21

Polymers and the Environment

S. Koltzenburg et al., *Polymer Chemistry*, DOI 10.1007/978-3-662-49279-6_21

Around 280,000,000 (280 million!) tons of synthetic polymers were produced for subsequent use in 2011. An annual increase in per-capita consumption of around 5% is expected through 2015. In light of these numbers, one must question the impact this consumption and use have on the environment. This concerns not only the resulting high volumes of waste produced but also issues such as recycling, energy, renewable raw materials, and sustainability. Close relationships and interactions exist between all these fields, which should not be ignored but are, nevertheless, all too often insufficiently considered in current discussions in these fields.

An all-encompassing solution to the problems that exist in these fields cannot be provided within the scope of this book; indeed, such a solution remains to be found. The aim of this chapter is to explain the basic concepts and terms that are relevant in relation to the above-mentioned interdependencies.

21.1 Introduction and Definitions

Some of the basic terms used when dealing with the recycling of plastics are defined in this section.

Reuse

The general term *reuse* encompasses all the options available for the processing of plastics, regardless of whether the waste products are directly processed into new plastics or whether they are reused in a different manner. This term also includes so-called *energy utilization* in particular, that is, the use of plastic waste for the purpose of producing energy.

Recycling

The recycling of plastic waste refers to the processing of old waste into new plastics, or their being processed to be put to another use, with the exception of energy recovery. Recycling thus refers to all types of *material utilization*.

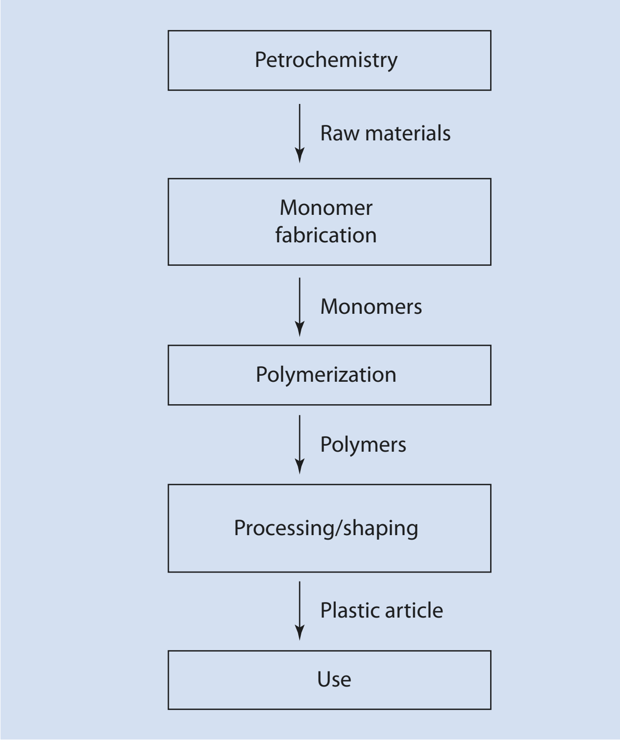
The relationship between these terms can thus be described by the following equation:

$$\text{Reuse} = \text{Recycling} + \text{Energy utilization}$$

21.2 Options Available for Recycling Plastics

Plastic waste occurs at every stage along the chain of production and use of plastics (◘ Fig. 21.1). Fundamentally, the waste can be recycled in four different ways, which are explained briefly in the following. The options available differ from one another according to the stage in the value chain where the waste occurs and at which stage the plastics can be reintroduced into the chain. Each of the four principle routes is used—for reasons that are easily understood but are explained—to considerably different extents.

Fig. 21.1 Synthetic polymer value chain



21.2.1 In-Plant Recycling

In-plant recycling refers to the reuse of plastic waste created during processing. Plastic waste products such as stamping remnants (*Chad*), *deburred* remnants from injection molded parts, or products not meeting the product specifications are used in this context. These waste products are collected, and, often simply after grinding, reused for the same process. The advantages are obvious. The accumulated waste not only consists of a single polymer, it is also clean. Thus, it is ideal for reuse in the same process, although it is often necessary to blend the recycled waste with virgin material to maintain the required mechanical properties; for this reason, this recycling option can be considered as general practice.

21.2.2 Direct Reuse

Many plastic parts can, generally, be used multiple times. Requirements for this are that they can be detached from other components to which they may be attached without damage, and that no wear and tear has occurred. The classic example is plastic shopping bags that are used multiple times. The above-mentioned requirements are, however, often only partly valid for plastic parts that are components in complex systems, such as materials used in automobile parts and electronic appliances. As a rule, using a plastic bag multiple times is not problematic; however, packaging that has come into contact with perishable goods, such as yogurt or fresh meat, needs to be carefully cleaned before being reused.

If the plastic parts need to be sorted and cleaned, the overall ecological and economic balance can become negative compared with other available options examined in this chapter. This is on account of the energy and the volume of cleaning agents (which often subsequently end up in the environment) needed for the cleaning stage. Reuse is, nevertheless, a frequently used recycling option for clean plastic parts.

21.2.3 Material Recycling

The term *material recycling* denotes the reintroduction of plastic waste into a manufacturing processes. For this purpose, plastic waste is collected after use—in Germany, for example, in the well-known "yellow sack"—and then given a new form (▶ see Chap. 17). However, complex processing of the waste is necessary between collection and forming. This includes:

- Sorting
- Crushing
- Washing
- Drying
- Extrusion
- Granulation

During sorting, the aim is to separate the individual plastic types from one another so as to obtain an extract as chemically pure as possible from the range of materials present in the collected materials. For this purpose a general, numerical classification of the most important types of plastics, shown in ◘ Table 21.1, has been introduced.

The classification can be found on the molded part in a triangle shaped out of arrows (◘ Fig. 21.2). The first number zero is occasionally omitted.

◘ **Table 21.1** Classification of polymers for recycling

Class	Material
01	Polyethylene terephthalate (PET)
02	High density polyethylene (HDPE)
03	Polyvinylchloride (PVC)
04	Low density polyethylene (LDPE)
05	Polypropylene (PP)
06	Polystyrene (PS)
07	Others

◘ **Fig. 21.2** Polymer labeling; here LDPE

As most polymers are immiscible with one another (▶ Chap. 2), good segregation is necessary to obtain a high-quality material for further processing.

However, as well as the obvious benefits in reducing waste, the materials recycling option also has significant disadvantages:

- The material history is unknown. During reprocessing, it can be expected that the material may have been decomposed and/or contains peroxide or keto groups from oxidation processes (▶ Chap. 15) or unsaturated double bonds (from elimination reactions). Likewise, polymers such as polybutadiene, which per se contain double bonds, may have further cross-linked.
- Additionally, as mentioned above, thorough cleaning of the waste is necessary which is costly.
- As mentioned in ▶ Chaps. 15 and 17, many synthetic materials contain additives such as pigments/dyes, fillers and reinforcing materials, plasticizers, and reacted or unreacted stabilizers. All of these cannot, generally, be separated from the polymers. As these accompanying substances can vary vastly from one batch of waste to another, it is exceptionally difficult to produce a consistent, high-quality product from the resulting product.

For these reasons, the plastics obtained from material recycling are generally significantly inferior with respect to their quality when compared with non-recycled ("virgin") polymers.

Furthermore, it should be noted that simple material recycling cannot be carried out on the following, widely used, polymer classes:

- Copolymers and polymer blends, which cannot be separated into single grades
- Duroplasts which, as a result of their cross-linked state, are insoluble and infusible and therefore cannot simply be reprocessed

All in all, material recycling only makes sense if the material available is clean and well-characterized. This is, for example, often the case for plastic drink bottles (largely poly(ethylene terephthalate)). However, in most other cases, the inferior material properties of the recycled material, the high costs of segregating the different plastic types, and the negative energy balance of the many complex individual steps all question the efficacy of material recycling of finished and used polymer articles.

21.2.4 Raw Material Recycling

So-called *raw material recycling* of synthetic material involves, for example, a degradation of the polymers via pyrolysis or solvolysis, in contrast to material recycling, discussed above, during which the macromolecules are not chemically altered. During this process, for example, the main chain of a polyolefin is thermally split into different olefins. Polymers with groups that can be hydrolyzed, and especially monomer polyesters, can be regenerated hydrolytically or by exposure to particular solvents. Mixtures of substances of low molecular weight form which, according to the starting material used, can be re-used as monomers, as basic chemicals, or as fuel. The processes used are usually relatively harsh and non-selective. However, they have the advantage that they can be used for synthetic waste that is not well separated and sorted according to type and for contaminated and/or composite materials. They are also suitable for copolymers and polymer blends. A typical example of a new industry that is developing based on such techniques is tire recycling. The high costs and energy required by such processes are problematic. The latter in particular is dealt with in more detail in the next section.

21.3 Plastics and Energy

The plastics value chain and the different recycling options that exist are considered in relation to the whole material flow of the petrochemical industry in this chapter. As well as this, the energy balance for polymeric materials is also discussed.

21.3.1 Energy Recovery from Synthetic Materials

Against the background of depleting amounts of fossil fuel, it is worth briefly considering the continuing role of crude oil as the most important raw material in the chemical and synthetic materials industries.

Worldwide, roughly 90 % of the oil produced is used in approximately equal proportions for both transport/mobility and heating/heat production, that is, uses in which this raw material is fed into oil-fired heating systems or vehicle motors. Barely 10 % of the oil produced is used for the production of chemical products. Around half of this amount becomes the raw material for synthetic materials. ◘ Figure 21.3 shows the flow of polymeric materials taking the different recycling options, discussed in ▶ Sect. 21.2, into consideration.

Consideration of ◘ Fig. 21.3 begs the question as to whether it would not make more sense first to use a large proportion of crude oil in the form of a chemical product and then to use it for the production of energy, rather than simply feeding it into a combustion process without any interim use. Naturally this only makes sense for chemical products that have an energy value comparable to that of crude oil. However, with regard to this last point, polymers are especially attractive, as ◘ Fig. 21.4 demonstrates. This figure clearly shows that polyolefins and polystyrene in particular, both have energy values corresponding almost exactly to those of fossil energy sources. Why this is the case becomes clear immediately when viewing the chemistry of these macromolecules (pure hydrocarbons). It was for polyolefins, in particular, that the term “firm crude oil” was coined.

Polymeric materials thus have a high potential with regard to their use as environmentally friendly energy sources. Their significance remains insignificant, probably because of a lack of political or societal acceptance rather than a rational or scientific reason. Although it is not intended to become involved in an environmental and political debate in this text, it must be clearly stated that it is neither ecologically, nor economically worthwhile to invest more energy in the recycling of a plastic than would be needed for its production. On the other hand, it is immediately clear that it makes good sense first to produce a yoghurt carton from crude oil and then to use the yoghurt carton for the production of energy rather than simply burning the crude oil.

There is no single recycling method for polymer waste better than any other. To recycle polymers in the best way from both economic and ecological points of view, a mix of

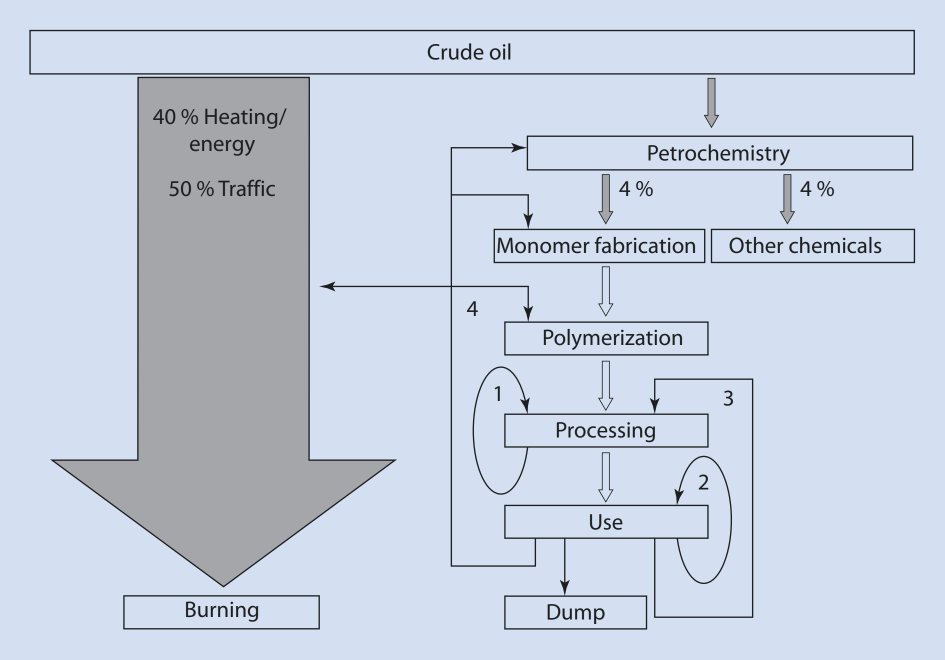


Fig. 21.3 Crude oil material flow including polymer recycling. (1) In-plant recycling. (2) Direct reuse. (3) Material recycling. (4) Raw material recycling. *Numbers* are approximations

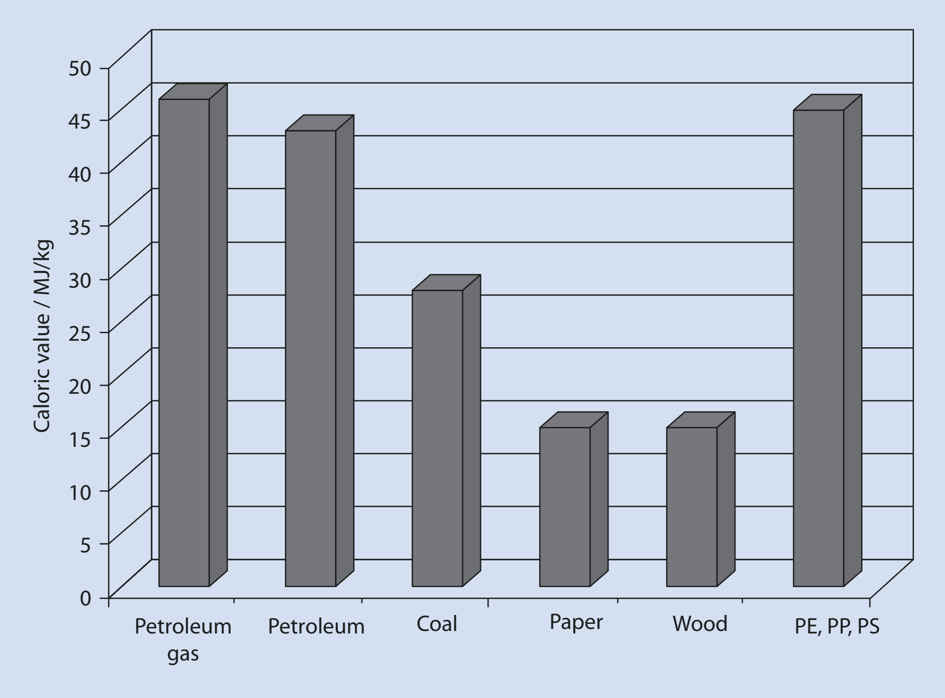


Fig. 21.4 Calorific value of selected materials

mechanical, chemical, and energy recycling is needed. Simply disposing of polymeric waste in landfills should, generally, not be an option. The relative importance of the individual recycling options should be considered in both economic and ecological terms. Furthermore, guidelines motivated solely by politics are usually not expedient.

21.3.2 Energy Footprint of Synthetic Materials

As well as their suitability as energy sources of considerable specific energy, waste synthetic material can often lead to a decrease in process energy consumption. This is made clear with the help of several specially selected examples in the following.

21.3.2.1 Synthetic Materials in Automobile Manufacturing

Roughly 50 % of the fuel consumption of an automobile is linearly dependent on the automobile's weight. Other factors, such as aerodynamic drag, for example, account for the other half. If one considers the average weight of a new vehicle, one can observe that vehicles have become increasingly heavier in recent years. This is, above all, because of extras that serve to increase comfort, such as air conditioning systems, but is also caused by necessary safety extras such as airbags or an altogether more stable car body design. The use of light metals such as aluminum is not feasible because of the high raw material costs. The use of plastics in engine and bodywork parts, for example, has made an important contribution to reducing weight increase. Prominent examples of the replacement of metals with plastics are in induction pipes or wheel trim caps made from polyamide. Bumpers have also been made using plastics for many years now. The use of plastics in other parts of the exterior of car bodies such as car roofs or mudguards is becoming more common and developments in tire technology contribute significantly to a reduction in vehicle fuel consumption.

21.3.2.2 Polymers in the Construction Industry

From the time of their invention, polystyrene foams (Styropor®) have been used on a massive scale for thermal insulation in buildings. The extraordinarily low thermal conductivity of the closed cell foams is being exploited (▶ Chap. 17). The energy consumption of old buildings can be decreased by 70 % by the introduction of modern insulation. Calculations show that subsequent insulation of all housing could decrease the total energy consumption of the Federal Republic of Germany by 20–30 %. Polyurethane foams are also used for insulation purposes in the construction sector.

If one takes the energy-saving potential of polystyrene foams into account, it quickly becomes clear that these materials have the potential, if used properly, to ensure that more crude oil is saved than was necessary for their production.

21.3.2.3 Synthetic Materials as Packaging

In many sorts of packaging, especially for foodstuffs, synthetic materials have become indispensable, if only for reasons of hygiene. In several cases, however, there are alternatives available from other classes of materials such as glass. Thus, the use of yoghurt containers that can be used multiple times are being demanded by some groups as an environmentally friendly alternative to plastic packaging. Such demands, however, often ignore the following considerations:

- The transport from production to point of consumption. For example, the transport of a 150-g portion of yoghurt requires the transport of 85 g of packaging material if the packaging is made of glass with an aluminum lid compared with ca. 5.5 g for the corresponding plastic package. This increases enormously the energy consumption of transportation in a refrigerated vehicle. The proportion of packaging for a plastic yoghurt container is 3.5 % in contrast to 36.2 % for glass packaging. In other words, the energy required by three lorries laden with yogurts in plastic packaging would be sufficient for only two lorries carrying yogurts in glass containers. It is evident that this is not beneficial for the environment.
- As has already been mentioned, reusable packaging, especially in the foodstuff sector, must be cleaned exceptionally thoroughly, which in turn consumes energy which could just as well be used for the production of new packaging. Furthermore, a significant amount of the cleaning agents ends up in the environment.

With this in mind, it is clear that the careful use of polymers can save significantly more energy than is necessary for their production. Even in uses for which this is not the case, the use of polymeric materials is frequently energetically and ecologically more favorable than using alternative materials.

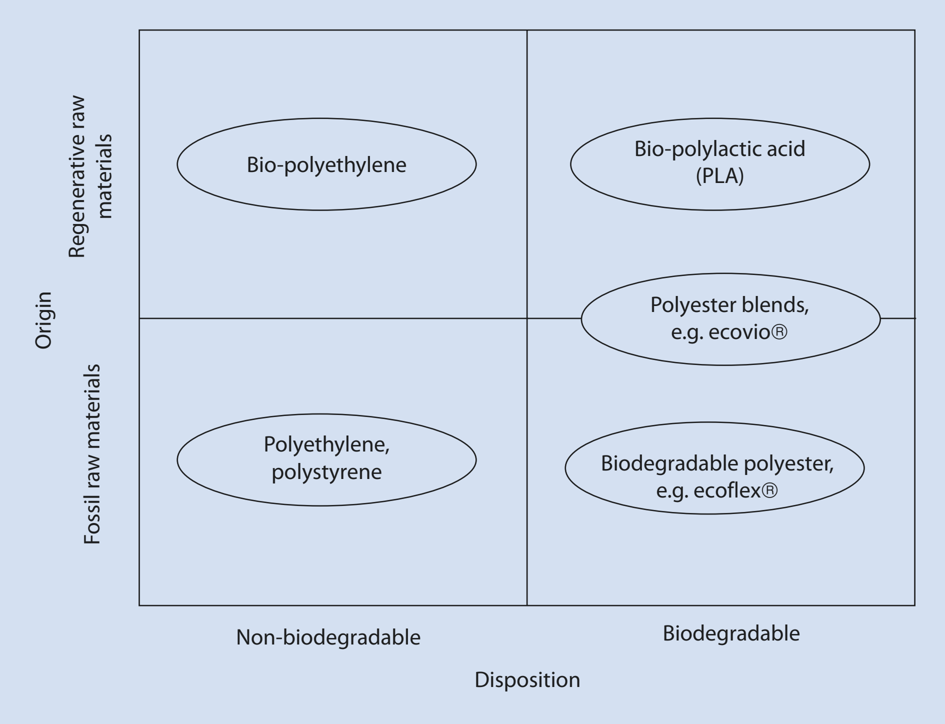
21.4 Biopolymers

The term "biopolymers" is today often mentioned in discussions. It is often ill-defined, as are the terms "biodegradable" and "bio-based".

Biologically degradable or *biodegradable* polymers are materials that can be degraded by microorganisms or enzymes within a reasonable length of time under ambient conditions. Materials that can be biologically degraded within a composting plant are referred to as *compostable* polymers. It should be obvious that the degradation products are nontoxic. Biodegradability is a function of the chemical structure of a polymer.

Polymers based on renewable materials are by definition macromolecules that are produced from renewable raw material sourced from nature. Biogenic polymers such as cellulose or chitin, which can be directly isolated from renewable sources, belong to this group, as do polymers that can be produced by chemical synthesis from renewable sources. The counterpart to these bio-based polymers are polymers based on typical raw materials, primarily crude oil, which is referred to as a *fossil resource*. The transition is not always clearly defined. Thus, for example, there are polymer blends made from polymers based on fossil resources mixed with bio-based polymers. Cellulose, for instance, is often modified using reagents from fossil sources.

Whereas the expression "bio-based" refers to the origin of the polymer or the raw material from which it was produced, the expression "biodegradable" defines the application or recycling options of the polymer at the end of its period of use. Because biological degradability is a function of the polymers structure but not of its raw material, polymers based on fossil resources can also be biodegradable. The opposite is also possible—polymers based on renewable resources that are not biodegradable.



■ **Fig. 21.5** Biopolymer classification; the named biopolymers are referred to in the text

Both properties are therefore in no way connected to one another and should be carefully differentiated. ■ Figure 21.5 graphically emphasizes this.

In general language use, it has unfortunately become commonplace to refer universally to both polymers of biological origins and biodegradable polymers as *biopolymers*.[1] When using this term it should always be made clear whether, in the particular context, biodegradable or bio-based materials are being referred to.

The following sections deal with bio-based and biologically degradable polymers in more detail.

21.4.1 Polymers Based on Renewable Raw Materials

At a first glance, the use of renewable resources as raw materials appears to be an attractive alternative to crude oil. The enormous diversity of organic reactions and especially "white biotechnology",[2] which has become increasingly efficient in recent years, enables many chemical products—such as the monomers that have been dealt with in previous

---

[1] Other literature limits the use of the term "biopolymer" to unmodified naturally occurring polymers such as proteins or natural rubber.

[2] The term *white biotechnology* is used to describe biotechnology used for industrial purposes. With this technology, basic raw materials, pharmaceuticals, fine chemicals, and monomers are produced using microorganisms or enzymes in so-called bioreactors.

chapters—to be produced not only from crude oil but also from renewable raw materials. At the time of writing, the proportion of renewable resources in the German chemical industry makes up around 15% of the total raw material demand. A large proportion of this percentage is natural fats and oils, which can be processed into chemical products. In addition, starch is hydrolyzed into glucose and then processed further into ethanol. The ethanol obtained can be dehydrated to become ethene, and this polymerized to polyethylene. Via this and other routes, many of the polymers currently made from petrochemical raw materials can be made from renewable resources. Moreover, as well as the polymers that can be produced by classical, chemical means from bio-based raw materials, a large number of polymers are directly available in nature. Starch, cellulose, lignin, chitin, proteins, natural rubber, and polymeric nucleic acids can be mentioned in this context.

There are, therefore, two fundamentally different approaches to producing polymers that are either completely or to a large extent bio-based:

1. The use or modification of naturally occurring macromolecules
2. The synthesis of conventional or even novel polymers based on low molecular weight building blocks derived from natural sources

In the following, both of these options are discussed in more detail.

21.4.1.1 Naturally Occurring Polymers and Their Derivatives

In the field of water soluble, so-called functional polymers (▶ Chap. 19), many of the polymers used are already bio-based. Although DNA does not play a role in technical applications, for obvious reasons, proteins, polysaccharides, and their derivatives are indispensable for many of applications. In contrast, natural polymers and their derivatives play only a minor role as structural polymers—classical materials—when compared with the use of fully synthetic materials such as polyethylene or polystyrene.

Proteins

Naturally occurring proteins or those obtained from natural sources have great significance for the food industry. This is not least because of the strict regulations for non-natural products in the foodstuff sector; synthetic polymers based on fossil resources therefore have barely any significance in this sector.

One material used in large amounts is gelatine. Gelatine is basically made up of the protein collagen and is obtained from the connective tissue of different livestock species, particularly from the skin and bones of pigs and cattle. Because of the continuing concern of the public as well as religious dietary rules, special types of gelatine are produced from fish.

Gelatine is, as the name already implies, a typical gelling agent, which is used as a thickening agent in cooking. Well-known examples are wine gums, jelly, brawn, and aspic. Gelatine is also used on a large scale in the pharmaceutical industry to coat medicinal capsules or as a thickener for liquid medicinal products. Furthermore, gelatine is used as a protective colloid for the stabilization of dispersions (▶ Sect. 19.1) of vitamins and carotenoids, for example.

Apart from these functional uses, proteins have not gained any great relevance in contrast to their synthetic analogues, the polyamides. The reason for this is that the degradation of the protein is undesirable for many of these applications. Moreover, the biological degradation of proteins often occurs in combination with the formation of degradation products with an unpleasant smell. An exception is the use of silk in the textile field.

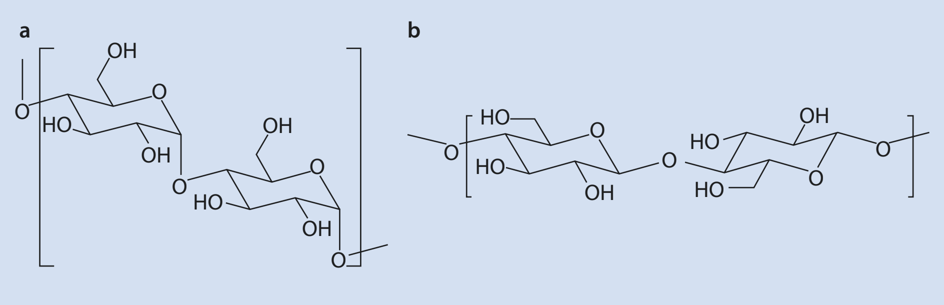


Fig. 21.6 Segments of the chemical structures of starch (**a**) and cellulose (**b**)

Spider silk proteins have an even better tensile strength than silk. However, so far it has not been possible to produce them on a technically relevant scale because of problems related to spider husbandry and breeding. Biotechnological processes that reproduce the amino acid sequence of spider silk have not produced fibers whose mechanical properties are comparable to spider silk with its more complex structure. The difference can be attributed to variations in the secondary and tertiary structures.

Polysaccharides and Their Derivates

Of the polysaccharides and their derivatives, starch and cellulose play the major role (Fig. 21.6). Both polymers are isomeric forms of poly-D-glucose, and differ from one another in the stereochemistry of the links between the glucose units. In starch, the glucose units are α-linked, whereas the building blocks of cellulose are linked to one another by β-links.

Starch is often used in its original form, that is, without chemical functionalization of its OH-functions, albeit the natural degree of polymerization is reduced to meet the specifications of the particular application by hydrolysis. Starch with a low degree of polymerization is also referred to as *maltodextrin*. Complete hydrolysis of starch leads to D-glucose, which can be further processed into other bio-based substances, such as bioethanol.

Starch is almost exclusively obtained from plant sources where it is part of the energy storage and is usually present in the form of fine granules.

Naturally occurring starch is generally a mixture of *amylose* and *amylopectin*. The difference between these two starch isomers is that amylopectin chains are highly branched whereas amylose chains are, largely, linear. The ratio of amylose to amylopectin depends to a large extent on the plant from which the starch has been obtained. Industrially, starch is mainly produced from potatoes, rice, cereals, and cassava.

Similar to gelatine, starch is widely used in the food industry, and is an essential component of noodles, flour, bread, and other baked goods. In addition, starch is also used in the paper industry as a binding or coating agent and in the pharmaceutical industry as an ingredient in pills, for example, as a filler, disintegrant, or binding agent (▶ Sect. 19.6).

Thus, the main applications of starch, as is the case for gelatine, are different from the classical uses of synthetic materials. From a technical point of view, its especially strong tendency to absorb water has proven to be a big problem; the absorption of water has considerable influence on the melting and glass transition temperatures and on the moduli. Thus the material properties and the temperature range in which the product can be used are dependent on its water content. The use of starch as a molded part is therefore limited to relatively undemanding applications such as loose filler materials for the packaging of sensitive goods. However, even this use is decreasing. Custom-fit molded parts made of polystyrene or polyethylene foam are becoming more popular. Blends can be made from starch with other polymers, for instance, biodegradable synthetic polymers, which are less prone to absorbing water and are thus more stable and whose properties are less affected by the material's history.

In addition to these two major polysaccharide representatives, a large number of other structures such as guar (E-412), xanthan (E-415), and alginate can also occur naturally. Many of these polysaccharides are used as thickeners, for example, in cosmetics, but also in the crude oil industry. A comprehensive discussion of the extraordinarily diverse range of polysaccharides would, however, go beyond the scope of this book. For further information the interested reader is referred to the specialist literature (e.g., Ramawat and Mérillon 2015; Aspinall 1983; Habibi and Lucia 2012).

21.4.1.2 Bio-based Polymers from Renewable Building Blocks

As has become clear from the previous section, a large number of monomers can be produced from renewable resources:

- Ethene (glucose → ethanol → ethene)
- Ethylene oxide (from bio-ethene)
- Diacids (e.g., for polyesters or polyamides)
- Polyols (e.g., for polyurethanes)

The properties of the polymers obtained are not dependent on whether the building blocks are derived from renewable or fossil raw materials (as long as the educts have identical degrees of purity) and the biodegradability of these materials is just as limited as their synthetic analogs. However, the "most important of all product properties"—production cost—is often critical. The production processes for products based on renewable resources are often more complex, and thus more costly, than the typical fossil-based processes, particularly in the field of large-volume, basic chemical products.

Before biodegradable and bio-based polymers are discussed, the term "biodegradable" is first explained in more detail.

21.4.2 Biologically Degradable Polymers

As has already been explained above, the biological degradability of a polymer is dependent on its chemical structure. Well-known examples of biologically degradable polymers are the naturally occurring polymers, such as starch, cellulose, lignin, chitin, and proteins mentioned above. As these are continuously produced by living organisms, but do not accumulate in nature, some form of degradation must take place. These polymers are used by microorganisms (bacteria, yeasts, fungi) as energy sources and degraded into biomass, water, carbon dioxide, and (depending on the ambient conditions) methane. In an oxygen-rich environment, the main products of so-called *aerobic* decomposition are water and CO_2. This is typically the case during controlled composting or degradation in soil. The carbon produced is then fed back into the biological cycle during photosynthesis. Alternatively, under *anaerobic* conditions, where little oxygen is available, methane as well as carbon dioxide is produced. Examples of anaerobic environments are deep water and rubbish tips. Anaerobic decomposition can also be used technologically to obtain biogas from biomass.

The microorganisms responsible for degradation have to be able to absorb the organic molecules and to metabolize them in their cells in order to be able to use them as a source of food. To facilitate this, two processes outside the microbial cell are necessary.

As a prerequisite, the polymer to be degraded must contain flexible structural units. In particular, any crystalline domains must be dissolved; this step is of course unnecessary for amorphous polymers or for the amorphous domains of partially crystalline materials.

The flexible chain segments must be chemically split into smaller molecules. Microorganisms secrete so-called *extracellular enzymes* that can split the polymer chains, often via hydrolysis. For this to take place, the chains have to be flexible enough to be able to penetrate the catalytic center of the enzyme. The fragments formed have to be water-soluble and able to pass through the cell walls or membranes of the microorganisms. After being taken up by the microorganism the fragmented parts are metabolized.

Not all polymer chains can be split enzymatically. In particular, polymers with simple, saturated hydrocarbon backbones are deemed to be either not very degradable or not degradable at all. An exception is polyvinyl alcohol.

Temperature, humidity, and oxygen content of the medium have a significant influence on the biological degradation. Of course, as well as the microbiological degradation pathways described here, thermal or photochemical degradation mechanisms mentioned in ▶ Chap. 15 also play a part in the degradation of polymers in the environment.

To establish whether a given polymer is biodegradable or not, there are different, partly national, standards. The most important is the European Standard EN 13432, the American ASTM D 6400-04, and the Japanese GreenPla. All of these standards define basic requirements for packaging materials which can decompose in industrial composting plants and are thus compostable. The most important test of aerobic degradability is the so-called *controlled composting test* according to ISO 14855. This test involves incubating the polymer with mature, defined compost at 58 °C in a compost container. Polymer decomposition is followed by measuring the amount of carbon dioxide formed.

Relatively large numbers of the polymers produced commercially in large volumes are biodegradable. This is true both for polymers based on fossil raw materials and for bio-based polymers. The most important examples are discussed in the following.

Biodegradable Polymers that are not Bio-based

An important class of fossil-based biodegradable polymers are the aliphatic or partially aliphatic polyesters. Examples are poly(ε-caprolactone) and a polyester based on adipic and terephthalic acids and butane diol, marketed under the name ecoflex®. Further examples of biodegradable polymers based on fossil fuels are polyvinyl alcohol, polyethylene oxide (depending on molar mass and which end groups are present), and polyaspartic acid. The latter is produced as shown in ◘ Fig. 21.7 from maleic anhydride, water, and ammonia.

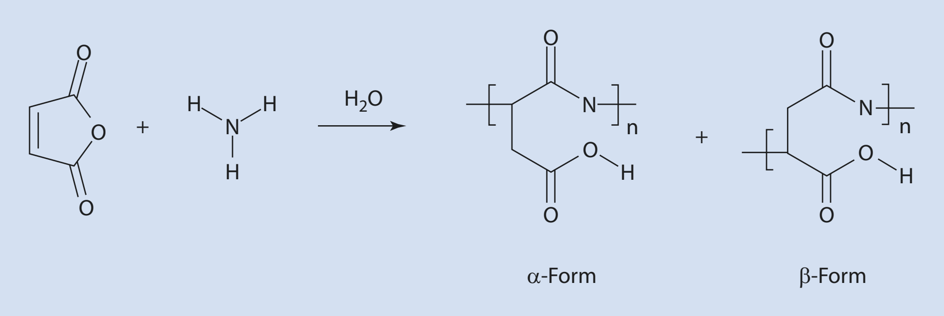


Fig. 21.7 Synthesis of polyaspartic acid from maleic acid anhydride, ammonia, and water

Biodegradable Polymers Based on Renewable Raw Materials

An example of a technologically manufactured, bio-based, and biodegradable polymer is polylactic acid. The lactic acid starting material is obtained by fermenting molasses or by the fermentation of glucose with the aid of different bacteria. The polymer is most often synthesized by ring-opening polymerization of the cyclic diester of lactic acid, lactide, the dimer of lactic acid.

Biodegradable Polymers that are Partially Bio-based

As has already been explained in the introduction to ▶ Sect. 21.4, one can, of course, mix biodegradable polymers that are based on different raw materials. The biological degradability of the polymer blend formed is not affected by this. An example of this kind of partially bio-based, completely biologically degradable polymer is marketed under the name ecovio®. It is a mixture of ecoflex® with polylactic acid.

21.4.3 Discussion

21.4.3.1 Bio-based Materials

Naturally occurring polymers such as lignin and chitin are often described in both the academic and industrial literature as materials available in abundance as waste from, for example, the paper and food industries. However, the details are often misrepresented. Thus, although lignin (a complex cross-linked polyphenol which makes up the bulk of plant cell walls) is a by-product of the paper industry, it is often used to provide a good proportion of the energy required in the paper manufacturing process because of its substantial fuel value. Some paper manufacturing companies (so-called paper mills) cover 80–100 % of their energy needs by burning lignin. Lignin is not by any means the primary product of a paper mill, but it is certainly not a valueless waste product as often suggested Furthermore, the lignin produced in the papermaking process tends to be of a dark color which makes any material recycling more complex. Chitin, a polymer of *N*-acetyl glucosamine, which makes up the bulk of the shells of crustaceans, can be considered as a large volume waste from the fish processing industry. However, the shells of crustaceans can, depending on the quality of the starting material, be converted into chitosan (by deacetylation) and then used in winemaking (fining agent), agriculture (pesticide), or in the pharmaceutical industry, but this is a complex and expensive process and, to date, chitosan is 10–20 times more expensive than other synthetic alternatives. Nevertheless, both these materials are currently the subject of considerable research.

In the last few years, it has become increasingly clear that the massive use of agricultural land for the production of chemical raw materials, such as bioethanol made from maize or sugar cane, has meant that the following problem has occurred. The amount of agriculturally useful land available worldwide is decreasing because of climate change and increasing soil erosion. At the same time, the world population is continuously increasing. Furthermore, the demand for high value foodstuffs, such as meat, whose production requires a particularly large area of arable land, is also increasing.[3] This means that, mid- and long term, it will become even more difficult than it already is to meet the nutritional needs of the world's population. Against this background, the use of arable land for the production of raw materials rather than food is controversial. The area of arable land needed to replace conventional polymers with polymers based on renewable raw materials to a significant extent is therefore not going to be available in the foreseeable future. The use of renewable resources for the production of plastics or other chemicals therefore has to be restricted to sources of raw materials not useful to humans either as food or for other purposes. Examples of such raw materials are wood waste or plants with low nutritional value which thrive in soil or areas where the production of high quality crops is not possible. The progress mentioned at the outset of this chapter in the fields of white genetic engineering and biorefineries gives reason to hope that useful and sustainable access to bio-based chemical building blocks that are not in competition with food production may be achievable.

21.4.3.2 Biodegradable Materials

For technological materials, for which as long a life span as possible and therefore long-term retention of mechanical and other properties is desirable, biodegradation is, of course, unwanted. This is, for example, the case for most of the uses in the automotive industry, in construction, and for the vast majority of electronic applications.

Thus, the use of biologically degradable polymers is limited to uses in which a long product life span is unnecessary. Examples include:

- Biodegradable garbage bags
- Disposable crockery
- Fast-food packaging
- Agricultural sheeting

The use of bio-based and/or biodegradable polymers would also often be sensible and technically possible in the case of functional polymers (▶ Chap. 19). The limited success of such materials can often be ascribed to their high production costs in comparison to fossil-based polymers.

---

[3] During its life, a cow eats, on average, 16 kg maize per kilogram of beef produced from the animal after slaughter.

Biological degradation is, generally, a slow process, especially under anaerobic conditions, such as in landfill sites. Additionally, as explained above, the climate-damaging greenhouse gas methane is released during anaerobic degradation. Ultimately, the use of biodegradable polymers, does not bring any benefits at all if the product eventually ends up in a landfill site. A comprehensive solution cannot be achieved simply by providing consumers with biodegradable products; practical and socially acceptable solutions for the product life time, including the management of its waste, need to be found.

The final disposal of waste in landfill sites is no longer permitted in Germany but is still accepted in many countries. The highest priority must therefore be to avoid the disposal of waste at landfill sites.

Conclusion

An all-encompassing solution to the challenges in all aspects of waste disposal, such as recycling, energy, and food requirements, cannot be provided within the scope of this book. However, it is important to ensure that any debate about polymer recycling is carried out within the broader context of the debate on energy and food. A practical solution can only be achieved if energy resources and agricultural land are employed to optimum advantage and the final disposal of waste in landfill sites is avoided wherever possible. Furthermore, a debate on the recycling options available for synthetic materials, especially in the areas of thermal recycling and bioplastics, based on well-founded information and free of political and ideological prejudices, is urgently needed.

References

Aspinall GO (ed) (1983) The polysaccharides. Academic, New York

Habibi Y, Lucia LA (2012) Polysaccharide building blocks: a sustainable approach to the development of renewable materials. Wiley, Hoboken, NJ

Ramawat KG, Mérillon JM (2015) Polysaccharides: bioactivity and biotechnology. Springer, Heidelberg