such composite designs are difficult to recycle so many used coffee cups end up as solid waste. Single-use coffee cups represent one of the best examples of our throwaway culture, offering the convenience of drinking coffee on the move but with little thought going into the consequences of this profligate use of resources for a product with a useful life measured in minutes. Billions of disposable coffee cups are produced every year.

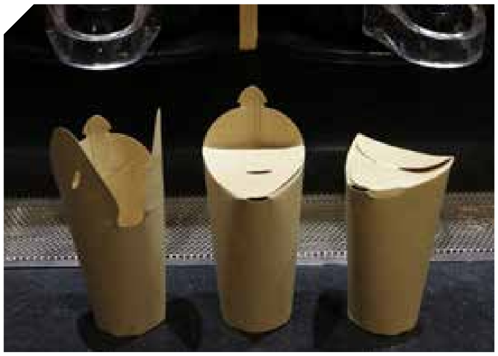

**Figure 4.20** The Triocup – a one-piece paper coffee cup with folding lid, image courtesy of Triocup.

Fortunately, several ideas have been advanced to tackle this problem[28]. One of the most promising is a one-piece paper cup produced by Triocup, co-founded by Tom Chan. This start-up was a winner of the 2017 Ellen McArthur Foundation Innovation Prize, in the Circular Design Challenge[29]. The cup is designed on origami principles, with a folding lid that prevents spills and obviates the need for a separate lid (Figure 4.20). The cup is suitable for industrial composting.

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[27] http://www.bangladesh.com/blog/prokritee-promoting-bangladeshi-handicrafts
[28] http://www.bbc.co.uk/news/business-40951041
[29] https://newplasticseconomy.org/innovation-prize/winners/triocup

## Case study 14 – Producing edible plates and cutlery from cereal crops

In many cultures it has been common practice to use foods such as flatbreads, made of wheat or maize flour, as a means of eating in preference to 'western-style' cutlery. There have been several initiatives to take this further and explore the potential of making plates, bowls and cutlery out of materials than can be eaten afterwards.

### The Patrada Project

The Patrada Project is based in Delhi and has been developed to help a group of women refugees from Afghanistan. The idea for the project came from a group of students from the Kikori Mor College of the University of Delhi[30]. The project operates within the ENACTUS framework, a global partnership of universities and businesses[31]. The ENACTUS model promotes entrepreneurship as part of a social enterprise, bringing together students, academics and business leaders in collaboration to bring about '*a better world*'.

**Figure 4.21** Bowls made by Afghan refugee women in Delhi, as part of the ENACTUS Patrada Project, image courtesy of Kikori Mor College

The Afghan women live in a marginalised community in the Bhogul area of Delhi and the project has enabled them to become more self-sufficient. They have been trained to make bowls, formed in moulds, using a flour paste from cereals such as wheat, rice and ragi (finger millet, *Eleusine coracana*). The bowls are available in a range of sizes and are marketed as *'designed not to last'* (Figure 4.21). The target market includes food outlets, cafes, ice cream parlours and bakeries, reducing the demand for plastic equivalents. The bowls can be consumed with the meal or otherwise will readily biodegrade.

### Bakeys cutlery

Bakeys was established in Hyderabad India in 2010 by Narayana Peesapaty[32]. The company produces edible spoons made by baking a dough consisting primarily of sorghum *(Sorghum bicolor)*, with some additional wheat and rice flour. Sorghum, a member of the grass family, is preferred as it considered to increase resistance to liquids and needs less water and added nutrients than other cereals such as rice and maize. S. bicolor is drought- and heat-resistant and represents an important food crop in South Asia, Africa and Central America. The company claim that the production of sorghum uses 2% of the energy required to produce polypropylene and 14% of the water required to produce maize-based PLA[33].

### Cupffee coffee cup

A start-up in the Czech Republic is experimenting with producing an edible coffee cup. The Cupffee is composed of a cereal-based crisp waffle and is claimed to hold coffee for up to 40 minutes[34].

## Case study 15 – Producing edible food packaging from seaweed

Seaweed represents a widespread, renewable natural resource and is used for a great many different purposes. Recent developments have included exploring opportunities for using seaweed-based materials for food packaging. Two examples are described below, both of which were winners of Circular Design awards, as part of the Ellen McArthur Foundation New Plastics Economy initiative.

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[30] https://www.enactuskmc.org/patradya
[31] enactus.org/
[32] http://www.bakeys.com/edible-cutlery/
[33] https://www.kickstarter.com/projects/1240116767/edible-cutlery-the-future-of-eco-friendly-utensils
http://worldcentric.org/sustainability/energy-savings
[34] http://www.cupffee.me/en/

## Evoware

Evoware is a social enterprise based in Indonesia. It has two main aims: i) to utilise seaweed as a renewable resorce, in a sustainable manner, as an alternative to plastic packaging; and, ii) to help impoverished seaweed farmers improve their livelihoods[35]. Evoware produces a thin-film packaging for dry goods. The edible grade is suitable for products such as food wraps and sachets for coffee or sauces, with the non-edible grade used for packaging items such as soap and sanitary pads (Figure 4.22). The packaging is reported to be almost odourless and tasteless and should last for up to two years in a cool, dry environment.

Figure 4.22 Food sachets made from seaweed; images courtesy of Evoware

## Skipping Rocks Lab

The Skipping Rocks Lab is a start-up based at Imperial College in London. It is part of the Climate-KIC start-up acceleration programme founded by the European Institute of Innovation & Technology[36]. The first initiative has been to develop a flexible packaging from seaweed for containing water and other fluids in 'bite-size' packages to satisfy the 'water-on-the-do' market , which they have named the 'Ooho' (Figure 4.23). The membrane is edible and can be flavoured and dyed. It is claimed to generate 20% of the $CO_2$ emissions and use 11% of the energy requirements of PET production, as well as being cheaper to produce. If it is discarded it will biodegrade in 4 – 6 weeks, *'just like a piece of fruit'*.

Further designs are being developed. The latest is the *Delta*, a small triangular water soluble sachet intended for use in restaurants and the hospitality sector. This design was a winner of the 2017 Circular Design Challenge, organised through the Ellen McArthur Foundation as part of the New Plastics Economy Initiative. It is intended that sachets will be produced and filled using a machine based at the user's premises: for example, sauces at a fast-food restaurant or shampoo for a hotelier. This gets around the disadvantage of the relatively short shelf-life of the seaweed-based membrane.

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[35] http://www.evoware.id//about_us/our_story
[36] https://eit.europa.eu/

Figure 4.23 The 'Ooho' - flexible and edible packaging for water and other fluids, made from seaweed and other plants; images courtesy of Skipping Rocks Lab, photo credit upper left Katherine Fawsett.

## Case study 16 – Non-edible products from seaweed

Algu is based on utilising brown seaweed, pulped waste paper and water, all of which are in plentiful supply in north-west Europe, where the material is manufactured. It is the inspiration of Louis Johnston, a member of the London-based Mandin Collective[37], a group of artists and designers inspired to create sustainable products from a wide variety of natural and waste materials. The type of macro-algae used belongs to the genus Fucus., which is ubiquitous on exposed shorelines in this region. The algae is dried and ground to a powder, before being mixed and heated with the pulped waste paper and water. This creates a viscous paste that can be pressed into moulds and left to dry, producing a wide variety of products (Figure 4.24).

Figure 4.24 Lampshades manufactured from minimally processed brown seaweed (Fucus sp.), by Louis Johnston of the Mandin Collective; images courtesy of the Mandin Collective.

Seaweed harvesting can be carried out in a sustainable manner, provided care is taken to avoid over exploitation and damage to the underlying substrate. Seaweed is available on shorelines throughout the ocean and there appears to be great potential to increase the range of applications based on alginate.

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[37] www.mandin.earth

# 5. Alternative materials - biomass-based compostable bio-polymers

## 5.1 An introduction to compostable polymers

There has been growing interest in the development of polymers with 'greener' credentials in recent years. This has led to the greater utilisation of renewable biomass-based feedstock, as well as materials that are more readily degraded in the environment (Figure 5.1). This has been accompanied by an increase in the use of the term 'biodegradable' (European Bioplastics 2015), but it is important to consider under what circumstances the description is justified. A definition of 'degradation', 'biodegradation' and 'compostable' is provided in Table 5.1. Most synthesised polymers are not biodegradable under normal environmental conditions, whether derived from fossil fuel or renewable biomass sources (United Nations Environment Programme 2015). Degradation will occur under favourable conditions, such as higher temperatures, physical abrasion and exposure to UV radiation, with the rate dependent on the type of polymer and presence of stabilising compounds. But this leads simply to weakening and fragmentation. Recommendations on the terminology for describing degradation have been published by the International Union of Pure & Applied Chemistry (IUPAC) (Vert *et al.* 2012).

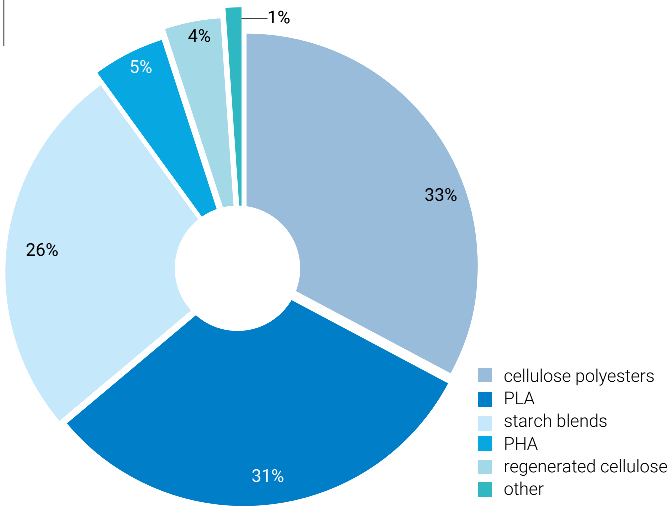

**Figure 5.1** Global production of biomass-based biopolymers in 2014 (European Bioplastics 2015).

**Table 5.1** Definitions of degradation, biodegradation and compostable.

| Term | Definition |
|---|---|
| Degradation | The partial or complete breakdown of a polymer due to some combination of UV radiation, oxygen attack, biological attack and temperature. This implies alteration of the properties, such as discolouration, surface cracking, and fragmentation |
| Biodegradation | Biologically-mediated process involving the complete or partial converted to water, $CO_2$/methane, energy and new biomass by microorganisms (bacteria and fungi). |
| Compostable – industrial (C-i) | Capable of being biodegraded at elevated temperatures under specified conditions and time scales, usually only encountered in an industrial composter (standards apply) |
| Compostable – domestic (C-d) | Capable of being biodegraded at low to moderate temperatures, typically found in a domestic compost system |

Several national and international standards have been developed for biodegradable and compostable materials (United Nations Environment Programme 2015). These stipulate the testing conditions and expected performance. Marketing a product as 'biodegradable' may give a favourable commercial advantage, but the description can be misleading. For example, several products initially labelled as 'biodegradable' in the state of California USA have not achieved such standards and restrictions have been placed on their marketing[38]. One standard was developed for the biodegradation on non-floating polymers under marine conditions in the USA (ASTM D 7081-05). However, this was withdrawn in 2014 and it does not appear to have been either re-instated or replaced.

Some polymers are biodegraded under composting conditions. There is scope for confusion over use of the term 'compostable', as this can refer to either an industrial or a home/domestic setting, but the difference is critical. In many cases, labelling a product or polymer as being 'compostable' only applies to the conditions generated within an industrial composting system, where temperatures can be maintained at around 60°C for many weeks. Normal domestic/garden compost bins or heaps operate at much lower temperatures (maximum 20-30°C, but lower during higher latitude winter months). Emadian *et al.* (2017) undertook a comprehensive review of the biodegradation properties of a variety of biomass-based biopolymers, demonstrating the substantial differences in reported behaviour under differing environmental conditions. Even a similar product made from the same polymer may show significant variability in degradation characteristics due to differences in production, as reported for PLA cleaning cloths by Vaverková and Adamcová (2015).

There are several standards for industrial composting that can be applied: DIN V 54900-1 (Germany), EN-13432 (EU), ASTM 6400-04 (USA) and GreenPla (Japan). Vincotte[39], a certification and standards agency based in Belgium, provides certification for industrial composting (OK Compost) and domestic composting (OK Home). This stipulates the conditions that have to be met, including disintegration of > 90%. A comparison of the test conditions and minimum performance standards for industrial and domestic composting is provided in Table 5.2. Vincotte also provides certification for materials being biodegradable in soil (OK SOIL) and biodegradable under marine conditions (OK MARINE). However, OK MARINE is based on the ASTM D 7081-05 standard, which was withdrawn in 2014, and it is not clear whether this certification is still valid. This is a matter for Vincotte to determine.

**Table 5.2 Comparison of standards for industrial and home composting (from: Song *et al.* 2009)**

| Process | Test conditions and minimum performance standards | |
|---|---|---|
| | **Industrial composting (EN 13432)** | **Home composting (Vincotte certification)** |
| Biodegradation | • Test at 58°C in 180 days<br>• Biodegradation minimum 90% | • Test at 20 – 30°C in 365 days<br>• Biodegradation minimum 90% |
| Disintegration | • Test at 58°C in 90 days<br>• Sieve 2mm mesh<br>• Disintegration > 90%<br>• Maximum 10% of dry weight allowed to be retained by 2 mmm sieve | • Test at 20 – 30°C in 180 days<br>• Sieve 2mm mesh<br>• Disintegration > 90%<br>• Maximum 10% of dry weight allowed to be retained by 2 mmm sieve |
| Designation | Din Certco/OK Compost | OK Home |

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[38] http://www.calrecycle.ca.gov/Plastics/Degradables/default.htm
[39] https://www.vincotte.be/en_be/home/

The synthetic polymers Poly(butylene succinate) (PBS), Polycaprolactone (PCL) and Polyvinyl alcohol (PVA) exhibit some enhanced degradable properties (United Nations Environment Programme 2015). For example, thin PVA film and thread dissolve in seawater, and are used by recreational anglers for setting bait. In earlier decades, PVA was used by oceanographers to release bunches of (plastic) seabed passive drifters. PCL is sometimes added to starch mixes (Section 5.2.3) to improve performance and is compostable, in an industrial composter. PVA and PBS films are used for agricultural mulching films, but the degree and rate of biodegradation is difficult to quantify (Lesinsky *et al.* 2005). Stoica-Guzun *et al.* (2011) reported that the addition of bacterial-cellulose to PVA produced a film that performed its intended function but which was more readily degraded in soil by a fungal strain *(Aspergillus feotidus)*.

## 5.2 Starch-based polymers

### 5.2.1 Sources of starch

Starch is a polysaccharide, consisting of linked glucose molecules, and is used as an energy store in plants. It is one of the most important forms of carbohydrate in the human diet. Common sources of starch include rice, maize, wheat, potatoes and cassava. It is composed of two sorts of macromolecule: amylose, which is a sparsely branched carbohydrate; and amylopectin, which is highly branched with a high molecular weight (Avérous and Halley 2009). Different plant species and varieties tend to have different proportions of amylose and amylopectin, as well as varying degrees of crystallinity and granule diameter (Table 5.3). This can affect the degree of processing required and the properties of the final product (Shogren *et al.* 2002, Bergel *et al.* 2017). The common availability of this feedstock has generated considerable interest in the potential for starch-based products to replace conventional plastics.

**Table 5.3 Composition of different starches (from: Avérous and Halley 2009)**

| Starch | Amylose content (%) | Amylopectin content (%) | Granule diameter (micron) | Crystallinity (%) |
|---|---|---|---|---|
| Wheat | 26-27 | 72-73 | 25 | 36 |
| Maize | 26-28 | 71-73 | 15 | 39 |
| Waxy starch | <1 | 99 | 15 | 39 |
| Amylomaize | 50-80 | 20-50 | 10 | 19 |
| Potato | 20-25 | 79-74 | 40-100 | 25 |

### 5.2.2 Thermoplastic starch

Some degree of thermal and mechanical processing is required to disrupt the complex crystal structure of starch, and achieve partial or complete gelatinisation. Closed cell expanded foams require the least disruption, with the addition of water and elevated temperatures, followed by extrusion into a variety of shapes. This material has good thermal insulation and shock-absorbing properties. Applications include loose fill to protect packaged goods in transit. The eventual goal is to produce a material that can replace EPS, especially for food packaging (Kaisangsri *et al.* 2014, Ahmadzadeh *et al.* 2016). Much of the research has focussed on the use of cassava starch, an important staple crop, and therefore readily available, in parts of Asia[40], Africa and South America. However, any form of starch can be used so the techniques and applications can be scaled to a widespread market, with the caveat that food security and affordability are not compromised (Table 5.4).

Minimally-modified starch foam readily dissolves in water, is compostable under domestic conditions and will degrade rapidly in the environment. This otherwise desired property does create a limitation

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[40] www.avanieco.com

on the range of applications starch foam can be used for. However, chitosan has been used to coat the foam, thereby decreasing water absorption and increasing the tensile strength (Bergel *et al.* 2017).

At higher temperatures and lower water content it is possible to produce thermoplastic starch (TPS), with the addition of a plasticiser such as sorbitol or glycerine (Shanks and Kong 2012). More conventional chemical treatments could be used but these may introduce potential unwanted by-products, requiring an additional purification phase. TPS is transformed from native starch using the same manufacturing techniques as conventional plastics, producing a homogenous molten phase that is then extruded (Avérous and Halley 2009). The structure of the feedstock can vary with geographical source and growing season, as well as plant variety, making it more difficult to control the properties of the synthesised TPS (Shanks and Kong 2012). In addition, the properties of TPS may make it unsuitable for some applications, such as food packaging, without further modification, for instance to improve moisture sensitivity.

**Table 5.4** SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of thermoplastic starch production and use

| | |
|---|---|
| S1. Utilises renewable natural resources<br>S2. Starch crops are readily available in most developing and developed countries, and are a staple in many countries in Asia, Africa and South America<br>S3. Can be composted in an industrial facility or decomposed by anaerobic digestion at end-of-life<br>S4. Rate of biodegradable in the environment is significantly faster than for conventional synthetic polymers | W1. Biocides and artificial fertiliser may be used on commercial crops, resulting in risks to human health and the environment<br>W2. Substitution for conventional polymers limited by intrinsic properties of the material<br>W3. Products composed of TPS may remain in the aquatic environment for several years before degrading, posing a risk to social well-being and the environment |
| O1. Expanded utilisation of renewable natural resources<br>O2. Development of social and economic independence in rural area<br>O3. Substitution for single-use consumer products such as shopping bags | T1. Loss of habitat and biodiversity<br>T2. Intensification of production will drive greater use of biocides and artificial fertiliser, and hence increased risks to human health and the environment<br>T3. Use of agricultural land for non-food use may drive up prices and impact food security |

### 5.2.3 Starch-based bio-composites

Starch-based micro and nano bio-composites are produced by combining TPS polymer with a filler such as cellulose or lignin fibres (La Mantia and Morreale 2011). This is done to improve the properties of the finished product and increase the range of applications. For example, the addition of cellulose fibres to a TPS matrix was reported to bring the following benefits (Avérous and Halley 2009):

- Higher mechanical properties
- Higher thermal resistance
- Reduced water sensitivity
- Reduced post-processing ageing

Soykeabkaew *et al.* (2015) have published a comprehensive review of starch-based polymers, summarising the various approaches that have been investigated. There are several natural fibres that can be use to produce bio-composites, with particular interest in utilising agricultural waste. For example, cassava bagasse consists of the fibres remaining after the extraction of starch from cassava. The addition of unmodified cassava bagasse to cassava-based TPS film was found to reinforce the film and reduce its water solubility (Edhirej et al 2017). Malt bagasse is a by-product of the brewing industry.

The addition of malt bagasse fibres (cellulose-lignin) was found to increase the strength of food trays made out of baked starch foams (Mello and Mali 2014). Bagasse from sugarcane processing has also been used to reinforce starch-based composites, resulting in improved performance (Vercelheze *et al.* 2012; 2013; Gilfillan *et al.* 2014). Jiminénez *et al.* (2016) reported that both the orientation and length of sugarcane bagasse fibres influenced the tensile strength.

Kaisangsri *et al.* (2014) tested the effects of adding a variety of plant-based materials to the production of cassava starch-based foams. These included zein (maize protein), gluten, soy, kraft fibre and palm oil. The addition of kraft fibre, zein and gluten were all found to increase the flexural strength and compressive strength of the foam, with 15% kraft providing the highest values. Other cellulose/lignin sources that have been investigated include flax and pine bark. The proportion of added cellulose fibre has a significant effect on the properties of the manufactured composite, thought to be due to interactions between the fibres as well as with the starch compound (Gilfillan *et al.* 2014).

The chemical composition of the starch raw material can have a significant influence on the physical properties of the finished product. Waxy maize starch consists of 100% amylopectin. It was first discovered in China in the early 20th Century but has been adopted in the maize-growing region of the USA and elsewhere. Its use to manufacture starch foams was found to provide higher tensile strength than standard maize starch, especially when combined with polyvinyl alcohol (PVOH) and softwood fibres (Shogren *et al.* 2002).

Non-cellulose polymers such as chitosan have been used to manufacture TPS composites. The addition of chitosan was reported to improve the water vapour and oxygen barrier properties of TPS films (Dang and Yosan 2016). The authors suggested that this material has potential for use as an edible film for food packaging, and pharmaceutical applications.

In addition, composites have been produced using clay minerals (Vercelheze *et al.* 2012, Rhim *et al.* 2013). These phyllosilicate minerals have a strongly layered, plate-like structure, with well-developed polarity on the plate edges and between the plates. This phenomenon is utilised by adjusting the conditions in the reaction vessel to encourage cation exchange between the organic (TPC) and inorganic (clay) components (Avérous and Halley 2009).

The potential for starch-based bio-composites to replace conventional plastics in many packaging applications appears to be very promising, although further work is required to maximise this potential. In particular, improvements need to be made to some fundamental aspects, such as mechanical properties and moisture sensitivity, before this category of polymers can replace conventional polymers in a wider range of applications (Xie *et al.* 2013). A comprehensive review of all-polysaccharide composites has been published by Šimkovic (2012).

### 5.2.4 Starch composites with synthesised polymers

Starch-based composites can also be produced with the addition of synthetic polymers, to improve performance and increase the range of potential applications (Figure 5.2). Starch-PCL is the most common starch blend, as it has a low melting temperature and can be readily hydrolysed. For example, it is used in the range of products marketed as Mater-Bi®, by Novamont in Italy (Bastioli and Marini 1998).

PCL is compostable but is derived from fossil fuel. Other starch blends included composites with biomass-based polymers (section 5.3), such as polylactic acid (PLA), polybutylene succinate (PBS), PBSA (polybutylene succinate-co-butylene adipate)), polyvinyl acetate (PVA) and polyhydroxyalkanoates (PHA). PLA, PBS and PBSA have the additional advantage that they can be produced by fermentation of biomass. The composition and environmental behaviour of the finished product will be influenced by the proportion and properties of the added polymer (Accinelli *et al.* 2017). Conventional recycling of composite materials requires separation of the polymers and is very is challenging, but if the composite can be recycled by composting or anaerobic digestion then the cost will be considerably reduced.

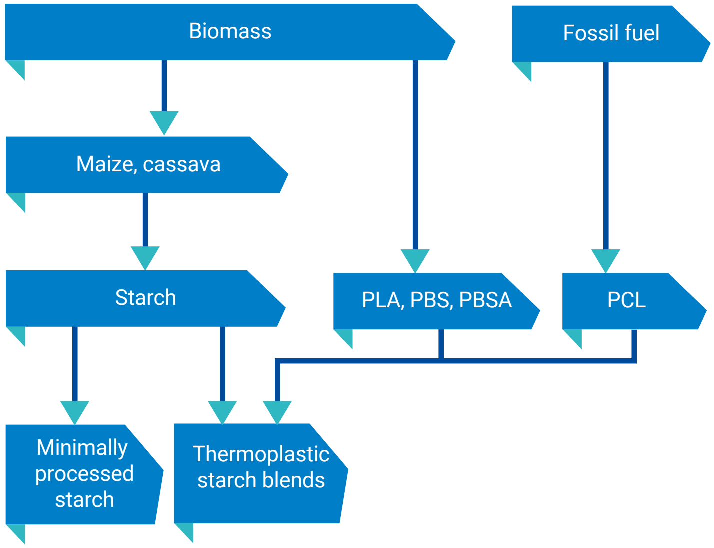

**Figure 5.2** Simplified schematic of the production of starch-based polymers

## 5.2.5 Non-starch thermoplastic bio-composite

It is possible to produced thermoplastic materials from natural sources other than starch, including alginate and chitosan. Alginate is extracted from species of brown algae, which have a global extent. Alginate has many industrial uses and annual production is > 50,000 tonnes (D'ayala *et al.* 2008). Gao *et al.* (2017) developed plasticised alginate using glycerol as a plasticiser, using similar thermo-mechanical disruption as used for TPS. One advantage of developing films based on alginate is that there is no direct competition with food production. The opposite applies for starch-based composites, which require the use of agricultural land to produce the raw material, potentially at the expense of food production. Alginate-based thermoplastics are still under development but show great promise.

Chitosan-based composites are manufactured using chitin. Chitin is abundant globally, forming the exoskeletons of insects and crustacea, such as shrimp. Chitosan is created by the partial de-acetylation of chitin with sodium hydroxide, with the degree of acetylation determining the crystallinity. Early interest focussed on biomedical applications, but this has broadened. The main source of chitin is the exoskeleton of crustacea, especially from aquaculture where it can be seen as an under-utilised waste product with a wide variety of potential applications (Cahú *et al.* 2012).

The potential of utilising of cutin-based polymers has been reviewed recently (Herredia-Guerroro *et al.* 2017). Cutin is an abundant waxy polymer (biopolyester) that occurs in plant cuticle, the protective layer that forms the outer surface of leaves, and other plant organs that do not have a periderm. One disadvantage of cutin is the wide range of monomers that occur, which introduce an additional complexity into the process. However, the type of cutin that occurs in the skin of tomatoes is composed predominantly of a single monomer (9(10),16-dihydroxyhexadecanoic acid). This will permit the development of relatively low cost and scalable technologies to be developed, based on hydrolysis by sodium hydroxide, allowing the utilisation of the waste from the large-scale horticultural production of tomatoes (Figure 5.3).

**Figure 5.3** Tomato skins – a source of cutin for a novel biomass-based polymer; ©Peter Kershaw.

### 5.2.6 Behaviour of starch and starch-based composites in the environment

Biomass-based polymers have widely differing behaviours under different environmental conditions. Starch-based polymers are often referred to as biodegradable (Fialho e Moraes *et al.* 2017; Ezeoha and Ezenwanne 2013), and it may be assumed that starch-based films and sheets are readily degraded in the environment. However, the rate at which degradation occurs will depend on the external conditions (Table 5.5). For example, Balestri *et al.* (2017) tested the rate of degradation of a commercially available starch-based carrier bag (Mater-Bi®), in marine sediments in the Mediterranean. They demonstrated that the bag retained 85% of its original mass after 6 months exposure. In addition, the presence of the bag significantly altered the sediment pore water chemistry, and influenced the seagrass species assemblage. In contrast, starch-based materials are readily compostable, in both a domestic and commercial setting.

Table 5.5 **Starch-based polymers, biomass source and common uses, together with biodegradable and composting properties (based on reported observations, where available, otherwise estimated): domestic composting C-d, industrial composting C-i, biodegradable B; degradation rate: high H, medium M or low L; qualitative sustainability indicator: blue high, medium purple, low red).**

| Material | Polymer | Common biomass source | Examples of common uses | Terrestrial | | | Aquatic |
|---|---|---|---|---|---|---|---|
| | | | | C-d | C-i | B | B |
| **Starch-based mixes** | | | | | | | |
| Expanded starch foams | starch | Maize, cassava, potato, rice | Loose packaging fill | H | H | H | H |
| Thermoplastic starch TPS | Starch | Maize, cassava, potato, rice | Thin-film bags | M | H | M | M |
| TPS-polmer composite | Starch-PCL/PLA | Maize | Mater-Bi®, films, agricultural mulch | M | H | M | M |
| TPS-biocomposites | Starch-cellulose/ | Alpaca | Clothing, other fabrics | M | H | M | M |

## 5.3 Synthetic biomass-based polymers

### 5.3.1 Introduction to synthetic biomass-based polymers

A variety of plant- and animal-based raw materials can be used to synthesize biomass-based polymers, depending on the intended use and processes employed. Cellulose and starch are the most common sources, but proteins and fats can be used. Poly(lactic acid) or polylactide (PLA) and polyhydroxylkanoates (PHA) have been synthesised in significant volumes and marketed as being biodegradable (Figure 5.4) (European Commission 2011, Wang *et al.* 2014). The justification for these claims will be discussed in later sections. PLA and PHA are both compostable, under industrial composting conditions (Table 2.4), but this does not apply to all polymers derived from biomass. In addition, some caution is needed when considering the biomass feedstock. If this consists of purposefully grown food crops, then the loss of production for human consumption should be considered in any Life Cycle Assessment, together with the use of water, fertiliser, biocides and energy (Chapter 7). If use can be made of agricultural waste, or the products of composting or anaerobic digestion, then the environmental credentials of PLA and PHA are easier to defend.

Products manufactured from PLA and PHA, such as bottles and films, may be indistinguishable from conventional plastics to the naked eye. However, reproducing properties such as vapour permeability and flexibility can be more difficult to achieve compared with equivalent polymers used for similar applications, such as PET and PS (Karamanlioglu *et al.* 2017).

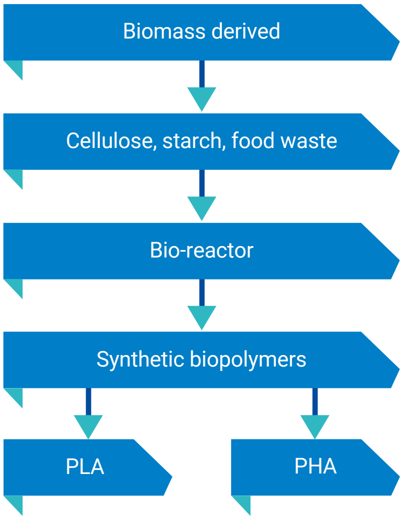

**Figure 5.4** Simplified schematic of the production of poly(lactic acid) (PLA) and polyhydroxylkanoates (PHA).

PLA is becoming more popular as a substitute for conventional plastics in the catering sector, where food waste and used PLA plates, cups and cutlery can be collected and the combined waste sent for either industrial composting or anaerobic digestion. This approach works best in a controlled closed loop environment, such as institutional catering in companies and hospitals, to prevent cross-contamination of PLA/PHA plastics with conventional plastics. This minimises the problem of compromising the composting/digestion of PLA/PHA by conventional polymers, and the recycling of conventional polymers by PLA/PHA. The closed loop approach allows the products of composting or anaerobic digestion to become the feedstock of the next generation of PLA/PHA (Chapter 7). The model provides a good contrast with conventional plastics used for catering, especially in an institutional setting (Section 2.5.2).

One farmer in Poland came up with a novel solution for dealing with an excess of post-harvest wheat bran. He experimented with mixing the bran with PLA to produce cutlery, in the proportion 1:9[41]. The product has a characteristic colour and texture which makes it easier to distinguish from conventional plastics, encouraging separation of waste streams. The bran-PLA utensils are designed for industrial composting. There is scope to copy this model more widely.

### 5.3.2 PLA production and use

Poly(lactic acid) is synthesised by polymerisation of lactic acid, produced by bacterial fermentation of sugars derived from a variety of biomass sources. This has allowed the commercial scale production of PLA, with major producers in the USA, Europe and Japan (Karamanlioglu *et al.* 2017). PLA is a bio-polyester with thermoplastic properties and a wide variety of applications, many of which are similar to conventional synthetic polymers. The main applications have been for various forms of packaging (Armentano *et al.* 2013) and in the catering industry (Figure 5.5), as it is safe to use for contact with food (Auras *et al.* 2004). A more recent development has been the production of PLA fibres (IngeoTM).

There has been interest in developing a method for producing lactic acid from methane by fermentation[42]. This introduces the potential to close the loop on PLA production by the generation of methane from the anaerobic digestion of PLA waste.

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[41] http://biotrem.pl/en/products/cutlery/

[42] http://www.natureworksllc.com/News-and-Events/Press-Releases/2016/03-09-16-NatureWorks-Methane-to-Lactic-Acid-Fermentation-Lab

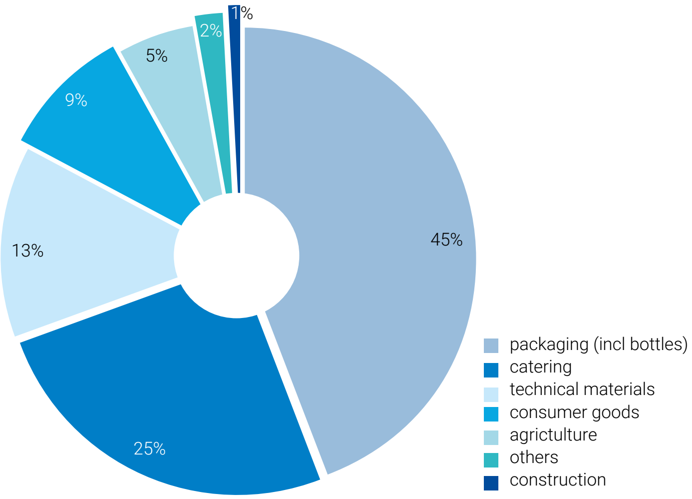

**Figure 5.5** Applications of PLA by sector (data from Karamanlioglu *et al.* 2017)

Some of the advantages and disadvantages of PLA production and use are presented as a SWOT analysis in Table 5.6, taken from De Matos *et al.* (2015).

**Table 5.6** SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of PLA production and use (based on: De Matos et al.2015).

| | |
|---|---|
| S1. Applications include disposable packaging and high added-value applications, including medical grade<br>S2. Can replace several fossil fuel-based polymers, such as polyethylene terephthalate (PET).<br>S3. Can be composted in an industrial facility or decomposed by anaerobic digestion at end-of-life | W1. Production costs may hinder its use in lower-value applications.<br>W2. Thermal and gas permeability are lower compared to fossil fuel-based polymers. |
| O1. Developments of new catalysts and melt polymerisation processes could reduce production costs.<br>O2. Producing lactic acid from waste/residues should decrease production costs.<br>O3. Since PLA is produced from a renewable source, carbon tax systems may increase its competitiveness against fossil fuel-based polymers. | T1. Limited biomass availability due to competition with other uses<br>T2. Relatively high cost of lactic acid may inhibit uptake in lower value applications. |

### 5.3.3 PHA production and use

Polyhydroxyalkanoates (PHAs) represent a large group of biogenic polyesters that can be generated by the bacterial fermentation of sugars or lipids, extracted from a range of biomass sources (Bugnicourt *et al.* 2014). They can exhibit thermoplastic or elastomeric properties. Early interest focussed on medical applications, but this has expanded into the packing industry (Bugnicourt *et al.* 2014).

Some of the advantages and disadvantages of PHA production and use are presented as a SWOT analysis in Table 5.7, taken from De Matos *et al.* (2015). Wang *et al.* (2014) noted that PHA-based polymers demonstrate a wide variety of properties, but further technical advances will be required before PHAs can replace conventional polymers in many applications.

Table 5.7 SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of PHA production and use (based on: De Matos et al.2015).

| | |
|---|---|
| S1. Similar properties to many commonly used fossil fuel-based polymers.<br>S2. Suitable for food packaging due to their low permeability to oxygen, PHA polymers are.<br>S3. Can be composted in an industrial facility or decomposed by anaerobic digestion at end-of-life | W1. PHA production costs are higher than those of fossil fuel-based polymers. |
| O1. The use of PHAs has been approved for both food contact material and surgical sutures.<br>O2. Synthesis of PHA from products of anaerobic digestion | T1. Biomass availability for the production of PHAs due to competition with other uses<br>T2. Cost of raw material. |

## 5.3.4 Behaviour of PLA and PHA in the environment

There is very limited degradation of PLA at ambient temperatures in soil and domestic composting, although degradation of PLA composites may be enhanced by the addition of natural fibres such as abaca (Teramoto *et al.* 2004) and kenaf (Surip *et al.* 2016). There is some concern that the extensive use of PLA for agricultural films may lead to a build up of PLA in soils (Rudnik and Briassoulis 2011, Karamanlioglu *et al.* 2017). In contrast, degradation of PLA and PHA does occur under commercial thermophilic composting (50-60 °C) conditions and by anaerobic digestion (Kucharczyk *et al.* 2016, Musiol *et al.* 2016). The few studies conducted to date suggest that degradation of PLA is very limited in aquatic systems (Karamanlioglu *et al.* 2017). A qualitative assessment of biodegradable and compostable properties in presented in Table 5.8.

Table 5.8 Starch-based polymers, biomass source and common uses, together with a qualitative assessment of worst-case biodegradable and composting properties (based on reported observations, where available, otherwise estimated): domestic composting C-d, industrial composting C-i, biodegradable B; degradation rate: high H, medium M or low L; qualitative sustainability indicator: blue high, medium purple, low red); the degree and rate of decomposition will depend on the application, for example a bottle vs. thin agricultural film, and the presence of additional co-polymers such as PCL.

| Material | Polymer | Common biomass source | Examples of common uses | Terrestrial | | | Aquatic |
|---|---|---|---|---|---|---|---|
| | | | | C-d | C-i | B | B |
| PHA | Polyhydroxyalkanoates | Biomass-derived sugars | Films, packaging, catering products | L | H | L | L |
| PLA | Polylactic acid | Maize, cassava starch | Films, packaging, hygiene products, catering products | L | H | L | L |

## 5.4 Case studies

### Case study 17 – University of Cambridge catering services

The University of Cambridge's catering services adopted a zero waste approach to food provision in 2015. They achieved this in partnership with Vegware™, an Edinburgh-based company with operational bases in the USA, Australia, New Zealand, UAE and Hong Kong. Vegware™ deals with the manufacture and marketing of compostable food packaging products, as well as providing training, waste audits and communications support to help effect change. A variety of materials are used, including paper, cardboard, TPS-bagasse composites and PLA (Figures 5.6, 5.7). These are disposed of with food waste into a single receptacle. The mixed waste is sent either for commercial composting or anaerobic digestion.

Vegware only uses card and paper from recycled or sustainable sources.

Water-based or plant-based linings make sure Vegware is completely compostable.

Recycled sugarcane fibre is fantastic - it's strong, sleek and sturdy. Microwave and freezer-safe. And we're reusing a waste material!

**Figure 5.6** Food packaging made from a combination of compostable materials, including paper, cardboard, cellophane and TPS-sugarcane bagasse composite; images courtesy of Vegware™.

Plant-based PLA contains less embodied carbon than oil-based PET plastic.

Made from high heat plant-based PLA, strengthened for hot use up to 85°C.

Made from recycled high heat PLA.

**Figure 5.7** Catering ware made from PLA thermoplastic; images courtesy of Vegware™.

Vegware™'s main focus is to assist 'corporate entities' to bring about a reduction in the use of conventional plastics, while reducing $CO_2$ emissions, raw material use and waste management costs. Clients include hospitals, large multinational companies, festivals and academic institutions. These are all places where the provision of food and dealing with the waste takes place within an organisation or site.

The challenge for the University of Cambridge was not trivial, with seven catering services, 6,500 sales transactions per day and 1,500 departmental events each year. Since adopting the compostable approach in 2015, each month the University saves 1.5 tonnes of carbon, saves 710 kg of virgin materials and sends 1.5 tonnes of used packaging for composting.

> **"The University Catering Service's commitment to sustainability contributes to enhancing the staff and student experience, and Vegware is a key part of this. The consideration of greater sustainability throughout the food chain inside the University helps encourage positive lifestyle changes outside of it for both students and staff."**
>
> **University of Cambridge Catering Manager**

## Case Study 18 – PHA-based textiles – Mango Materials

Mango Materials[43] is based in San Francisco. The company was incorporated in 2010 and has worked since to develop PHA as a price-competitive alternative to conventional fossil fuel-based polymers. The raw material is methane, obtained from the bacterial degradation of organic waste. A recent development has been the production of PHA fibre (Figure 5.8). As a bio-based polyester it has the functionality of conventional synthetic polyester fibres, but has the significant advantage of being compostable, and will biodegrade in a landfill, producing more methane. The company believe that fibres will break down in wastewater treatment plants, and that they would be digested if consumed by marine organisms. They are currently conducting experiments under terrestrial and aquatic conditions. If these claims are substantiated independently this could signal a major breakthrough in textile production.

**Figure 5.8** Schematic illustrating the production cycle of PHA-based products, including fibres; images courtesy of Anne Schauer-Gimenez of Mango Materials

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[43] http://mangomaterials.com/

# 6. Alternative materials – re-usable objects

## 6.1 Designed for re-use

At one time almost all containers would have been re-used many times, whether made from pottery, gourds, metal, glass or other materials. This only changed with the introduction of cheap plastic alternatives. As market demands and societal expectations have changed so the demand for disposable food and drink containers has grown enormously. With the growing realisation that this pattern of consumption is unsustainable, and that it creates a substantial waste problem, it is a good time to reconsider some of the practices we have abandoned, and look for new opportunities to combine these with modern technologies.

Using re-fillable containers for food and drink fluids is an obvious and practical solution to disposable vessels. For example, the demand for single-use PET water bottles could be significantly reduced if clean drinking water was made available for individuals and households to fill re-fillable containers. It has been estimated that, on a global basis, we use 1 million bottles per minute (Greenpeace 2017). For many people, disposable bottles are used for convenience not necessity, encouraged by heavy marketing.

Many non-plastic goods can be found an additional use once their primary use is over. This approach is sometimes referred as 'up-cycling'. It can be applied to single-use items, such as wooden chopsticks; fabrics which may be too worn otherwise unwanted; and, 'waste' materials from the manufacturing process. The effect of promoting these approaches, as well as adopting re-usable products, is to reduce the overall demand on resources, and continue to provide an alternative to the plastic equivalent (Table 6.1).

**Table 6.1** **SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of re-usable materials as a substitute for conventional synthetic polymers.**

| | |
|---|---|
| S1. May be used multiple times<br>S2. Can substitute for plastic food and drink containers<br>S3. Can make use of objects and materials that would otherwise classified as waste W1. Initially energy intensive to producee | W2. Higher weights of glass and metal will increase transport costs<br>W3. Limited opportunities for substitution of conventional synthetic polymers |
| O1. Market potential to expand, exemplified by increasing use of re-fillable metal drinks bottles | T1. Limited appeal to wider markets<br>T2. Higher initial cost inhibits take-up |

## 6.2 Case studies

### Rationale for the selection of case studies

The case studies have been selected to provide examples of how disposable packaging can be avoided altogether or how the life of materials can be extended. Some of the examples are a new variation on an old theme. Others are examples of how new technologies can provide novel solutions for dispensing food and drink, including for people living in poorer communities. There are also two examples of up-cycling in the catering and fashion industries.

### Case study 19 – Metal drinks and food containers

In the 19th and 20th Centuries miners in the United Kingdom typically would carry their lunch underground in a 'snap tin', a metal box, to keep out dust, water and rodents[44]. They would drink water from a metal canteen, again to keep the dirt out and provide a safer solution than relying on a glass bottle, in a rough working environment. As patterns of demand and consumption evolved, and new materials became available, so began the rise in popularity of the plastic food containers and the ubiquitous drinks bottle, from the 1960s onwards, often made from PE or PET.

The benefits of returning to re-usable metal bottles and containers are being reconsidered as a partial solution to the mountain of PET drinks bottles produced annually. Metal drinks containers provide a long-lasting solution to minimising PET bottle usage. They are also a safer (and lighter) alternative to glass bottles when travelling or being used outside the home. Insulated models are available to keep the contents hot or cold, and they can be used to carry advertising messages (Figure 6.1).

**Figure 6.1** Re-useable stainless steel and aluminium bottles and a re-useable stainless steel mug, promoting the sustainability message, ©Peter Kershaw

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[44] http://www.miningheritage.co.uk/snap-tin/

### The Elephant Box company

Plastic boxes are often used as a convenient and practical way to store food. This can present disadvantages depending on the type of polymer used and the nature of the food, in terms of staining, odour retention and durability. Elephant Box is a UK-based company that supplies a variety of storage solutions made from stainless steel[45]. They are designed for longevity and for multiple re-use (Figure 6.2). This helps to meet possible concerns about the use of resources in manufacture. Elephant Box started by linking with a manufacture in Chennai India and are expanding into China. The company has a programme to check working practices meet adequate standards and that the operations are sustainable.

**Figure 6.2** A selection of stainless steel re-usable containers and vessels, for food storage and consumption; images courtesy of Liz from Elephant Box.

## Case Study 20 – Liquid dispensing machine for developing economies - Algramo

Algramo is based in Chile and was founded by José Manuel. A common problem in many lower income communities is getting access to small quantities of household liquid products. Such households are unable to avoid bulk quantities and tend to buy single portions of liquids in plastic sachets. The same communities often lack basic solid waste provision with the result that there is substantial littering. Algramo have designed a dispensing machine (Figure 6.3) that allows small quantities of liquids to be purchased at an affordable price using small re-usable containers, removing the need for disposable packaging[46]. Algramo was a winner of the 2017 Ellen McArthur Foundation Innovation Prize, in the Circular Design Challenge.

**Figure 6.3** Dispensing machine for installation in retail stores, allowing small quantities of household products to be purchased using small re-fillable containers; image courtesy Algramo.

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[45] https://elephantbox.co.uk/

[46] https://www.algramo.com/ re-fillable dispensing machine

## Case Study 21 – Product dispensing systems for developed economies

### MIWA

The concept behind MIWA, short for Minimum Waste, was the inspiration of Petr Baca from the Czech Republic. Starting in 2014, he wanted to create a packaging solution that avoided relying on limited life packaging, and the need for disposal or recycling. He gathered a team with the necessary complementary skills to develop the MIWA solution. In essence this utilises re-usable capsules and in-store modular units, providing effective supply chain and in-store management. The capsules are used to transport goods from the producer to the wholesaler, and then to individual stores in which food is delivered to food outlets. Customers can select products using a smart interface and bring their own containers for filling (Figure 6.4). Empty capsules are collected, and sent to a washing centre, then returned to the producers.

**Figure 6.4** The MIWA packaging solution, utilising re-fillable capsules; images courtesy MIWA.

The system is scalable, being adaptable for major supermarkets or individual traders. There are potential cost savings in using a common packaging size for the producers and customers can purchase precise quantities, reducing the likelihood of waste. MIWA was a winner of the 2017 Ellen McArthur Foundation Innovation Prize, in the Circular Design Challenge, and has an ambition of becoming a global hub for minimum waste awareness-raising activities.

### Direct farm sales of dairy products

The supply of milk to households in many European countries was traditionally done using glass bottles, particularly for home delivery. This practice has greatly diminished with the advent of PE plastic containers and changes in retail habits. However, there is a growing market for direct farm sales using automatic dispensing machines for milk and other dairy products. This has the advantage to the farmer of providing a better economic return for farm products,  in a retail market often dominated by a handful of major supermarket chains.  An advantage to the consumer can be access to a specialised product (e.g. unpasteurised or specialist breed milk, yoghurt, cheese of butter) directly from the farm, the sale of which may otherwise be restricted (Figure 6.5). The responsibility for sterilising the bottles lies with the consumer, but this can readily be achieved using a domestic dishwasher. The bottles can be reused multiple times, reducing the demand for the PE equivalent. This is a model that has wider application.

**Figure 6.5** Milk bottles, filled by an automatic dispensing machine, used for direct farms sales, Suffolk UK ©Peter Kershaw.

## Case study 22 – Chemistry conference, Japan 2013

Conferences can generate a lot of materials that frequently end up being underused or disposed of. There has been a growing trend for organisers of meetings and conferences, especially those with an environmental theme, to adopt more sustainable practices.

The organisers of a major conference of the Japan Society of Environmental Chemistry, which took place in 2013, wanted to minimise the use of plastic and the generation of plastic waste by the delegates. In a country where use of plastic food packaging is ubiquitous, this was quite challenging. The intention to reduce wastage was emphasised in the conference flyer, sent out to advertise the event (Figure 6.6). The text is translated as follows:

### ‘Challenges in 2013 conference

1. Minimal plastic wastes

To reduce the generation of plastic wastes during the conference, several attempts will be introduced. To reduce PET bottles, all the participants will receive metallic bottles for drinks when they will register. The metallic bottles are pre-rinsed and ready to use. Participants can fill drinking water (source is groundwater; no endocrine disrupters has been confirmed by Takada’s laboratory) at water coolers located at several points in the conference venue. In addition, organizers will supply iced flavored tea with charge at several locations in the venue. (Chair persons will receive insulated metallic bottles which are special gift from head organizer who is also organizer of IPW). Name tags are made of cardboard. Bags for set of the abstracts and the other information documents are paper bags. Drinks and lunches on lunch-on-seminars will be provided by paper containers. Your understanding and cooperation would be appreciated.’

― 今年度の特色 ―

1. Minimal plastic waste

**Figure 6.6** Delegates at a conference of the Japan Society of Environmental Chemistry in 2013, with metal re-fillable water bottles issued at registration to minimise the use of PET bottles; the text is an extract of the Conference flyer, explaining the aim to minimise plastic waste at the conference; the single bottle is a newer design with a bamboo lid, shown with a re-fillable bamboo-handled fountain pen; images courtesy of Hideshige Takada.

To discourage the purchase of bottled drinks in PET bottles, each delegate was issued with a stainless steel water bottle at registration, and paper and cardboard were used wherever possible.

This is an excellent example of what can be achieved with a combination of determination and imagination.

## Case Study 23 – CupClub re-usable coffee cups

CupClub[47] is the inspiration of Safia Quereshi, co-founder of the design studio 'Studio [D] Tale', based in London and Cape Town. It is intended to reduce the use of disposable coffee cups in the 'fast food' and 'take-away' markets by offering a 'cradle-to-cradle' solution. This is achieved setting up a subscription service in which more robust reusable cups can be dropped off at any participating outlet (Figure 6.7). This will obviate the need for separate collection and re-cycling, a particular problem when dealing with standard paper cups which have a PE lining, requiring specialist facilities.

**Figure 6.7** Re-usable coffee cups connected by smart phone to customers – the model for CupClub; image courtesy of Safia Queresi (pictured) of CupClub.

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[47] http://www.cup-club.co.uk/

Following a successful pilot, the scheme is due to be launched in London in 2018. But the intention is to roll the scheme out to cities worldwide, with Hong Kong and mainland China being seen as a key market, for example. It is planned to extend the range to include other products used in the 'take-away' sector. The team have devised a number of strategies to ensure the scheme can be sustained, including by keeping track of individual cups, via the 'internet of things', setting up a network of checkouts and drop-off points and rewarding customers, so that they stay part of the system.

## Case study 24 – ChopValue - 'up-cycling' chopsticks

ChopValue was founded in Vancouver by Felix Böck. Vancouver inhabitants have a great interest in the cuisine of East Asia, getting through an estimated 100,000 chopsticks in Vancouver's restaurant every day. ChopValue have the aim to make better use of this resource. Restaurants participating in the scheme are provided with bins to dispose of single-use bamboo chopsticks. These are collected weekly and taken to a manufacturing facility, where they are cleaned and then pressed into sheets using a water-based, low-emission adhesive. The sheets are then machined into a variety of objects including coaster sets, shelving units, hexagon tiles and side-tables, and finished with a food-grade wax (Figure 6.8). A combination of manual labour and semi-automated processes minimise energy use.

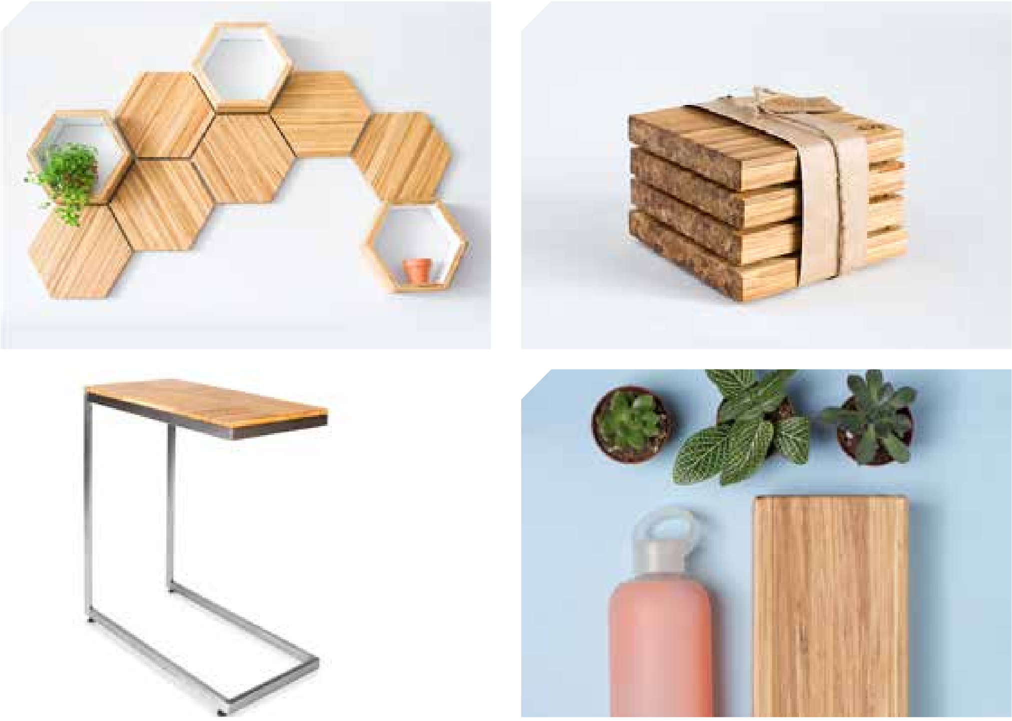

**Figure 6.8** Products made from re-cycled chopsticks, collected, processed and marketed by ChopValue of Vancouver Canada; images courtesy of Atiya Livingston of ChopValue.

Canada as a whole imports 5 billion chopsticks a year from China, which is the major producer and exporter. Use per head is greatest in Japan, with an estimated annual use of 200 pairs of disposable chopsticks. The efforts of ChopValue are not going to halt this enormous use of resources, but at least it does add value to an otherwise discarded product, providing useful objects and minimising the use of other materials, including plastics (e.g. chopping boards, floor coverings).

## Case study 25 – Sustainable clothing design using natural fabrics

### STUDY Design New York: re-using ‘waste’ fabric

Tara St James runs the STUDY fashion design studio in New York. The company has adopted a zero waste philosophy, following more traditional practices of minimising the waste of fabric when designing and cutting[48]. Any waste fabric that is produced is re-purposed and used to manufacture additional clothes items, designed imaginatively for that specific purpose, in collaboration with other small companies in the Brooklyn clothing community. For example, waste fabric from the manufacture of the Twist Dress is used to produce the Weaving Hand Sweatshirt.

In addition, the purchaser is encouraged to adopt a more sustainable end-of-life approach. The garment label reads: ‘*End of life – Repair when possible, donate when no longer loved, recycle if you can*’. Other companies are adopting more sustainable ‘green fashion’ practices[49]. For example, the Swedish company Nudiejeans offers a repair service at several of its outlets, to encourage customers get the most out of their jeans[50].

**Figure 6.9** Examples of fabrics produced using sustainable principles by STUDY Design of New York; images courtesy of Tara St James of STUDY Design

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[48] http://study-ny.com/zero-waste-1
[49] http://www.bbc.co.uk/news/science-environment-41570540
[50] https://www.nudiejeans.com/blog/swedish-origins

# 7. Pursuing the sustainability goals - social, economic and environmental considerations

## 7.1 Agenda 2030

Tackling marine plastics should be seen as part of a wider philosophy of encouraging more sustainable production and consumption, including discouraging the ‘buy often discard often’ pattern seen in wealthier societies, where plastic consumption is much higher.

Agenda 2030 and the UN Sustainable Development Goals (SDGs) provide an over-arching framework within which the issues around marine plastic and microplastic pollution should be considered (Figure 7.1, Sustainable Development Solutions Network 2015, United Nations Environment Programme 2016). Thirteen targets from five SDGs (SDG 6, 11, 12, 14 and 15) were highlighted by United Nations Environment Programme (2016) as being particularly relevant to reducing the inputs and impacts of waste plastic in the ocean (Table 7.1).

If the scope of enquiry is widened, to encompass the promotion of alternatives to the use of conventional plastics, then additional SDG targets become relevant. SDG targets 1.4, 8.3, 9.3 and 9.4 relate to promoting social and economic resilience through encouraging: self-ownership of land and natural resources; access to environmentally sound technologies; entrepreneurship; small and medium size business development; and, access to advice and financial support (Table 7.1). These are needed particularly in rural, and sometimes marginalised, communities in developing countries. It will help to promote the expansion of promising initiatives, some of which were exemplified as case studies in Chapter 4.

SDG 1 aims to end poverty in all its forms everywhere. This is a highly desirable goal, but there are likely to be consequences in terms of society’s choices and behaviour in adopting plastics and alternative materials, which should not be ignored. The use of plastics is positively correlated with GDP and per capita incomes. If this increased use is not accompanied by improved infrastructure and the development of more sustainable consumption patterns (SDG 12) then the volume of plastics entering the ocean will continue to increase. Conversely, the provision of safe drinking water as economies develop will minimise the use of single-use plastic bags and bottles for potable water. Poverty reduction will minimise the practice of buying small quantities of everyday products, such as cleaning liquids and powders, in small disposable plastic sachets, and allow greater consumer choice. SDG target 12.5 refers to substantially reducing waste generation. Perhaps one of the most dramatic changes witnessed in recent years has been the spread of plastic bag bans to reduce the enormous quantities of plastics waste being generated in many urban areas, most recently in Kenya[51]. Here the use of traditional materials and alternative bags made from natural materials is being actively encouraged.

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[51] https://www.washingtonpost.com/news/worldviews/wp/2017/08/28/plastic-bags-can-now-earn-you-4-years-of-imprisonment-in-kenya/?utm_term=.991ae5133864

**Figure 7.1** The 17 UN Sustainable Development Goals

**Table 7.1** SDG targets related to reducing marine plastics and encouraging the sustainable development of alternatives to conventional plastic

| |
|---|
| **Goal 1 – end poverty in all its forms everywhere**<br>• 1.4 By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance |
| **Goal 6 – ensure availability and sustainable management of water and sanitation for all**<br>• 6.3 By 2030, the proportion of untreated wastewater should be halved |
| **Goal 8 – promote sustained, inclusive and sustainable economic growth and productive employment and decent work for all**<br>• 8.3 Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services |
| **Goal 9 – build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation**<br>• 9.3 Increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets<br>• 9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities |
| **Goal 11 – make cities and human settlements inclusive, safe, resilient and sustainable**<br>• 11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management |

**Goal 12 – ensure sustainable consumption and production patterns**

- 12.1 Implement the 10-year framework of programmes on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries
- 12.2 By 2030, achieve the sustainable management and efficient use of natural resources
- 12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment
- 12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse
- 12.b Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products

**Goal 14 – conserve and sustainably use the oceans, seas and marine resources for sustainable development**

- 14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution
- 14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans
- 14.7 By 2030, increase the economic benefits to Small Island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism
- 14.a Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing States and least developed countries
- 14.c Enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in UNCLOS, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of The Future We Want

**Goal 15 – protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**

- 15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species

## 7.2 Towards a cradle-to-cradle approach

### 7.2.1 The principles of green design

The need to promote more sustainable practices is accepted as a given, by a wide cross-section of society. But tools are needed to convert the concept of sustainability into practical outcomes. Anastas and Zimmerman (2003) introduced the twelve principles of green engineering to provide a framework to promote more sustainable engineering design and the approach was furthering expanded to encompass Cradle-to-Cradle design by McDonough *et al.* (2003).

**The three tenets of the cradle-to-cradle philosophy:**

1. **Waste equals food**
2. **Use current solar income**
3. **Celebrate diversity**

**(McDonough *et al.* 2003)**

**Table 7.2 Summary of the Principles of Green Chemistry and Engineering, from Tabone *et al.* (2010)**

| 12 Principles of Green Chemistry | |
|---|---|
| GC1 | Prevention (overall) |
| GC2 | Atom economy |
| GC3 | Less hazardous chemical synthesis |
| GC4 | Safer solvents and auxiliaries |
| GC5 | Designing safer chemicals |
| GC6 | Design for energy efficiency |
| GC7 | Use of renewable feedstocks |
| GC8 | Reduce derivatives |
| GC9 | Catalysis |
| GC10 | Design for regeneration |
| GC 11 | Real time analysis of pollution prevention |
| GC12 | Inherently safer chemistry for accident prevention |

| 12 Principles of of Green Engineering | |
|---|---|
| GF1 | Inherent rather than circumstantial |
| GF2 | Prevention instead of treatment |
| GF3 | Design for separation |
| GF4 | Maximise mass, energy, space and time |
| GF5 | Output-pulled versus input pushed |
| GF6 | Conserve complexity |
| GF7 | Durability rather than immortality |
| GF8 | Meet need, minimize energy |
| GF9 | Minimise material diversity |
| GF10 | Integrate local material and energy flows |
| GF 11 | Design for commercial afterlife |
| GF12 | Renewable rather than depleting |

| 12 additional Principles of Green Chemistry | |
|---|---|
| A 1 | Identify by-product: quantify if possible |
| A 2 | Report conversions, selectivities and productivities |
| A 3 | Establish a full mass balance for the process |
| A 4 | Quantify catalyst and solvent losses |
| A 5 | Investigate basic thermochemistry to identify |
| A 6 | Anticipate other potetial mass and energy transfer |
| A 7 | Consult an chemical or process engineer |
| A 8 | Consider the effect of the overall process on |
| A 9 | Help develop and apply sustainable measures |
| A 10 | Minimise use of utilities and other inputs |
| A 11 | Identify safety and waste minimisation are compatible |
| A 12 | Monitor, report and minimise |

In addition, principles of green chemistry have been developed and integrated in an overall framework for sustainable technology development (Table 7.2, Tabone *et al.* 2010; Mulvihill *et al.* 2011). The approach can be applied to a wide range of technological fields, including the development of more sustainable synthetic and semi-synthetic polymers and utilisation of natural resources, covering design, production, manufacture, use and post-use or end-of-life stages. Work carried out within the frameworks of the Stockholm and Basel Conventions is very relevant to ensuring the development of materials that are intrinsically safer to manufacture, use and recycle (United Nations Environment Programme 2002; 2017a; 2017b).

### 7.2.2 Applying green design in packaging applications

It is clear that packaging makes up a significant fraction of plastic-related material that reaches the ocean, through a variety of entry points (Chapter 3). It follows that greater emphasis is needed to minimise the proliferation of excessive packaging, reduce the leakage of waste packaging to the environment and to examine the potential of less problematic alternative materials. A framework for guiding the selection of more sustainable packaging design was proposed by Gronman *et al.* (2013), recognising the environmental, technical, economic and social aspects of the combined product-packaging value chain (Figures 7.2, 7.3). This included considering the minimum requirements for the product to be packed, the selection of the optimal material combination, potential challenges, detailed design, comparative LCA of potential alternative packaging combinations and continuing review of the selected option. The main driver for this study was to minimise food waste, rather than minimise the generation of packaging waste and its wider impact. However, the approach is valid for the design of sustainable packaging using non-conventional polymers or natural materials.

A seagull perched on a public garbage bin pulling out litter with its beak
Photo Credit: Shutterstock/ GParker

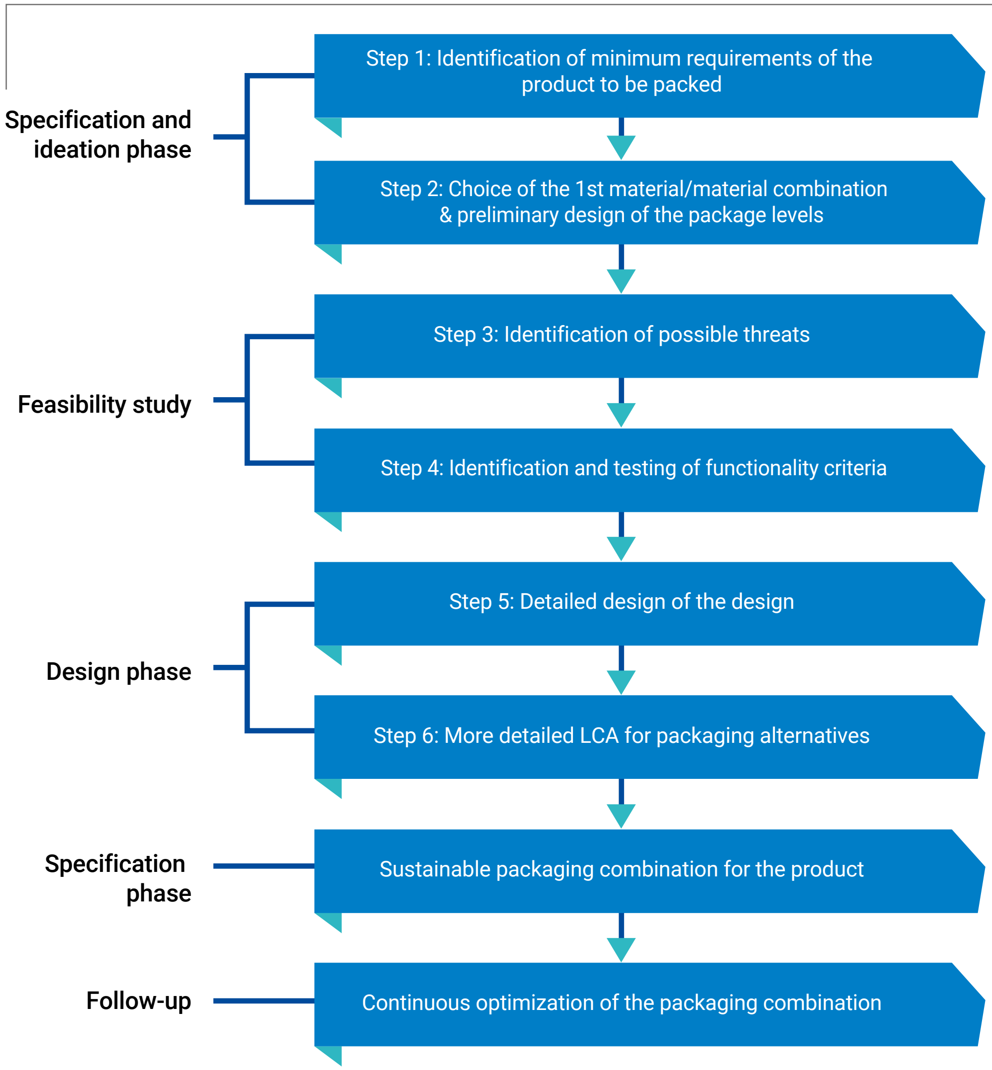

**Figure 7.2** Simplified framework to guide design of more sustainable food packaging, adapted from Gronman *et al.* 2013.

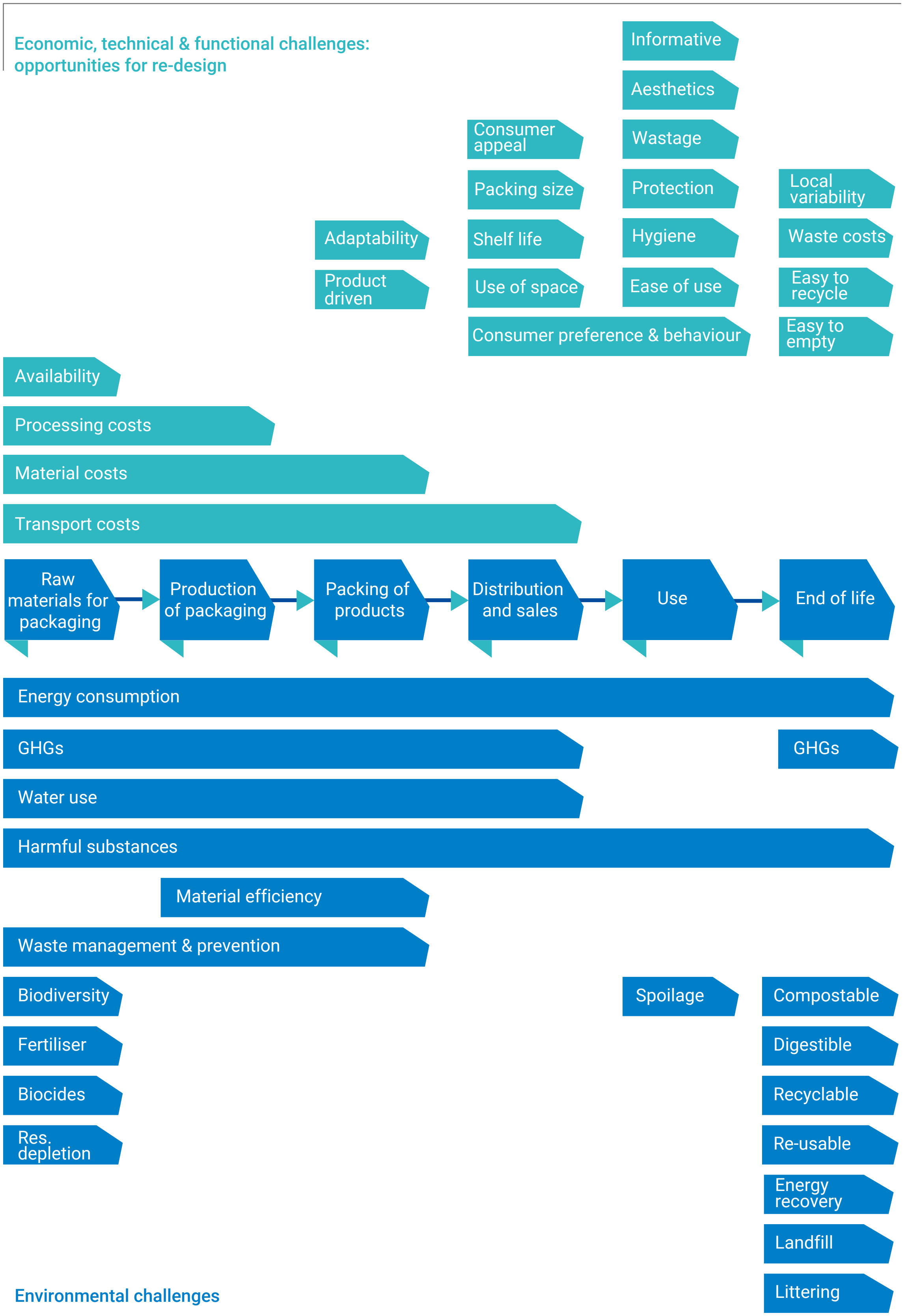

**Figure 7.3** Environmental, economic, technical and functional challenges of the packaging value chain, adapted and further developed from Gronman et al. 2013.

Several major international companies, including Dell (Chapter 5) and Unilever, have been able to reduce the total quantity of packaging used, and the proportion of packaging relying on conventional polymers, by adopting practices that are compatible with the companies' overall sustainability goals (United Nations Environment Programme 2014, United Nations Environment Programme 2016, Dell 2017).

## 7.3 Life cycle analysis of natural materials and thermoplastics (conventional & biomass-based biopolymers)

### 7.3.1 Overall considerations for life cycle analysis

Life Cycle Analysis (LCA) can provide a quantitative or semi-quantitative estimate of the requirements and impacts of a process or product. Typically this will include considerations of resource use (e.g. raw materials, energy, water) and potential impacts in the production, manufacturing and distribution phases (e.g. gaseous emissions, biocides, process chemicals). All LCAs depend on making a number of assumptions about the factors to be included and their relative importance. Some factors, such as energy use, are much easier to quantify than others, such as the environmental impact of process chemicals. Differences in the number of factors included and judgements about their relative importance can lead to fundamental differences in the LCA outcome of similar processes and products (United Nations Environment Programme 2016). In many cases the LCA is limited to examining that part of the value chain from the raw material to factory gate.

**Most Life Cycle Analyses do not include the product end-of-life stage**

Although an LCA limited to the production phase is more straightforward to perform, it is still subject to significant variability depending on the assumptions that are made. Sometimes the LCA is extended to the point of use. But, usually there is very little consideration of the full life cycle of the product, which should include the post-use or end-of-life stages. This should encompass the social, economic and environmental impacts of waste production and management, including plastics and microplastics that enter the ocean, and the role of improved solid waste management. There have been attempts to encourage greater extended producer responsibility, to force manufacturers to consider the end-of-life impacts of their products (Organisation for Economic Co-operation and Development 2001; 2005; United Nations Environment Programme 2014), but it has proved difficult to introduce such changes in practice.

The European Joint Research Centre have developed a methodology to calculate the Product Environmental Footprint (PEF) and applied it to assess the environmental sustainability of bio-based products and their supply chains, using an LCA perspective (De Matos *et al.* 2015). This was applied to the three 'pillars' of the bio-economy: i) food and feed, ii) bio-based products, and iii) bioenergy, including biofuels. The second 'pillar' included consideration of the production of lactic acid, polylactic acid (PLA) and polyhydroxlkanoates (PHA). These are discussed in sections 7.3.4 and 7.3.5.

### 7.3.2 Including use and end-of-life stages

Most LCAs of the production of materials and goods fail to consider the use and post-use or end-of-life phases. This is understandable, because it may be difficult to obtain data of comparable accuracy for the post-use phase, compared with accounting for factors such as total water and energy use, gaseous emissions and waste minimisation. But this will result in a flawed analysis of the whole Life Cycle, leading to an underestimate of the whole social, economic and environmental costs. For example, one LCA of shopping bags concluded that using conventional polyethylene (HDPE) was a better environmental option than using paper or cotton (Environment Agency 2010). But this conclusion was based only on the carbon footprint; it did not consider other factors including the end-of-life impact.

Those costs that remain largely unaccounted for are often not borne by those benefitting from the goods or services provided. Badia *et al.* (2017) argued that it is essential to include the specific application of a biopolymer when considering end-of-life disposal options. This is in order to establish the optimum balance between the properties of the product during use and the most cost-effective manner of its disposal or further use. For example, this could include the beneficial use of waste, promoting more effective waste management, ease of use, public commitment/acceptance, improved implementation and compliance.

One of the consequences in conducting a numerical LCA is that many of the social and environmental costs are very difficult to monetise, and even more so when the extent of the social or environmental impact is poorly quantified. Environmental economists have devised methods to try and overcome some of these difficulties, but large uncertainties remain. There are some exceptions. For example, if there is a reduction in the biomass of a particular fish stock, due to 'ghost fishing' by ALDFG, an estimate can be made of consequential reduction in fish landings and hence a reduction in the income of a fishing community. But, the possible impact of the loss of income, and potentially the reduction in protein, on the mental and physical health of the community may be very difficult to quantify and monetise.

In another example, we could perform an LCA on the production and manufacture of a polyethylene bag and conclude it is a very resource-efficient commodity, compared to bags made from cotton, in terms of demands on raw materials, water and energy and greenhouse gas emissions. But, if we include the end-of-life phase the analysis becomes much more complex. Many marine mammals and reptiles have been found to contain plastic bags when their gut contents are examined in autopsies, usually of beached animals (Secretariat of the Convention on Biological Diversity 2012). In the case of sea turtles, some species predate jellyfish, and it thought that the turtles mistake a floating plastic bag for a jellyfish. Unfortunately, turtles do not possess a mechanism for regurgitating the bags. There may be a consensus that allowing sea turtles to be killed by discarded plastic bags is unacceptable. But, if it is deemed necessary to support this opinion with market-based evidence, then we have to rely on concepts such as 'willingness to pay' (United Nations Environment Programme 2016). This may be justified in countries which are relatively wealthy, or which have higher environmental awareness, but it can be very hard to transpose these results to other regions, with very different social and economic priorities.

Somehow we need to devise a more sophisticated approach for calculating the net social, economic and environmental benefit of following alternative approaches, such as might be applied to the choice between goods made from natural materials, biomass-based biopolymers and synthetic polymers. Society is poorly served by a reliance on the current flawed methodologies.

### 7.3.3 Comparing biomass-based, semi-synthetic and synthetic fibres

Several LCA studies have compared the production of textiles or other products from natural fibres and semi-synthetic or synthetic polymers. The results differed markedly due to the choice of assumptions and approach. One of the most striking examples of divergent outcomes concerns LCAs of cotton and viscose (rayon), manufactured from cellulose. A cradle-to-factory-gate analysis by Shen *et al.* (2010), part-funded by the rayon industry, concluded that rayon manufactured in Europe had the lowest environmental impact of the materials included in the analysis, in the order rayon < PET < PP < cotton. The LCA was based on the demand for energy, land and water, and the global warming potential. It included several other factors including human toxicity, freshwater eco-toxicity, terrestrial eco-toxicity, eutrophication potential, ozone depletion and acidification. The authors concluded that production of viscose in Asia had a greater impact than the European equivalent, on the basis of the use of pulp and caustic soda, but was still preferable to cotton. The analysis assumed cotton production was based on industrialised systems used in the USA and Canada; i.e. 'organic' methods were not considered. Perhaps more importantly, the study ignored the substantial evidence of serious occupational and wider health impacts of the use of carbon disulphide in the viscose production process, a practice believed to be as widespread in Asia today as it used to be in Europe and the USA throughout the 20th Century (Bock 2016).

In contrast, a more comprehensive analysis of a variety of natural and synthetic fibres led to the conclusion that the production of organic cotton and flax had a much lower impact than viscose (Muthu *et al.* 2012). The authors developed an environmental impact and sustainability model which took account of both the production and end-of-life phases. The model included a LCA of the production phase, using scores of energy use, water consumption and $CO_2$ emissions. The additional elements included were $CO_2$ absorption, $O_2$ emissions, use of renewable resources, land use, the application of fertilisers and pesticides and human health impact. The end-of-life phase was represented by scores of recyclability and biodegradability, based on Horrocks *et al.* (1997) and Chen and Burns (2006). All these factors were used derive an Environmental impact Index (EI) (Figure 7.4) and an Ecological Sustainability Index (ESI) (Figure 7.5). The ESI was calculated by dividing the EI of each fibre by the maximum EI score. The analysis will be subject to similar uncertainties as any other LCA, over the selection of variables, assumptions made, weightings given and scoring systems. However, the Muthu *et al.* (2012) study represents one of the few attempts to take the end-of-life stage into account, and is particularly relevant in the present assessment of alternative materials.

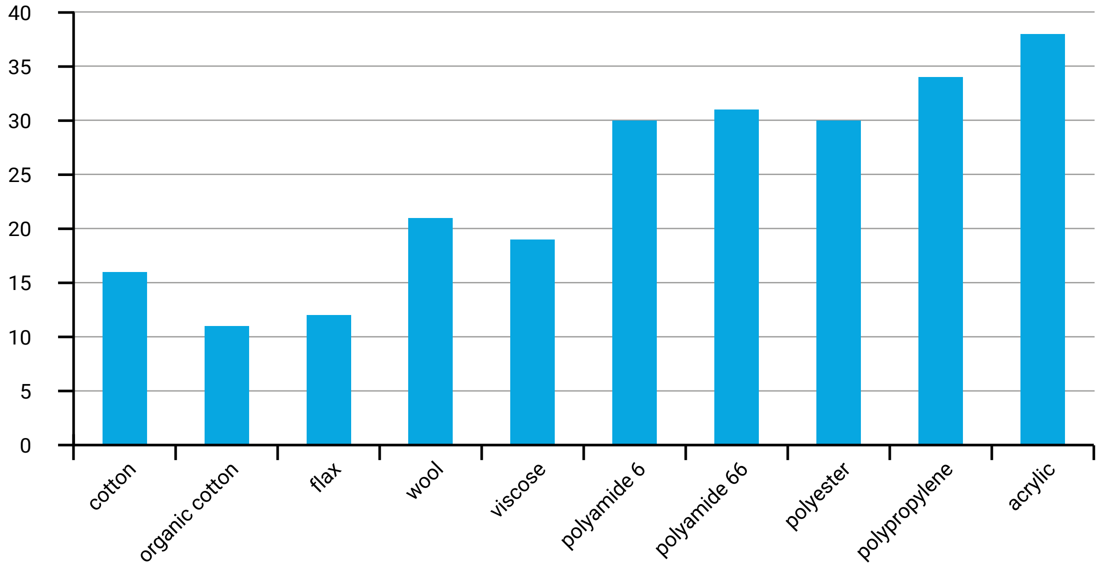

**Figure 7.4** Environmental impact Index (EI) scores for a variety of fibres: C – cotton, OC – organic cotton, F – flax, W – wool, V – viscose, PA-6 polyamide 6, PA-66 - polyamide 66, PES – polyester, PP – polypropylene, A – acrylic; adapted from Muthu *et al.* 2012.

The impact of utilising biomass either directly or indirectly to produce textile fibres can be highly variable. Dependencies include the types of plants being grown or animal products being used, the manner of production and the overall sustainability of the process. For example, bamboo is often marketed as a having excellent 'green' credentials, due to its rapid growth and lower requirements for other resources. However, there have been concerns raised about the felling of natural forest to expand bamboo production in some regions (Vogtlander *et al.* 2010). The utilisation of flax depends on the process of retting, where leaves are left to soak in water to allow the useful fibres to be separated. The process can lead to contamination of water supplies if not adequately managed. If this occurred it would affect the EI score according to the model of Muthu *et al.* (2012). Astudillo *et al.* (2014) conducted an LCA of silk production in India. The authors reported that silk had a higher impact than other natural fibres due to water, fertiliser and energy use. They concluded that the high impact was due partly to farmers not following recommended procedures, and that there was scope for making improvements. The main lesson is that all analyses will have large uncertainties and it would be imprudent to adopt

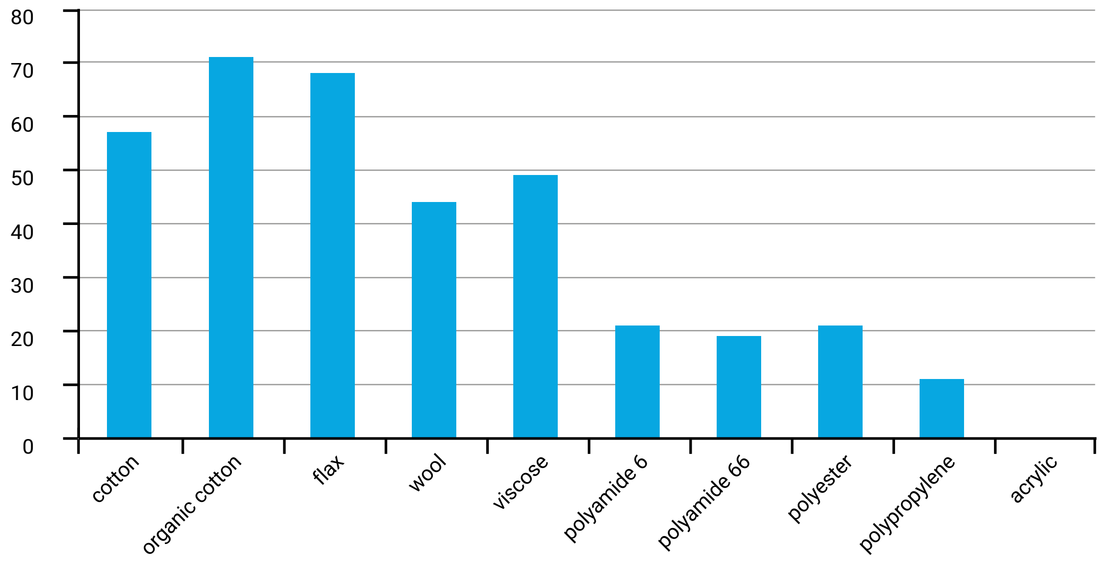

**Figure 7.5** Ecological Sustainability Index (ESI)scores for a variety of fibres: C – cotton, OC – organic cotton, F – flax. W – wool, V – viscose, PA-6 polyamide 6, PA-66 - polyamide 66, PES – polyester, PP – polypropylene, A – acrylic; adapted from Muthu *et al.* 2012.

a single approach on which to base management or consumer decisions as to what constitutes the 'greenest' solution.

An initial assessment has been attempted of the characteristics of the main elements of the cradle-to-factory, manufacture and end-of-life stages for the production of a range of natural, semi-synthetic and synthetic biomass-based biopolymers (Table 7.3). The main application considered was fibre production but this approach could be extended further, to include additional applications and a wider range of polymers. Qualitative scores of low, medium or high were assigned on the basis of either published data cited in the report, or by inference. Favourable status was indicated by blue, moderate by purple and unfavourable by red. A number of assumptions were made in assigning scores and these are likely to mask variations in agricultural practise (e.g. intensity of production), industrial processes and disposal options. Lower scores for fibre production for TPS, PLA and PHA were assigned on the basis that these polymers had not been used on a large scale for fibre manufacture, at the time of the analysis.

**Table 7.3 (a)** Qualitative indicators of sustainability for the production of textiles and other products from biomass sources, **from harvesting to the manufacturer.** Indicators are based on estimates of the relative environmental and human health impact, for a series of stages or characteristics in the production process, from sources cited in the text or by inference; where **BLUE indicates high, PURPLE indicates medium and RED indicates low sustainability.** In addition, the relative importance or impact of each stage is assigned a value of low (L), medium (M) or high (H). (Cot = cotton, Org = organic, Hem = hemp, Lin = linen, Abac = abaca, Rami = ramie, Woo = wool, Sta = starch, TPS = thermoplastic starch, CP - composite, Ray = rayon).

| | Natural | | | | | | | | | Natural by-products | | Semi-synthetic | | | | Synthetic | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Polymer** | **Cot.** | **Org Cot** | **Hem** | **Lin** | **Jute** | **Abac** | **Rami** | **Woo** | **Silk** | **Coir** | **Piña** | **Sta** | **TPS** | **TPS CP** | **Ray** | **PLA** | **PHA** |
| Sustainability characteristics | | | | | | | | | | | | | | | | | |
| Land use | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M |
| Potential to use waste material | 🟥 L | 🟥 L | 🟥 L | 🟥 L | 🟥 L | 🟥 L | 🟥 L | 🟥 L | 🟥 L | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H |
| Water use | 🟥 H | 🟥 H | 🟦 L | 🟦 L | 🟦 L | 🟥 H | 🟦 L | 🟦 L | 🟦 H | 🟦 L | 🟦 L | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M |
| Energy use | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H |
| Fertiliser use | 🟥 H | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟥 H | 🟦 L | 🟦 L | 🟥 H | 🟦 L | 🟥 H | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M |
| Biocide use | 🟥 H | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟪 M | 🟪 M | 🟦 L | 🟥 H | 🟪 M | 🟪 M | 🟪 M | 🟥 L | 🟪 M | 🟪 M |
| Environmental impact (combined) | 🟥 H | 🟪 M | 🟥 L | 🟥 L | 🟥 L | 🟥 L | 🟪 M | 🟥 L | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟪 M |
| Human health impact | 🟪 M | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟥 H | 🟦 L | 🟦 L |
| Overall socio-ecological impact | 🟥 H | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟪 M | 🟥 L | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟥 H | 🟪 M | 🟪 M |

**Table 7.3 (b)** Qualitative indicators of sustainability for the production of textiles and other products from biomass sources, **during manufacture**. Indicators are based on estimates of the relative environmental and human health impact, for a series of stages or characteristics in the production process, from sources cited in the text or by inference; where **BLUE indicates high, PURPLE indicates medium and RED indicates low sustainability.** In addition, the relative importance or impact of each stage is assigned a value of low (L), medium (M) or high (H). (Cot = cotton, Org = organic, Hem = hemp, Lin = linen, Abac = abaca, Rami = ramie, Woo = wool, Sta = starch, TPS = thermoplastic starch, CP - composite, Ray = rayon).

| | Natural | | | | | | | | | Natural by-products | | Semi-synthetic | | | | Synthetic | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Polymer** | **Cot.** | **Org Cot** | **Hem** | **Lin** | **Jute** | **Abac** | **Rami** | **Woo** | **Silk** | **Coir** | **Piña** | **Sta** | **TPS** | **TPS CP** | **Ray** | **PLA** | **PHA** |
| Sustainability characteristics | | | | | | | | | | | | | | | | | |
| Water use | L | L | L | L | L | L | L | L | L | L | L | L | M | M | M | M | M |
| Energy use | L | L | L | L | L | L | L | L | L | L | L | M | M | M | H | H | H |
| Chemical processes | L | L | L | L | L | L | L | L | L | L | L | L | M | M | H | H | H |
| Waste production | L | L | L | L | L | L | L | L | L | L | L | L | L | L | H | L | L |
| Human health impact | L | L | L | L | L | L | L | L | L | L | L | L | L | L | H | L | L |
| Environmental health impact | L | L | L | L | L | L | L | L | L | L | L | L | L | L | H | L | L |

**Table 7.3 (c)** Qualitative indicators of sustainability for the production of textiles and other products from biomass sources, **during use and at the end-of-life.** Indicators are based on estimates of the relative environmental and human health impact, for a series of stages or characteristics in the production process, from sources cited in the text or by inference; where **BLUE indicates high, PURPLE indicates medium and RED indicates low sustainability.** In addition, the relative importance or impact of each stage is assigned a value of low (L), medium (M) or high (H). (Cot = cotton, Org = organic, Hem = hemp, Lin = linen, Abac = abaca, Rami = ramie, Woo = wool, Sta = starch, TPS = thermoplastic starch, CP - composite, Ray = rayon).

| | Natural | | | | | | | | | Natural by-products | | Semi-synthetic | | | | Synthetic | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Cot.** | **Org Cot** | **Hem** | **Lin** | **Jute** | **Abac** | **Rami** | **Woo** | **Silk** | **Coir** | **Piña** | **Sta** | **TPS** | **TPS CP** | **Ray** | **PLA** | **PHA** |
| Sustainability characteristics | | | | | | | | | | | | | | | | | |
| Compostable- d | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟪 M | 🟪 M | 🟥 L | 🟥 L | 🟥 L |
| Compostable- i | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H |
| Anaerobic digestion | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H |
| Generation of fibres | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟥 H | 🟪 M | 🟪 M |
| Entry to ocean via wastewater | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟥 H | 🟪 M | 🟪 M | 🟪 M | 🟪 M | 🟥 H | 🟪 M | 🟪 M |
| Biodegradable in sea | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟦 H | 🟪 M | 🟪 M | 🟥 L | 🟥 L | 🟥 L |
| Overall environ. impact in ocean | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟦 L | 🟪 M | 🟪 M | 🟪 M | 🟥 H | 🟥 H |

### 7.3.4 Comparing PLA and PHA with conventional synthetic polymers

Tabone *et al.* (2010) conducted a comparison of the sustainability of production of PLA and PHA with a range of conventional polymers derived from fossil fuels plus bio-PET. They concluded that there was an overall reduction in the environmental impact of production by following green design principles (section 7.2). But, the LCA ranking did not coincide with the Green Design ranking (Table 7.4). Some of the largest environmental impacts were associated with the production of the biomass for PLA and PHA due to land use changes, and the application of fertilizers (energy use, eutrophication) and biocides (ecotoxicological effects), reflected in the low LCA scores. Clearly these environmental effects will be influenced by factors such as the degree to which fertilizers and biocides are used (e.g. organic versus non-organic principles), the type of biomass used, and whether biomass is grown specifically for polymer production or utilises agricultural waste. Polyolefins such as PP, HDPE and LPDE are produced efficiently as direct products from oil refining and attracted the highest LCA scores. The analysis was limited to the 'cradle-to-gate' production phase, and the authors recommended that the use and end-of-life stages should be included in future studies. This would allow disposal options to be compared, such as recycling of conventional polymers and the potential use of the products of PLA composting (Karamanlioglu *et al.* 2017) and anaerobic digestion of PHA for energy production or as a raw material for new PHA production (Section 7.3.5). The inclusion of this end-of-life option would alter the results of the LCA in favour of the biomass-based biopolymers. In a related study, Shen *et al.* (2012) compared PET and PLA bottles and concluded that PET had a lower impact. Again, the analysis was limited to the 'cradle-to-gate' production phase, so the results have limited value.

**Table 7.4 A comparison of rankings for PLA, PHA and a range of conventional polymers, based of Green Design and Life Cycle Analysis scores; from Tabone *et al.* 2010.**

| Material | Green Design Rank | LCA Rank |
|---|---|---|
| PLA (NatureWorks) | 1 | 6 |
| PHA (utilizing stover) | 2 | 4 |
| PLA (general) | 2 | 8 |
| PHA (general) | 4 | 9 |
| HDPE | 5 | 2 |
| PET | 6 | 10 |
| LDPE | 7 | 3 |
| Bi-PET | 8 | 12 |
| PP | 9 | 1 |
| Polystyrene | 10 | 5 |
| PVC | 11 | 7 |
| PC | 12 | 11 |

### 7.3.5 Food packaging - balancing the social, economic and environmental goals

Packaging can play a critical role in maintaining the condition of food and food products and minimising waste in the production, transport, storage, retail and post-purchase stages. Food production has very significant environmental impacts, in terms of: land use change, loss of biodiversity, increased greenhouse gas emissions, use of fertilisers and resultant eutrophication, and the use of biocides. Therefore, minimising post-harvest food losses can have a substantial environmental benefit (Grolleaud 2002; Williams and Wikström 2011). Williams and Wikström (2011) conducted an LCA of food production and food packaging and argued that the environmental benefit of using packaging to minimise waste had a greater advantage than the impact of producing the packaging. The study was conducted in a European context, and this was reflected in the selection of foodstuffs used in the analysis (beef, cheese, milk, bread and tomato ketchup) and some of the assumptions about the consumer phase (use of car for transport, access to fridge for storage). The extent to which the findings apply to other environmental and social settings is unclear.

The elements included in the LCA were:

- Agricultural production
- Industrial food processing
- Production of packaging and packaging material
- Transport in the agriculture, industry, retail and consumer phases
- Retail and consumer phases

The main environmental considerations included can be summarised as:

- Energy use - $CO_2$ emissions dependent on energy generation mix
- Gaseous emissions from agricultural production, packaging, transport – acidification, greenhouse gases
- Eutrophication from agricultural production
- Food waste – e.g. $CO_2$ and methane production in landfill and home compost, increase energy use for wastewater treatment

All these factors can be expected to vary with: environmental setting; types of biomass being grown; degree of intensification of agricultural production; and, degree of sophistication and industrialisation of food production, storage and transport. The authors reported that the relative importance of the environmental impact of the packaging depended on the environmental impact of the agricultural production of the goods being packaged. For meat and cheese, the environmental impact of the packaging was much less than that of production. For tomato ketchup, the relative impact of the packaging was much higher. It is not clear whether the loss of production of $CO_2$ and methane, which occurs under normal non-farmed conditions, was factored into the analysis, when considering the contribution of landfill and composting. But, the LCA study did not include the impact of packaging waste on the environment, in common with most LCA studies.

If the methane produced under composting or anaerobic digestion is captured than this can be used as a source of bio-energy (Rostkowski *et al.* 2012) and also for production of new compounds. This will alter the results of the LCA, and allows the development of a closed–loop system (section 7.4).

## 7.4 Alternative materials and the circular economy

### 7.4.1 Opportunities for shifting the balance in packaging

The wider adoption of alternatives to conventional polymers provides an opportunity for re-assessing the linear production-use-disposal model beyond the familiar Reduce, Re-use, and Recycle 3 Rs mantra. Adding natural materials and biomass-based bio-polymers, such as PLA, PHA and starch blends, opens up new opportunities in developing closed loop and more sustainable and circular production, use and re-use patterns (Figure 7.6). The promotion of a composting or anaerobic digestion stage should allow a much greater proportion of plastic waste, especially food-contaminated waste, being diverted from landfill.

Most natural materials can be composted under domestic composting conditions, meaning they are amenable to small-scale re-utilisation for soil conditioning in remote or poor communities.

The wider availability of scale-able industrial composting would allow much greater uptake of biomass-based plastics accompanied by greater utilisation of food waste and lower demand for landfill. Anaerobic digestion provides an alternative approach. Advantages include being able to generate

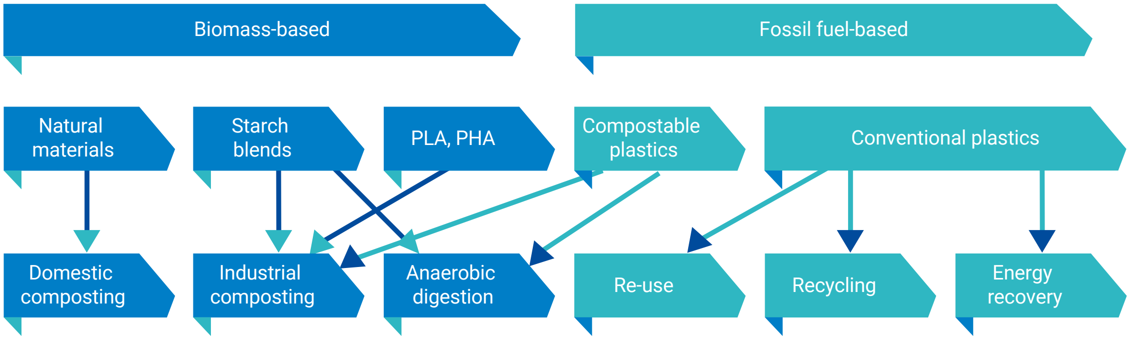

**Figure 7.6** Simplified schematic of end-of-life options for biomass-based materials and fossil fuel-based synthetic polymers (original by P J Kershaw).

energy from the waste product (methane). In addition, compostable fossil fuel based polymers can be accommodated by either industrial composting or anaerobic digestion. However, digesters require a regular supply of waste material of similar quality in order to work efficiently, combined with a relatively high skill level. This, and the high start-up costs may limit its application. A closed-loop system for food waste and food packaging is illustrated in Figure 7.7.

It is important to note that there are two key caveats to promoting the use of PLA, PHA and starch-blend products more widely: i) they have to be excluded from the recycling stream, to avoid compromising the quality of re-cycled conventional polymers; and, ii) PLA and PHA will behave like conventional polymers in the aquatic environment, and contribute to an increase in ocean plastics if not disposed of correctly.

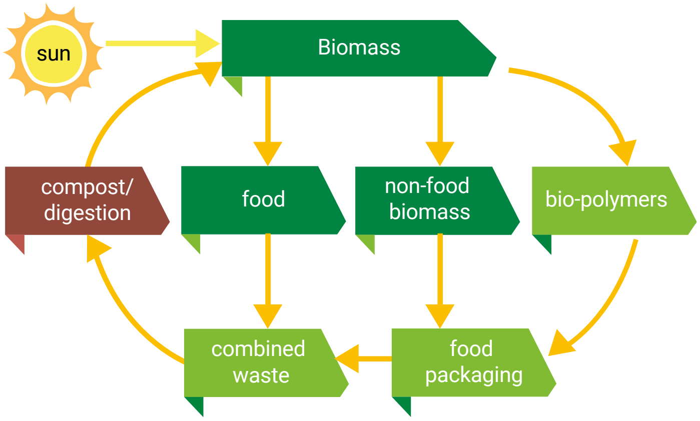

**Figure 7.7** Simplified schematic of a closed-loop system for food waste and food packaging, based on the exclusive use of: compostable synthesised bio-polymers, such as PLA, PHA and starch blends, and other compostable materials (original by P.J. Kershaw).

**The widespread adoption of PLA and PHA food packaging will only be sustainable in closed-loop systems, with ready access to industrial composting or anaerobic digestion facilities. This must be considered a pre-requisite, to separate PLA and PHA from the circular production model of conventional polymers.**

There is also evidence that the use of PLA in certain applications, such as mulching films, may be leading to a build-up of PLA in the terrestrial environment (Karamanioglu *et al.* 2017). Clearly, the introduction of PLA and PHA food packaging in itself will not reduce the quantities of food packaging prevalent in the marine environment. But, it does present an opportunity to simplify waste management of a significant proportion of this waste category, if introduced in appropriate circumstances. Provision of industrial composting and/or anaerobic digestion facilities is a pre-requisite before PLA and PHA are introduced into the retail sector. They are not suitable for uncontrolled retail use, typified by the casual 'fast-food' sector.

### 7.4.2 Fibre production

Textile production has been transformed by the introduction of synthetic and semi-synthetic fibres. What has become apparent in the past decade is that textiles represent a very substantial source of micro-fibres to the ocean, introduced largely in wastewater. An addition input results from the widespread use of fibres in shipping, fisheries and aquaculture, for ropes and nets. Fibres of synthetic polymers will persist in the ocean, as made clear in Chapter 3.

It appears unlikely that the present demand for textiles will decrease unless there is a change in the production model. Niinimäki and Hassi (2011) have suggested that there is the potential to promote more sustainable use of textiles in the clothing sector, adopting the principles of 'slow fashion', with greater attention being paid to longevity, repair and reducing textile waste. However, it is not clear whether this philosophy can make a significant difference outside niche markets in wealthier societies.

Tangled mess of nets and ropes washed up on the Oregon beach

Photo Credit: Shutterstock/ Jennifer Bosvert

# 8. Future trends and opportunities

## 8.1 Future trends in fibre production

### 8.1.1 Empowering impoverished or rural communities

An analysis of the potential for growth of natural fibre production, entitled 'Unlocking the Commercial Potential of Natural Fibres', was published in 2012 (Food and Agricultural Organisation of the United Nations 2012). This focussed on sisal and the scope for the further development of composites using natural fibres. The report concluded that sisal production had declined over the preceding 15 years, principally due to competition from PP and other synthetic fibres, but that there was great scope for reversing this trend.

The authors pointed out that sisal production held advantages for rural communities in low-income countries. Several sisal-producing countries are classified as Least Developed Countries (where average annual per capita gross income < $US 740). Sisal can survive arid conditions, in which other crops may fail, providing a reliable income source in times of drought. Declining production due to the loss of traditional markets, such as the production of twine, has had an adverse impact on export earnings. Thus, attention to halting the decline in traditional markets and expanding into new markets, as a partial replacement for conventional plastic fibres, will bring about multiple benefits, and help meet several SDG targets.

The degree to which smallholders can benefit more from interaction with the supply chain is considered to depend on several factors, including how well it reflects economic priorities, social structures and gender dynamics (Millard 2017). In may communities women are better placed to bring knowledge about natural resource use into the decision making process, simply because they are usually more involved in subsistence agriculture and utilising natural resources such as water and firewood (WWF 2012). In addition, there is scope to reduce barriers to accessing credit facilities, which would help micro and small businesses (Gichuki *et al.* 2014).

### 8.1.2 Making better use of waste

In terms of technical development there is a need to develop materials that are carbon-neutral over the whole production cycle. Greater use can be made of the waste products of horticultural and agricultural production, to reduce potential conflicts with food production.   Governments need to examine the consequences of giving subsidies to certain sectors, to ensure that the perceived benefit (social, economic, environmental or political) is balanced against the actual cost, especially of environmental damage. For example, subsidising maize production as a raw material for bio-fuels or biomass-based polymers makes little environmental sense if accompanied by excessive use of water, fertiliser and biocides. There may be a social and economic benefit to the farming community, and a consequential political benefit, but the overall cost from environmental degradation may be far greater, if adequately quantified.

The absence of the end-of-life phase in most LCA analyses undermines the conclusions that can be drawn from these studies. In particular, it is likely to imply a greater benefit to adopting conventional plastics than either natural materials or biomass-based biopolymers. There is a clear need for environmental economists to work with agronomists, material scientists, environmental scientists and others, to devise more realistic and reliable techniques for whole life cycle analysis assessment. This should include consideration of the use of waste materials for manufacturing new products, as well as the benefits of adopting a network of commercial composting and anaerobic digestion facilities.

### 8.1.3 Novel technologies in materials science – giving nature a helping hand

A series of technological innovations and advances in knowledge have occurred in recent years in the fields of chemical engineering, biological, molecular and materials sciences. These were not intended necessarily for application in the field of developing alternatives to conventional plastics, although the development of PLA, PHA and fibre composites have all benefitted from these advances. But, a number of novel applications have been developed precisely due to the application of these advanced 'disruptive' technologies.

#### Synthetic leather

Leather from animal skins consists of collagen. The New York-base Modern Meadows has shown it is possible to grow collagen fibres in the laboratory, and synthesise leather[52]. They have succeeded in scaling up the process for commercial production. This will allow those who are unwilling to wear leather derived from animals to buy goods such as shoes or bags made from synthesised leather, instead of relying on conventional plastics.

#### Synthetic silk

Silk obtained from commercial silk moth farming has a relatively high environmental impact, on the basis of an LCA analysis that included water, energy and fertiliser use (Astudillo *et al.* 2014). Bolt Threads[53], a company based in California, has developed a technology that allows the production of silk protein (fibroin) using a genetically modified yeast strain. This allows the production of large quantities of fibroin by fermentation using water and sugar. Fibres are produced by wet spinning allowing the manufacture of silk textiles – no silk moths are harmed in the process.

## 8.2 Scope for developing the case studies

The examples of alternatives to conventional plastics provided in Chapters 4, 5 and 6 have clear application within the circumstances in which they have been developed. But the more interesting question is to what extent can these examples be scaled up or transferred to other regions with differing social, cultural, economic and environmental circumstances. Providing a definitive answer to this question is well beyond the scope of this report, but some key features of each of the potential solutions have been summarised in three tables, corresponding to Chapters 4, 5 and 6 (Table 8.1, 8.2, 8.3). The table provides a qualitative assessment of the degree of technical complexity involved, the start-up costs, whether the solution is suitable for tropical/sub-tropical or temperate regions, the scope for scaling-up and a summary of advantages and disadvantages. The main conclusion is that there are very many opportunities to extend, adapt or otherwise promote all these solutions, provided proper account is taken of the social and economic circumstances and there is involvement of all parties who may be expected to benefit or otherwise affected by the proposed solution.

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[52] http://www.modernmeadow.com/our-technology/
[53] https://boltthreads.com/about-us/

**Table 8.1** Qualitative assessment of the technical complexity, start-up costs, regional relevance (TR - tropical/sub-tropical, TE – temperate), possibility to scale up, advantages and disadvantages of solution involving natural materials: L- low, M – medium, H- high; blue - most favourable, red - least favourable.

| Solutions involving natural materials – Chapter 4 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Examples | Technical complexity | | | Start-up cost | | | Climatic region | | Possible to scale up | | | Advantages | Disadvantages |
| | L | M | H | L | M | H | TR | TE | L | M | H | | |
| Paper & card | L | M | | L | M | | Y | Y | | | H | Widely available<br>Readily compostable | Production can lead to environmental degradation |
| Protective packing based on fungal mycelium | | M | | L | M | | Y | Y | | | H | Can use a wide variety of agricultural & other organic wasteReadily compostable | Not water resistant |
| Personal care products based on natural materials (e.g. wood and bristle) | L | | | L | | | Y | Y | | M | | Will degrade in the environment | Limited market access |
| Products made from sisal, jute, sea grass and other natural fibres | L | | | L | | | Y | Y | | M | | Provides empowerment in impoverished rural communities | Possible over-exploitation of resources<br>Limited market access |
| Bamboo straws | L | | | L | | | Y | N | | M | | Provides empowerment in impoverished rural communities | Limited market access |
| Plates & bowls from leaves | L | | | L | | | Y | N | | M | | Provides empowerment in impoverished rural communities<br>Can utilise agricultural waste | Limited market access |
| Objects from peel | L | | | L | | | Y | Y | L | | | Can utilise waste from commercial operations | Limited applications |
| Piñatex™ 'leather' | | M | | | M | | Y | N | L | | | Can utilise waste from commercial operations | Limited applications |
| Products made from water hyacinth | L | | | L | M | | Y | N | | M | | Helps to control invasive species | Limited market access |
| Compostable coffee cups | | M | | | M | | Y | Y | | | H | Elegant solution to major problem with existing disposable coffee cups | Dependent on acceptance by established market |
| Edible plates and cutlery from cereals | L | | | L | | | Y | Y | | M | | Solution to littering from 'fast-food' outlets | Limited market access |
| Edible packaging from seaweed | | M | H | | M | | Y | Y | | M | | Solution to littering from 'fast-food' outlets | Limited market access |
| Non-edible products from seaweed | L | M | | L | | | Y | Y | | M | | Uses of widespread renewable resource | Limited applications & market access |

**Table 8.2** Qualitative assessment of the technical complexity, start-up costs, regional relevance (TR - tropical/sub-tropical, TE – temperate), possibility to scale up, advantages and disadvantages, of solutions involving biomass-based, compostable, synthetic biopolymers: L- low, M – medium, H- high; blue - most favourable, red - least favourable.

| Solutions involving biomass-based, compostable, synthetic biopolymers – Chapter 5 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Examples | Technical complexity | | | Start-up cost | | | Climatic region | | Possible to scale up | | | Advantages | Disadvantages |
| | L | M | H | L | M | H | TR | TE | L | M | H | | |
| Thermoplastic starch (TPS) packaging | | M | | | M | Y | Y | | | | H | Uses renewable stable cereal crops such as cassava and maize<br>TPS bags can be used for food waste in industrial composters | Potential competition for food crops, leading to price increases & food insecurity<br>Time-dependent degradation in ocean<br>Limited applications compared with conventional synthetic polymers |
| Starch-based bio-composite packaging | M | | | M | | Y | Y | | | | H | Increased range of applications over pure TPS<br>Can use agricultural waste as fibre source | Composites need to be compostable to avoid separation and recycling<br>Time-dependent degradation in ocean<br>Inferior to conventional synthetic polymers for some food applications |
| PLA-based catering products | | H | | | H | Y | Y | | M | | | PLA plates & utensils can be included with food waste for industrial composting or anaerobic digestion<br>Lactic acid can be produced from organic waste | Requires establishing a closed-loop system to keep separate from conventional plastics<br>Does not degrade in the ocean<br>High production costs |
| PHA-based packaging & textiles | | H | | | H | Y | Y | | M | | | PHA packaging can be included with food waste for industrial composting or anaerobic digestion<br>PHA can be synthesised from waste-generated methane | High production costs |

**Table 8.3** Qualitative assessment of the technical complexity, start-up costs, regional relevance (TR - tropical/sub-tropical, TE – temperate), possibility to scale up, advantages and disadvantages, of solutions involving re-usable materials: L- low, M – medium, H- high; blue - most favourable, red - least favourable.

| Solutions involving re-usable materials – Chapter 6 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Examples** | **Technical complexity** | | | **Start-up cost** | | | **Climatic region** | | **Possible to scale up** | | | **Advantages** | **Disadvantages** |
| | **L** | **M** | **H** | **L** | **M** | **H** | **TR** | **TE** | **L** | **M** | **H** | | |
| Metal dinks and food containers | | M | | | M | | Y | Y | | M | H | Robust, lightweight and hygienic solution to protecting foodstuffs and transporting fluids | Initial high cost<br>Requires availability of safe drinking water for re-filling |
| Liquid dispensing machine for cleaning products – developing economies | | | | | M | | Y | Y | | M | | Allows dispensing of small volumes of household cleaning materials into re-usable containers<br>Eliminates use of small disposable sachets | Initial cost<br>Need to enrol support of existing retailers and customers |
| Food dispensing machine – developing economies | | | H | | | H | Y | Y | | M | | Allows dispensing of variable volumes of foodstuffs into re-usable containers<br>Reduces need for disposable packaging | Initial high cost<br>Need to enrol producers, wholesalers, retailers and customers |
| Re-usable coffee cup (CupClub) | | M | | | M | | Y | Y | | M | | Eliminates need for disposable coffee cups<br>Eliminates need to carry a personal cup | Need to enrol retailers, corporate chains and customers<br>Relies on the acceptance & availability of the 'internet of things'<br>Limited to relatively affluent urban areas |
| Up-cycling chopsticks | L | | | L | | | Y | Y | | M | | Makes use of a waste product<br>Manufacture value added products | Need to enrol restaurant outlets |
| Sustainable clothing design | L | M | | L | M | | Y | Y | | M | | Encourages efficient use of fabrics<br>Encourages repair and longevity | Need to enrol producers, designers, retailers and customers |

## 8.3 The role of the Clean Seas Campaign

The Clean Seas Campaign[54] was initiated by the United Nations Environment Programme in February 2017. The self-declared aim of the campaign is to:

> **'……… address the root-cause of marine litter by targeting the production and consumption of non-recoverable and single-use plastic. To do this effectively, we need citizens to be aware, engaged and active in addressing the problem in their own lives and beyond.'**

It is intended that the campaign should connect individuals, civil society, governments and industry to:

> **'… transform habits, practices, standards and policies …..'**

Forty three had formerly joined the campaign by March 2017, out of a total of total of 1280 'pledges' from individuals, companies, NGOs and governments. The campaign contributes to the goals of the Global Partnership on Marine Litter[55], an open-ended voluntary partnership for international agencies, NGOs, business, governments (GPML) and local authorities, with UN Environment acting as the Secretariat. The GPML provides an on-line platform for the collection and distribution of news and other information[56].

Although the Clean Seas remit does not cover alternative materials per se there are obvious connections between reducing consumption of non-essential single-use plastic and promoting the use of alternative materials. It is anticipated that both the Clean Seas and GPML initiatives will be used to disseminate the results of this report and encourage greater uptake of the solutions presented in it.

## 8.4 Encouraging the appropriate response

Reducing the quantities of plastics and microplastics reaching the ocean is a complex and multi-faceted problem, but it is tractable compared with several other global environmental issues, such as ocean acidification and climate change. There is no one simple solution, but rather a whole series of incremental steps are necessary, taking account of the technical, social and economic needs and circumstances of different countries and regions.

For example, a mobile phone app. has been created[57] to encourage greater uptake of re-fillable bottles, in the UK, by indicating the location of retail outlets and water fountains in public buildings and spaces. This is a model that will work in well-organised societies in which the availability of potable water is not questioned. However, in very many societies this is not the case. If people are to be weaned off disposable plastic bottles and bags, as their only reliable source of clean drinking water, then provision must be made for public clean water to be supplied. One excellent example is the placing of water ATMs in some of the poorest parts of Nairob[58], in a public-private partnership, monitored via the 'cloud'. This is a solution that has wide application.

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[54] http://cleanseas.org/
[55] https://sustainabledevelopment.un.org/partnership/?p=7471
[56] http://marinelitternetwork.com/
[57] http://refill.org.uk
[58] http://www.grundfos.com/cases/find-case/water-atms-offer-low-priced-water-to-nairobis-poorest-residents.html

Political support for a more sustainable approach to our use of resources is essential. That support is growing, as evidenced by the adoption of the SDG targets, recognition within the UNEA process, Regional Seas Action Plans and G7 and G20 Marine Litter Action Plans. These developments are to be welcomed but they are not sufficient in themselves to bring about the required changes. There is an important role for private sector to recognise the need to change and seize the opportunities this provides. There is a responsibility for corporations to implement more sustainable business practices and incorporate sustainability in their business models. There is an opportunity to tap the resources and resourcefulness of local communities to sustainably develop local economies and achieve greater resilience and autonomy, in particular by utilising available plant and animal resources.

Almost all commercial and industrial sectors, together with public sector organisations and civil society, use conventional plastics. We all have a role to play in exploring opportunities for reducing conventional plastic use and replacing them with alternative materials or biomass-based biopolymers. There is a need for innovation and entrepreneurship. This could be encouraged by competition[59].

All human activity has an impact on the planet. We have to be careful that a mission to reduce one type of impact, in this case ocean plastics, does not result in the unintended consequence of increasing another (e.g. increasing use of water, fertiliser and biocides for increased production of non-organic cotton). The advantage of adopting an incremental response is that it is possible to make mistakes and learn from them, an essential element of adaptive management.

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[59] UN Environment Innovation Challenge http://www.unep.org/newscentre/global-innovation-challenge-opens-students-fight-marine-plastic

# 9. Conclusions and recommendations

## 9.1 Conclusions

### Occurrence of plastics in the marine environment:

1. Plastics used for packaging and other single-use applications are ubiquitous in the marine environment and often are the dominant category in surveys of identifiable objects.
2. Microplastic fibres of synthetic and semi-synthetic polymers have been found in deep ocean sediments, arctic sea ice and a wide variety of marine organisms, including in commercial fish and shellfish.
3. The widespread distribution of single-use plastics and microplastic fibres in the ocean provides the justification for focusing on these applications when assessing whether there are options for utilising alternative natural materials, or less problematic synthetic polymers.

### Utilisation of alternative materials:

4. It is neither possible nor desirable to remove all plastics from society, but alternatives can have a significant role in reducing our dependence.
5. The use of alternatives must be part of a broader strategy towards more sustainable production patterns, particularly for packaging and other single-use items, including the principles of redesign, reduce, reduce and facilitating recycling.
6. It is critical to balance the aim of reducing plastic packaging waste with reducing food waste.
7. The purposeful agricultural production of biomass to supply the biopolymer industry has to be balanced against the need to support food production and preserve biodiversity.
8. There is scope to increase the use of agricultural and horticultural waste as a source of natural fibres and as a raw material for biopolymer production.
9. An increasing number of packaging solutions using alternative materials are being developed and bought to market.
10. There remains an issue of scaling up some potential solutions to support a mass market; factors such as raw materials supply, availability of appropriate skills, access to financing, infrastructure and the degree of technological development will be key, especially in developing economies.
11. Biomass-based biopolymers such as PLA, PHA and TPS show great potential, especially for packaging and other single use, provided they are used in closed loop-systems. Their promotion as a 'greener' alternative is unjustified in the absence of the effective provision of industrial composting or anaerobic digestion facilities; i.e. they are not suitable for dispensing 'fast food' in uncontrolled public spaces.
12. The increasing use of PLA, PHA and TPS and similar biopolymers will not reduce per se the amount of plastic waste reaching the ocean or ending up in landfill. In addition, there is a risk that such polymers will contaminate recycling waste streams
13. The utilisation of natural materials, either directly or as a biomass source, is dependent on prices in the agricultural and horticultural sectors. These can be highly variable and unpredictable. Building in flexibility in the selection of different materials is an advantage.
14. Many countries have started to introduce restrictions on the availability of thin walled plastic bags, commonly used for carrying shopping. This creates an incentive to promote the use of bags constructed from natural materials, designed for multiple uses.

## Life Cycle Analysis (LCA):

15. Currently most LCAs that attempt to compare the sustainability of different types of polymer are incomplete, as they do not deal adequately with the end-of-life phase of the production cycle.
16. The social, economic and environmental impacts of the end-of-life phase are often difficult to quantify, and improved methods are needed, guided by appropriate expertise in all facets of the end-of-life phase.
17. Agricultural production often involves the use of water for irrigation and may involve the intensive application of artificial fertilisers and biocides. This may result in unwelcome environmental and social impacts. These elements must be included in an LCA.
18. A more sophisticated approach is required for calculating the net social, economic and environmental benefit of following alternative approaches, such as might be applied to the choice between goods made from natural materials, biomass-based biopolymers and synthetic polymers. This should include consideration of human health aspects in the production and manufacturing stage.

## Encouraging change:

19. Focussing on related SDG goals and targets (e.g. SDG 1, 6, 8, 9, 11, 12 and 15) will help to achieve SDG 14.1
20. Moving towards more closed-loop, carbon-neutral production cycles, including the use of industrial composting and anaerobic digestion, will demonstrate the beneficial use of waste, and should promote more effective waste management, ease of use, public commitment/acceptance, improved implementation and compliance. Natural alternatives to conventional plastics, and the use of biomass-based biopolymers, have an important role to play in such systems.
21. Governments have a moral responsibility to examine the consequences of supporting certain sectors, to ensure that the perceived benefit (social, economic, environmental or political) is balanced against the actual cost, especially of environmental damage.
22. Recognising that all elements of society have a role to play in exploring opportunities for reducing conventional plastic use and replacing with alternative materials or biomass-based biopolymers. There is a need for innovation and entrepreneurship, which could be encouraged by competition.
23. Empowering women, who often make the bulk of domestic spending decisions, will have a disproportionately beneficial effect in changing consumption behaviours and reducing unnecessary use of conventional plastics.
24. Encouraging the Parties to the Stockholm and Basel Conventions to implement the recommended guidelines on the import, export, recycling and disposal of goods and materials containing POPs.

## 9.2 Recommendations

1. Promote the findings and recommendations resulting from the FAO Year of the Fibre initiative.
2. Support sustainable development in rural communities to make better use of natural resources.
3. Promote the greater utilisation of agricultural and horticultural waste as a source of natural fibres and biomass for the production of biopolymers.
4. Encourage a collaborative and mutually beneficial approach towards meeting SDG target 14.1 particularly taking account of SDGs 1, 6, 8, 9, 11, 12 and 15.
5. Promote more gender-specific research on the impacts of plastics on human health and the environment.
6. Encourage further research into the use agricultural and horticultural waste for novel purposes.
7. Promote clear labelling of materials suitable for industrial compositing and discourage use of the term ‘biodegradable’ without further clarification of the conditions under which biodegradation will occur.
8. Encourage the further development of national and international standards definitions and standards (i.e. EN, ASTM, ISO …. ), covering composting, anaerobic digestion and biodegradation, in a variety of terrestrial and aquatic environments.

9. Support additional research into the behaviour, fate and effects of natural materials, semi-synthetic polymers and biomass-based biopolymers in the natural environment, including associated chemicals.
10. Support awareness-raising campaigns on the impacts of plastics on society and the environment, the potential of alternative materials and the role of women in bringing about change.
11. Require the public and private sector to fully cost the social and environmental impacts of their current business models.
12. Encourage policy implementation of the Precautionary Approach and Polluter Pays Principle, to promote the use of more sustainable products and practices.
13. Ensure products are adequately labelled so that users and consumers are provided with clear, comprehensible and accurate information of which to base purchase decisions.

Marine plastic debris on a beach in Malta
Photo Credit: Alain Bachellier

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