Algal Biofuels: Feasibility Analysis and Policy Recommendations

An Inquiry-Driven Thesis

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Inspiring Innovation and Discovery

Abstract

Oil's role in facilitating human progress cannot be understated. However, the demand for oil is increasing, reserves are becoming depleted and more dangerous to access, and the environmental consequences are becoming harder to ignore. The need for an alternative is clear. Biofuels offer such an alternative.

Grown transportation fuel, or biofuel, has the potential to meet increasing demand, increase energy security, increase local jobs, and be carbon neutral. An analysis of the currently available biofuel production processes, with a specific interest in algal biofuel production, reveals that there is still a great deal of work to be done before this potential can be realized. In order to spur this required development, a number of policy options are considered.

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The Future of Fuel

Decreasing oil dependancy

Oil has been a vital component in the rapid progress of humankind (Yergin, 1991). However, the negative effects of its use are becoming clear. Of Canada's 100 Mt increase in greenhouse gas (GHG) emissions between 1990 and 2009, 54Mt were due to the fossil fuel industries, and transportation was responsible for 44Mt (Environment Canada, 2011). Worldwide, oil was responsible for 37% of the almost 29 billion tonnes of the greenhouse gas CO_2 released into the atmosphere in 2009 (IEA, 2011). Any serious attempt to address climate change must deal with the issue of oil.

Access to oil is implicated in many international difficulties. Two recent examples are the Iranian threat to close the Straight of Hormuz, cutting off access to 20% of the oil trade (Stewart, 2012), and the tensions surrounding ownership of possible oil sources in the South China Sea (Eckert & Mogato, 2011). Of the approximately 46 years worth of proven oil supply in the world, over half remains in the middle east (BP, 2011).

In order to strengthen Canada's energy security, alternative sources need to be found closer to home. However, accessing these sources is increasingly difficult and dangerous, as exemplified by the Deepwater Horizon disaster which released 4.9 million barrels of crude oil into the Gulf of Mexico, and contaminated 665 miles of coastline (Repanich, 2010). Biofuels offer the potential to create domestic energy sources which will not only decrease Canada's dependancy on other countries, but will also provide domestic jobs in this field. As Steven Chu, U.S. Secretary of Energy stated, “Developing the next generation of biofuels is key to our effort to end our dependence on foreign oil and address the climate crisis - while creating millions of new jobs that can’t be outsourced.” (USDOE, 2010)

Biofuel for transportation

The search for cheap, reliable, renewable energy sources is being undertaken on many fronts. Solar photovoltaics and wind are two types of stationary energy generators where constant progress is being made in increasing efficiency and decrease costs. A photovoltaic system at the Toronto Fire Hall covers 18.8m^2, and generated 4,043kWh of electricity over one year (Paraschiv & Haust, 2009). This works out to an average of 215kWh/m^2 for the year. For comparison, current technology using photosynthetic algae is capable of producing 1.4L of algal biofuel per square meter of space (McKenna, 2012). Using the diesel energy density of 35.86MJ/L, this translates to 14kWh of energy produced over a year per square meter of algae cultivated. Even with the expected tenfold increase as the technology is perfected (Robertson et al., 2011), this still leaves algal biofuels producing just over half of the energy that would be produced by an equivalent amount of *currently* available solar panels. For this reason, algal biofuels will not be able to compete with other clean technologies for electricity production; however, as will be seen, for transportation it can serve a very useful niche.

While the electrification of vehicles is one promising alternative being pursued, this method has clear obstacles which are not shared by biofuels. Countries like Australia and China generate 68 - 94% of their electricity from coal (IEA, 2011), so CO_2 is emitted at the electricity generator instead of at the vehicle's tailpipe. Second, electricity is difficult to store in portable form. Batteries take a long time to recharge, have a limited capacity, and are expensive. The Nissan Leaf, for example, takes 7-18 hours to fully recharge on a residential electrical source, and will only drive approximately 160km before it needs to be recharged (Nissan, n.d.). A plug-in hybrid has the benefits of an electric motor and an internal combustion engine, but The U.S. National Research Council predicts that even after the lifetime fuel cost savings, it will be decades before they become cost competitive with conventional automobiles (NRC, 2009).

The transition to fossil-fuel free transportation will be easier through the use of drop-in biofuel products which can be used in exactly the same way as regular fuel. Other clean fuels suggested for transportation, such as hydrogen, natural gas, electricity, or even other forms of biofuels would require massive capital investments to roll out new infrastructure to support the technology, and drivers would have to replace their vehicles. Drop in biofuels like biodiesel and biogasoline, and the blending of bioethanol into gasoline can use the facilities currently in place, and drivers do not have to replace their cars to reap the environmental rewards. This drop-in advantage is large enough that only this type of biofuel will be considered below.

With the transportation sector responsible for over 34% of Canada's energy consumption (Stats Can, 2012), substituting a more sustainable, environmentally friendly energy source for fossil fuels will make a significant difference. Algal biofuels hold the potential to be that energy source.

The Evolution of Biofuel

Types of biofuel

As described by Brennan and Owende (2010), there are three generations of biofuels. The first generation of biofuels are produced from food crops such as sugarcane, beets and maize. The second generation of biofuels require a feedstock of lignocellulosic biomass, the earth's most abundant biological material, from waste materials and other non food crops (Timilsina & Shrestha, 2011). While algae derived biofuel is often considered part of the second generation of biofuels, Brennan and Owende suggest it is a third generation because of the significant ways in which it is different from these other two forms.

As can be seen in Figure 1, the global production of biofuel has been rapidly increasing up to the current 105 billion litres per year. Most of the biofuel being produced is ethanol, which accounts for 2.7% of the global road transportation fuel being consumed and comes mainly from corn in the U.S. (57%), and from sugarcane in Brazil (33%) (Shrank & Farahmand, 2011).

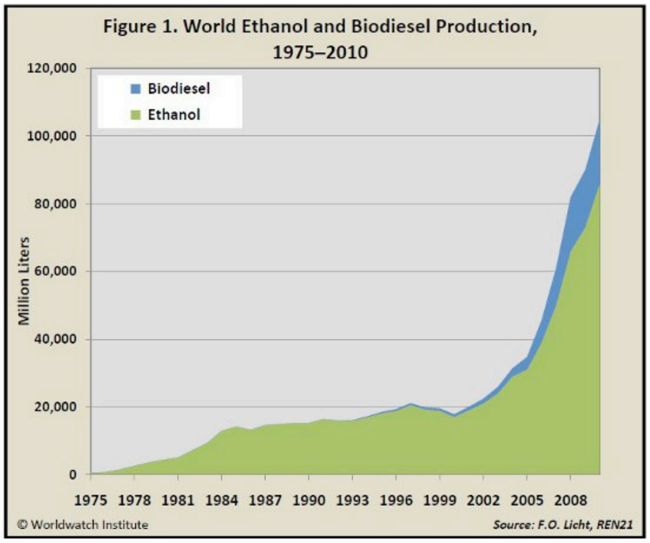

Figure 1: Amount of biofuel produced worldwide (from Shrank & Farahmand, 2011).

Ethanol is produced from fermentation of the sugars present in the food-crop, followed by distillation (Timilsina & Shrestha, 2011). According to the International Energy

Agency (IEA, 2011), the well-to-wheel GHG reductions associated with corn-derived ethanol is 10-50%; for sugarcane ethanol it is 70-120%, and for biodiesel from oilseed it is 30-60%. Canadian companies are actively creating first-generation biofuels. Greenfield, for example, is producing 600 million litres of ethanol annually from corn (Greenfield, 2012). While these are promising figures, first generation biofuels have a number of drawbacks, mainly: fertilizer and pesticide use, land use change, food security, competition with food for arable land, and water requirements.

Drawbacks to biofuel

Photosynthetic organisms used in creating biofuel consume CO_2 as they grow. When their energy is released, through burning for example, that CO_2 is released. It would seem, on the surface, that using biofuels should be carbon neutral - the amount of CO_2 sequestered by the organisms is equal to that from burning the fuel. However, many of the activities related to the organisms' cultivation and processing are not carbon neutral. For instance, Nobel Laureate Paul Crutzen has argued that, for rapeseed and maize, the nitrogen emissions from fertilizing alone negates any emission benefit to using these processes to replace fossil fuels (Crutzen et al., 2008).

Another aspect to consider when accounting for emissions in growing biofuel is the land upon which it is grown (EEA, 2011). A mid-latitude mixed woods composed of deciduous, evergreens and conifer trees contains a carbon density of 7.00 kg of carbon per square meter; however the carbon embodied in farm lands is one-tenth of that, at 0.7-0.8 kgC/m^2 (Olson, Watts, & Allison, 1985). If the woods are cut down to make farmland to grow biomass for conversion to biofuel, over 6 kg of sequestered carbon (22 kg of CO_2) will be released per square meter converted. Before the first seed is planted, the project has already amassed a large carbon footprint. However, if a sand desert, with its 0.05 kgC/m^2 is used to create the same biomass, a land-use analysis would actually derive a carbon sequestration of approximately 0.7 kgC/m^2. This issue is not solely related to biofuels. Clearing of forest for oil and gas extraction, mostly in the Boreal plain and Boreal Shield East, has increased from to 5.3 kha per year in 1990 to 10.6 kha per year in 2009 (Environment Canada, 2011). In terms of land use, an ideal fuel would be grown in an area where it increases the carbon density of relatively barren lands.

The efficiency of the conversion to energy also needs to be considered. Biomass burns with a lower efficiency and contains less energy per unit of carbon, so the CO_2 emissions per unit of energy of a biomass burning power plant is usually higher than that of a fossil-fuel burning plant (EEA, 2011). There is clearly a need to carefully account for the full lifecycle, including land repurposing. Blindly substituting biofuel for fossil fuel may in fact result in increased carbon emission and an acceleration in global warming - precisely the effects biofuels are meant to mitigate.

In addition to its implications for carbon emissions, land repurposing also affects a country's food security. In the US, one-quarter of all corn grown was used to produce ethanol (CBO, 2009). This means less corn was produced than otherwise could have been, or less other food crops were produced. Due to supply and demand, this will affect the marketplace. According to the WTO, “[t]he increase in internationally traded food prices from January 2002 to June 2008 was caused by a confluence of factors, but the most important was the large increase in biofuels production from grains and oilseeds in the U.S. and EU” (Mitchell, 2008).

In many regions of the world, water scarcity is already the limiting factor for crop growth (CA, 2007). Locations where there is not enough water to irrigate additional crops for biofuels may experience intense competition over water resources between food and biofuel (Havlik et al. 2011). This leads to the ethical question of whether it is reasonable to use food for fuel when almost a billion people throughout the world are undernourished (FAO, 2010; De Fraiture et al., 2008).

These drawbacks led to increased interest in the second generation of biofuels which, it was hoped, would address many of these problems.

Second generation biofuels

Second generation biofuels are based on lignocellulosic feedstocks, which can be broken down into three types: agricultural residues, forest residues, and energy crops (Carriquiry, Du, & Timilsina, 2011). While first generation biofuels make use of food crops - corn for example - second generation biofuels use the agricultural residues of the corn, i.e. the husks and stalks. Forest residues come from leftovers from logging, and primary and secondary processing. Energy crops are non-food crops grown specifically for energy purposes, for example switchgrass and miscanthus. The polysaccharides from the lignocellulosic material are either broken down into sugars and processed in the same manner as a first generation biofuel, or gassified into syngas which is then processed into a number of different types of fuel through Fischer-Tropsch synthesis (Timilsina & Shrestha, 2011). Canada-based companies producing second generation biofuels include Enerkem in Edmonton, Alberta, Westbury, in Quebec, and Sherbrooke, Quebec; Lignol in Burnaby, British Columbia; Iogen in Birch Hills, Saskatchewan and Ottawa, Ontario; Tembec Chemical Group in Temiscaming, Quebec (IEA, n.d.). One interesting development in this field has been the discovery of a fungus, *Glioc- ladium roseum*, which uses cellulose as a feedstock and produces hydrocarbons directly (Strobel et al., 2008), and the genetic modification of a microbe to digest cellulose and produce biobutanol (Fairley, 2011). There is still a great deal of work to be done to make this fuel source economically viable, however, as cellulosic ethanol currently costs two to three times more on a energy equivalency basis with fossil fuel (Carriquiry, Du, & Timilsina, 2011). Further, second generation biofuels do not adequately address many of the shortcomings of first generation biofuels. The results of the study by Jacobson (2009) seen in Figure 2 found that, out of 12 technologies (wind, photovoltaic, concentrated solar power, geothermal, hydro, wave, tidal, nuclear, coal with carbon capture storage, corn ethanol and cellulosic ethanol), ranked according to 11 categories (resource abundance, CO_2e emissions, mortality, footprint, spacing, water consumption, effect on wildlife, thermal pollution, chemical/radioactive waste, energy supply disruption, and reliability) corn ethanol was the second worst, followed by cellulosic ethanol (Jacobson, 2009).

	Weight (%)	Wind -BEV	Wind-HFCV	PV-BEV	CSP-BEV	Geo-BEV	Hydro-BEV	Wave -BEV	Tidal-BEV	Nuc-BEV	CCS-BEV	Corn -E85	Cel-E85
[a]Resource abundance	10	2	3	1	4	7	10	6	5	9	8	11	12
[b]CO_2e emissions	22	1	3	5	2	4	8	7	6	9	10	12	11
[c]Mortality	22	1	3	5	2	4	8	7	6	10	9	11	12
[d]Footprint	12	1	2	8	9	5	10	4	3	6	7	11	12
[e]Spacing	3	8	9	5	6	2	10	7	1	4	3	11	12
[f]Water consumption	10	1	6	5	9	4	11	1	1	7	7	12	10
[g]Effects on wildlife	6	1	3	5	2	4	8	7	6	9	10	11	12
[h]Thermal pollution	1	1	2	4	8	3	7	6	5	12	11	10	9
[i]Water chemical pollution/ radioactive waste	3	1	3	5	2	4	8	7	6	10	9	12	11
[j]Energy supply disruption	3	3	4	2	6	7	11	5	1	12	8	9	9
[k]Normal operating reliability	8	10	1	10	5	6	2	10	9	7	8	3	3
Weighted Average		2.09	3.22	5.26	4.28	4.60	8.40	6.11	4.97	8.50	8.47	10.6	10.7
Overall rank		1	2	6	3	4	8	7	5	9-tie	9-tie	11	12

- Table 1: 12 technologies for transportation rated on 11 categories

(1 is best, 12 is worst) (from Jacobson, 2009)

The need for something better

Perhaps the biggest constraint of first and second generation biofuels is their scalability. In 2010, the world consumed 12,002.4 million tonnes of oil equivalent, or just over 500 EJ (ExaJoule = $1x10^{18}$J) of energy (BP, 2011). In all, 8 billion tonnes of biological material was harvested by humans worldwide - including food, feed, fibre, lumber and wood - with a contained energy of approximately 300 EJ (Haberl et al. 2007). This suggest that even if *all* of the biologically produced material harvested was turned into energy, there would still be a 40% shortfall in covering the current energy demands. If biofuels are to fulfill a large portion of the energy demands, a solution must be found to create large quantities of *additional* biomass without putting too much extra stress on the environment. As discussed above, first and second generation biofuels suffer from problems associated with fertilizer and pesticide use, land use change, food security, competition with food for arable land, and water requirements. Algae biofuels overcome many of these challenges and, with further development, may provide the solution.

Algal Biofuels

The biology of algae

Algae used to be considered ‘aquatic plants’, but due to their lack of roots, stems, leaves and embryos, some now classify them separately (Singh & Gu, 2010).

“Algae” can refer to microalgae, cyanobacteria (blue-green algae), and macroalgae (seaweed) (USDOE, 2010). Macroalgae are larger in size, but produces little oil, and so are not useful as biofuel producers. Cyanobacteria, now technically a type of bacteria, are rather unique in that they lacks organelle compartments (i.e. they are prokaryotes), making them more amenable to genetic engineering techniques (Robertson et al., 2011). Two classes of microalgae, green algae (Chlorophyceae) and diatoms (Bacillariophyceae), have shown the most promise for use in producing biofuels. Diatoms possess a cell wall which contains substantial quantities of polymerized Silicon, making it harder to breakdown (Sheehan, 2008).

The productivity of algal cultures depends on the maintenance of an appropriate temperature, gas exchange (removal of O_2, addition of CO_2), provision of light for photosynthetic algae, and availability of the proper nutrients (Abayomi, Tampier, Bibeau, 2009). Carbon, nitrogen, and phosphorus are the main nutrients required for algae growth, along with trace amounts of silica, calcium, magnesium, potassium, iron, manganese, sulfur, zinc, copper and cobalt (Christenson & Sims, 2011).

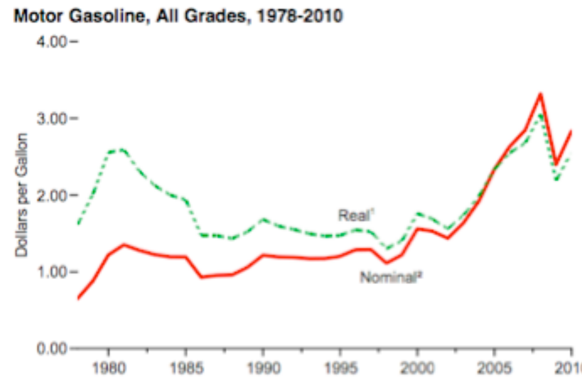

Figure 2: Change in price of oil over time (from U.S. Energy Information Administration 2010)

Research exploring algae as a potential biofuel source started in ernest in 1978 when rising oil prices led the U.S. Department of Energy's Office of Fuels Development to establish the Aquatic Species Program (ASP) (Sheehan et al., 1998). As Figure 2 indicates, the price of oil began to drop through the 80's, and so interest in finding alternatives began to dwindle (EIA, 2010). In 1996 the ASP was shut down. Currently, as the price of oil once again trends upwards, the interest in algal biofuels has been rekindled. Significant advances made in science and technology over the past decade and a half make the potential benefits of algal biofuel that much more possible to realize. The main benefits of algae are: 1) high productivity, 2) non-food feedstock, 3) non-productive land use, 4) relative indifference to water source, 5) co-products, 6) recycling of waste stream (USDOE, 2010).

High productivity

Microalgae are among the fastest growing plants in the world, and per unit area yield an estimated 7 - 31 times more oil than palm oil, the next most productive crop (Demirbas & Demirbas, 2011). As can be seen from Table 2, even if the algae's oil composition only makes up 30% of its dry weight, it still has almost ten times the amount of oil that can be retrieved from an oil palm - the second best option.

Crop	Oil Yield (L/hectare)
Corn	172
Soybean	446
Canola	1190
Rapeseed	1190
Jatroph	1892
Oil Palm	5950
Microalgae (30% oil)	58700
Microalgae (70% oil)	136900

Table 2: Productivity of select crops (from Singh and Gu, 2010)

Feedstock and land use

As discussed in the previous section, using corn and other food products as a feedstock takes away from the amount of food available for consumption. Algae does not require the use of fertile land which could otherwise be growing food crops, and therefore has no impact on the food supply or food costs. In fact, depending on the cultivation methods, algae could be grown on land which does not serve any other purpose, such as brownfields, thereby increasing the carbon density of the land upon which it is grown.

Indifference to water source

Freshwater is a vital resource which is in short supply, and will further decrease as climate change takes effect (Williamson, Saros & Schindler, 2009).Unlike many of the crops used for first and second generation biofuels, algae does not require clean freshwater in which to grow (Pittman, Dean & Osundeko, 2011). In fact, using waste water from municipal, industrial or agricultural sources is an attractive option as it may provide the necessary nitrogen, phosphorus and other nutrients required for algal growth, thereby alleviating the need to add fertilizer (Pittman, Dean & Osundeko, 2011). Nitrogen and phosphorus in wastewater are pollutants which are difficult to remove, but they are cleaned from the water as they are absorbed as nutrients for algal growth. Cultivating algae on wastewater is therefore a win-win situation for the algae, which has its nutritional needs satisfied, and for the water, which has cleaning services provided (Christenson & Sims, 2011).

Waste to energy

There are a number of industries which create large quantities of CO_2 as a byproduct of operation. Efforts have been made to integrate the algae biofuel creation process into these industries to stop the CO_2 emissions at the source. The microalgae *Botryococcus braunii 765* is one strain which has shown that it is able to thrive in flue gas CO_2 concentrations ranging from 2% - 20% (Ge, Liu & Tian, 2011). This makes it feasible for use at industrial plants. For example, Pond Biofuels has established an operation which utilizes the CO_2 created as waste during the concrete manufacturing process as feedstock for algal growth (Pond Biofuels, 2011). Also rich in CO_2 resources are coal-

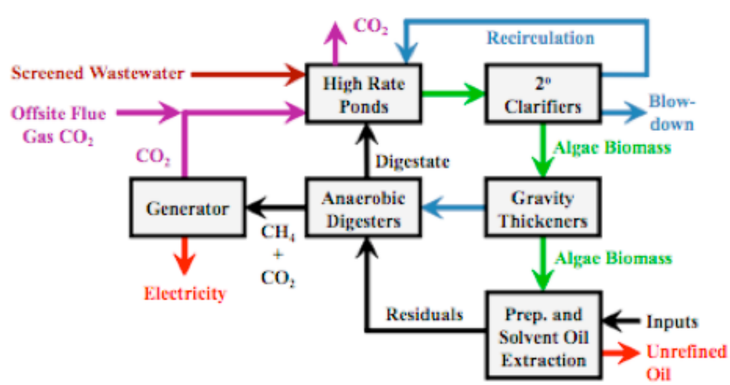

Figure 3: Process diagram for growing algae on waste (from Lundquist et al. 2010).

fuelled power plants, where conjoined algal biofuel production could lead to a net greenhouse gas avoidance of 26.3% (Brune, Lundquist & Brenemann, 2009). However, even after making use of these waste resources, price is still a barrier to growing algae for biofuel. Using the CO_2 waste from an ethanol refinery it was calculated that the biofuel would still cost over $30/gallon ($113/L) to produce (Rosenberg et al., 2011).

Coproducts

The costs currently associated with algal biofuels are prohibitively high, so high-value byproducts from the algae could be used to offset the overheads as the technology matures (Oltra, 2011). Depending on the strain, algae produce a number of valuable coproducts (Raja et al., 2008). Pharmaceuticals and high-end cosmetics in particular are generating a lot of interest. For example, certain algal strains are known to produce eicospentaenoic acid (EPA) and docosahexaenoic acid (DHA) which are Omega-3 fatty acids (Demirbas & Demirbas, 2011). The current list price for these chemicals are $96/100mg for EPA and $51/100mg for DHA (www.caymanchem.com). The market for such products will likely become saturated once significant quantities of biofuel are produced (Lundquist et al., 2010), but they may provide the initial financial leverage to develop the biofuel industry. The biomass left over after the oil has been extracted could also be used for applications such as livestock feed, fertilizer, or electricity production via direct burning or digester gas methane combustion (Brune, Lundquist & Benemann, 2009).

Heterotrophs and mixotrophs

There are three ways in which algae generate the energy they store in the form of lipids: autotrophically, heterotrophically, and mixotrophically. Autotrophic algae use CO_2 from their surroundings and energy from the sun. Heterotrophic algae, like humans, feed on high energy food sources like sugars and capture some of the energy from breaking these foods down into simpler, lower energy substances. Mixotrophic algae act like autotrophs or heterotrophs depending on the available energy source - if sunlight is available, it will act like an autotroph, but if sugars are available, it will act like a heterotroph (Perez-Garcia et al., 2011).

Heterotrophs do not require any sunlight to grow. These heterotrophic algae instead obtain their energy from the breakdown of external carbon sources. For glucose (Singh & Gu, 2010), the reaction is:

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$$

Under aerobic conditions, heterotrophic algae use either the Embden-Meyerhof Pathway (EMP) or the Pentose Phosphate Pathway (PPP), to liberate some of the energy contained in the glucose molecule (Perez-Garcia et al., 2011). This energy is captured and used by the algae to perform its metabolic functions, or stored in the form of fatty acids contained inside a lipid (Sheehan et al., 1998).

Solazyme is a company out of San Francisco which uses genetically engineered heterotrophic algae to produce biofuels (Solazyme, 2012). A United Airline 737 jetliner flight in November 2011 was the first commercial flight to use a blend of Solazyme's biofuel (40%) with regular jet fuel (60%)(Louis, 2011). The U.S. Navy has also shown serious interest in the technology, signing a contract with Solazyme to buy 450,000 gallons (approx. 1.7 million L) of biofuel at approximately $26 a gallon (Herndon, 2011). While Solazyme scales up and the matures its technology enough to become competitive in the fuel markets, the company supplements its revenue by using its expertise with algae to produce components of high-end cosmetics (Walsh, 2011).

One way in which the fermentation process may become more viable is through sourcing a cheap carbon feedstock which would otherwise be disposed of. For example, the waste molasses from sugar production has be shown to be sufficient to provide the carbon source and nutrients required to obtain an oil yield from grown algae of 40.8 g/L (Yan et al. 2011). However, as Canada gets about 90% of its sugar from imported sugar cane shipped from South America, Central America, and Australia (Canadian Sugar Institute, n.d.), this solution is unlikely to be either economically or environmentally sound. On a small scale, though, it is quite feasible. Fermentation was found to be the best technology for using algae to produce biofuel in a B.C. study which calculated that, using current technology, algal oil produced through fermentation would cost $2.58 /L, compared to between $14.44 and $24.60 /L for phototrophic algae (Alabi, Tampier, & Bibeau, 2009). Other studies have looked into using corn powder as a carbon source. For example, *C. protothecoids* was fermented with corn powder hydrolysate to derive an oil yield of 8.56 g/L (Xu, Miao & Wu, 2006). Essentially, though, using heterotrophic algae for fermentation simply replaces the yeast from first and second generation biofuels with algae, and results in oil instead of ethanol. Because a food crop is still required to provide the sugars, heterotrophic algal biofuels suffer from all the same problems as first and second generation biofuels. The ability of autotrophic algae to avoid these downfalls makes them a preferable option for biofuel production.

Autotrophic Algal Biofuel

The basic process to produce biofuel from autotrophic algae is: cultivation, harvest/separation, drying, extraction, and upgrading.

Cultivation

As depicted in Figure 4, there are three basic cultivation methods for algae. Heterotrophic algae are grown in fermentation tanks. Autotrophic algae can be grown in either an open pond, or a photobioreactor (PBR).

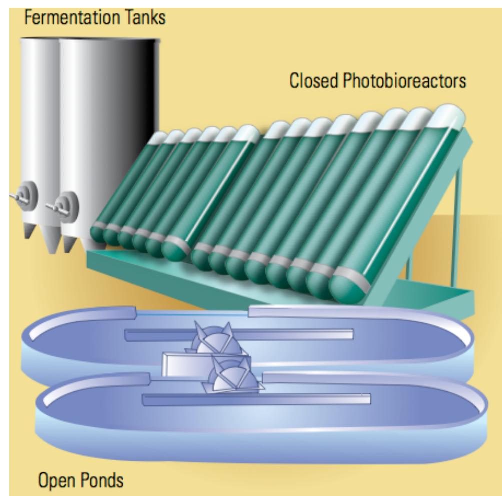

Figure 4 : Algae cultivation methods (from Lundquist et al., 2010)

Open ponds fall into three categories: unmixed, circular, and raceway (Lundquist et al., 2010). Unmixed is simply a pond which can be used to grow algae. Little to no upfront work is required, but they cannot be controlled and have little productivity. Circular ponds use a centrally-located mixer, but do not scale well above 1,000m^2. Raceway ponds are the most commonly used open pond type. In this setup a paddle wheel mixer is used to keep the water moving along a path, usually oval in shape. The depth of the pond is usually 30-50cm deep. One commercial endeavour using open pond technology currently underway is Sapphire Energy Inc. This company is building a demonstration scale plant in Luna County, New Mexico where they expect to consume 56 metric tons of CO2 per day to produce 100 barrels of green crude oil per day (English, 2011). Open ponds account for 26% of the worldwide use of algae cultivating technologies (Singh & Gu, 2010).

Many of the issues with growing algae in open ponds has to do with the inability to control the growing environment for the algae. Exposure to the elements risks contamination from pollution which enters from outside the system, and contamination and dominance by an external strain of algae or other unwanted organism (Ugwu, Aoyagi, Uchiyama, 2008). Because the water is exposed to the air, large amounts of water will evaporate and need to be replaced on a regular basis (USDOE, 2010).

A major concern for growing algae in Ontario is the heating requirements to maintain growth rates. Winter temperatures in Hamilton, for example, usually fluctuate between -1 to -10^{o}C (Environment Canada, 2012). Rosenberg et al. (2011) did a feasibility study for an algal biomass production plant in Idaho, on the south shore of lake Erie. They found that even after using the waste heat stream from an ethanol biorefinery, 70% or more of the annual operating costs would still go towards maintaining adequate heat conducive to algal growth. Their study used open raceways, though, so the heating requirements may be significantly lowered using an enclosed photobioreactor.

Cultivation in photobioreactors

Photobioreactors (PBRs) are closed systems which allows for much better control over the growth environment. They come in many shapes and sizes, such as tubular, flat, and column (Brennan and Owende, 2010). With tubular PBRs the algal medium circulates through tubes 0.1m or less in diameter and aligned vertically, horizontally, inclined or in a helix. Flat plate PBRs flow the algal medium over a flat plate. Column PBRs are similar to vertically aligned tube PBRs but instead of the algal medium flowing, it is the gas which is moving through the tube as it is aerated in through the bottom, and waste oxygen from the algae is offgassed at the top. The largest hurdle to PBRs is the high capital cost for construction - upwards of ten times the cost of an open pond system - but the greater control translates to higher yields compared to open ponds (Abayomi, Tampier, Bibeau, 2009). Notwithstanding this issue, PBRs account for 52% of the algae cultivating technologies used worldwide (Singh & Gu, 2010).

Harvesting/separation

The small size of microalgae makes harvesting them from the water a costly, energy intensive step, accounting for up to 30% of algal biofuel production costs (Abayomi, Tampier, Bibeau, 2009). There are four types of methods for this process: mechanical, chemical, electrical and biological (Christenson & Sims, 2011).

The main mechanical harvesting techniques are sedimentation/floatation, centrifugation, filtration, and immobilization. Sedimentation and floatation simply require making the algae-containing mixture still and waiting for the algae to settle to the bottom or rise to the top of its container. This is a very slow process, and due to differing buoyancy rates between strains of algae, its effectiveness is also unpredictable (Christenson & Sims, 2011). Centrifugation improves the speed and effectiveness of this process by spinning the algae-containing water at high speed, but this comes at the expense of being highly energy intensive and having a high capital and maintenance costs (Brennan & Owende, 2010). Filtration involves the use of a membrane which allows water to pass through, but not the algae. Because of the algae's small size, the filters are expensive and clog quickly, making membrane replacement a costly concern. A similar approach would be to trap and grow the algae directly in a alginate, agarose, polyacrylamide or some other immobilizing material such as is used in wastewater treatment (de-Bashan & Bashan, 2010). The extra costs for the material, and the extra step of implanting and removing the algae from the material make this solution unlikely to prove financially viable.

Chemical flocculants require the addition of a chemical such as aluminum sulfate or ferric chloride. The +3 charge of the aluminum or iron will cause the algae to coagulate and then flocculate out of solution (Brennan & Owende, 2010). Depending on the downstream processing of the algae, or intended coproduct uses, the presence of these heavy metals in the final product may be problematic.

Another way to take advantage of the negative charge of algal cells is through the use of electrophoresis. This electrical method uses a magnetic field to pull the algae out of solution. Again, the high energy and equipment costs are prohibitive to making this technology useful for large-scale operation. (Uduman et al. 2010).

Biological harvesting can be accomplished by using pH, biopolymers, or microbes to act as a flocculant to precipitate the algae out of solution (Christenson & Sims, 2011). This type of solution is dependant on the characteristics of the specific strain being used.

One particularly unique biological solution is to have planktivorous fish such as tilapia eat the algae, then harvest the fish and extract the oil from the fish (Livefuels, 2011); however, killing animals to power car would certainly raise some ethical concerns.

Drying

Depending on the process used for oil extraction, once the algae has been separated from the bulk of the water, it must be further dried. Simply laying the algae out in the sun is the most straightforward solution, but it takes a long time, requires a great deal of space, and the algae is susceptible to being eaten by animals (Prakash et al., 1997). Other options exist, such as spray drying and freeze drying, but these are prohibitively expensive for a biofuel application (Brennan & Owende, 2010).

Oil extraction

Once the algae have been prepared, they are ready to have their oils extracted. The most commonly considered methods are using an oil press, solvent, ultrasound, and supercritical fluid extraction (Singh & Gu, 2010). The oil press for extracting oil from algae is the same as would be used for extracting oil from seeds and nuts (Singh & Gu, 2010). Pressing is, however, a slow process not conducive to the high volume, low cost required for biofuel production. Solvents like hydrochloric acid and sodium hydroxide can be used to break apart the cell wall and/or membrane, spilling the cell's contents into solution (Brennan & Owende, 2010). Once the cell is open, the oil rises to the top and the biomass sinks to the bottom making it easy to retrieve both and reuse the water. Ultrasound extraction works on a similar principle. OriginOil is a commercial example using ultrasound, electromagnetic pulses and pH modification via CO2 to break apart the algal cell wall and separate the oil from the biomass (OriginOil, 2012). Solvents and ultrasound are less effective techniques when the cell membrane and cell wall of the algal strain are stronger. Supercritical methods, as described below, may also be used.

Upgrading

Energy is stored in algae in the form of TAGs (triacylglycerols) which are composed of three fatty acid chains attached to a glycerol backbone (Sheehan et al., 1998). The fatty acids must be removed from the backbone, then modified to fuel through one of a number of different channels. Cracking, or hydrocracking produces gasoline or jet fuel using the same processes and facilities as are used in the petroleum industry (Tran et al., 2009). Transesterification happens in the presence of heat and a strong base catalyst according to the following (Ramachandran et al., 2009):

triglycerides + free fatty acids + alcohol ---> alkyl esters + glycerine

The alkyl esters are separated by a vaporizer under high vacuum, and the biodiesel is ready for use in an unmodified diesel engine (USDOE, 2010).

Research is also underway investigating the use of supercritical methods to convert the TAGs into biodiesel. High pressure (e.g. 100-300 bar) and high heat (350-450 ^{o}C) applied to algal oil in the presence of a stoichiometric quantity of methanol will produce biodiesel (Deshpande et al., 2010). Although the operating costs appear to be cheaper (11¢/L vs 13¢/L for conventional methods) the technology is unproven in large-scale.

The need for development

These steps of cultivation, harvesting/separation, drying, extraction, and upgrading currently involve too many capital costs and energy inputs to be cost competitive with traditional fuels. However, the technology is still new, and there is a great deal of room for innovation and development to overcome this challenge.

Future Developments

The next step

Major developments must make algal biofuel significantly cheaper to produce if biofuel is to compete with fossil fuel in the marketplace. Even after accounting for the related emissions, food prices, pesticide/fertilizer use and supply security, the cost of producing algal biofuel was found by one study to be over three times the cost for an equivalent amount of energy from fossil fuels (Kovacevic & Wesseler, 2010).

One promising avenue to overcome many of the hurdles associated with algae-based biofuels is to add three functions to the algae (Robertson et al., 2011):

1) A switch to flip between growth and alkane production

2) Direct alkane production

3) An alkane secretion method

Advances in genetic engineering of the algal cytoplasmic DNA (Robertson et al., 2011), or chloroplast DNA (O'Neill et al., 2011) make this ever more possible. Bringing these three traits together in one algal strain will overcome many of the barriers associated with biofuel production.

Production switch

Algae must split their limited energy resources between promoting growth and storing the energy for the future in the form of oil. Since investigation into algae as a producer of biofuel began, a main focus has been to find the trigger which makes the algae produce oil (Sheehan et al., 1998). The ideal situation would be one where the algae's growth function could be used to achieve a critical mass, and then a switch could stop growth and have all of the algae's energy directed towards producing oil.

Direct alkane production

As discussed above, once algal oil is separated from the biomass, it must be upgraded to convert it from a TAG to the hydrocarbon forms required for combustion in an engine. Through selective breeding and/or genetic engineering, algae can be modified to directly produce alkanes or other hydrocarbons instead of fatty acids. Certain microorganisms are known to do this naturally. Schirmer et al. (2010) were able to isolate the genetic coding for the acyl-cyl carrier protein reductase and the aldehyde decarbonylase which are necessary and sufficient for this metabolism to occur in *Escherichia coli*. Isolating the genetic code was a significant step towards expressing these genes in algae and avoiding the need to upgrade algal oil after it is produced.

Alkane secretion

The harvesting and drying of algal biomass, followed by oil extraction from the biomass are energy intensive steps, typically accounting for 70-80% of the total cost of biofuel production (Molina Grima et al., 2003). One way to significantly bring down the costs of biofuel production would be to find a way around these processes. As noted by Ramachandran et al. (2009), "[w]e do not harvest milk from cows by grinding them up and extracting the milk. Instead, we let them secrete the milk at their own pace, and selectively breed cattle and alter their environment to maximize the rate of milk secretion." Liu et al. (2010) have found that by genetically engineering cyanobacteria to include a mutant of an *E. coli* acyl–acyl carrier protein (ACP) thioesterase (TE), they were able to derive an organism that continuously secreted oils which could then be collected from the culture medium. This is similar to the approach the commercial enterprise LS9 is using, with the major difference being that LS9 uses bacteria (LS9, 2011). As the oil is produced and is secreted from the cell, it will form a layer of oil on top of the mixture which can easily be separated. The large energy and financial costs associated with harvesting, drying and extracting the oils would be vastly reduced if algae could likewise be modified to transport the product out of the cell.

Commercial ventures

The use of genetic engineering to increase the yields from cultivation and avoid the capital and energy costs associated with harvesting/separation, drying, extraction, and upgrading holds great potential in making algal biofuel a viable option. Two companies pursuing this path are Joule Unlimited and Synthetic Genomics. Joule Unlimited recently received $70 million to commercialize their technology which is currently obtaining approximately 1,500 gallons per acre per year (McKenna, 2012). They calculate a practical maximum solar conversion efficiency of 7.2%, which translates into 15,000 gallons/acre/year (Robertson et al., 2011). In partnership with ExonMobil, Synthetic Genomics is another company well positioned to leverage its strengths in genome sequencing to make significant inroads towards making algal biofuels an economically and environmentally superior alternative to fossil fuels (ExxonMobil, n.d.). These companies will still require time, resources, and a conducive environment to realize their potential. Government policy will play a key role in facilitating this.

Policy

Current policy

Algal biofuel offers great potential for sustainably decreasing the current dependancy on oil. Algal biodiesel is poised to become a significant source of energy, contributing upwards of 20% to our energy needs by 2040 if it receives strong support from governments in developed countries (Lee, 2011). Much research and development still needs to be done, however, before this technology can be scaled up enough to produce fuel which is cost competitive with oil. Implementation of appropriate policy changes is required to accelerate this process. The main tools which government has at its disposal are tax incentives, mandates and enforcement mechanisms, government purchases, the establishment of fuel quality standards, accounting of externalities, public-private partnerships, and public awareness (Worldwatch, 2006). The Canadian government currently has a number of programs applicable to algal biofuel production which make use of these tools.

Commercialization of a product requires that there be a market for it. A market for biofuels was encouraged through the Renewable Fuels Regulation (Canada, 2010), which states that 5% of gasoline much be from renewable sources. This allotment is currently being filled primarily by first and second generation biofuels, but algal biofuels also qualify. The federal government has committed to using its purchasing power to encourage the biofuel industry as well. In section three of the 2006 Alternative Fuels Act it states that when it is economically feasible to do so, "... seventy- five per cent of motor vehicles operated by all federal bodies and Crown corporations will be motor vehicles operating on alternative fuels ... “(Canada, 2006).

Four separate programs provide funding to encourage the development of the biofuel industry in Canada. $186 million has been set aside for the ecoAgriculture Biofuels Capital Initiative (ecoABC) which provides up to $25 million per project to assist farmers in constructing or expanding a renewable fuel production facility (Agriculture and Agri-Food Canada, 2011). The ecoEnergy for Biofuels Initiative (ecoEnergy) was established to encourage the biofuel industry, and has $1.5 billion over 9 years earmarked for this purpose. Sustainable Development Technology Canada (SDTC) has $500 million over 8 years to assist in the construction of large scale, next-generation renewable fuels facilities. A further $10 million over two years was made available for renewable fuel research and analysis (Canada, 2010). All together this adds up to just under $2.2 billion in funding over the life of the programs.

Policy changes

There are a number of policy changes which would further spur the development of biofuels in Canada. In 2008, Canadian federal and provincial governments provided $2.84 billion in subsidies to the oil industry (IISD, 2010). This is more money per year given to a mature industry than is set aside for the entire lifetime of the biofuel subsidies. At the 2009 G20 meeting in Pittsburgh, leader’s agreed that “[i]nefficient fossil fuel subsidies encourage wasteful consumption, reduce our energy security, impede investment in clean energy sources and undermine efforts to deal with the threat of climate change" (G20, 2009). Following through on this commitment and removing these subsidies will level the playing field and create a fairer marketplace in which biofuels can better compete.

Interest in biofuels began due to the oil crises of the 1970s. Once the price of oil dropped back down, the financial incentive to find alternatives, and therefore the interest in biofuels, also dropped (Timilsina & Shreshtha, 2011). If biofuel becomes a threat, it is possible that OPEC may drop the price of oil to once again decimate investment and progress in biofuels. Setting a basement price on the value of a barrel of oil would provide investors with the confidence that their efforts will not be undermined by fluctuations in oil prices. This confidence would translate into more dollars invested in developing the technology and market for biofuels.

Burning fossil fuels emits CO_2 into the atmosphere which was previously stored in hydrocarbons underground. While there are, and will continue to be economic costs associated with these emissions, in Canada these are not borne by the producer or consumer of those fossil fuels. The Kyoto Protocol tried to put a price on creating carbon emissions, but this has recently been rejected by the Canadian government (Postmedia News, 2011). The main impetus to develop biofuel is to avoid contributing to the atmospheric buildup of greenhouse gasses leading to climate change. Charging for carbon emissions will further reduce the advantage given to the fossil fuel industry and provide a clearer signal of the benefits biofuels have to offer.

Conclusion

Oil has played a pivotal role in human progress, but the need to develop a cleaner, more dependable alternative is clear. Great hopes were placed in first and second generation biofuels to provide a locally grown, carbon neutral replacement. However, issues associated with fertilizer and pesticide use, land use change, food security, competition with food for arable land, and water requirements have shown the limitations of these solutions. Algal biofuel is uniquely positioned to meet the increasing demand for transportation fuel, increase energy security, increase local jobs, and be carbon neutral. There is still a great deal of work to be done before this potential can be realized, however, both from a technical perspective, and from a policy perspective. The high production costs and market obstacles in particular need to be diminished if algal biofuels are to become a viable alternative to fossil fuels. Policy changes will be crucial in spurring the development of this technology in order to reap the vast rewards offered by transitioning to algal biofuels.

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