Chapter 3

New biofuels – scientific developments

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Box 3.1: Overview

The development of new biofuels technology is a rapidly growing field. New biofuels are expected to contribute to efforts to reduce net greenhouse gas emissions, improve energy security and aid development, while at the same time circumventing the shortcomings identified for some current biofuels, as discussed in Chapter 2. The unifying principles of development of new biofuels centre on the use of abundant feedstocks that can be produced without harm to the environment or local populations, with minimal competition with food production and minimal input of resources such as land, and that can be processed efficiently to yield high-quality liquid biofuels that are deliverable in sufficient quantities.

Various feedstocks have been proposed, each of which has its own challenges at each stage in the production pathway. In Chapter 3, we discuss continuing developments in production and processing for some of the main proposed feedstocks. The coverage is illustrative rather than exhaustive, discussing the examples of lignocellulosic and algal biofuels.

Lignocellulosic biofuels
Lignocellulosic biofuels use all of the plant instead of just the starch or sugary parts. Residue products from arable food agriculture, such as straw, could be used as feedstocks. In this way, food crop plants could become effectively dual-use, producing both food and fuel. A second option is to use plants grown solely for the production of lignocellulosic biofuels, such as trees and grasses (e.g. willow, poplar, switchgrass and miscanthus).

In addition to the greater utilisation of biomass compared with biofuels produced from food crops, there is significant potential to improve feedstock characteristics such as yields, water use, and pest and frost resistance using advanced plant breeding strategies and genetic modification. However, technology in this field is mostly still at the research and development stage. Moreover, lignocellulosic biofuels require more sophisticated processing than current biofuels, and this is currently very costly. However, given further technological advances, there are options to improve efficiency and bring down costs significantly.

Algal biofuels
Algae constitute a diverse group of aquatic photosynthetic organisms that produce an equally diverse range of chemicals, including an array of oils that can be used to produce biodiesel, avoiding some of the technical challenges of converting lignocellulose to liquid fuels. They do not require freshwater and can be cultivated in wastewater or sea water, and it is expected that under optimal conditions they will produce high yields. Algae can be cultivated in open ponds or closed photobioreactors, or in hybrid systems. Currently, the production of algal biofuels is experimental, and costs are very high. Again, there is significant potential for improvements of feedstocks and processing, for example using genetic modification or synthetic biology.

In the two final sections, Chapter 3 offers a brief description of both jatropha – a novel feedstock that has recently gained attention as a crop for developing countries – and the biorefineries approach, which aims to process and refine biofuels from a variety of sources and make use of as many of the by-products as possible.

Introduction

3.1 The previous chapters laid out the issues associated with current biofuels. At the heart of concerns about some biofuels are claims about their inefficiency and lack of convincing greenhouse gas (GHG) emissions savings, environmental degradation through deforestation, high-input cultivation using large amounts of fertiliser and taking up significant amounts of land, and competition with food production. Many of the issues discussed with respect to biofuels production have now been widely recognised (see Chapter 2). However, with the drivers as discussed in Chapter 1 still as forceful as ever, interest in liquid biofuels has not diminished. On the contrary, there is currently a great deal of activity to create a new generation of biofuels.

3.2 There are greater hopes that these new biofuels can contribute to efforts to reduce net GHG emissions and thus to mitigate climate change, and to contribute to energy security and development, while at the same time circumventing the shortcomings identified for some of the current biofuels established today. This chapter describes some of the most prominent new developments in biofuels science and discusses their potential for avoiding the problems of some current biofuels.

New biofuels

3.3 The unifying principles of development of new approaches to biofuels centre on abundant feedstocks that:

- can be produced without harming the environment or local populations;
- are in minimal competition with food production;
- need minimal resources, such as water and land;
- can be processed efficiently to yield high-quality liquid biofuels; and
- are deliverable in sufficient quantities.

3.4 Proposed solutions to the problems of established biofuels from food crops are focused on alternative feedstocks, but these are more problematic with respect to the associated technologies required to process them efficiently. There are several main proposals for feedstocks, each of which has its own challenges at each stage in the production pathway. In the following sections, we will give an overview of some of the new approaches in science and industry to develop biofuels. Our coverage is illustrative rather than exhaustive and discusses lignocellulosic and algal biofuels. We have selected these two technologies because they are the dominant approaches currently under investigation.

Lignocellulosic biofuels

Feedstocks

3.5 The edible 'food' parts of the plants used for current biofuels production represent only a small proportion of the carbon fixed by the plant – albeit one which is converted relatively easily into fuel. Most of the dry mass of the inedible parts of the plants is made up of cell walls, which are an abundant source of biomass. Making use of these parts for fuel production could thus circumvent direct competition with food. Many new approaches are therefore aimed at developing methods that allow the cell walls, i.e. the lignin and cellulose in the cell walls, to be used for the production of so-called lignocellulosic biofuels, which are often referred to as 'second generation' biofuels.

3.6 Lignocellulosic feedstocks that appear promising include agricultural and municipal residues and wastes, currently unused parts of established biofuels crops, and dedicated biofuels crops. We will focus on two main proposals for lignocellulosic feedstocks. The first option is to use residues from arable food agriculture, such as straw, as feedstock enabling crop plants to become effectively dual-use,[292] producing both food and fuel. A second option is to use plants such as trees and grasses which are grown solely for the production of lignocellulosic biofuels. This approach involves specialist biofuels crops, where breeding programmes and agricultural systems can focus on optimal feedstock production, without the constraints of food production inherent in dual-use crops.

Dual-use crops

3.7 There is a long list of agricultural lignocellulosic residues that could be processed to produce biofuels, including straw and stover from food crops such as wheat, barley and corn, and

[292] Note that 'dual-use' is used as a neutral term here, unlike its use in discussions about defence/security, where it can denote both beneficial and malevolent applications of a technology.

forestry waste. In 2006, an estimated 2.9 million tonnes of straw was available to the UK after traditional uses had been taken into account. In addition, the total amount of available forestry residues is estimated to be approximately 2 million 'oven-dried tonnes'[293] per year, again after accounting for traditional uses.[294] This represents a potential source for fuel production which does not make any demands on food directly or indirectly, as no additional land other than the land already in use is necessary.

3.8 The efficient conversion of lignocellulose to biofuels is an area of very active research at present[295] and the success of lignocellulosic biofuels is critically dependent on developing efficient processing. For dual-use crops where a substantial volume of residues derives from a specific agricultural source such as straw, there is interest in improving its quality for processing, for example by modifying cell wall structure, without compromising food production (discussed below in Box 3.3 on biofuels crop improvement strategies).

3.9 An additional issue with agricultural residues is their limited supply. As straw can be used to provide organic amendment to soil to maintain good soil condition, some suggest that a maximum of only 40 per cent of straw should be used in ethanol production or other industrial purposes.[296] Moreover, farmers require compensation for parting with their straw, as it is not a cheap waste product but rather has economic value (calculations, taking into consideration the current cost of buying in replacement fertiliser for the nutrients exported in straw and the balance of costs in baling and removing wheat straw, come out at a minimum wheat straw value of around £113 per hectare or £32 per tonne). Therefore, although agricultural residues are highly attractive feedstocks, they are inherently limited in their supply, as well as in the degree to which they can be improved to achieve maximum energy recovery and yield liquid biofuels.

Dedicated lignocellulosic biofuels crops

3.10 Many of the constraints associated with using residues from arable food agriculture can be avoided by using dedicated biofuels crops. For dedicated biofuels crops, there is the prospect of breeding high-yielding crops with greater energy-conversion potential and which require minimum inputs. However, while dedicated crops do not lead to direct competition with food crops, the danger exists that agricultural resources – mainly land – are diverted away from food production, and that the overall demand for these resources intensifies. An important goal for dedicated biomass crops is therefore to be able to use land that is unsuitable for food agriculture ('marginal' land) or as part of a crop rotation programme ('idle' land; see Box 3.2).

Box 3.2: Type of land: 'marginal', 'idle' and 'additional' land

One of the main goals of new approaches to biofuels is to cultivate crops which can grow on land unsuitable for food agriculture, thus avoiding competition between food and fuel. This kind of land is often dubbed 'additional' land (i.e. it can be used without impacting on food agriculture), or 'marginal' land (i.e. it is land with a low carbon stock).

However, the reality of this is far more complex than calculating the number or acres of additional land or marginal land available for biofuels production. A plurality of terms is used to describe land types (e.g. there is also 'idle', 'subprime agricultural', 'degraded' land, etc.) and, although these terms are typically used to refer to the quality of land and its suitability for agriculture, in the absence of agreed definitions the terms tend to be used heterogeneously. For example, idle land has been used to refer to underused agricultural land, which may have a low carbon stock and low biodiversity, but it can also be used to refer to good-quality land that has never been used before, which therefore may have a high carbon stock and could also be used for food agriculture. Moreover, marginal land, even if unsuitable for food agriculture, might be otherwise important, for example in delivering ecosystem services.

This lack of definition increases the difficulty in evaluating how much suitable land is available for biofuels production. This was recognised in 2008 by the *Gallagher Review*, which established its own definitions for terminology used in its

[293] This is the mass of wood that has been completely dried, i.e. has zero moisture content.
[294] AEA Technology (2009) *Evaluation of opportunities for converting indigenous UK wastes to fuels and energy: report to the National Non-Food Crops Centre*, available at: http://www.nnfcc.co.uk/tools/evaluation-of-opportunities-for-converting-indigenous-uk-wastes-to-fuels-and-energy-report-nnfcc-09-012/at_download/file, p6.
[295] Various responses to the Working Party's consultation.
[296] Lafond GP, Stumborg M, Lemke R *et al.* (2009) Quantifying straw removal through baling and measuring the long-term impact on soil quality and wheat production *Agronomy Journal* **101**: 529–37.

report.[297] However, these definitions of "idle land" and "marginal or degraded land" still leave a lot of room for interpretation.

It is likely that, because land can be used for many purposes and because it often has a function even when it is *not* put to some particular use, even the development of crops which can grow on low-quality land will not entirely circumvent the problem of competition for land. However, while they are not the perfect solution that they have sometimes been promised to be, high-yielding crops with low input requirements certainly are one of the ways towards easing the pressures on land demand worldwide. Their development in biofuels might moreover provide valuable experiences and insights for other types of agriculture.

Voices from the consultation

"Use of marginal land is likely to have negative biodiversity impacts."[298]

"…most 'underutilized' lands are utilized for other purposes, and except for deserts, there are few wastelands available."[299]

"In some cases the agreement is to grow biofuels on 'idle' or 'marginal' land under the assumption that the unoccupied land is never used, which ignores groups such as nomadic herders who depend on land at certain times of the year."[300]

3.11 Focus on these characteristics has driven particular interest in perennial crops, which are nutrient-efficient and, once established, require no tillage. Pest-resistant dedicated biofuels crops are also a reasonable prospect because there is no need to breed out toxic compounds – produced by many plants in defence against pests – if such crops are not intended for the food chain.[301] However, since the production of animal feed from processing residues is often a desirable aspect of the biofuels life cycle assessment (LCA) as it adds favourably to the economic and GHG emissions balance, the advantages of feedstock specialisation just for biofuels production might be outweighed by the economic consequences of not yielding animal feed as a co-product.

3.12 In the development of novel, dedicated, non-food, biofuels feedstocks, such as those derived from perennial grasses and short rotation trees, the ideal would be to produce the highest energy yields possible with the lowest inputs in terms of water, fertilisers and pesticides, on the smallest amount of land that is otherwise unsuitable for food agriculture. Hence, a lot of activity currently surrounds improving yields in such crops, while reducing input needs and increasing stress tolerance (discussed in Box 3.3 below). In contrast to cereal crops, which have been domesticated for millennia and are the focus of significant research and development, perennial bioenergy crops have a limited history of breeding and development for yield improvement and other traits. Thus, there is the potential for energy yield increases in dedicated energy plants and, furthermore, there is a prospect of rapid progress given recent developments in advanced plant breeding strategies (APBSs; discussed below). Indeed, significant advances have already been made.[302]

3.13 The current focus, particularly in the UK, is on perennial native trees cultivated under short rotation coppicing (SRC), such as willow and poplar, and on foreign species of perennial grasses such as miscanthus and switchgrass. The crops can produce high biomass yields with limited nitrogen fertiliser inputs, which minimises pollution and improves their GHG emissions savings. The crops discussed below are among the most promising examples for temperate regions such as the UK. As well as providing energy, they could have some beneficial effects on ecosystem services. All perennials have high carbon dioxide sequestration, and SRC willow is

297 Renewable Fuels Agency (2008) *The Gallagher Review of the indirect effects of biofuels production*, available at: http://www.renewablefuelsagency.gov.uk/sites/renewablefuelsagency.gov.uk/files/_documents/Report_of_the_Gallagher_review.pdf, p33.
298 Anonymous respondent, responding to the Working Party's consultation.
299 Jonathan Gressel, responding to the Working Party's consultation.
300 Dr Thomas Molony, Centre of African Studies, University of Edinburgh, responding to the Working Party's consultation.
301 Pest resistance does not always mean that toxic compounds are present. Pest resistance can also be based on secondary metabolites normally produced in the plant but in different ratios or amounts.
302 Karp A and Shield I (2008) Tansley Review: bioenergy from plants and the sustainable yield challenge *New Phytologist* **179**: 15–32.

high in biodiversity and can also act as a riparian filter which helps to reduce run-off from arable land or be used for phytoremediation (i.e. treating environmental problems through the use of plants, for example removing toxins from contaminated soils).

Willow: technological potential and challenges

3.14 Willow (*Salix*) has a long tradition of cultivation in the UK for the production of wicker. It is a fast-growing tree and has some of the highest carbon dioxide exchange rates, light-use efficiencies and photosynthetic capacities of woody species; these are factors which can contribute to high yields and thus make willow an attractive crop for biofuels production. Willow is also promising as it can achieve high yields with low fertiliser and pesticide input. Furthermore, great genetic diversity exists (there are between 330 and 500 species of willow), which can be used in breeding programmes to improve yields further. To date, several studies have already achieved yield increases.[303] However, there are technological challenges. Willow requires water to achieve high yields; it is therefore only likely to be sustainable in areas where water is not limited. Poplar (*Populus*) is an alternative to willow as it shares several characteristics. However, it has less genetic diversity, can require more water than willow and can also be very susceptible to disease caused by rust.

Miscanthus: technological potential and challenges

3.15 Miscanthus species are perennial grasses that originate from East Asia. They constitute good feedstocks for biofuels production as they utilise a photosynthesis pathway (C4) which enables greater yields and water-use efficiency than, for example, willow or poplar. In addition, the growth efficiencies of miscanthus have been shown to be highest at the lowest nitrogen level used;[304] miscanthus could thus be grown on soils that would otherwise be unsuitable for arable agriculture. Although miscanthus originates from tropical regions, it can grow well across Western Europe, depending on the genotype grown and the climatic conditions.[305] In addition, there is potential for genetic improvement (e.g. to improve yields or to introduce additional traits such as drought tolerance), given that there is considerable genetic diversity within the genus that has mostly not yet been exploited.[306] Once again, however, there are some constraints. For example, advanced plant breeding programmes may – depending on the crop and trait desired – take some time to generate feedstocks, which is a limitation common to all biofuels feedstocks subjected to advanced breeding (discussed below). Despite high water-use efficiency, miscanthus yields are affected by water availability in soil,[307] and therefore the environmental sustainability of miscanthus plantations is dependent on ensuring adequate water supply. To this end, decisions regarding the situating of plantations must take account of soil and geological data.[308] Research has shown that, in the UK, miscanthus plantations are water-limited in some areas.[309]

Switchgrass: technological potential and challenges

3.16 A native species to the US, switchgrass (*Panicum virgatum*) shares a number of characteristics with miscanthus in that it too is a C4 grass and therefore is high yielding and has high water-use

303 Karp A and Shield I (2008) Tansley Review: bioenergy from plants and the sustainable yield challenge *New Phytologist* **179**: 15–32.
304 Lewandowski I and Schmidt U (2006) Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach *Agriculture, Ecosystems & Environment* **112**: 335–46.
305 Clifton-Brown JC, Lewandowski I, Andersson B *et al.* (2001) Performance of 15 miscanthus genotype at five sites in Europe *Agronomy Journal* **93**: 1013–9.
306 Clifton-Brown J, Chiang Yu-C and Hodkinson TR (2008) Miscanthus: genetic resources and breeding potential to enhance bioenergy production, in *Genetic improvement of bioenergy crops*, Vermerris W (Editor) (New York: Springer), pp273–94.
307 Richter GM, Riche AB, Dailey AG, Gezan SA and Powlson DS (2008) Is UK biofuel supply from miscanthus water-limited? *Soil Use and Management* **24**: 235–45.
308 Ibid.
309 Ibid. Indeed, water use of miscanthus – despite being a C4 crop – has been found to be higher than that of willow owing to the dry leaves of the standing miscanthus winter crop intercepting rainfall (willow loses its leaves but miscanthus holds on to many of its leaves until harvest in early spring). Personal communication, Jon Finch, Centre for Ecology & Hydrology, UK.

efficiency. Yields of this species have been improved by more than 50 per cent through conventional breeding over the last 10 years, but they are still substantially lower than those of miscanthus. There is, however, considerable genetic variation in switchgrass, promising further opportunities to improve yields and introduce other traits advantageous to biofuels production. It has been suggested that switchgrass could potentially act as an 'entry crop' for biofuels production to help farmers cope with the transition from other perhaps more economic crops to biofuels feedstocks. For example, such entry crops could be grown on marginal land and would not require new machinery. They might not necessarily be desired in the long term but they could facilitate the economic transition from more traditional agriculture.[310] Switchgrass can be multifunctional and be used for grazing as well as for biofuels. In addition, it would not require new machinery and would be suitable for cultivation on marginal land.

Improving dedicated lignocellulosic crops

3.17 Most of the dedicated biofuels crops discussed above are currently subject to research and development to improve their characteristics as feedstocks for biofuels production. Targets for research centre on improving LCAs by improving technological aspects, and include:[311]

- maximising yield per unit area of land;
- reducing fertiliser requirements (although these are already lower than for food crops);
- reducing pesticide requirements;
- affording drought and/or other stress tolerance;
- improving ease of harvesting and storage;
- enhancing suitability for processing (e.g. production of digestive enzymes by plants, and modifying lignin); and
- ensuring health and safety in the production pathway.

3.18 This is a demanding list of properties but, given the genetic diversity available in these crops, increasing knowledge of the exact modifications required, and a variety of methods for altering traits (conventional, marker-assisted and genomics-assisted breeding, as well as genetic modification), there is optimism that dramatic progress can be made.

Technologies for the genetic improvement of biofuels crops

3.19 The basic principle of all plant breeding is that genetic variation within the species of interest is 'shuffled' by crossing different varieties. In the progeny of these crosses, offspring are identified that have improved performance for some characteristic beyond that found in the parental lines, and/or that combine multiple desirable characteristics that are present separately in the parents. The improvements in characteristics are achieved by bringing together genetic variation present in the parents in new combinations.

3.20 Two major factors limit the power of conventional plant breeding. The first is that the selection of lines with improved characteristics can be very labour- and time-intensive. It takes many years and fields of land and a lot of work to, for example, measure the yields of trees to compare the

[310] Dr Gordon Allison, University of Aberystwyth, responding to the Working Party's consultation.
[311] See, for example: Karp A and Shield I (2008) Tansley Review: bioenergy from plants and the sustainable yield challenge *New Phytologist* **179**: 15–32; Sticklen MB (2008) Plant genetic engineering for biofuel production: towards affordable cellulosic ethanol *Nature Reviews Genetics* **9**: 433–43.

progeny. The second problem is one that becomes progressively worse as breeding programmes proceed. For existing crop plants, which have been under selection for millennia, elite lines have been developed with exceptionally high performance in comparison with their ancestors, and genetic diversity within breeding populations has decreased over time. Under these circumstances, it becomes particularly difficult to introduce new traits not present in the breeding populations, even if they are present in wild relatives. For example, these might include resistance to a new pest strain or, as in the case of biofuels, new cell wall properties that have been lost from breeding stocks because they have not been of interest and therefore not previously selected for by breeders. Introducing traits from wild relatives into elite backgrounds is very time-consuming, difficult and labour-intensive because progeny of crosses between the elite line and the wild relative will have half their genes from the wild relative, effectively destroying the carefully constructed combination of genes in the elite line. To restore these gene combinations, individuals from the progeny carrying the desired trait from the wild relative must be back-crossed to the original elite line for many generations, each time diluting out the genes from the wild relative, while maintaining the one desired trait.

3.21 Various APBSs have been developed to overcome these problems. These take advantage of knowledge about the molecular genetic basis for particular traits, or detailed knowledge of the genomes of elite lines. If it is known that a particular trait, such as resistance to a particular fungal strain, is caused by a particular variant of a particular gene, then instead of having to identify lines in the progeny of crosses that have the desirable trait by infecting them all with the fungus and seeing which ones are less susceptible, the breeder can screen the lines when they are tiny seedlings to identify those with the desired gene variant by a relatively simple laboratory-based test. This is called marker-assisted breeding.[312] It can be effective even if the exact gene in question is not known, because genetic variation nearby on the chromosome, which is likely to be co-inherited with the desired trait, can be used instead.

3.22 More recently, as the cost of DNA screening has dramatically reduced, it has become possible to screen the progeny for many thousands of genetic variations simultaneously. This can speed up the reassembly of elite genomes following crosses with wild relatives, by allowing selection of plants that match closely the elite line at thousands of sites across the genome. This approach is called genomics-assisted breeding.[313] As knowledge about the relationship between genes and traits improves, genomics-assisted breeding can be used not only to speed up the selection of progeny with reassembled elite genomes but also to select lines with new desired combinations of genes.

3.23 These APBSs are in their infancy but they are sufficiently well established to give confidence that they will continue to accelerate breeding programmes substantially. Furthermore, they are built entirely on conventional, well-accepted crossing regimes and thus they have not triggered the concerns associated with genetic modification (discussed in Chapter 5). They are, however, currently very expensive and technically demanding, so it is mostly large multinational plant breeding companies that are exploiting them.

3.24 Meanwhile, genetic modification approaches also have much to offer in providing different solutions to the very same problems as conventional plant breeding. In particular, genetic modification provides an attractive solution to the problem of introducing single new traits into an elite line. Assuming a single gene that provides the trait is known, direct introduction of the gene into the elite background can circumvent many years of crossing. Furthermore, genes from entirely different species can be introduced, allowing traits not otherwise accessible to be added. For example, in the case of biofuels production, this might include the introduction of cell wall-modifying enzymes from microbes.

[312] Collard BCY and Mackill DJ (2008) Marker-assisted selection: an approach for precision plant breeding in the twenty-first century *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**: 557–72.

[313] Varshney RK, Graner A and Sorrells ME (2005) Genomics-assisted breeding for crop improvement *Trends in Plant Science* **10**: 621–30.

Lignocellulose processing

3.25 Another challenge in producing new biofuels from the feedstocks described above is processing these into the fuel. Whatever the feedstock, lignocellulosic biofuels production is more difficult to achieve than converting the edible portions of food crops into fuel. Instead of being readily available for processing through relatively simple chemical processes, the sugars in the cell walls are polymerised (i.e. essentially 'locked') into chains and embedded with a component called lignin, making lignocellulose.

3.26 Generally, the biomass components of interest for biofuels production can be divided into three fractions: lignin, cellulose and hemicellulose. Lignin provides stability to plants and helps to protect them against microbial and enzymatic degradation. It provides the so-called 'recalcitrance of the cell wall',[314] which has to be overcome to release the sugars necessary for fermentation-based biofuels production. The other two fractions, cellulose and hemicellulose, are two types of sugar chain that differ in the diversity of their constituent sugars. As cell walls mature, the sugar chains become cross-linked with lignin forming a tough, waterproof resin. Many different compounds of lignin can be found in plants and this adds to the challenge in developing approaches to lignin degradation. However, the lignin itself is of significant value as it is composed of phenolic compounds that can provide a feedstock that is very similar to standard petrochemical feedstocks.

3.27 New lignocellulosic biofuels production aims to release more of the energy that is captured within the more recalcitrant fractions, as well as targeting the cellulose which is more readily processed. This is important as, altogether, these fractions constitute the majority of any readily grown biomass. In general, processing lignocellulose involves two main stages: pretreatment and conversion.[315] Lignocellulosic feedstocks need to be pretreated before they can be converted into biofuels. Pretreatment generates intermediates that are both easier to process, thus reducing subsequent conversion costs, and denser than the raw material, thus making it easier to transport and allowing for more centralised provision of subsequent processing steps and biofuels collection points. In most pretreatments, a mechanical digestion step is followed by biochemical pretreatment (lignocellulosis – using chemicals and enzymes, or microorganisms that produce enzymes) or thermochemical pretreatment (pyrolysis – burning in the absence of oxygen, or gasification – partial combustion).[316]

3.28 Intermediate products need to be converted to stable fuels through further conversion and refining using the appropriate method. Hydroprocessing can convert plant oil or bio-oil (produced by pyrolysis) into an end-product that can be refined in a conventional refinery.[317] Ways to hydrolyse a range of biomass will have to be developed as it is more economical to develop a strategy that could be applied to a range of feedstocks (thus enhancing applicability and mitigating potential shortages in supply.) Genetic modification of microorganisms to enable higher efficiency of digestion of lignocellulosic biomass or production of cheaper enzymes is a major target for current research, but work is also looking at processing into intermediates such as biobutanol, which can be produced from high-quality syngas (derived from gasification) using the bacterium *Clostridium acetobutylicum* as a catalyst.

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314 Himmel ME, Ding S-Y, Johnson DK *et al.* (2007) Biomass recalcitrance: engineering plants and enzymes for biofuels production *Science* **315**: 804–7.

315 For a review, see: The Royal Society (2008) *Sustainable biofuels: prospects and challenges*, available at: http://royalsociety.org/WorkArea/DownloadAsset.aspx?id=5501, pp20–8.

316 The Royal Society (2008) *Sustainable biofuels: prospects and challenges*, available at: http://royalsociety.org/WorkArea/DownloadAsset.aspx?id=5501.

317 Ibid.

Improving lignocellulose processing

3.29 Improving the processing (i.e. both pretreatment and conversion) of lignocellulose to obtain biofuels at a relatively low cost is very important in order for them to become an economically viable option. In addition, during processing, it is important to be mindful of water and chemical inputs, as well as outputs (toxic residues, soil and water pollution, etc.). Finally, energy and carbon inputs should be low, with as much carbon recycling as possible, and high energy outcomes, to contribute to a positive overall LCA and an optimum overall GHG emissions balance. Owing to these manifold challenges and the many different developments under way, it is currently not possible to determine the best or most successful processing strategy. There is significant potential to improve processing towards increased sustainability, cost-effectiveness and energy efficiency. Depending on the feedstocks and on other elements of the production process, it is most likely that several processing pathways will emerge. The advances detailed in Box 3.3, which include several biotechnological approaches, are therefore just examples of technologies under development to give an impression of the challenges and the potential for improving processing for new biofuels.

Box 3.3: Improving lignocellulosic processing

Improving biochemical processing of lignocellulosic biomass

Currently problems exist with inefficient cellulolysis (the breakdown of cellulose to release simple sugars), for example owing to the generation of lignin and hemicellulose-derived inhibitors.[318] Furthermore, current pretreatment strategies are costly.[319] Bioprospecting for enzymes from cell wall-digesting organisms – such as microbes from termite guts, the gribble[320] or fungi – is being used to isolate novel enzymes. For example, enzymes that digest polysaccharides, such as cellulases, are being sought with improved enzymatic activities. Lignin degraders such as white rot fungi are also important as these release vital energy and compounds that are more valuable than sugars. There are also programmes of research to develop cellulases with increased cellulase activity, and to lower their cost.[321]

Genetic modification of microorganisms to enable more efficient conversion of lignocellulose to ethanol is also a major research target.[322] For example, *Escherichia coli* has already been developed for improved fermentation of lignocellulose, and with a greater ethanol tolerance.[323] Ethanol concentrations increase as the fermentation process proceeds and can inhibit fermentation, thus requiring the costly and energy-intensive step of distillation. Increased ethanol tolerance reduces this need. Another example is the production of a genetically modified microbe that produces biobutanol using sugars from sugar cane, corn and wheat, and ultimately – it is intended – cellulosic feedstocks.[324] This technology is similar to current bioethanol production but makes use of a genetically modified microbe that produces butanol rather than ethanol. Butanol is more advantageous than ethanol as a biofuel in terms of energy content, combustibility, ease of transporting as well as miscibility with diesel.

Improving thermochemical processing of lignocellulosic biomass

Every step of the thermochemical pathway could benefit from further technological advances. However, developing these new technologies requires – at least initially – considerable capital input, without guarantees as to which pathways will turn out to be the most effective and energy-efficient process.

There is a lot of continuing activity to improve pyrolysis yields through different types of pyrolysis reactor, with particular attention to keeping the process energy efficient to maximise the net energy balance. Investigations are being aided by using thermo-analytical, chromatographic and other analytical techniques to scan the biomass before pyrolysis, to determine optimal conditions for the process. These same analytical approaches can also be applied to gasification, potentially resulting in purer gasification products. Several advances in gasifiers might also enable improvements in energy yields. The subsequent conversion stage is also undergoing research to help improve biofuels processing: for example, work is currently under way to develop Fischer–Tropsch reactors with greater outputs, and to improve Fischer–Tropsch catalysts.[325] It is suggested that some advanced thermochemical technologies that make use of lower

[318] Banerjee S, Mudliar S, Sen R *et al.* (2010) Commercializing lignocellulosic bioethanol: technology bottlenecks and possible remedies *Biofuels, Bioproducts & Biorefining* **4**: 77–93; Gray KA, Zhao L and Emptage M (2006) Bioethanol *Current Opinion in Chemical Biology* **10**: 141–6.
[319] Weng JK, Li X, Bonawitz ND and Chapple C (2008) Emerging strategies of lignin engineering and degradation for cellulosic biofuel production *Current Opinion in Biotechnology* **19**: 166-72.
[320] These are small organisms that are able to break down cellulose in wood to sugars.
[321] Banerjee S, Mudliar S, Sen R *et al.* (2010) Commercializing lignocellulosic bioethanol: technology bottlenecks and possible remedies *Biofuels, Bioproducts & Biorefining* **4**: 77–93.
[322] Ibid.
[323] Rubin EM (2008) Genomics of cellulosic biofuels *Nature* **454**: 841–5.
[324] BP, responding to the Working Party's consultation.
[325] Atkinson D (2010) Fischer-Tropsch reactors for biofuels production: new technology needed! *Biofuels, Bioproducts & Biorefining* **4**: 12–6.

temperatures and pressures, and are therefore less expensive, will be demonstrated in the UK during the first half of this decade.[326]

Technologies for the genetic improvement of microbes used in biofuels production
There is massive uncharted microbial diversity on the planet, with microbes living on the most unlikely sources of carbon, and hence able to digest and process even the most recalcitrant hydrocarbons. These microbes could offer solutions to many of the biochemical processing challenges found in biofuels production, both in lignocellulosic processing and in algae, described later in this chapter. However, as with crop plants, it is also the case that there is considerable potential for genetic improvement using genetic modification approaches. Furthermore, substantial systems engineering of microbial metabolism using synthetic biology strategies has been proposed as one way to improve biofuels production, for example by allowing the production of optimal or tailored biofuel molecules.[327]

'Synthetic biology' is used in various ways. At one end of the spectrum, genetic modification approaches in which several genes are introduced have sometimes been described under this heading. For example, introducing genes encoding several new enzymes into a microbe, thus allowing it to degrade a particular biomass compound through sequential steps, might be described as synthetic biology by some, and this could advance processing. However, a more common definition involves more whole-scale bioengineering, for example starting with a minimal microbial genome and adding much more substantial sets of genes, building in entire metabolic and catabolic networks designed to optimise the performance of the microbe for a specific task. This latter approach is still some way off but is potentially promising for the production of new biofuels.

Using algae to process lignocellulosic biomass
Another approach is the cultivation of a type of algae that is able to make use of sugar from both sugar cane and cellulosic feedstocks, and convert it to intermediates for biodiesel production.[328]

Estimated time frame to commercialisation

3.30 There is a great range in terms of the maturity of the technologies discussed in this section. While some are at the pilot stage, or nearing or entering commercial production, others have been reported from laboratories and are decidedly at the research and development stage. The field is diverse, with public institutions (such as universities), industry and public–private joint ventures all working in parallel. It is also a global community, with many advances being reported from research teams in emerging economies. Moreover, different supportive policies are in place around the world, some of which significantly influence the attractiveness to invest in new biofuels research and development, and thus the speed of development. In sum, it is very difficult to estimate when the production of biofuels from dual-use or dedicated energy crops will be possible at reasonable costs and on a sufficiently large scale to have a significant impact. A study conducted by the consulting company Accenture in 2009 analysed more than 100 companies, and interviewed scientists and over 30 companies. The study concluded that the uses of wastes or dedicated energy crops were promising in terms of cost and time to market.[329] However, whereas use of dedicated energy crops was deemed as scalable, there was some uncertainty over the use of wastes given that large-scale production would require collection and transport. Respondents to the Working Party's public consultation gave time estimates for lignocellulosic biofuels ranging between the next few years and 10 years:

> **"…we feel confident that both pretreatment and processing will be improved with the next 5 years. However to make commercial plants fully optimal may take 10 years."**[330]

> **"Some [biochemical conversion pathways] are likely to be commercialised in the next year or so, and [to] be economic by about 2013/2014."**[331]

[326] NNFCC, responding to the Working Party's consultation.
[327] Robert Henry, responding to the Working Party's consultation.
[328] BP, responding to the Working Party's consultation.
[329] Accenture (2009) *Betting on science: disruptive technologies in transport fuels – study overview*, available at: http://www.accenture.com/SiteCollectionDocuments/PDF/Accenture_Betting_on_Science_Study_Overview.pdf, p16.
[330] Rothamsted Research, responding to the Working Party's consultation.
[331] Biotechnology and Biological Sciences Research Council Sustainable Bioenergy Centre (BSBEC), responding to the Working Party's consultation.

> **"By 2020 through a combination of enzyme cost reduction, capital cost optimisation, and feedstock yield improvement and cost reduction, it is projected that production costs [for use of energy grasses] will attain similar levels to Brazilian sugar cane ethanol."[332]**
>
> **"According to key stakeholders interviewed during the [Sustainable Consumption Institute, University of Manchester] project, lignocellulosic technologies are in the prototype stage and will probably be commercially available by 2020."[333]**
>
> **"5-year timescale [for syngas systems using wastes]?"[334]**

Algal biofuels

Feedstock

3.31 An alternative biofuels feedstock which currently receives significant attention is algae. Algae constitute a diverse group of aquatic photosynthetic organisms that produce an equally diverse range of chemicals which have long been considered as biotechnological targets. There are two major categories of algae: macroalgae, familiarly known as seaweed, and microalgae, of which there are many different species that live as either single cells or colonies. It is the microalgal species that are being most intensively investigated as a possible source of biofuels; however, some also consider macroalgae as a promising potential feedstock.[335]

3.32 The production of algal-based biofuels (ABBs) – sometimes referred to as third generation biofuels – was first prompted by the energy crisis in the 1970s; and between 1978 and 1996 the US Department of Energy's Aquatic Species Program investigated the production of biodiesel from high lipid-content algae. Despite the significant knowledge produced from these studies, funding for this area of research was reduced, primarily owing to the lowering in price of crude oil. Recently, research on ABBs has re-emerged as an active area of research and development, funded by a number of the major energy companies as well as the US Government.[336]

3.33 Use of algae as a biofuels feedstock has several potential benefits, given optimal technological facilities. Algae secrete an array of oil-related compounds that can be used to produce biodiesel, thus avoiding the technical challenges of converting lignocellulosic biomass to biofuels. They can use wastewater as a source of nutrients and waste combustion gas as a source of carbon dioxide (with benefits for bioremediation and carbon dioxide emissions mitigation). They are also expected (with added carbon dioxide) to produce a higher biomass yield per unit area than crop plants. Algae could minimise or avoid competition with food production for land and nutrient use, and using marine algae (i.e. algae that can be grown in the sea) might reduce the need for freshwater. Finally, algae are compatible with biorefineries, producing a variety of fuels and valuable co-products, such as vitamins.

3.34 However, despite these potential benefits, technological challenges regarding the use of algae as feedstocks do exist. For example, in the UK, algal growth is likely to be limited by temperature and hours of sun for cultivation systems that rely on natural light, such as open

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332 BP, responding to the Working Party's consultation.

333 Sally Gee, Manchester Institute of Innovation Research, responding to the Working Party's consultation.

334 Prof Keith Smith, responding to the Working Party's consultation.

335 Society for General Microbiology, responding to the Working Party's consultation.

336 For example, Shell and HR BioPetroleum – a renewable energy technology company based in Hawaii – have established the joint venture Cellana to build a demonstration facility in Hawaii for ABB: http://www.hrbp.com/News/121107.html. It was announced in January 2011 that HR BioPetroleum would become the sole owner. ExxonMobil has partnered with Synthetic Genomics Inc. – a US company interested in genomics-driven technology – to research and develop ABBs: http://www.syntheticgenomics.com/media/press/71409.html. In 2010, the US Department of Energy (DOE) awarded 24 million USD to three research consortia to address the existing difficulties in the commercialisation of ABBs. Arizona State University, University of California, San Diego, and Cellana each lead a consortium: http://www1.eere.energy.gov/biomass/news_detail.html?news_id=16122.

pond systems (discussed below). As with dedicated biofuels crops, improvements are required to make production of ABBs economically viable. Potential research targets include:[337]

- increasing the efficiency of photosynthesis to increase biomass productivity;
- increasing the growth rate;
- increasing the oil content (currently, algae can be stimulated to produce high levels of lipids using conditions of stress but this is usually at the expense of growth);
- improving the tolerance to high temperatures to reduce the expense incurred by cooling in subsequent processing stages; and
- reducing photoinhibition – a phenomenon that reduces growth rate at high light intensities, which can occur at midday in tropical zones and temperate climates.

3.35 In addition, the number and diversity of algal species available (more than 60,000 estimated) presents both an advantage and a problem. The problem arises in that there is still a lack of detailed characterisation of many algal species, for example the factors required for optimal growth or the biochemical pathways for oil synthesis. This presents barriers to optimising the cultivation or processing stages, which is necessary to achieve economic viability. However, such diversity can also be advantageous as it may be possible to use algal strains native to a particular location, exploiting their adaptation to local conditions, and thus enabling some optimisation of growth rates. The company PetroAlgae based in Florida claims to have been able to bring down costs and to scale up production of an ABB in a sustainable way simply by choosing the optimum algal subspecies.[338]

3.36 Classical breeding approaches are being pursued using genetically diverse parent strains to expand the gene pools in the breeding populations, with the hope of producing algal varieties with improved biofuel properties. There is also the possibility of improving algal species by advanced breeding and genetic modification, making use of genetic and metabolic engineering as well as synthetic biology. For example, scientists have genetically modified algae that continuously secrete oils through their cell walls.[339] The oils float to the surface of the pond, where they can be easily collected and turned into biodiesel; this facilitates large-scale industrial production. If commercially scalable, this could bypass the processes usually required for algal oil extraction and thus eliminate a costly process (which is described below). Oil extraction could also be aided by genetic modification of biological traits that influence extraction efficiency, such as cell wall strength. In terms of the technologies required for this, the same principles apply as in crops.

Algal cultivation

3.37 Algal cultivation involves the growth of algal biomass. Like lignocellulosic processing, algal cultivation has several challenges to overcome in order to produce biofuels economically; these challenges are in maximising yield and conformity of products, as well as in harvesting and extraction of the biofuel. Algal cultivation systems require water, carbon dioxide and nutrient sources, and light and space in which to exist, as well as stable temperatures within the range 20–30 degrees Celsius.[340] The choice of algal species determines the conditions required for cultivation. Currently, the most common microalgal cultivation systems are open pond systems

[337] Chisti Y (2007) Biodiesel from microalgae *Biotechnology Advances* **25**: 294–306.
[338] Personal communication, Andrew Beck, then Vice President of Public Affairs, PetroAlgae, Florida, US (November 2009).
[339] Synthetic Genomics Inc. (2009) *Next generation fuels and chemicals*, available at: http://www.syntheticgenomics.com/what/renewablefuels.html#1. This research was backed recently by the oil company ExxonMobil to scale up the process.
[340] Chisti Y (2007) Biodiesel from microalgae *Biotechnology Advances* **25**: 294–306.

and closed photobioreactors (PBRs). Both of these have some limitations. Cheaper open pond systems are vulnerable to contamination, loss of water and carbon dioxide, lack of natural light and temperature fluctuations, all of which can lower biomass productivity and growth. Closed PBRs allow greater control of conditions with better productivity, but are very expensive, and the problem of sufficient exposure to sunlight can still exist (some systems make use of artificial lighting). Currently, hybrid systems are being investigated which could combine the benefits while avoiding the problems of open and closed systems. Another strategy which integrates cultivation with treatment of wastewater is also under development. If these strategies for algal cultivation are successful, they could enable the production of significant volumes of ABBs at a reasonable cost; however, several hurdles have to be overcome first, many of which arise with scaling up to commercial operations. For example, although nutrient source management and water management are feasible at small scales, both technical and economic challenges occur at commercial scales.[341] In addition, little is known about artificial pond ecology or pathology, and such knowledge is important to develop risk mitigation/remediation strategies for large-scale cultivation.[342] Culture stability for commercial-scale algal cultivation is also an issue.[343] In sum, there is a lot of potential in advancing the production of ABBs, and this should not be discarded lightly. However, at this early stage of development it is too early to estimate whether efforts will be successful, or which of the strategies has the greatest potential for success.

Algal biomass harvesting and processing

3.38 There are two different routes to produce algal biofuels (see Box 3.4). Using algal oils produces algal biodiesel which is similar in chemical and physical properties to diesel derived from fossil oil and which compares well with the international biodiesel standard for biodiesel use in vehicles.[344] In comparison with diesel, algal biodiesel is non-toxic and has reduced levels of particulates, carbon monoxide, soot, hydrocarbons and sulphur oxides. It is also cited as being more suitable for aviation use than first generation biodiesel, having a low freezing point and high energy density. Processing all the algal biomass is similar to lignocellulosic processing and results in the same end-products. Again, it is too early to select the best route, and the most successful and economic way of processing algae into fuel will most probably be to use several methods in conjunction.

Box 3.4: Algal harvesting and processing

Algal harvesting

After cultivation, the algal biomass is harvested to allow isolation of the products. The solution containing the algal cells has to be concentrated to solutions that are 20–100 per cent more concentrated than the starting material.[345] A number of harvesting techniques are currently in use, including sedimentation in a gravity field, centrifugation, flotation and filtration.[346] However, it is likely that a combination of these approaches will be required.

Algal processing

There are two different routes for biofuels production from algal biomass: one makes use of the algal oils, which must first be extracted from the biomass; the other makes use of all the algal biomass.

Algal oils

There are two main methods for extraction of algal oils: drying the biomass and treatment with solvents to extract the products; and cell disruption to release the contents. The advantage of drying the biomass is that higher lipid yields can be obtained owing to the better access of the solvents to this dried matter. However, the high energy costs associated with drying are likely to be prohibitive when the process is scaled up for biofuels production. Cell rupture techniques avoid the need for solvents but to date this has not been done on a large scale. Oil extraction can be a costly process. Furthermore, the composition of extracted algal oils makes them susceptible to oxidation when stored, and this can limit

341 US Department of Energy (2010) *National algal biofuels technology roadmap*, available at: http://www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf, p31.
342 Ibid.
343 Ibid.
344 Brennan L and Owende P (2010) Biofuels from microalgae: a review of technologies for production, processing, and extractions of biofuels and co-products *Renewable and Sustainable Energy Reviews* **14**: 557–77.
345 Greenwell HC, Laurens LML, Shields RJ, Lovitt RW and Flynn KJ (2010) Placing microalgae on the biofuels priority list: a review of the technological challenges *Journal of the Royal Society Interface* **7**: 703–26.
346 Ibid.

their use.[347] Once extracted, the algal oils are converted into biodiesel using standard procedures as described in Chapter 2.

Algal biomass
Biochemical processes and thermochemical methods (comparable to those used in lignocellulosic processing as described above) are also used to convert algal biomass into liquid fuels.[348] Thermochemical liquefaction affords the advantage of being able to break down wet algal biomass into materials with higher energy densities. Results have already shown that it is a viable option for the conversion of algal biomass to liquid fuel. For pyrolysis, there is a great deal of promising research. Bio-oils produced by this method from algal biomass are of a higher quality than those extracted from lignocellulosic materials. However, technical challenges exist as the pyrolysis oils contain unwanted agents and are unstable and viscous.

Algal biomass could also potentially be fed into anaerobic digestion (AD) or fermentation plants. AD (digestion in the absence of oxygen) converts biomass to a methane-rich gas and is appropriate for matter with high moisture content and thus suitable for wet algal biomass. By some estimates, this approach could recover the equivalent amount of energy as extracting the algal oils, while having biomass left over that could be recycled in further algal growth cycles. Technical challenges exist in that the composition of microalgae, such as high protein content, can affect the efficiency of AD. Standard fermentation, i.e. the conversion of sugars, starch and cellulose to alcohol, could make use of the starch present in microalgal biomass. This process has also been regarded as a conversion pathway for the residual biomass after algal oil extraction.

Co-products of algal-based biofuels production

3.39 Algal oils represent just one of potentially many products that can be derived from algae and have market value. Algal biomass can contain significant amounts of proteins, carbohydrates and other nutrients, such that residues left over after oil extraction could be used as animal feed. The residues could also be used to produce biogas via anaerobic digestion, which could be used to power the ABBs production facility with excess gas/power being sold. Alternatively, the residues could undergo biochemical conversion to bioethanol/biobutanol, or thermochemical conversion and chemical catalysis to synthetic fuels for transport. Depending on the microalgae used, production of other products such as omega-3 fatty acids can be achieved. The nature of co-products available depends on whether only the algal oils or the whole algal biomass is used to produce ABBs. Making use of any component with market value (the biorefinery approach, described below) could help drive down the cost of producing ABBs.

Estimated time frame to commercialisation

3.40 Despite significant enthusiasm for ABBs production, their stage of development is even less mature than that of lignocellulosic biofuels. Some have said that the potential of ABBs has been "greatly exaggerated".[349] In contrast to this, several companies interviewed by Accenture estimate that they will have commercial production in place by 2014. However, owing to the technological challenges of establishing the most cost-effective processing pathway for scaling up production and lowering costs, Accenture estimates that it will probably take longer than five years. Respondents to the Working Party's consultation and the members of industry who were interviewed as part of the Working Party's evidence gathering were more divided regarding the expected time frame for commercialisation of ABBs than regarding lignocellulosic biofuels.

> **"Some [biochemical conversion routes for lignocellulosis] are likely to be commercialised in the next year or so, and be economic by about 2013/2014. Commercialisation of algal biofuels is likely to take longer."**[350]

[347] Brennan L and Owende P (2010) Biofuels from microalgae: A review of technologies for production, processing, and extractions of biofuels and co-products *Renewable and Sustainable Energy Reviews* **14**: 557–77.
[348] Reviewed by Brennan L and Owende P (2010) Biofuels from microalgae: a review of technologies for production, processing, and extractions of biofuels and co-products *Renewable and Sustainable Energy Reviews* **14**: 557–77.
[349] van Beilen JB (2010) Why microalgal biofuels won't save the internal combustion machine *Biofuels, Bioproducts & Biorefining* **4**: 41–52.
[350] Biotechnology and Biological Sciences Research Council Sustainable Bioenergy Centre (BSBEC), responding to the Working Party's consultation.

> **"Algae, including freshwater algae…seems to hold considerable promise, and could be commercialized within a few years."[351]**
>
> **"General reading also indicates that several large international companies are investing heavily in algal sources. 10-year timescale for commercial sources?"[352]**
>
> **"…research into advanced liquid biofuels from algae is at a very preliminary stage and the timeframe for implementation could be measured in decades, rather than years."[353]**
>
> **"By 2030, ABBs will account for 6 per cent of diesel and 12 per cent of aviation fuel worldwide."[354]**
>
> **"Cellana estimates that commercial production from its pilot project could be within four to five years from now."[355]**

Jatropha

3.41 Jatropha has recently gained a lot of attention as another biofuels feedstock. Jatropha is a perennial shrub that originated in Central America and is now widespread in the tropics and neighbouring regions. Besides biofuels, it has many different uses (e.g. jatropha plantings to act as hedges to keep out livestock, and medicinal or veterinary use). Jatropha has a high oil seed content and its oil can be processed using the technology common to established biofuels production (i.e. biodiesel production from palm or rapeseed oil; see Chapter 2). Jatropha has been dubbed a ''wonder shrub' and is considered attractive for more tropical regions; there is currently much activity in South-East Asia, southern Africa, and South and Central America.

3.42 Interest in jatropha grew mainly because it is a non-food crop that in principle can grow in semi-arid areas on marginal and saline land.[356] On this basis, jatropha cultivation for biofuels production has been promoted as it would not, it has been claimed, compete with food crops. Use of jatropha as a biofuels feedstock has several advantages. It grows fast and it could, through varietal improvement and using good farming practices, produce high levels of oil per unit area in subhumid and subtropical environments (investment into plant breeding has already grown). In addition, jatropha oil has chemical and physical properties that make it suitable for processing into biodiesel; but, even without processing, jatropha oil can be used directly in certain diesel engines, lamps and cooking stoves. By-products of jatropha cultivation also have value; for example the seed cake from non-toxic varieties (toxic and non-toxic varieties exist) can be used for animal feed, and fruit shells and seed husks can be burned or used to produce biogas.

3.43 However, use of jatropha as a biofuels feedstock is faced with several techno-economic challenges.[357] Although jatropha can grow in inhospitable environments, to produce good yields it requires sufficient amounts of water and nutrients. Jatropha can also vary in yield, oil content and quality, and it can take between three and five years for jatropha to reach economic maturity. Harvesting is labour-intensive and mechanisation is difficult owing to variation in when seeds develop. Jatropha oil is also less suitable for direct use as a diesel substitute in cooler climates owing to its viscosity. If toxic varieties of jatropha are used, the use of by-products such as seed cake for animal feed is prevented, thus eliminating the additional value of the by-products. In addition, although knowledge is improving, relatively little is known about how to improve yields since jatropha does not have a long history of cultivation. Varieties that are high-yielding have not yet been identified and there is lack of understanding about how to use agronomic practices to produce high yields.

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351 Jeffrey A McNeely, responding to the Working Party's consultation.
352 Professor Keith Smith, responding to the Working Party's consultation.
353 Society for General Microbiology, responding to the Working Party's consultation.
354 Fact-finding meeting with members of industry, 2 March 2010.
355 Ibid.
356 For a review of jatropha's strengths, see: Food and Agriculture Organization of the United Nations (2010) *Jatropha: a smallholder bioenergy crop – the potential for pro-poor development*, available at: http://www.fao.org/docrep/012/i1219e/i1219e.pdf, p24.
357 Ibid, p25.

3.44 However, several of these difficulties could be addressed by advances in biology. For example, toxicity could be decreased by genetic modification and/or APBSs, and the crop could also be altered to fit mechanical cultivation, thus decreasing the requirement for human labour and increasing economic viability. The jatropha genome sequence has been reported[358] and this could represent a very important step in identifying trait genes and molecular markers for the future development of improved versions of jatropha.

Biorefineries

3.45 For all the feedstocks discussed above, the final part of the processing route in biofuels production includes steps to refine the fuel product. This can be done in a biorefinery – a system similar to an oil refinery which is used to produce fuels and useful chemicals from biomass.[359] A biorefinery can be either a transformed oil refinery or a newly built facility. Potentially, it would be possible to integrate all steps in the processing of biofuels within one facility, particularly if a range of biomass feedstocks could be converted using the same strategy.

3.46 A biorefinery aims to optimise the use of resources and to minimise waste so that the benefits and profitability of a biofuels supply chain are maximised. Thus, biorefineries integrate biofuels production with production of chemicals and energy, which are co-products and can also have market value, for example algae produce vitamins as a co-product. The co-products differ depending on which feedstocks are processed and how; however, their production may be important to both the economic viability and environmental sustainability of biofuels production. With current biofuels, typical examples of valuable co-products are the use of plant remains after fuel extraction as animal feed and the use of sugar cane bagasse to produce energy. New biofuels production affords several other potential avenues for producing valuable co-products.

3.47 Biorefineries will ideally be designed to be modular in nature so that they are able to make use of a wide range of feedstocks and adapt to changes in demand for certain chemicals, should these change. For the UK, the feasibility of two major types – that could be deployed by 2020–2025 – has been considered.[360] These include a relatively small whole-crop biorefinery complex producing a single biofuel type and several high-value co-products (including chemicals such as lactic acid) and a larger, two-platform biorefinery complex producing two types of fuels and various co-products from mixed biomass feedstocks. Already, there is a sugar beet biorefinery at Wissington, Norfolk.[361]

3.48 Future research might focus on controlling the portfolio of co-products, optimising their production and characteristics for end use. Work is also continuing to optimise the flow of materials and energy between different production units.[362] However, if biofuels production is the primary goal then co-product generation will be limited by necessity. With regard to environmental sustainability, biorefineries could employ energy recycling to reduce energy use, and carbon-sequestering processes to reduce GHG emissions. A biorefinery that sequesters

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358 In 2009, Synthetic Genomics Inc. and the Asiatic Centre for Genome Technology announced the completion of a first draft of the jatropha genome, see: http://www.syntheticgenomics.com/media/press/52009.html. More recently, in 2010 Life Technologies and SG Biofuels reported that they had sequenced the genome to a greater confidence, see: http://www.lifetechnologies.com/news-gallery/press-releases/2010/life-techologies-ad-sg-biofuels-complete-sequece-of-jatropha-geo.html.

359 For a review on biorefineries, including types, future directions and technical challenges, see: Fernando S, Adhikari S, Chandrapal C and Murali N (2006) Biorefineries: current status, challenges, and future directions *Energy & Fuels* **20**: 1727–37; Cherubini F, Jungmeier G, Wellisch M *et al.* (2009) Toward a common classification approach for biorefinery systems *Biofuels, Bioproducts & Biorefining* **3**: 534–46.

360 Tamutech Consultancy (2007) *Mapping the development of UK biorefinery complexes (NFC 07/008): a report prepared for the National Non-Food Crops Centre* (London: NNFCC), pp17–32.

361 IEA Bioenergy (2011) *Task 42 Biorefinery: database*, available at: http://www.iea-bioenergy.task42-biorefineries.com/nc/biorefinery-database/pf-single-view/?tx_powermailfrontend_pi1[show]=35&cHash=b557ce78562d926a4d440494dc6b33f7.

362 Octave S and Thomas D (2009) Biorefinery: toward an industrial metabolism *Biochimie* **91**: 659–64.

some or all of its carbon dioxide emissions might result in a biofuels supply chain with a negative GHG metric overall, obviously also depending on the feedstock and land use impacts.

3.49 In sum, well-designed integrated biorefining appears to be a particularly promising way forward. Currently, industry is moving along the lines of extracting every drop out of the biomass in the same way that every drop is extracted out of crude oil. The initial driver for this was economic but the positive impact on energy output and GHG emissions has been recognised.

New approaches to biofuels: the promise and the problems

3.50 These examples of new approaches to biofuels illustrate the significant potential for improvement in the field and the options available to avoid the problems of the current generation, in particular regarding land use, environmental impacts and competition with food crops. However, in order to reap such benefits, several technology bottlenecks need to be overcome, and costs need to be reduced, in particular with regard to processing. Most of the technology discussed in this chapter is at the development stage and prohibitively expensive. Hence, in addition to various feedstock improvements and advances in processing and integrated biorefining, it is important that technologies are supported which have potential to be implemented at a large scale in a cost–effective way.

3.51 Chapter 4 presents an ethical framework and Ethical Principles that should be satisfied by all current and new biofuels development and production. Later chapters examine the interaction between policy and technology development, which can have important impacts on the direction of the development of new approaches to biofuels.