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Maximum Potential Biodiesel Production

Jon H. Van Gerpen
jonvg@uidaho.edu, (208) 885-7891

As biodiesel has become a widely successful alternative to petroleum-based diesel fuel, the total production is limited by the amount of feedstock. Larger quantities of oilseeds can be grown but large land areas are required which causes competition for food crops. In tropical areas, oil palm can be grown with up to 600 gallons of oil per acre (compared with about 60 for soybean) but increased production may require destruction of rain forest. Microalgae have been proposed as a solution to biodiesel's feedstock limitation. Although currently expensive to grow, microalgae can be exceptionally productive, producing far more oil than terrestrial plants. Unfortunately, poorly informed advocates have made wildly exaggerated claims for the amount of oil that can be produced such as 20,000 gallons/acre and even as high as 100,000 gallons/acre. This TechNote will discuss the inherent limitations on oil production and show that reasonable estimates for algae oil production should be far lower.

Biodiesel is concentrated solar energy. When made from plant oil, the connection between the sun and the fuel is direct and easy to make. The biodiesel is made from the plant's oil, which was produced by the plant using energy from the sun. Even with biodiesel from animal fats, the ultimate energy source is the sun even if it passes through a slightly longer path that includes the animal feed and the animal's digestive tract.

Plants use a biochemical process called photosynthesis to convert the energy in a unit of sunlight into carbohydrates to produce the protein, starch, fiber, and oil that the plants use to survive and reproduce. This is true whether we are considering soybeans, corn, canola or wheat. Even microbial plants, like microalgae, use the same general process.

Some microbes, may appear to produce energy without the sun. For example, the yeast that convert the glucose from corn starch into ethanol can live in large fermentation tanks without light. But in that case, the yeast is simply converting the energy from the starch, which the corn plant produced using sun light, into the ethanol. Even microbes that live without sunlight need an energy source that can be traced back to the sun.

So, when biodiesel is produced from plants, the plants can be thought of as solar energy collectors. Like all solar collectors, the amount of energy collected is determined by the amount of area exposed to the sun.

The intensity of the light from the sun at the average distance of the earth from the sun is equal to 1,366 Watts/m^2, which is a number called the solar constant. The actual intensity incident on the earth will be less than this because some of the light is absorbed by dust, clouds, and gases in the atmosphere. And seasonal effects introduce the variation of the angle at which the sun strikes the earth's surface, which is more perpendicular during summer months and at a shallow angle during the winter, especially at locations far from the equator. In addition, photosynthetic plants are only able to use light in a fairly narrow band of wavelengths between 400 and 700 nanometers.

When these factors are taken into account the available light is called the photosynthetically available radiation (PAR) and it varies around the United States from 40 to 200 Watts/m^2 depending on the location and season. It is common to use annualized average values of PAR for a given region that are representative of continuous sunlight 12 months of the year, 24 hours/day. These values range from 70 to 90 W/m^2 for the continental United States [http://www.atmos.umd.edu/~srb/par/04status.htm].

The photosynthesis process itself has a limiting thermodynamic efficiency of about 27% for the conversion of the PAR to stored biomass energy. This is the energy associated with the requirement for 8 photons to capture one molecule of CO_2 and produce carbohydrate $(CH_2O)_n$. Most plants are far less efficient than this with typical terrestrial plants only able to convert PAR into biomass with an efficiency of about 1%. This large reduction in efficiency is due to issues such as light reflection, light not striking the plant surface (incomplete canopy), photosaturation (too much light intensity for the plant), plant energy being used for purposes other than energy storage, and many other factors. Some researchers believe that it may be possible with genetically optimized microbes grown in bioreactors with carefully regulated lighting to achieve an efficiency of 10% although commercial scale success has not yet occurred.

It is possible to do a calculation that estimates the maximum biomass energy that can be produced from a photosynthetic plant-based system. If we assume that the facility is located in the United States, a PAR value of 90 W/m^2 is a reasonable maximum that could be achieved in the Southwestern states. If the system used algae in bioreactors, an optimistic energy conversion efficiency of 10% can be assumed. For one acre of land, the maximum amount of energy stored annually will be:

$$90\ \text{W/m}^2 \times (1\ \text{J/W-s}) \times 3600\ \text{s/hr} \times 8{,}760\ \text{hr/yr} \times 4{,}049\ \text{m}^2\text{/acre} \times 0.10 \times (1\ \text{MJ}/106\ \text{J}) = 1{,}149{,}203\ \text{MJ/acre}$$

This estimate of 1.15 million MJ of stored energy per acre includes everything that composes the plant tissues such as protein, fiber, starch and oil. High oil content algae can contain 70% of its dry body weight as oil. If this oil were converted to biodiesel with no loss of energy for processing and with the assumption of one gallon of biodiesel from one gallon of oil, the maximum amount of biodiesel (1 gal of biodiesel = 135.56 MJ/gal) that could be produced would be:

$$\frac{(1{,}149{,}203\ \text{MJ/acre} \times 0.7)}{135.56\ \text{MJ/gallon}} = 5{,}934\ \text{gal/acre}$$

Thus, a plant-based biodiesel production system could only reasonably be expected to produce about 6,000 gallons of biodiesel per acre using the most optimistic assumptions. With more realistic assumptions, the limiting value for algae is likely to be 1,000-2,000 gallons/acre. Terrestrial plants such as canola and soybean have the additional disadvantage that roughly half of the biomass that is produced is contained in the root system and is not typically harvestable. As mentioned earlier, the most productive oil producing plant, the oil palm, produces about 600 gallons of biodiesel/acre per year.

So, reasonable estimates for algae production are 2-3 times higher than is achievable using terrestrial plants. This is a major increase but is far below some of the extravagant claims that have been made by some promoters. Higher production levels are possible when some other energy source is used, as noted earlier, or when artificial lighting is used. But no financially attractive source of alternative energy has been found.

If solutions can be found for algae's currently high production cost, it may become a major source of oil for biodiesel allowing this alternative diesel fuel to expand beyond its existing feedstock limits. But enthusiasm for this opportunity should be tempered by realistic assessments for the limitations imposed by the physics of the energy conversion processes.