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Biodiesel: Algae as a Renewable Source for Liquid Fuel

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The world is facing declining liquid fuel reserves at a time when energy demand is exploding. As supply dwindles and costs rise, nations will be forced to utilize alternative energy sources. Coal, both non-renewable and environmentally destructive, is the most likely near-term candidate for replacing oil as a primary energy source. In order to achieve a secure and stable energy supply that does not cause environmental damage, renewable energy sources must be explored and promising technologies should be developed. Biodiesel derived from green algae biomass has the potential for high volume, cost effective production. It can be carbon neutral and produced intensively on relatively small areas of marginal land. The quality of the fuel product is comparable to petroleum diesel and can be incorporated with minimal change into the existing fuel infrastructure. Innovative techniques, including the use of industrial and domestic waste as fertilizer, could be applied to further increase biodiesel productivity.

I. Introduction

The world is entering a period of declining non-renewable energy resources, popularly known as 'Peak Oil', while energy demand is increasing. The world's oil production is expected to decline in between one and ten decades (Crookes, 2006). As a result of this impending energy crisis, both governments and private industry are examining alternative sources of energy. Other non-renewable sources of energy exist, such as coal and uranium; however, these sources are limited and will also inevitably decline in availability.

Coal is the likely immediate candidate for replacing oil as an energy supply. It is energy rich, can be converted to liquid fuel, and is still very abundant. It is particularly plentiful in the United States, China, and India. These three countries are heavily industrialized and have ever-increasing energy demands. The transition to coal is already under way with the planned construction of dozens of new coal fired power plants in these three countries alone (Clayton, 2004).

Our reliance on fossil fuels has caused carbon dioxide (CO_2) enrichment of the atmosphere, and is the primary contributor to the generally-accepted phenomenon called global warming. Because using coal produces even greater CO_2 emissions than oil, the depletion of oil will be unlikely to improve this pattern of CO_2 enrichment.

In order to realize a stable energy alternative that will meet world demand while mitigating climate change, it is necessary to develop renewable clean fuels. Ironically, most renewable energy initiatives are focused on electricity generation, while the majority of world energy consumption, about two thirds, is derived from liquid fuels (Hankamer et al., 2007). The need for renewable sources of portable, liquid fuel is starting to receive greater attention, and much of this attention has been focused on biomass-derived liquid fuels, or biofuels (Schneider, 2006; Haag, 2006). Government organizations and major corporations are beginning to seriously invest in the biofuels market, in both research and commercial production; however, the many existing alternatives such as ethanol, hydrogen, and conventional biodiesel fail to be cost competitive with petroleum (Scott and Bryner, 2006).

This research paper examines the feasibility of biodiesel as a potential replacement for petroleum-based liquid fuels. In particular, the use algae as a source of biomass for fuel production is investigated, in terms of its productivity, practicality, and innovative potential to create a cost competitive, environmentally friendly, and renewable source of liquid fuel.

II. Biodiesel

Biodiesel is a biofuel consisting of monoalkyl esters that are derived from organic oils, plant or animal, through the process of tranesterification (Demirbas, 2007). The biodiesel transesterification reaction is very simple:

$$\text{Triglyceride} + 3\ \text{Methanol} \xleftrightarrow{\text{Catalyst}} \text{Glycerine} + 3\ \text{Methyl Esters (Biodiesel)}$$

This is an equilibrium reaction where an organic oil, or triglyceride, can be processed into biodiesel, usually in the presence of a catalyst, and alkali such as potassium hydroxide (Christi, 2007; Demirbas, 2007). An excess of methanol is used to force the reaction to favour the right side of the equation. The excess methanol is later recovered and reused. At 60 ˚C, the reaction can complete in 90 minutes.

The triglyceride is a complex molecule that plants and animals use for storing food energy; in more simple terms, it is fat. The process of making biodiesel occurs as follows: A) the triglycerides, methanol, and catalyst are placed in a controlled reaction chamber to undergo transesterification, B) the initial product is placed in a separator to remove the glycerine by-product, C) the excess methanol is recovered from the methyl esters through evaporation, and D), the final biodiesel is rinsed with water, pH neutralized, and dried (Xu et al., 2006).

Unlike petroleum fuels, the relative simplicity of biodiesel manufacture makes its production scalable. Many existing vendors are small time producers. Biodiesel is a somewhat 'mature' fuel, and was used as a diesel alternative in the early twentieth century (Demirbas, 2007). This has allowed biodiesel to attain a level of 'grassroots' popularity among environmental advocates and visionaries.

The energy density of biodiesel is comparable to petroleum diesel. The high heating value of petroleum diesel is 42.7 MJ/kg. Values for biodiesel vary depending on the source of biomass. Typically, biodiesel derived from seed oils, such as rapeseed or soybean produces, 37 MJ/kg, while biomass derived from algae yields 41 MJ/kg (Rakopoulos et al., 2006; Xu et al., 2006). Although the lower energy biodiesels based on seed oils are the most common, they have enough energy density to make them a viable alternative to petroleum diesel.

Adopting biodiesel has a number of advantages. Firstly, because the fuel is derived from biomass, it does not contribute to atmospheric CO_2 emissions. Second, biodiesel emissions are, on the whole, lower than petroleum diesel. Substituting biodiesel for petroleum diesel results in substantial reductions of soot, sulphur, unburned hydrocarbon, and polycyclic aromatic hydrocarbon emissions (Rakopoulos et al., 2006; Aresta et al., 2005; Demirbas, 2007). Third, the infrastructure needed for biodiesel already exists. Biodiesel can be used in existing diesel engines blended with petroleum diesel, or can be run unblended in engines with minor modifications (Crookes, 2006; Rakopoulos et al., 2006; Bowman et al. 2006). Because biodiesel has twice the viscosity of petroleum diesel, its lubrication properties can actually improve engine life (Bowman et al. 2006). Fourth, biodiesel has low toxicity and is biodegradable (Aresta et al., 2005; Demirbas, 2007). Fifth, like petroleum diesel, biodiesel has a more complete combustion than gasoline, giving a cleaner burn (Bowman et al., 2006).

Biodiesel is not without problems. First, it does produce increased NO_x emissions, relative to petroleum diesel, owing to the higher compression ratios typically used in biodiesel engines (Crookes, 2006; Pradeep and Sharma, 2007). Second, using biodiesel does reduce the power output of a diesel engine compared to using petroleum diesel; although this is only around 2% overall (Schneider, 2006). Third, the production of biodiesel results in glycerine by-products and wash wastewater. Fourth, the price of biodiesel is typically higher than petroleum diesel. Although scale of production is a contributing factor, the high cost of biomass is the most important consideration. The rising cost of oil is changing this imbalance and in 2007, both fuels have ranged between $3.00 to $3.50 U.S. per gallon (Energy Information Administrator, 2007; U.S. Department of Energy, 2007). Fifth, and most importantly, the biomass feed stocks for making biodiesel are diverted from other important uses, typically food production. This can force a trade off between food security and energy security.

The increasing competitive advantages of biodiesel are raising interest among investors and consumers alike. This interest has been expressed through a booming market:

> "The global biodiesel industry is among the fastest-growing markets the chemical industry has ever seen … world capacity, production, and consumption of biodiesel grew on average by 32%/year during 2000-05, and the industry looks set for even faster growth rates …" (Scott and Bryner, 2006).

Biodiesel can be made from virtually any source of organic oil. Typical sources include restaurant waste oil, animal fats, and seed oils. The supply of waste oil is very limited; however, it is a popular source for small scale, independent producers. Large commercial producers often use seed oils, such as soybean, rapeseed, palm, and corn oils. Unfortunately, biodiesel derived from seed oil diverts from the food supply and the increasing competition for seed causes the oil, and resulting biodiesel, to become increasingly expensive.

It has been estimated that 0.53 billion m^3 of biodiesel would be needed to replace current US transportation consumption of all petroleum fuels (Christi, 2007). Neither waste oil nor seed oil can come close to meeting the requirement for that much fuel; therefore, if biodiesel is to become a true replacement for petroleum, a more productive source of oil is needed (Scott and Bryner, 2006; Christi, 2007).

III. Algae as a Source of Biomass

The algae that are used in biodiesel production are usually aquatic unicellular green algae. This type of algae is a photosynthetic eukaryote characterized by high growth rates and high population densities. Under good conditions, green algae can double its biomass in less than 24 hours (Christi, 2007; Schneider, 2006). Additionally, green algae can have huge lipid contents, frequently over 50% (Christi, 2007; Schneider, 2006). This high yield, high density biomass is ideal for intensive agriculture and may be an excellent source for biodiesel production (See Table 1).

Table 1. A comparison of the oil content found in green algae. Oil content is only one criterion for selecting the species for cultivation. Growth rate, density, and survivorship must also be considered. (Data from Christi, 2007)

Species	*Oil Content (% based on dry weight)*
Chlorella sp.	28 - 32
Nitzschia sp.	45 - 47
Nannochloropsis sp.	31 - 68
Schizochytrium sp.	50 - 77

The annual productivity and oil content of algae is far greater than seed crops. Soybean can only produce about 450 litres of oil per hectare. Canola can produce 1,200 litres per hectare, and Palm can produce 6000 litres. Now, compare that to algae which can yield 90,000 litres per hectare (Christi, 2007; Haag, 2006; Schneider, 2006). It is possible that the U.S. demand for liquid fuel could be achieved by cultivating algae in one tenth of the area currently devoted to soybean cultivation (Scott and Bryner, 2006).

Algae have a number of unique benefits. As an aquatic species, they do not require arable land for cultivation. This means that algae cultivation does not need to compete with agricultural commodities for growing space. In fact, algae cultivation facilities can be built on marginal land that has few other uses. The water used in algae cultivation can be fresh water or saline, and salt concentrations up to twice that of seawater can be used effectively (Brown and Zeiler, 1993; Aresta et al., 2005). This means that algae need not compete with other users for fresh water. Algae also have a greater capacity to absorb CO_2 than land plants, and are also not prone to photosynthetic inhibition under conditions of intense sunlight (Brown and Zeiler, 1993).

After oil extraction from algae, the remaining biomass fraction can be used as a high protein feed for livestock (Schneider, 2006; Haag, 2007). This gives further value to the process and reduces waste.

Algae cultivation is typically performed in two ways; open ponds and bioreactors. Open race-way based ponds are the preferred method of large scale algae cultivation, and they have been used since the 1950's to produce food supplements and pharmaceuticals (Christi, 2007). A paddlewheel circulates the material down a raceway while providing aeration, mixing, and preventing the material from settling on the bottom (figure 1). This is a relatively simple system that uses the sun as the primary energy source. Unfortunately, race-way system suffers from relatively low algae densities, environmental variability, water evaporation, and a high land foot print (Christi, 2007; Haag, 2007). Because the ponds are open to the environment, maintaining specific species of algae, to the exclusion of others, can be difficult (Haag, 2007).

Bioreactors are the preferred method for scientific researchers, and recently for some newer, innovative production designs. These systems are more expensive to build and operate; however, they allow for a very controlled environment (figure 2). This means that gas levels, temperature, pH, mixing, media concentration, and light can be optimized for maximum production (Christi, 2007). Unlike open ponds, bioreactors can ensure a single alga species is grown without interference or competition.

Biodiesel production from biomass sources has a number of problems. First, most biomass sources, such as waste oil, animal fat, and vegetable oil have a limited supply (Ma and Hanna, 1999). Second, many of these sources have competitive uses, such as food or cosmetic production. Third, the resources that were used to create the biomass have competition with other uses, and this includes arable land. Third, because of the limited supply and competition, many sources of biomass have become increasing expensive (Haag, 2006).

Algae cultivation has the potential to address all of these issues. First, algae biomass can be produced at extremely high volumes and this biomass can yield a much higher percentage of oil than other sources. Second algae oil has limited market competition. Third, algae can be cultivated on marginal land, fresh water, or sea water. Fourth, innovations to algae production allow it to become more productive while consuming resources that would otherwise be considered waste.

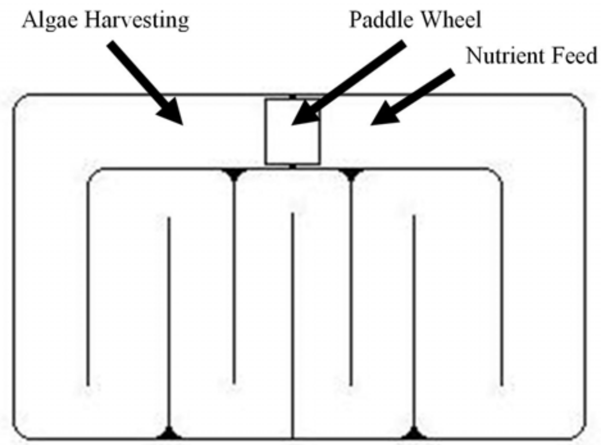

Figure 1. A simplified raceway pond design (Modified from Christi, 2007).

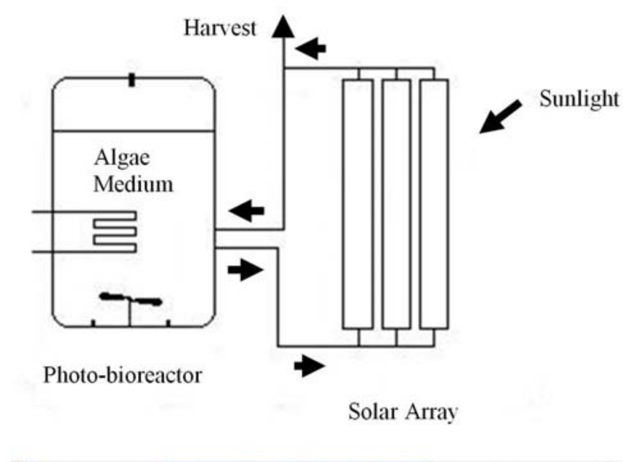

Figure 2. A simplified photo-bioreactor design (Modified from Christi, 2007).

Because of its recognized potential, algae cultivation is being investigated in large pilot projects, both public and private, to determine if it may be the key to providing large quantities of oil-rich biomass for biodiesel production. This strategy is by no means recent. The idea of cultivating algae for the purposes of biodiesel production was first seriously investigated by the U. S. Department of Energy's Aquatic Species Program. This eighteen year program, started in 1978, attempted to identify the species and conditions that would maximize oil yield while minimizing capital input (Sheehan et al., 1998; Schneider, 2006). Advancements were made in algal physiology, biochemistry, molecular biology, and cultivation. The project also yielded a collection of high oil producing species. The research was performed in open ponds and the yields were in the range of 30 g m^{-2} d^{-1}. Although this project is no longer in operation, it has provided an excellent research base for new initiatives.

The economic environment has changed since the Aquatic Species Program was terminated, and changed in a way to make algae cultivation more cost competitive. High oil prices, low biofuel feedstock, and high government incentives are improving the outlook for private investors interested in algal biodiesel (Haag, 2007). Large energy corporations, such as NRG Energy, Inc., have already begun pilot projects (NRG Inc., 2007). Governments, seeking fuel security and climate change mitigation, are also initiating new algae-based biofuel projects through policy and investment (Scott and Bryner, 2006).

IV. Innovative Approaches to Improving Yields

Algae cultivation has four basic, and equally important, requirements: carbon, water, light, and space. By maximizing the quality and quantity of these requirements, it is possible to maximize the quantity of oil-rich biomass and the return on investment. Ironically, this can often be done by using underutilized resources or waste products, which can provide additional benefits or even offset the cost of production. This requires innovative approaches. Because maintaining idea growth conditions requires a highly controlled environment, new and innovative approaches to algae production tend to use bioreactors. Although this increases complexity and cost, it has resulted in some very impressive results, doubling or even tripling the 30 g m^{-2} d^{-1} yields obtained in the Aquatic Species Program (Schneider, 2006).

Carbon, from carbon dioxide (CO_2), is the first requirement. In order to maximize algal growth, CO_2 needs to be provided at very high levels, much higher than can be attained under natural conditions. Rather than becoming an expense, this need for CO_2 fertilization creates a unique opportunity to offset costs by consuming air pollution. The flue gases from industrial processes, and in particular from power plants, are rich in CO_2 that would normally be released directly into the atmosphere and thereby contribute to global warming. By diverting the CO_2 fraction of the flue gas through an alga cultivation facility, the CO_2 can be diverted back into the energy stream and the rate of algal production can be greatly increased (Pulz, 2007). Although most of the CO_2 will ultimately be deposited in the atmosphere, we can realize a greater energy return for each molecule of carbon. The ultimate goal, of course, will be to provide greater return on investment for the algae cultivation facility. This process is being investigated at several sites using both bioreactor designs and open ponds (Schneider, 2006).

Water, containing the essential salts and minerals for growth, is the second requirement. Fresh water is a valuable resource as are the salts and minerals needed; however, algae cultivation can be coupled to another type of environmental remediation that will enhance productivity while mitigating pollution. High nutrient wastewater from domestic or industrial sources, which may already contain nitrogen and phosphate salts, can be added to the algal growth media directly (Schneider, 2006). This allows for algae production to be improved cheaply, while simultaneously treating wastewater. Alternately, salt water can be used, either from saline aquifer or sea water. This means that competition for water will be low.

Abundant light, which is necessary for photosynthesis, is the third requirement. This is often accomplished by situating the facility in a geographic location with abundant, uninterrupted sunshine such as the American Southwest (Brown and Zeiler, 1993). This is a favoured approach when cultivating in open ponds. When working with bioreactors, sunlight quantity and quality can be further enhanced through the use of solar collectors, solar concentrators, and fibre optics in a system called photo-bioreactors (Scott and Bryner, 2006; Christi, 2007). These technologies allow optimal sunlight to reach the algal cells either by allowing them to float in arrays of thin, horizontal tubes or by directing light, through a fibre optic matrix, through the bioreactor chamber itself.

Space is the fourth requirement. Other biomass sources require terrestrial cultivation on valuable arable land. This causes a diversion of agricultural produce from the food supply to the energy supply and increases cost of production. Algae cultivation is unique in that it does not require arable land; algae can be cultivated in ponds, in fresh or salt water bodies, or in bioreactors. This versatility means that an algae production facility can theoretically be located any where there is cheap, available land. Bioreactor facilities have a comparatively low footprint (Christi, 2007).

Through a combination of these light, water, and carbon fertilization techniques, the production of high density algae is starting to be achieved. Two experimental facilities, the Oakridge National Laboratory and the ASP Red Hawk Power Plant, have demonstrated very high yields using advanced photo-bioreactor based designs. The Oakridge National Laboratory yields 60 $g\ m^{-2}\ d^{-1}$ of algae, and the APS Red Hawk Power Plant yields algae with an astounding average of 98 $g\ m^{-2}\ d^{-1}$ (Schneider, 2006; Pulz, 2007).

Laboratory studies, exploring methods to maximize both density and oil content, have demonstrated that there is yet much unrealized potential. Xu et al. (2006) cultivated the algae *Chlorella protothecoids* in a light deprived, heterotrophic environment with inexpensive hydrolyzed corn starch as the sole food source. The algae were not only able to adapt to this environment, they reached a high population density of 15.5 g/L. As the algae adapted to the environment, they lost their photosynthetic organelles and almost doubled their oil content, going from 30% to 55.3%. The significance of research such as this is that it demonstrates that algae cultivation is still in its infancy. With time and experience, algae cultivation should be able to achieve dramatic improvements in density, growth rates and oil production. This will require improved growing methods, species selection, cultivation techniques, and bio-engineering.

V. Conclusion

Biodiesel has great potential; however, the high cost and limited supply of organic oils prevent it from becoming a serious competitor for petroleum fuels. As petroleum fuel costs rise and supplies dwindle, alternative fuels will become more attractive to both investors and consumers. For biodiesel to become the alternative fuel of choice, it requires an enormous quantity of cheap biomass. Using new and innovative techniques for cultivation, algae may allow biodiesel production to achieve the price and scale of production needed to compete with, or even replace, petroleum.

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