Biofuels: A Look into the Future of Sustainable Transportation

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Introduction

With growing concerns over finite oil supplies and global climate change, scientists have begun to look to alternative, more sustainable fuel sources. One such source that has garnered recent media attention is "biofuel", or any fuel derived from living matter. Although gasoline itself is a biofuel (derived from ancient decayed plant matter), it is becoming clear that reliance on this energy source will not support our needs indefinitely. Non-fossil biofuels are an attractive alternative because their feedstocks, or raw materials, are things readily available on the planet's surface. While in most cases this would be plant matter, new research is showing that, in addition to certain plants, algae and certain anthropogenic waste products can be made into biofuels as well. Through literature review and analysis, this paper will describe and compare four different sources of biofuels in attempts to explore the future of energy worldwide.

LCA

Life cycle assessments (LCAs) have become the standard measurement for many commercially produced goods; biofuels are no exception. By accounting for every input from the raw materials to the finished fuel, LCAs are exhaustive in their analysis of biofuels production, from seeds to wheels. These analyses form the basis of the conclusions and recommendations stated in the corresponding section. For the sake of clarity and brevity of this review, some assumptions have been made. These assumptions are as follows:

- that the crop in question is grown in its ideal climate (eliminating the irrigation water variable)
- that the crop is grown on already-established farmland (eliminating the land-use change variable); and
- that the amount of fuel for planting, harvesting, and transporting the crops is constant in all cases.

The intention of these assumptions is to facilitate easier comparisons between types of biofuel based on variables from the *nature* of the fuel analyzed. Further, it is critical to note that neither algal nor upcycled biofuels require land-use change or rely on an "ideal climate" for water and temperature requirements. Therefore, the aforementioned assumptions are ideal for creating a level playing field on which these four feedstocks can be compared objectively.

Types of Biofuel

Ethanol

Ethanol is a first generation biofuel, meaning that it is formed directly from freshly-harvested plant material. This conversion takes place during microbial anaerobic metabolism of plant-derived sugars and starches. 61% of bioethanol produced world-wide is obtained from sugar cane while the remaining 39% is produced from different cereals such as sorghum and corn (Copello, 2007). Ethanol can also be produced from agricultural crops such as corn, potato, and sugar cane. The molecular formula for ethanol is CH_3CH_2OH (EtOH). Once the ethanol has undergone the fermentation process, the next step is distillation. Distillation takes place in a still where water and fermented ethanol are heated to separate the two substances. Because fermented ethanol evaporates more rapidly than water, the evaporated ethanol can be collected in a separate chamber. Removing the unnecessary water produces a more pure and useful ethanol fuel (Kvaalen, et al., 1984).

Ethanol is a transportation fuel, meaning it is mixed with diesel fuel and gasoline. Through this mixing, less petroleum fuels are burned. However, ethanol is more expensive than fossil fuel, but is a cleaner burning fuel that creates less dangerous emissions. Today, almost all gasoline sold in the U.S. has some ethanol mixed in, up to 10% ethanol mixed with 90% gasoline at most gas stations across the country (Biofuels, 2014).

One major concern about ethanol as a biofuel is the competition between crops being used for food production and crops being used for fuel energy. This is of concern because large amounts of land are required to produce crops for ethanol. If these lands are then being used to produce crops for ethanol as a biofuel, then they are not being used for food production. This could result in an increase in food prices.

Biodiesel

Biodiesel is an alternative fuel made from an organic oil, be it plant- or animal-derived. In standard diesel engines it can replace standard petrodiesel in a 1:1 ratio, although it is more commonly used in a mixture to stretch the mileage (Cherubini, 2009). The production of diesel from the oilseeds requires a pre-drying phase in which the seeds are partially desiccated to facilitate easier oil extraction. They are then pressed to extract most of the available vegetable oil, and the residual oil in the cakes is removed with hexane; the leftover meal contains protein and can be sold as animal feedstock. The resulting oil is pretreated with a small amount of concentrated phosphoric acid, which removes unwanted phospholipids and certain heavy metals; it is then processed into biodiesel via transesterification (Requena et al., 2011).

The transesterification process reacts triglycerides with methanol in the presence of a strong base catalyst to produce a mixture of fatty acid methyl esters (biodiesel) and a side-product, glycerin. The glycerin can be further purified to reach pharmaceutical quality and sold (Requena et al., 2011). Comparisons of several different LCAs and reported values indicate that this entire process requires about 10.6 megajoules of energy per liter of biofuel produced (Pradhan et al., 2011).

Although essentially any oleaginous crop can be used as a feedstock for biodiesel, this review focuses on four plants chosen for their prevalence in current agriculture systems, desirable climatic requirements, or unique physiology.

Glycine max (Soybean)

Soybean has been used in the United States as an oilcrop since as early as the 1940s ("Soybean as a Biodiesel Feedstock", 2009). Although it has a relatively low oil yield (20% of the seed weight), it remains the most-produced oilcrop in the United States due to the high protein content in its meal, an impressive 40% (Requena et al., 2011). This makes the meal a very attractive additive to cattle feed and has been factored into this analysis.

Soybeans, an annual crop, require full sun, a soil temperature around 60 °F, and ambient temperatures between 60-70 °F for optimal growth. They are frost intolerant. Under these conditions, the dry beans can be harvested in as little as 100 days (Albert, 2009). Because they are a legume and have a symbiotic relationship they have with certain nitrogen-fixing bacteria, soybeans generally require less nitrogen fertilizer inputs than other crops (Requena et al., 2011).

Brassica napus (Rapeseed)

Rapeseed (a very close relative of canola) is a temperate, annual oilcrop and stars as the most common source of biodiesel in Europe. It is a desirable crop in a rotation because of its deep tap roots that help churn the soil and extract nutrients from relatively large depths (Herkes, 2014). Its seeds are generally about 40% oil by weight and its meal ranges between 35-40% protein; it is already part of many large-scale farm operations throughout the North American Great Plains (biofuelstp.eu, n.d.).

Camelina sativa (False Flax)

This annual broadleaf oilseed grows optimally in temperate climates and has lower fertilizer, pesticide, and water requirements than rapeseed and soybean, and an oil content of 43.9% by weight (Ciubota-Rosie et al., 2013). Its meal is comparable to that of soybean, with a protein content varying from 45-47%. It is well suited to growth in colder climates like Montana and has a short season of as little as 85 days (Putnam, 1997). In fact, there are already dozens of research farms studying camelina across eastern Montana and southern Canada.

Jatropha curcas (Physic Nut)

Jatropha curcas is a small tree that thrives in arid and semiarid climates and has a life span of 50 years (biofuelstp.eu, n.d.). The seeds range from 30-40% oil (in some cases getting as high as 75%) and are toxic to animals and humans, meaning that the resulting meal is useless in terms of supplementing animal feed. However, *Japtropha* has been shown to grow well on marginal land, or areas that would otherwise not be used for crop production due to low water conditions or the presence of pollutants or high salinity (Verma, 2012). Current research by Jatropower AG in Switzerland is showing tremendous promise in the development of non-toxic jatropha, making its meal of commercial value for an animal feed additive (biofuelstp.eu, n.d.).

<u>Algal Biofuels</u>

Algal biofuels are third generation biofuels as they do not compete with land use for food or other biofuel feedstocks (Brennan et al., 2010). They are created from microalgae, which are single-celled organisms that photosynthesize and some species can double their mass several times within a day. In certain species of algae, more than half of the mass is lipids, which are extracted to create biofuel. Algae require light, sugars, carbon dioxide, nitrogen, phosphorous, and potassium and the cultivation process is simple (Brennan et al., 2010). Once grown, the algae are harvested from the cultivation systems. The lipids are then extracted through a variety of different methods and processed through different refining techniques to create biofuel or green fuel.

Algal biofuel production has several benefits. Algae are incredibly productive and can produce more lipids per acre than many other crops. Cultivation of algae do not compete with arable land for crop production (Male, n.d.). Some algae species thrive in seawater and wastewater (Handler et al., 2014). Algal biofuels could mitigate carbon dioxide by trapping it from the atmosphere. Solar energy is used to fix carbon dioxide into their biomass, therefore the water they are cultivated in is typically enriched with carbon dioxide. Production of algal biofuels provides an opportunity to utilize carbon dioxide from power plants and other facilities that produce carbon dioxide (Benemann, 2008). The lipids from algae can be combusted to generate heat, anaerobically digested to produce methane, fermented for ethanol production, or fed to livestock. (Benemann, 2008).

Cultivation of algal biomass is done in two main cultivation systems, open pond or closed photobioreactor (Singh et al., 2010). Open ponds are open tanks or natural ponds where fertilizers are added and the gas exchange occurs naturally; raceway systems are the best form of open ponds and are shallow and mixed (Singh et al., 2010). The closed photobioreactors have higher productivity, lower contamination, capture carbon dioxide efficiently and all of the conditions are more controlled, but the cost is much higher to start-up and to operate (Bruton et al., 2009).

Algal biofuels could be used as a replacement for petroleum, which is the main fuel source utilized today. Life cycle analyses provide a way to explore multiple facets of algal biofuels production; growth, harvesting, and extraction can be investigated in a way which the energy consumed and created along with fiscal costs is studied. Many of the microalgae cultivation systems utilize the open pond system with solar energy being the light source for photosynthesis. Algal biofuels have been studied for a variety of reasons. Microalgae tend to have high per-acre productivity (Dassey et al., 2014). Land that cannot be cultivated for other crops can be utilized for microalgae production.

Algal biofuel systems need to take into account culturing, harvesting, extraction and oil breakdown into molecules forming biodiesel and glycerin (Khemani, 2011). Currently the average energy of algal biodiesel is 37.8 MJ/kg whereas for conventional fossil fuels such as gasoline and diesel, the average energy is 43 MJ/kg. A conservative projection of productivity for algae with a lipid content of 20% in a 1-acre pond that is 40 cm deep is about 15 grams of algae per square meter per day. Some species however can have a greater lipid amount and greater productivity depending on the cultivation system (Dassey et al., 2014). The pond systems need mixing to occur at a velocity of about 0.25 meters per second, and therefore energy is needed in order to run a paddlewheel or other mixing device (Table 1).

Microalgae are also known for their ability to fix carbon dioxide and convert it into biomass at faster rates than other typical biofuel crops (Kumar et al., 2010). Typically 2 g of carbon dioxide is needed for every gram of biomass created to maximize the growth rate (Dassey et al., 2014). It is possible to utilize carbon dioxide trapped after combustion from coal-fired power plants (Table 1).

Water is necessary in the cultivation of microalgae, and depending on the size of the system, there is a wide range in the amount of water needed, i.e., 32-656 L H_2O/L oil (Dassey et al., 2014). It is possible to recycle the harvest water, which decreases the water used. Evaporation is also a concern for the open pond systems, and there are water losses that occur throughout the process (Table 1).

Fertilizers are necessary to culture the algae. In the study completed by Dassey et al. (2014) the molar ratio of phytoplankton was used for microalgae to determine an approximate amount of nitrogen and phosphorous needed for the cultivation process (Table 1).

Table 1. Algal cultivation processes (Dassey et al, 2014).

Production Estimate (L/acre/yr)	5,170
Growth Rate (g/m2/day)	15
Mixing Energy kWh/m3/d (v= 0.25 m/s)	0.023
CO2 (kg/kg algae)	1.9
Energy (KWh/m3 CO2) *$58/ton of post combustion CO2 from coal fired power plant.	1.28*
Evaporation loss (cm/day)	0.33
Pumping Energy (kWh/m3)	0.045
Nitrogen (g/kg algae) **Ammonia	91.6**
Phosphorous (g/kg algae) ***Diammonium phosphate	12.7***

Algae can also be cultivated in wastewater, reducing the need for fertilizers and potentially decreasing the overall fiscal and energy cost. Jiang et al. (2011) showed that the biomass production in wastewater settings increased by 32% when municipal wastewater and seawater were used in a 50/50 mixture compared to only freshwater.

Almost a quarter of the fiscal and energy cost of production of algal biofuels is in harvesting (Dassey et al., 2014). The different harvesting methods involve one to many steps that can either be physical, chemical or biological processes all with different efficiencies and energy requirements. (Dassey et al., 2014; Table 2).

Table 2. Harvesting techniques and energy requirements (Dassey et al., 2014).

Method	**% Efficiency**	**Energy Required (kWh/kg algae)**
Centrifugation	100	0.338
Settle-Centrifugation	65	0.235
Flocculation/ph-settling-belt press	90	0.458
Flocculation-DAF-centrifugation	70	1.44
Flocculation-DAF-belt press	70	1.086
Electrocoagulation-DAF-centrifugation	76	1.133

Various lipid extraction and energy conversion techniques are utilized and the yields from the techniques can vary. Based on studies completed, solvents appear to be the best for extracting the oil from the algal cells. The solvents lyse cell walls, increasing the yield of lipids from the algal cells. Some studies utilized the biomass to produce methane and methanol instead of using the lipids (Dassey et al., 2014; Table 3).

Another part of the analysis is the shipping energy requirements however, it is being assumed that since all of the biofuels would require shipping and transportation, that part of the analysis can be removed by assuming it would be a similar cost across the board for all of the different biofuels.

Table 3. Extraction Methods – Extraction methods and comparison of energy requirements and fuel energy produced (Dassey et al, 2014).

Lipids (%)	Method	Energy Consumed (kWh/kg algae)	Fuel Energy (kWh/kg algae)
17.5	Hexane -> transesterification	1.77	1.838
unknown	Anaerobic digestion -> methane production	0.896	2
50	Hexane/ethanol -> transesterification	1.996	4.287
30	Hexane -> transesterification	0.684	3.247
2	CFLES	4.416	1.867

<u>Upcycled Biofuels</u>

Upcycled biofuels are derived from any feedstock that would otherwise be discarded, or from byproducts of other industries. These fuels include both ethanol and biodiesel, as well as biogas, a mostly-methane gaseous fuel that can be used the same as natural gas (Martin and Paraspour, 2012), straight vegetable oil, and any other similarly obtained fuel.

The best known upcycled biodiesel is that which is made from used cooking oil. Since biodiesel can be made from any vegetable oil, using oil that would otherwise be discarded seems logical. Used cooking oil generally has solid particulate from whatever was cooked in it suspended, so it requires filtering (Souza et al., 2012). Aside from this, the processes used to create biodiesel from the oil are identical to those when using fresh oil. The primary limitation to large-scale used-cooking-oil biodiesel production is the availability and collection of used cooking oil.

In addition to processing cooking oil into biodiesel, it can also be burned as-is in a modified engine (Greasecar Vegetable Fuel Systems, 2010). This is a simple and straightforward method once it is applied, but requires a modification of the engine, whereas cooking-oil biodiesel modifies the fuel to be burned in a standard diesel engine. Since the feedstock is identical, so are most of the limitations, however the modified engine avoids the need to bring oil to a refinery.

The main upcycled version of ethanol is cellulosic ethanol. This is more difficult to produce than traditional sugar or starch derived ethanol, but has the advantage, common to all upcycled fuels, of not competing with food crops. This can be produced from almost any plant, and frequently discussed is such as straw and other crop detritus, as well as paper waste and wood waste from the timber industry. Norway is in the process of implementing wood-derived cellulosic ethanol for a portion of their fuel needs. (Bright et al., 2010).

Biogas is produced by anaerobic digestion of organic matter (Martin and Paraspour 2012). It can be produced from any organic wastes, making it attractive for upcycling. This can include anything you would consider compostable, as well as the sludge from wastewater treatment. The process produces alongside biogas substances called digestate, which can be used as fertilizer, since it is high in nitrogen.

Conclusions

It is unrealistic to think that a nation will change its entire energy infrastructure overnight; however, with growing concerns over the environmental impacts of petroleum-based fuels, many nations are turning their attentions to sustainable, renewable energy sources. The European Union is spearheading this movement: on October 23, 2014, EU leaders signed an agreement to cover at least 27% of their energy demands with renewable sources by 2030 (Europa.eu, n.d.). While the United States has taken some steps towards promoting wind, hydro, and solar energy, there has yet to be any definitive measures relating to alternative vehicle fuel. Although only 28% of the total energy usage in the U.S. is attributed to transportation, biofuels are an attractive option for increasing sustainability in this sector (“Annual Energy Review 2011”). However, the limits on current technology will play a pivotal role in what type of biofuel would make the most sense as a major candidate for replacing gasoline.

Winden et al. (2014), suggest that, at present, ethanol production requires closer examination before consideration as a replacement for gasoline. This is dependent on the kind of feedstock that is being used to produce the ethanol. Additionally, if individuals wish to find a more environmentally friendly alternative to gasoline, the second-generation cellulosic products should be considered.

Based on current technology and farming infrastructure, the most viable feedstock for biodiesel would be rapeseed because of the very high oil content of the seeds, wide range of climate tolerance, comparatively low water requirements, and ease of integration into crop rotations. The most promising feedstock for the future would be *Jatropha* due to its lower water and soil quality requirements, as well as current research into genetic modifications to improve edibility and oil yield.

Algal biofuels have a lot of potential. However, in many cases the amount of energy consumed far exceeds the amount of energy produced from algal biofuel processes on a commercial level. Many fossil fuels are utilized in the current processes to form algal biofuels; the entire process needs to be more sustainable in order to be the future of renewable energy. The most costly inputs are the nutrients and the most costly processes are harvesting and extraction of lipids. Some studies have shown that utilizing wastewater could cut the costs by eliminating the need for the additional nutrients. The ability to create these biofuels on areas of land that are not conducive to cropping systems is a major benefit. The rapid algae growth rate is a strong driver to finding more efficient methods of harvesting and extracting the lipids from the algal cells.

The use of already-present waste products in upcycled biofuels is simultaneously the biggest asset and the biggest limitation on their use. Because they use waste products, upcycled biofuels do not compete with food crops or with other production. In addition, feedstocks do not have to be produced specifically, leaving the input costs effectively only transport and processing. However, because it relies on the byproducts of other industries, the available feedstock is tied to that, and therefore supply is limited. This means that upcycled feedstocks, while an excellent way to use more of the resources that we have, cannot provide for all or even most of our fuel needs (Bright et al., 2010). From first-generation to upcycled feedstocks, there are many sustainable sources for vehicular fuel available to the modern consumer. However, the sources of biofuel become irrelevant in a society not concerned with sustainability. Unfortunately, this seems to be the case in the United States, where only 9% of our transportation energy comes from a renewable source (Annual Energy Review 2011, 2011). In an ideal scenario wherein interest in adopting sustainable fuel sources increases dramatically, we think that biodiesel and upcycled fuels would be the easiest, most feasible sources to adopt currently, with a slow conversion to algal biofuels as technology advances. This conclusion is based on the following factors: the science and infrastructure already exist for biodiesel production, meaning that it can be easily phased into our current fuel system; upcycled fuels place the responsibility and costs of fuel onto the consumer, and is perhaps the best way for transportation to *immediately* become more sustainable; and algal biofuels do not compete directly with crops for arable land *or* freshwater (since wastewater can be used for production), making them a very attractive sustainable fuel source, *especially* with the rate of technological advancement from current research. While advances in technology will certainly make the production of any the aforementioned biofuels more efficient, we have decided, based on our respective analyses, that biodiesel and upcycled fuels are the most attractive options for current sources of sustainable energy, while algal biofuels--and their current technological limitations--are the way of the future.

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