Biofuels: the next generation

Grant A Stanley

School of Engineering and Science, Victoria University,
PO Box 14428,
Melbourne, VIC 8001
Email g.stanley@cqu.edu.au

Geoff J Dumsday

CSIRO Molecular and Health Technologies
Bag 10, Clayton South MDC
VIC 3169
Tel (03) 9545 2344
Fax (03) 9545 2109
Email geoff.dumsday@csiro.au

There are many issues with the continued use of fossil fuels for energy, including finite supply, energy security and their contribution to rising atmospheric CO_2 concentrations and climate change, leading to substantial, increased interest in the research and development of renewable energy. In 2006, renewable energy provided only 2.5% of global energy needs, which is well short of the national renewable energy targets of many countries for the period 2020-2030, including Australia [1]. For these reasons there is substantial investment in the development of renewable fuel technologies [1]. Bioethanol and biodiesel derived from biomass are alternative fuels for which production capacity and demand is rapidly increasing.

Bioethanol

Traditionally, ethanol has been produced by fermentation of the sugar products from starch and sugar crops such as cassava, rice, wheat, barley, sorghum, corn or sugarcane [2]. This first-generation process is currently the main source of ethanol, with global production doubling between 2004 and 2007 to 50 billion litres [3]. However, the continued use of first-generation ethanol is problematic for socio-economic reasons such as competition with food crops causing food shortages and spiralling food prices, and for environmental reasons with life cycle analyses estimating that its production and use contributes to reductions in greenhouse gas (GHG) emissions of only 20-30% compared to fossil fuels [4]. The future of bioethanol requires the development of lignocellulose-to-ethanol processes, to produce what is otherwise known as cellulosic or second-generation ethanol.

Lignocellulose, the basic component of plant cell walls, includes materials such as herbaceous crops, agricultural waste and forest residues. The US Department of Agriculture estimated that 1.3 billion tons/year of lignocellulosic biomass could be produced by the US agriculture sector and from forestland, with minimal changes in land use and agricultural and forestry practices; this could provide enough biofuel to supplement 30-40% of US fuel demand [5]. Lignocellulosic materials typically contain 55-90% cellulose and hemicellulose: these carbohydrates can be converted to sugars and subsequently fermented to ethanol. There are many reasons for using lignocellulosic feedstocks to produce ethanol, including the absence of competition with food crops for land, it is a non-food source and it is plentiful. Furthermore, the energy balance for lignocellulose-derived ethanol is five times better than corn-based ethanol, contributing to a reduction in GHG emissions of around 80-100% compared to fossil fuels [6,7].

There has been considerable investment in the development of the cellulosic ethanol industry, resulting in the construction of many pilot-scale plants globally, including a proposal for a cellulosic ethanol pilot plant in Australia (see http://www.ethtec.com.au), over the last few years [4] and more recently in the USA with the construction of commercial-scale, second-generation ethanol plants (Table 1). Although this is significant, there has been relatively slow progress due to the hurdles in developing commercially viable cellulosic ethanol technologies, with the greatest challenges for biochemical-based processes being efficient and economic hydrolysis of the feedstock and its subsequent fermentation. Unlike starch, which contains homogenous and easily hydrolysed polymers, each lignocellulose feedstock type presents its own challenges in ease of hydrolysis and fermentation [8]. Research in this area continues to focus on improving feedstock characteristics, reducing pretreatment costs, improving enzyme efficacy, lowering enzyme production costs, the development of productive and high yielding ethanologenic microorganisms and improving overall process integration [9]. Nonetheless, the intensive research effort has considerably reduced the costs associated with producing cellulosic ethanol in the last few years. For example, POET LLC lowered the production cost of their cellulosic ethanol from US$1.09 per litre to US$0.62 per litre in the last year and they expect to bring it down to US$0.52 per litre in 2010 [10]. With this in mind, it is anticipated that the cost of producing cellulosic ethanol will continue to decline, suggesting a promising future for cellulosic ethanol as a transport fuel.

Biodiesel

This is currently the most common type of biofuel used in European countries. First-generation (made from food crops) and second-generation (made from non-food crops) biodiesel is made from vegetable oils and animal fats by chemically reacting oil or fat with an alcohol in the presence of a homogeneous and heterogeneous catalyst; this results in a mixture of methyl esters comprising the biodiesel and glycerol [11,12]. The issue with continued use of oil crops is that their relatively low oil yields per hectare demands a significant amount of agricultural land if they are to completely replace petroleum fuels [13]. It is estimated that around 61% of all agricultural cropping land in the US would need to be dedicated to oil palm if it were to completely meet US fuel needs [14]; as with first-generation ethanol feedstocks, the continued use of oil crops for biodiesel production would place it in direct competition for land needed for food, fodder and other crops.

Biodiesel made from microalgae, referred to as second- or third-generation biodiesel depending on the source, is a more promising and sustainable alternative to previous biodiesel generations. Compared to terrestrial plants, algae have high growth rates and may be grown in supplemented seawater and

Table 1. Some cellulosic ethanol plants in the USA (operational or under construction as of February, 2010).

Company	Feedstock	Capacity (million litres per year)
Abengoa Bioenergy	Wheat straw, corn stover	44
BlueFire Ethanol	Urban wastes	68
California Ethanol	Sugarcane bagasse	208
Ecofin	Corn cobs	5
ICM Inc.	Switchgrass, corn stover	5.7
Iogen Corp	Agricultural residues	68
Gulf Coast Energy	Wood waste	265
Mascoma	Wood	151
Pacific Ethanol	Wheat straw, stover and poplar residuals	10.2
POET LLC	Corn cobs	76 (Scotland, USA) 118 (Emmetsburg)
Range Fuels	Wood waste	76
RSE Pulp and Chemical	Wood chips	8.3
SunOpta	Wood chips	38
Verenium Corporation	Bagasse	5.3
Verenium/BP Biofuels	Bagasse	136
Xethanol	Citrus peels	30
ZeaChem	Poplar, sugar, wood chips	5.7

low-quality saline water such as that produced from wastewater treatment plants [15]. Some other advantages of using microalgae as biodiesel feedstock include their ability to accumulate large quantities of lipids and oils, sequester fossil-fuel generated CO_2 from power stations in integrated biorefinery systems and produce value-added by-products [16].

The composition of microalgae biomass includes neutral lipids, polar lipids, wax esters, sterols, hydrocarbons and phenyl derivatives such as terpenes and quinones [16]. Algae synthesise fatty acids to produce glycerol-based membrane lipids that may constitute about 5-20% of their dry cell weight; hydrocarbons and other types of lipids are usually found in algae at quantities less than 5%, although some algae species may produce significantly more hydrocarbons. For example, *Botryococcus braunii* can produce long chain hydrocarbons at up to 80% of its dry cell weight [17]. Microalgae are very competitive at producing biodiesel compared to previous-generation biodiesel feedstocks. For example, oil palm annually yields around 4,800 litres/hectare of biodiesel, whereas the yield of microalgae-based biodiesel can potentially be as high as 98,000 litres/hectare [14]. Compared to its predecessors, third-generation biodiesel production can have a substantially lower impact on other agricultural activities.

Most research into the development of microalgae-based biodiesel production systems focuses on the development of low-cost, large-scale production systems. Open pond systems require less capital investment but have lower productivities, resulting mainly from the impact of large temperature and pH variations, poor mixing and contamination by invasive algae, parasites and microorganisms [18]. Photobioreactors offer greater control and reduced contamination but require much greater capital investment and energy input; a problem compounded by the massive scale required for biodiesel production. There are many different photobioreactor types that can be categorised according to three basic configurations, *viz.* tubular, flat plate and stirred tank [19]. Tubular and flat plate reactors are the most popular designs due to their use of free and readily available sunlight as a light source, whereas stirred tanks require artificial illumination.

Commercial scale microalgae production continues to be economically challenging, with most research focused on improving production technology, especially that associated with algal harvesting and the extraction of algal oil. Although producing stable microalgae transformants is currently difficult, genetic engineering of microalgae has the potential to contribute significantly to reducing the costs of producing third-generation biodiesel [20]. Such approach could be used to improve algal oil yields, growth rates, photosynthetic efficiency and stress tolerance [14]. Most processes for producing third-generation biodiesel are still under development, with a number of pilot scale facilities in operation. However, the attractiveness of this approach will ensure continued investment into developing the microalgae-based biodiesel industry, leading to improved productivities and further reductions in processing costs.

References

1. Wall, J.D. *et al.* (eds) (2008) *Bioenergy.* Washington, DC, USA: ASM Press.
2. Kim, S. & Dale, B.E. (2004) Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenerg.* 26, 361-365.
3. Tollefson, J. (2008) Energy: not your father's biofuels. *Nature* 45, 880-883.
4. Demain, A.L. (2009) Biosolutions to the energy problem. *J. Ind. Microbiol. Biotechnol.* 36, 319-332.
5. Perlack, R.D. *et al.* (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge Natl. Lab., pp. 1-78. (http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf)
6. Sheehan, J. *et al.* (2004) Energy and environmental aspects of using corn stover for fuel ethanol. *J. Ind. Ecol.* 7, 117-146.
7. Wu, M. *et al.* (2006) Energy and emission benefits of alternative transportation liquid fuels derived from switchgrass: a fuel life cycle assessment. *Biotechnol. Prog.* 22, 1012-1024.
8. Sassner, P. *et al.* (2008) Techno-economic evaluation of bioethanol production from three different lignocellulosic materials. *Biomass Bioenerg.* 32, 422-430.
9. Stanley, G.A. & Hahn-Hägerdal, B. (2010) Fuel ethanol production from lignocellulosic raw materials using recombinant yeasts. In: *Biomass to Biofuels: Strategies for Global Industries* (Vertës, A.A. *et al.* eds), John Wiley & Sons Ltd., pp. 261-291.
10. Voegele, E. (2009) POET reduces cost of cellulosic ethanol production. *Ethanol Producer Magazine* December.
11. Kulkarni, M. *et al.* (2006) Solid acid catalyzed biodiesel production by simultaneous esterification and transesterification. *Green Chem.* 8, 1056-1062.
12. Meher, L.C. *et al.* (2006) Technical aspects of biodiesel production by transesterification-a review. *Renewable Sustain. Energy Rev.* 10, 248-268.
13. Chisti, Y. (2007) Biodiesel from microalgae. *Biotechnol. Adv.* 25, 294-306.
14. Chisti, Y. (2008) Biodiesel from microalgae beats bioethanol. *Trends Biotechnol.* 26, 126-131.
15. Osamu, K. & Carl, H.W. (1989) *Biomass Handbook*. Gordon Breach Science Publisher.
16. Naik, S.N. *et al.* (2010) Production of first and second generation biofuels: a comprehensive review. *Renewable Sustain. Energy Rev.* 14, 578-597.
17. Hu, Q. *et al.* (2008) Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. *Plant J.* 54, 621-639.
18. Borowitzka, M.A. (1999) Commercial production of microalgae: ponds, tanks, tubes and fermenters. *J. Biotechnol.* 70, 313-321.
19. Carvalho, A.P. *et al.* (2006) Microalgal reactors: a review of enclosed system designs and performances. *Biotechnol. Prog.* 22, 1490-1506.
20. León-Bañares, R. *et al.* (2004) Transgenic microalgae as green cell factories. *Trends Biotechnol.* 22, 45–52.

Biographies

Grant Stanley is Dean of Medical and Applied Sciences at CQUniversity Australia. His research interests include industrial microbiology, especially the application of microorganisms for fermentation, bioremediation and wastewater treatment.

Geoff Dumsday is a senior research scientist at CSIRO. His research interests are focused on industrial microbiology, specifically the use of microbial systems for the production of useful products, ranging from vaccines and enzymes to the production of small molecules from a range of starting materials, particularly biomass.