1

The Biorefinery Concept–An Integrated Approach

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1.1 The Challenge of Sustainable Development

Reconciling the needs of a growing world population with the resulting impact on our environment is ultimately the most complex and important challenge for society. Sustainable development requires an assessment of the degree to which the natural resources of the planet are both in sufficient quantity and in an accessible state to meet these needs, and to be able to deal with the wastes that we inevitably produce in manipulating these resources (including process and end-of-life waste). We can express this in the form of an equation based on the Earth’s capacity $EC$, the total population exploiting it $P$, the consumptive (essentially equating to economic) activity of the average person $C$, and an appropriate conversion factor between activity and environmental burden $B$.

$$EC = P \times C \times B$$

In a period, such as the present time, of growth in $P$ and $C$, the latter through economic growth in the developing world, notably India and China, (and an assumption that $EC$ is not limitless and that we may not be far short of reaching its limit) we can only move towards sustainability through a reduction in $B$. 
How can we reduce \( B \)? There are only two appropriate routes:

- Dematerialisation (use less resource per person)
- Transmaterialisation (replacement of current raw materials including energy)

Dematerialisation has, to some extent, been a natural part of our technological progress, with less and less resources (e.g. measured as amount of carbon) being used to generate a unit of activity (e.g. measured on the basis of gross domestic product). We have been progressively developing more efficient technologies and legislation and other pressures have forced the processing industries to reduce waste and to make use of that waste through recycling and reuse. However, there are conflicting societal trends that reduce these positive effects on \( B \). Our increasing wealth has brought with it an increase in levels of consumption with individuals using their increasing wealth to buy more goods and to buy more often. The average number of cars, area of housing, quantity of clothes, food purchased and consumer goods (e.g. electronics) per person in the wealthier countries inexorably increases, while the lure of advertising encourages people to change their personal possessions at a rate way above that commensurate with the items’ wear and tear.

Transmaterialisation is a more fundamental approach to the problem, which, with the goal of sustainable development, would ultimately switch consumption to only those resources that are renewable on a short timescale. Clearly petroleum, which takes millions of years to form, is not an example of such a sustainable resource. For the method to be truly effective, the wastes associated with the conversion and consumption of such resources must also be environmentally compatible on a short timescale. The use of polyolefin plastic bags for example, which have lifetimes in the environment of hundreds of years, is not consistent with this (no matter how they compare with alternative packaging materials at other stages in their lifecycle), nor is the use of some hazardous process auxiliaries which are likely to cause rapid environmental damage on release into the environment.

While manufacturing processes have largely become more efficient, both in terms of use of resources and in terms of reduced waste, industry needs to regularly and thoroughly monitor its practises through full inventories of all inputs and outputs. Gate-to-gate environmental footprints help to identify hotspots where new technology can make a significant difference, and help to determine the value of any changes made. In chemical processes, green chemistry metrics such as mass intensity and atom efficiency need to be used alongside yield, and companies need to assist their researchers and process chemists by developing in-house guides (e.g. over choice of solvent), assessment methods, and recommended alternative reagents and technologies. In their present form, these mechanisms are, however, largely limited to further steps towards dematerialisation. Progress towards transmaterialisation requires additional features to be taken into consideration and in some cases a very different way of thinking of the problems. We must add the sustainability of all manufacturing components, inputs and outputs. Are the feedstocks for a particular manufacturing process from sustainable sources? Are the
process auxiliaries sustainable? Are the process outputs – product(s) and waste – environmentally compatible e.g. through rapid biodegradation (ideally with the waste having a valuable use, even if it is a completely different application, so that the inevitable release into the environment, as is the fate for all materials, is delayed).

For organic chemicals, transmaterialisation must mean a shift from fossil (mainly petroleum) feedstocks (which have a cycle time of >10^7 years) to plant-based feedstocks (with cycle times of <10^3 years). This immediately raises several fundamentally important questions: Can we produce and use enough plants to satisfy the carbon needs of chemical and related manufacturing, while not compromising other (essentially food and feed) needs? Do we have the technologies necessary to carry out the conversions (biomass to chemicals) and in a way that does not completely compromise the environmental and transmaterialisation characteristics of the new process?

1.2 Renewable Resources — Nature and Availability

We need to find new ways of generating the chemicals, energy and materials, as well as food that a growing world population (increasing ‘P’) and growing individual expectations (increasing ‘C’) needs, doing so while limiting environmental damage. At the beginning of transmaterialisation is the feedstock or primary resource, and this needs to be made renewable (see Table 1.1). An ideal renewable resource is one that can be replenished over a relatively short timescale or is essentially limitless in supply. Resources such as coal, natural gas and crude oil come from carbon dioxide ‘fixed’ by nature through photosynthesis many millions of years ago. They are of limited supply, cannot be replaced and thus are non-renewable. In contrast, resources such as solar radiation, winds, tides and biomass can be considered as renewable resources, which are (if appropriately managed) in no danger of being over-exploited. However, it is important to note that, while the first three resources can be used as a renewable source of energy, biomass can be used to produce not only energy, but also chemicals and materials – the focus of this book.

By definition, biomass corresponds to any organic matter available on a recurring basis (see Figure 1.1). The two most obvious types of biomass are wood and

<table>
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<tr>
<th>Table 1.1</th>
<th>Different types of renewable and non-renewable resources</th>
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<tbody>
<tr>
<td>Non-Renewable Resources</td>
<td>Renewable Resources</td>
</tr>
<tr>
<td>Coal</td>
<td>Sun</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Tides and Hydro</td>
</tr>
<tr>
<td>Crude oil</td>
<td>Biomass</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
</tr>
</tbody>
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crops (e.g. wheat, maize and rice). Another very important type of biomass we tend to forget is waste (e.g. food waste, manure, etc). These resources are generally considered to be renewable as they can be continually re-grown/regenerated. They take up carbon dioxide from the air while they are growing (through photosynthesis) and then return it to the air at the end of life, thereby creating a ‘closed loop’ (Deswarte, 2008).

Food crops can indeed be used to produce energy (e.g. biodiesel from vegetable oil), materials (e.g. polylactic acid from corn) and chemicals (e.g. polyols from wheat). However, it is now becoming widely recognised by governments and scientists that waste and lignocellulosic materials (e.g. wood, straw, energy crops) offer a much better opportunity, since they avoid competition with the food sector and, often, do not require as much land and fertilisers to grow. In fact, only 3% of the 170 million tonnes of biomass produced yearly by photosynthesis is currently being cultivated, harvested and used (food and non-food applications) (Sanders et al., 2005). Indeed, according to a recent report published by the USDOE and the USDA (2005), the US alone could sustainably supply more than one billion dry tons of biomass annually by 2030. As seen in Table 1.2, the biomass potential in Europe is also enormous.

About 10% of all the oil we extract in the world is used to make organic chemicals and related materials. A remarkable additional 10% is used for energy to drive the
Table 1.2  Biomass potential in the EU (European Commission, 2006)

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<thead>
<tr>
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<th>Biomass Potential (MToe)</th>
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<tbody>
<tr>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>Organic Wastes</td>
<td>100</td>
</tr>
<tr>
<td>Energy Crops</td>
<td>43–46</td>
</tr>
<tr>
<td>Forest Products</td>
<td>43</td>
</tr>
<tr>
<td>Total</td>
<td>186</td>
</tr>
</tbody>
</table>

chemical reactions. In the EU, this corresponded to 166 million tonnes in 2000. While increases in efficiency of chemical manufacturing in the EU have been considerable, an OECD estimate has shown that the chemical industry worldwide produces about 4% of global carbon dioxide emissions (10^{12} tonnes). A shift away from fossil resources should thus benefit both resource depletion, pollution and global warming.

1.3 Impact on Ecosystem Services

Ecosystem services are the goods and services provided by coupled and ecological social systems. They are at the heart of our quality of life by providing the materials on which we base our lifestyles, and we all inevitably depend on the sustainable use of ecosystem services. The millennium ecosystems assessment brought this to our attention (*Ecosystems and Human Well-Being*, 2007) by stating that the ability of many ecosystems to deliver valuable services has been compromised by resource over-exploitation and by environmental degradation.

The figures provided by the European Biofuels Research Advisory Council (see Table 1.2) suggest an increasing potential for the conversion of biomass to biofuels in Europe over the next 20+ years, but can the European environment cope with ever-increasing biomass exploitation? We must give greater consideration to the associated stresses on large areas of land and associated systems, including water, food production and recreation (even the use of low value/waste materials such as straw and grasses will have effects). In general, when considering such enormous changes in ecosystem services exploitation we need to:

- Study the associated changes in the quality and availability of local ecosystem services
- Consider how activities in one region can affect ecosystem services elsewhere
- Study the linkage between livelihoods, human well-being and ecosystem services
- Consider how to manage the ecosystem services under pressure.
6 Introduction to Chemicals from Biomass

1.4 The Biorefinery Concept

1.4.1 Definition

One way to mitigate the negative effects of local ecosystem services is to convert biomass into a variety of chemicals (Chapters 2 and 4), biomaterials (Chapter 5) and energy (Chapter 6), maximising the value of the biomass and minimising waste. This integrated approach corresponds to the biorefinery concept and is gaining increased attention in many parts of the world (Kamm and Kamm, 2004; Halasz et al., 2005). As illustrated in Figure 1.2, the biorefinery of the future will be analogous to today’s petrorefineries (Realff and Abbas, 2004; National Renewable Energy Laboratory, www.nrel.gov/biomass/biorefinery.html).

Similarly to oil-based refineries, where many energy and chemical products are produced from crude oil, biorefineries will produce many different industrial products from biomass. These will include low-value, high-volume products, such as transportation fuels (e.g. biodiesel, bioethanol), commodity chemicals, as well as materials, and high-value, low-volume products or speciality chemicals, such as cosmetics or nutraceuticals. Energy is the driver for developments in this area, but as biorefineries become more and more sophisticated with time, other products will be developed. In some types of biorefinery, food and feed production may well also be incorporated.

1.4.2 Different Types of Biorefinery

Three different types of biorefinery have been described in the literature (van Dyne et al., 1999; Kamm & Kamm, 2004; Fernando et al., 2006):

- Phase I biorefinery (single feedstock, single process and single major product)
- Phase II biorefinery (single feedstock, multiple processes and multiple major products)

![Figure 1.2 Comparison of petrorefinery vs. biorefinery](image)
Phase I Biorefinery

Phase I biorefineries use one only feedstock, have fixed processing capabilities (single process) and have a single major product. They are already in operation and are proven to be economically viable. In Europe, there are now many ‘phase I biorefineries’ producing biodiesel. They use vegetable oil (mainly rapeseed oil in the EU) as a feedstock and produce fixed amounts of biodiesel and glycerine through a single process called transesterification (see Figure 1.3). They thus have almost no flexibility to recover investment and operating costs. Other examples of phase I biorefinery include today’s pulp and paper mills, and corn grain-to-ethanol plants.

Phase II Biorefinery

Similarly to phase I biorefineries, phase II biorefineries can only process one feedstock. However, they are capable of producing various end products (energy, chemicals and materials) and thus respond to market demand, prices, contract obligation and the plant’s operating limits. One example of a phase II biorefinery is the Novamont plant in Italy, which uses corn starch to produce a range of chemical products including biodegradable polyesters (Origi-Bi) and starch-derived thermoplastics (Mater-Bi) (www.materbi.com). Another example of this type of biorefinery is the Roquette site at Lestrem in France that produces a multitude of carbohydrate derivatives, including native and modified starches, sweeteners, polyol and bioethanol from cereal grains (www.roquette.fr/index_eng.asp, see Figure 1.4).

Roquette produces more than 600 carbohydrate derivatives worldwide and is now leading a major programme (the BioHub™ programme, supported by the French Agency for Industrial Innovation) aiming to develop cereal-based biorefineries and, in particular, a portfolio of cereals-based platform chemicals (e.g. isosorbide) for biopolymers, as well as speciality and commodity chemicals production (www.biohub.fr).
Introduction to Chemicals from Biomass

Ultimately, all phase I biorefineries could be converted into phase II biorefineries, if we can identify ways to upgrade the various side streams. A phase I biodiesel processing plant, for example, could turn into a phase II biorefinery, if we can develop technologies that can convert biodiesel glycerine (crude glycerol) into valuable energy and chemical products (see Chapter 4 for potential chemical products from glycerol). In fact, it is recognised that energy or biofuel generation will probably (at first) form the ‘back bone’ of numerous phase II biorefineries, due to large market demand. Interestingly, crude oil refining also started with the production of energy, and has ended up employing sophisticated process chemistry and engineering to develop complex materials and chemicals that ‘squeeze every ounce of value’ from a barrel of oil (Realff and Abbas, 2004).

Phase III Biorefinery

Phase III biorefineries correspond to the most developed/advanced type of biorefinery. They are not only able to produce a variety of energy and chemical products (phase II biorefineries), but can also use various types of feedstocks and processing technologies to produce the multiplicity of industrial products our society requires. The diversity of the products gives a high degree of flexibility to changing market demands (a current by-product might become a key product in the future) and provides phase III biorefineries with various options to achieve profitability and maximise returns. In addition, their ‘multiple feedstock’ aspect helps them to secure feedstock availability and offers these highly integrated biorefineries the possibility to select the most profitable combination of raw materials (de Jong
et al., 2006). Although no commercial phase III biorefineries exist at present, extensive work is being carried out in the EU (e.g. Biorefinery Euroview, BIOPOL, SUSTOIL), the US (the present leading player in this field) and elsewhere on the design and feasibility of such facilities. Full-scale phase III (zero-waste) biorefineries are probably more than a decade away – according to a recent report from the Biofuels Research Advisory Council, large integrated biorefineries are not expected to become established in Europe until around 2020 (European Commission, 2006).

Currently, there are four phase III biorefinery systems being pursued in research and development, which will be discussed in more detail in this chapter:

- Lignocellulosic feedstock biorefinery
- Whole crop biorefinery
- Green biorefinery
- Two-platform concept biorefinery.

**Lignocellulose feedstock biorefinery** A lignocellulose feedstock biorefinery will typically use ‘nature-dry’ lignocellulosic biomass such as wood, straw, corn stover, etc. The lignocellulosic raw material (consisting primarily of polysaccharides and lignin) will enter the biorefinery and, through an array of processes, will be fractionated and converted into a variety of energy and chemical products (see Figure 1.5).

The Icelandic Biomass Company is currently running a demonstration plant processing 20,000 tonnes per year of lignocellulosic biomass, including hay, lupine straw and barley straw (Kamm and Kamm, 2005). The plant can produce up to 7 million litres of ethanol per year, and a variety of chemical products from lignin and the various side streams. The University of York, in collaboration with a number of industrial partners, also demonstrated that supercritical CO$_2$ could be used – as an initial stage in a biorefinery – to extract high value wax products (e.g. nutraceuticals, insect repellents) from straw prior to converting the lignocellulosic

![Figure 1.5](image) Simplified schematic diagram of a lignocellulosic feedstock biorefinery
fraction into paper, strawboard, high quality mulch or energy (Deswarte et al., 2007).

Another example of an imminent lignocellulosic feedstock biorefinery is Processum in Sweden, which corresponds to an integrated cluster of industries converting wood into energy, and different chemicals and materials (see Figure 1.6). This is probably one of the best examples of industrial symbiosis – one industry uses the waste of another as a raw material (Gravitis, 2006). Amongst the member companies are Nobel Surface Chemistry (production of thickeners for water-based paints and the construction industry), Domsjo Fabriker (production of global scale dis- solving pulp and paper pulp), Ovik Energy (energy production and distribution) and Sekab (production of ethanol, ethanol derivatives and ethanol as fuel).

In reality, while the sole products of existing pulp and paper manufacturing facilities today are pulp and paper (phase I biorefinery), these facilities are geared to collect and process substantial amounts of lignocellulosic biomass. They thus provide an ideal foundation to develop advanced lignocellulose feedstock biorefineries. Additional processes could be built around pulp mills, either as an extension or as an ‘across-the-fence’-type company (Agenda 2020).

**Whole crop biorefinery** A whole crop biorefinery will employ cereals (e.g. wheat, maize, rape, etc) and convert the entire plant (straw and grain) into energy, chemicals and materials (see Figure 1.7).
The first step will be to separate the seed from the straw (collection will obviously occur simultaneously, to minimise energy use and labour cost). The seeds may then be processed to produce starch and a wide variety of products, including ethanol and bioplastics (e.g. polylactic acid). The straw can be processed to products via various conversion processes, as described above for a lignocellulosic feedstock biorefinery.

POET (formerly known as Broin Companies), the current largest producer of ethanol in the world, are currently building a commercial whole crop biorefinery in Iowa, with a completion date expected in 2011 (www.poetenergy.com). Through the ‘LIBERTY project’ (jointly funded by POET and the US Department of Energy), a grain-to-ethanol plant (Voyager Ethanol), will be converted from a 50 million gallon per year conventional corn dry mill facility into a 125 million gallon per year commercial-scale biorefinery designed to utilise advanced corn fractionation and lignocellulosic conversion technology to produce ethanol from corn fibre and corn stover (see Figure 1.8). The facility will also produce a number of valuable product, including corn germ and a protein-rich dried distillers grain (Dakota Gold® HP or DGHP), which can be used as an animal feed.

**Green biorefinery** Green biorefinery is another form of phase III biorefinery that has been extensively studied in the EU (especially Germany, Austria and Denmark) over the last decade. It takes ‘natural wet’ green biomass (such as green grass, lucerne, clover, immature cereals, algae, etc.) and converts it into useful products including energy, chemicals, materials and feed, through the use of a combination of different technologies, including fermentation (see Figure 1.9). Typically, green biomass is separated into a fibre-rich press cake and a nutrient-rich green juice (Andersen and Kiel, 2000). The green juice contains a number of useful chemicals such as amino acids, organic acids and dyes. The press cake can be used for fodder or to produce energy, insulation materials, construction panels, biocomposites, etc.
A green biorefinery demonstration plant has recently been set up in Brandenburg (Germany) and produces high-value proteins, lactic acid and fodder from 30,000 tonnes per year of alfalfa and wild mix grass. Another example of this form of phase III biorefinery is the Austrian Green Biorefinery, which is based on the processing of green biomass from silage (see Figure 1.10). A demonstration facility, which is currently being built in Utzenaich, will produce a range of chemicals (e.g., lactic acid, amino acids) and fibre-derived products (e.g., animal feed, boards, insulation materials, etc.) as well as electricity and heat (it will be attached to an existing biogas plant).

Two-platform concept biorefinery Another form of biorefinery, which has been recently defined by the National Renewable Energy Laboratory (NREL) (www.nrel.gov/biomass/biorefinery.html) is the two-platform concept biorefinery.
As depicted in Figure 1.11, the feedstock is separated into a ‘sugar platform’ (biochemical) and a ‘syngas platform’ (thermochemical). Both platforms can offer energy, chemicals, materials, and potentially food and feed, and thus make use of the entire feedstock(s). The ‘sugar platform’ is based on biochemical conversion processes and focuses on the fermentation of sugars extracted from biomass feedstocks. The ‘syngas platform’ thermolytically transforms biomass into gaseous or
liquid intermediate chemicals that can be upgraded to transportation fuels, as well as commodity and specialty chemicals (Wright and Brown, 2007a).

No biorefinery of this type currently exists in Europe, but sugar conversion technologies (e.g. wheat grain-to-ethanol fermentation) and the gasification approach (e.g. Choren’s Carbo-V® process) are independently used (NNFCC, www.nnfcc.co.uk). Opinions vary widely on the best strategy to combine these two platforms. However, it is most likely that multiple biorefinery designs will emerge commercially – as new technologies are developed – depending on the location of the plant and the feedstock(s) used.

It is interesting to note that the sugar platform and many other (non-thermochemical) processes likely to be incorporated into a biorefinery, will almost certainly generate some waste products that will be difficult to convert into value-added materials and chemicals. Such wastes and residues represent an important source of energy within the biorefinery and are an ideal candidate for thermochemical conversion (Ragauskas et al., 2006).

1.4.3 Challenges and Opportunities

Biorefinery products (energy, chemicals and materials) will most likely have to compete with existing and future petroleum-derived products. As seen in Table 1.3 (comparison of biorefinery and petrorefinery characteristics in terms of feedstock, conversion processes and products), the two types of refinery display major differences, which translate into a number of challenges and opportunities to the deployment of biorefineries.

**Feedstock**

In contrast to fossil resources, which are found in rich deposits (‘mine mouths’ or ‘well heads’), biomass is widely distributed geographically (multiplicity of ‘farm

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<tr>
<th>Feedstock:</th>
<th>Petrorefinery</th>
<th>Biorefinery</th>
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<tr>
<td>Location</td>
<td>Rich deposits in some areas</td>
<td>Widely distributed</td>
</tr>
<tr>
<td>Density</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Availability</td>
<td>Continuous but finite</td>
<td>Seasonal but renewable</td>
</tr>
<tr>
<td>Chemical composition</td>
<td>Hydrocarbons, not functionalised</td>
<td>Highly oxygenated and functionalised</td>
</tr>
<tr>
<td>Conversion processes</td>
<td>Optimised over 100 years</td>
<td>Require further research and technological development</td>
</tr>
<tr>
<td>Products</td>
<td>On the market and to high specification</td>
<td>Quality needs to be standardised</td>
</tr>
</tbody>
</table>
gates’) (Gravitis, 2007; Wright and Brown, 2007b). In addition, biomass typically exhibits a low bulk density and a relatively high water content (up to 90% for grass), which makes its transport much more expensive than the transfer of natural gas or petroleum.

Reducing the cost of collection, transportation and storage of biomass through densification is thus critical to developing a sustainable infrastructure capable of working with significant quantities of raw material (Hess et al., 2003). In addition, the economics of many conversion processes, which are batch operations, would be dramatically improved through an increase in density, as the inherent low density of biomass limits the amount of material that can be processed at any one time. The most common strategy used to increase biomass density is grinding. By chopping bailed straw, for example, a 10-fold densification can typically be achieved. An alternative strategy, which can provide a material of even higher density, is pelletisation (see Chapter 6 for more information). Through conversion of ground straw into pellets, the density of the material can be further increased by a factor of three (Deswarte et al., 2007). This pre-treatment also offers the added benefit of providing a much more uniform material (in size, shape, moisture, density and energy content), which can be much more easily handled. Pre-processing might be done ‘on the farm’, but can also be done during harvesting. An example of technology recently developed to address the engineering challenge presented by low bulk density biomass such as wheat straw, is a multicomponent harvester, which can simultaneously and selectively harvest wheat grain and the desired parts of wheat straw in a single pass (Hess et al., 2003).

Another issue associated with the use of (fresh) biomass is its perishable character or susceptibility to degradation. Taking straw (again) as an example, fermentation will begin if the moisture content of bailed straw is kept above 25% for a prolonged period of time, resulting in a dramatic reduction in the quality of the raw material. In some cases, spontaneous combustion in the stacks can even take place (Kadam et al., 2000). This issue is particularly important given that, in contrast to fossil resources (which are of permanent availability – continuously pumped and mined), the availability of biomass is seasonal (Thorsell et al., 2004). Thus, in order to ensure a continuous all year round operation of the biorefinery, biomass may have to be stabilised (e.g. dried) prior to (long-term) storage. The Austrian Green Biorefinery, for example, tackles this problem by processing not only direct-cut grasses, but also silage, which can be prepared in the growing season and stored in a silo (Koschuh et al., 2005; Thang and Novalin, 2007).

In summary, it is essential that we develop a cost-effective infrastructure for production, collection, storage and pre-treatment of biomass. As highlighted by Nilsson and Kadam, the economic success of a large biorefinery will greatly depend upon the fundamental logistics of a consistent and orderly flow of feedstocks. (Nilsson, 1999; Kadam et al., 2000). Localised small-scale (and perhaps mobile) pre-treatment units will be necessary to minimise transportation costs and supply the biorefinery with a ‘stabilised’ feedstock (e.g. in the form of a dry solid or a liquid (pyrolysis oil)), which can be stored and thus allow the biorefinery to run...
continuously all year long (Sanders et al., 2005). Such an approach will present the added benefits of reducing the environmental impact of transportation (Koschuh et al., 2005) and allowing farmers to gain a greater share of the total added value of the supply chain.

conversion Processes

The major impediment to biomass use is the development of economically viable methods (physical, chemical, thermochemical and biochemical) to separate, refine and transform it into energy, chemicals and materials (European Commission, 2005). Indeed, biorefining technologies (some of which are already at a stage of commercialisation, while others require further research and technological development) have to compete with processes that have been continuously improved by petrorefineries over the last 100 years (and have a very high degree of technical and cost optimisation). In particular, biorefineries will have to develop clever process engineering to deal with separation – by far the most wasteful and expensive stage of biomass conversion, and currently accounting for 60 to 80% of the process cost of most mature chemical processes. The production of chemicals (e.g. succinic acid) and fuels (e.g. bioethanol) through fermentation processes, for example, generates very dilute and complex aqueous solutions, which will have to be dealt with using clean and low-energy techniques. In fact, given that so many of our carefully isolated, functionalised and purified chemical products end up in formulations, it would also seem wise to seek methods that can convert the multicomponent systems we obtain from biomass into multicomponent formulations with the correct set of properties we require in applications such as cleaning, coating and dyeing (Clark, 2007). Most importantly, all the processes employed in future biorefineries will have to be environmentally friendly. It is essential that we use clean technologies and apply green chemistry principles throughout the biorefinery so as to minimise the environmental footprints of its products and ensure its sustainability (Clark et al., 2006; see Chapter 3).

Biorefineries will be multidisciplinary in nature and would therefore require operators with very different skills and expertise (e.g. agriculturalists, chemists and biotechnologists). The recent formation of new industrial alliances between agribusiness giants, such as Tate & Lyle and Cargill, with well-established chemical companies, such as Dow and Dupont, and upcoming biotechnology industries (including the likes of Genecor and Novozymes) already demonstrates the paramount importance of cross-sector collaborations (Realff and Abbas, 2004).

Products

One of the main drivers for the use of bioenergy and bioproducts is their potential environmental benefits (e.g. carbon dioxide emission reduction, biodegradability). It is thus essential that we assess the environmental impact of all the energy and chemical products we manufacture (across their life cycle) to make sure that they...
are truly sustainable and present real (environmental and societal) advantages compared to their petroleum-derived analogues (Gallezot, 2007).

A major issue for biomass as a raw material for industrial product manufacture is variability. Questions of standardisation and specifications will therefore need to be addressed as new biofuels, biomaterials and bioproducts are introduced onto the market. Another major challenge associated with the use of biomass is yield. One approach to improve/modify the properties and/or yield of biomass is to use selective breeding and genetic engineering to develop plant strains that produce greater amounts of desirable feedstocks, chemicals or even compounds that the plant does not naturally produce (Fernando et al., 2006). This essentially transfers part of the biorefining to the plant (see Chapter 2 for some example of oils with modified fatty acid content).

In contrast to fossil resources, biomass feedstocks are composed of highly oxygenated and/or highly functionalised chemicals (see Table 1.4). From an energy point of view, this means that the calorific value of biomass is substantially lower than those of fossil fuels (oxygenated compounds don’t burn well!). It is therefore preferable to treat biomass before using it as an alternative fuel or source of energy (see Chapter 6 – Production of Energy From Biomass). This also means that we must apply significantly different chemistries to such highly functionalised chemicals so as to build these up into the valuable chemical products our society is built on (Clark, 2007). In fact, since the production of commodity and specialty functionalised chemicals from fossil resources typically requires highly energy-intensive processes, biomass represents a particularly attractive alternative source of these valuable compounds (Sanders et al., 2005). As highlighted by Ragauskas, the use of carbohydrates as a raw material for chemical production could potentially eliminate the need for several capital-intensive oxidative processes used in the petroleum industry (Ragauskas et al., 2006).

### Table 1.4 General chemical compositions of selected biomass components and petroleum (Pun et al., 2007)

<table>
<thead>
<tr>
<th>Biomass Component</th>
<th>Chemical Composition</th>
<th>Petroleum Component</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose/starch</td>
<td>([C_6(H_2O)_{12}]_n)</td>
<td>Gasoline</td>
<td>(~C_6H_{14}-C_{12}H_{26})</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>([C_5(H_2O)_{12}]_n)</td>
<td>Diesel</td>
<td>(~C_{10}H_{22}-C_{15}H_{32})</td>
</tr>
<tr>
<td>SW lignin</td>
<td>([C_{10}H_{12}O_4]_n)</td>
<td></td>
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</table>

**Biorefinery Size**

Opinions vary widely on the optimal size of future biorefineries. However, it is our belief that biorefineries will correspond to a combination of large-scale facilities (which can take full advantage of economies of scale and enjoy greater buying power when acquiring feedstocks) and small-scale plants (which can keep transport
costs to an absolute bare minimum and take full advantage of available process integration technologies) (European Commission, 2005). Their optimal size, which will obviously depend upon the nature of the feedstock(s) processed, the location of the plant and the technologies employed (not ‘one size fits all’!), will correspond to a balance between the increasing cost of transporting pre-treated biomass and the decreasing cost of processing as the size of the biorefinery goes up. Proven full-scale technologies and demonstration biorefinery plants are required before commercial-scale biorefineries of any size can be built.

1.5 Conclusions

Current industrial economies are largely dependent on oil, which provides the basis of most of our energy and chemical feedstocks – in fact, over 90% (by weight) of all organic chemicals are derived from petroleum (Witcoff and Reuben, 1996). However, crude oil reserves are finite and world demand is growing. In the meantime, there is increasing concern over the impact of these traditional manufacturing processes on the environment (i.e. the effect of CO₂ emissions on global warming). In order to maintain the world population in terms of food, fuel and organic chemicals, and tackle global warming, it has been recognised by a number of governments that we need to substantially reduce our dependence on petroleum feedstock by establishing a bio-based economy (van Dam et al., 2005).

For this purpose, long-term strategies that recognise the potential of local renewable resources should be developed. Of paramount importance will be the deployment of biorefineries (of various sizes and shapes) that can convert a variety of biofeedstocks into power, heat, chemicals and other valuable materials, maximising the value of the biomass and minimising waste. These integrated facilities will most likely employ a combination of physical, chemical, biotechnological and thermochemical technologies, which ought to be efficient and follow green chemistry principles so as to minimise the environmental footprints and ensure the sustainability of all products generated (a cradle-to-grave approach). Local pre-treatment of (low bulk density and often wet) biomass will be critical to the development of a sustainable infrastructure capable of working with significant quantities of raw material. Thus, specific attention should be given to the development of these (local) processes. The challenge of the next decade will be to develop demonstration plants, which will require cross-sector collaborations and attract the necessary investors required for the construction of full-scale biorefineries.

References


