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Algae for Biofuels – Economic and Environmental Costs

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Algae are an intriguing feedstock for the development of renewable biofuels in the United States. See SRAC Publication No. 4309, *Algae for Biofuels – Production and Conversion* for a discussion on varieties of algae grown for industrial purposes, algal production methods, and conversion processes of industrial products from algae. The role of economics, existing markets, and environmental impacts related to these algal systems will be discussed in this publication.

A common theme of this factsheet is that most existing industrial algae production systems are expensive, and these costs can only be covered by marketing algal products in high-value, niche markets. Determining how relatively low-value fuel products can be produced with algae is a difficult proposition with existing technologies. Economics is a critical consideration for a potential algae grower to investigate. Sometimes algae are also thought of as a more sustainable source of biomass because they require a small footprint for cultivation, consume carbon dioxide from the atmosphere at a higher rate than terrestrial plants per acre, and improve air and water quality. However, using a total system approach several environmental impacts become apparent that must also be considered. The environmental benefits and consequences are discussed as part of a review of life cycle assessments in this factsheet.

Markets and Economics

Current Algae Markets

The current market for algae represents the production of a wide range of high value products in extremely small niche markets (Fig. 1). Macroalgae products represent the larger worldwide market share at $6 billion (7.5 million tons per year (6.8 mmt/yr) in 2004 with products produced from microalgae at approximately $1.25 billion (5,000 tons per year (4,536 mt/yr). These markets are controlled by a small number of specialty producers in tightly controlled environments with the majority produced in small batches. Algae products by market segment represented in Fig. 1 include:

Biomass: aquaculture, feed additives, functional foods, health foods, and soil amendments
Antioxidants: antioxidant extract (CO_2), ARA, β carotene, DHA, PURA extracts, tocopherol
Coloring Substances: astaxanthin, phycocyanin, phycoerythrin
Special Products: isotopes, toxins

Low value products (such as biofuel) need to be produced at relatively low costs on a large scale to stay economically viable. Considering the current algae market, microalgae with lucrative, but small niche markets are more profitable than macroalgae primarily used for food and feed products. Assuming biodiesel has a value of $4 per gallon, a ton of algae at 30 percent lipid concentration (probable upper limit) would produce $312 of biodiesel with no value coming from byproducts (using a similar

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conversion as soybean: 0.13 gallons per pound (1.08 l/kg) oil). Since algae have greater value in non-fuel applications, high cost production methods can be economically competitive for those uses.

Algal Production Costs

A wide range of economic costs exist for the production of algae as a biofuel feedstock. Because algal production technology for biofuels is still in its infancy and there is a lack of any industrialized systems producing algae on the scale required for biofuel production, economic values vary depending on the specific system modeled, parameter estimates chosen, and byproduct allocation. Thus, values provided in this document should be used for comparative purposes and not as direct cost estimates.

For comparison, crude palm oil, generally the lowest cost plant-derived oil, sold for $465 per ton or $1.97 per gallon ($512/mt or $0.52/l) in 2006. With algae cultivation yielding biomass with 30 percent lipid concentration, production and oil extraction would need to be at or below $139.50 per ton ($153.77/mt) to be competitive as an alternative feedstock, not taking into account byproduct utilization. Generally in the U.S. the major biodiesel feedstock is soybean which had a March 2013 commodity price of $14.60 per bushel ($480 per ton ($529/mt)) at 20 percent lipid concentration or approximately $1.20 per pound ($2.64/kg) oil. Comparisons of algal oil to crude oil projected that 55 percent lipid concentration in a genetically improved algae would require production costs alone of $340 per ton ($375/mt) to be competitive against petroleum diesel (at $100/barrel crude oil).

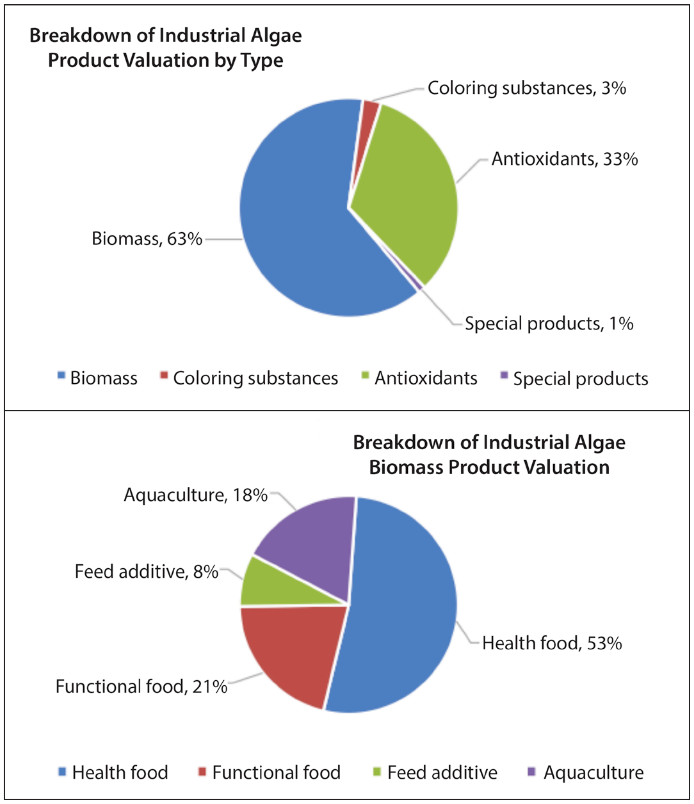

Figure 1. Current industrial algae product market valuation estimates (top) and market valuation for biomass-based algae products (bottom). (Source: Pulz et al. 2000)

The production of algae for health food in a closed system (i.e. tightly controlled environment) can be accomplished at approximately $13,260 per ton ($14,617/mt) compared to $180 per ton ($198/mt) for algal production in an open system (i.e. grown in a pond) as an electricity feedstock. These values represent the general trend of production costs when comparing systems designed for high value industrial products with those considered for energy markets.

Open vs. Closed Systems

Capital costs for a closed system have been estimated at approximately $9.29 per square foot ($100/m^2) surface area compared to the estimated $0.87 per square foot ($9.4/m^2) for open systems. Operating costs are also considered to be higher in closed systems due to the high energy demand for pumps. Closed systems do have a higher productivity rate (9.08 tons per hour (8.24 mt/hr)) than open systems (5.45 tons per hour (4.94 mt/hr)) due to the increased surface area and closely controlled environment.

Current algae production costs for high value products show that open systems are cheaper than closed, $23,636 per ton ($26,054/mt) and $30,909 per ton biomass ($34,071/mt), respectively. An overlapping range of values from various publications is reported with raceway ponds ranging from $2,400 to $15,000 per ton ($2,646 to $16,535/mt) and photobioreactors from $2,905 to $75,000 per ton ($3,202 to $82,673/mt) (high and low value products included). A summary of production costs for various algal production systems are provided below (Table 1).

Table 1. Algal production cost by production enterprise (Adapted from Chisti 2007; Jorquera et al. 2010; and Richardson et al. 2012)

Production System	Production Cost
Biofuel feedstock	
Tubular (closed)	$9,450/ton
Flat plate (closed)	$419/ton
Raceway (open)	$227/ton
Lipid Production	
Open Systems	$12.72/gallon
Closed Systems	$31.63/gallon
100 ton/yr operation	
Open Systems	$3,800/ton biomass
Closed Systems	$2,950/ton biomass

While the majority of these economic models support the use of open systems as a means to create large-scale production systems capable of producing low cost algae, there are numerous production considerations that are not considered in these economic modeling exercises. One of the greatest challenges with open systems is maintaining a singular algal culture (monoculture) in the tank or pond. An open system is much more susceptible to contamination from rain water, animals, birds, other microorganisms, and other algae species which are not considered in current economic models. Therefore, aside from considerations regarding initial investment and production costs of a given system, algae selection and the biological and chemical needs of growing a productive and robust culture need to be taken into account.

Combined System

A combined system has been proposed to optimize both biomass and oil yield in an algae production system. Optimal growth conditions for some microalgae species produce only 5 to 20 percent oil and with nutrient deprived conditions this increases to 20 to 50 percent. This may be possible through the use of an open system for optimal growth conditions followed by a nutrient deprived closed system for maximum oil production, or vice versa. A combined system has the potential to reduce feedstock production costs by optimizing both growth and oil production in separate unit operations. These combined systems do have a number of drawbacks including determination of optimization points between the systems, additional handling and infrastructure costs, and an increased potential for contamination so additional research is required to determine the best conditions for such a system and the associated economic benefits.

Production Scale

Economies of scale refers to the advantages in cost due to the increased size of manufacturing operations. Generally for industrial operations, as the quantity of production increases the cost per unit decreases. This is usually not a linear rate that goes to zero but some curved function that approaches an optimized size for minimum production costs. It does not apply well to total systems where costs outside of manufacturing have a major impact on total cost. This is seen in the production of bioethanol from mature cured stalks of corn with the ears removed (corn stover) where transportation costs outweigh the benefits of lower manufacturing costs at plant sizes above 8,000 tons/day (7,252 mt/day). If a plant were to be larger than 8,000 tons/day (7,257 mt/day), the cost to produce ethanol from corn stover might be lower, but the shipping costs would negate this advantage.

Costs for closed ($2,950/ton ($3,252/mt)) and open systems ($3,800/ton ($4,189/mt)) at 100 tons per year (110 mt/yr) would decrease to $470/ton ($518/mt) and $600/ton ($661/mt) of biomass, respectively, for a 10,000 ton per year (11,023 mt/yr) system. In contrast an assessment of five microalgae systems by Amer et al. (2011) shows that the reduction in cost does not scale well with the increase in production size (Table 2). The table demonstrates how production costs ($/ton) for algae vary compared to the first year cost to produce algae in a 120 acre (50 ha) pond. This is a result of the modular nature of these systems where economies of scale do not apply well. Generally, the economics do not improve significantly moving from a 124 acre to a 1,236 acre to a 12,355 acre (50 ha to a 500 ha to a 5,000 ha) algae production facility.

Table 2: Variations in algae production cost for bioenergy with changes in cultivation size and time (Adapted From: Amer et al. 2011)

Production System	Product*	Size (acre)	1st year (%)	2nd year (%)
Open Pond	TAG	124	$10,200/ton (baseline)	-8.8%
		1,236	-26.5%	-35.3%
		12,355	-29.4%	-37.3%
	FAME	124	$6,800 (baseline)	-13.2%
		1,236	-39.7%	-55.9%
		12,355	-44.1%	-55.9%
Solar Photobioreactor	FFA	124	$31,700 (baseline)	-32.2%
		1,236	-5.7%	-37.2%
		12,355	-3.8%	-36.0%
	FAME	124	$26,700 (baseline)	-36.7%
		1,236	-6.0%	-42.7%
		12,355	-4.1%	-41.2%
LED Photobioreactor	TAG	124	$33,000 (baseline)	-23.3%
		1,236	0.9%	-23.3%
		12,355	12.4%	-11.8%

*Product Key: TAG = triacylglycerol, FAME = fatty acid methyl ester, FFA = free fatty acid

Byproduct Utilization and Externalities

After the oil is extracted, there is a large quantity of excess material present with low economic value making it imperative to develop strong byproduct markets to ensure profitability of an algae production system. There are also externalities that may provide some additional profit to these systems. Externalities are unintended benefits such as the ability of algae to produce oxygen, clean the air, clean water, sequester carbon, etc.

Byproducts: Proteins and Carbohydrates

Though the desired product in many of these biofuel production systems is algae oil for biodiesel production, a large amount of biomass material is produced as a byproduct. This material consists of two major components: proteins and carbohydrates. If this material is not marketed properly, it may require disposal, thereby increasing production costs instead of supplementing profits. An increase in lipid concentration will decrease the protein and carbohydrate fractions of algal biomass. Using different environmental factors to influence cultivation methods drastically alter the composition of algae between these three components (Fig. 2). Separation of the protein and carbohydrate portions is possible for use in specific markets including animal feed (including aquaculture), soil additive, and bioenergy feedstock.

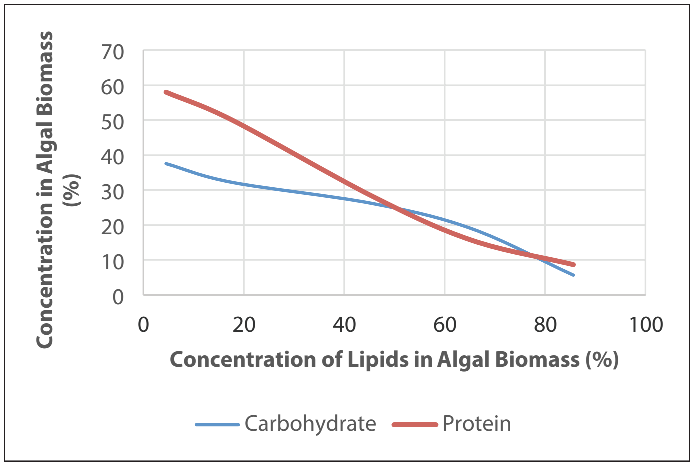

Figure 2. Varying lipid concentration impact on Chlorella composition (Source: Spoehr & Milner 1949)

To fit the animal feed market, feed tests are required to determine specific characteristics of the algal biomass after lipid extraction. These potential feed products may have to discount markets where algal oil is of interest for feed such as in dairy cattle. Use as a soil amendment is usually a last option for this biomass material as generally the cost of spreading will barely cover the soil benefits provided by the material. However, use as a soil additive is still a better option than having to pay for material disposal. It is also possible to recycle some of the residual biomass material into the existing algal growth cycle to reduce nutrient requirements. Yet, this may not be a reasonable option if wastewater is being used as a major source of nutrients. Analysis of the biomass material is important in either case to determine what kinds of benefits the material can provide.

Through the use of byproducts to increase the value of algae biodiesel, system profitability was achieved at a price of $125 per barrel ($3.97 per gallon ($1.05/l)), but without the valuation of byproducts the system was unprofitable even at a biodiesel price of $200 per barrel ($6.35 per gallon ($1.68/l)). These values were derived through the use of nutrient recycling to reduce costs and sale of high value proteins to the animal feed market.

Multiple bioenergy products can be produced from the residual algal material including methane, heat/electricity, cellulosic ethanol, and other renewables. If used as a cellulosic ethanol feedstock, additional byproducts become available including condensed distillers solubles, dried distillers grains with solubles, and food grade CO_2 which all have strong existing markets.

Externalities: CO_2 Mitigation and Wastewater Processing

Algae require carbon dioxide to grow and thrive. As they consume CO_2, it is removed from the atmosphere and stored in their cellular structure. The removal of CO_2 from the Earth's atmosphere is beneficial to the environment, and some groups have assigned monetary value to this benefit. It is important to account for CO_2 mitigation correctly when dealing with an algae system. Even if power plant flue gas is used as a carbon feedstock, if all of the algae is combusted, there is no net reduction. However, the energy produced by the algae will offset other fossil fuel heating sources which can be counted after production is taken into account.

With the closing of the Chicago Climate Exchange in 2010, there is no current U.S. market to freely trade carbon emissions. Private contracts with some utilities and major corporations are still possible though they generally do not provide a high rate of return. Some studies show that a CO_2 mitigation credit would reduce algal oil production costs to those similar to soybean oil. If there is not a guaranteed contract, it should be assumed that there are no direct cost savings from CO_2 mitigation.

In place of purchasing fertilizer as a nutrient source during growth, it is possible to cultivate algae using nutrient rich wastewater. This can be from industrial, agricultural, or municipal sources; though it is important to ensure that the correct macro- and micro-nutrient levels are maintained for optimal growth. This can reduce production costs and minimize costly wastewater treatment operations. Creation of cooperative relationships like these can help to increase economic benefits.

Life Cycle Assessment

What is LCA?

A Life Cycle Assessment (LCA) is a quantitative process for determining environmental impacts of a wide range of systems. The governing standards for LCA stem from the International Standards Organization (ISO). These standards set a basic overview of the four main steps involved in completing and LCA: 1) Goal and Scope Definition; 2) Life Cycle Inventory Analysis; 3) Life Cycle Impact Assessment and 4) Interpretation. A basic outline of the LCA process is shown in Fig. 3.

The *goal and scope definition* goes through basic set-up information to ensure uniformity throughout the LCA. Creation of a Life Cycle *Inventory* (LCI) pulls together emissions information throughout the system that is being investigated. This information does not need to be made up of directly measured values. Data commonly used are from a set of standard emission rates for similar processes. After the LCI is compiled a set of *impact* factors are used to convert the emissions to a standard set of impacts (i.e. methane to CO_2 equivalents). The final phase of *interpretation* occurs throughout the process as the data is compiled and refined.

It is worthwhile to mention that some publications mention life cycle energy as the parameter of interest. This evaluation method follows a methodology similar to LCA but with energy use as the major focus.

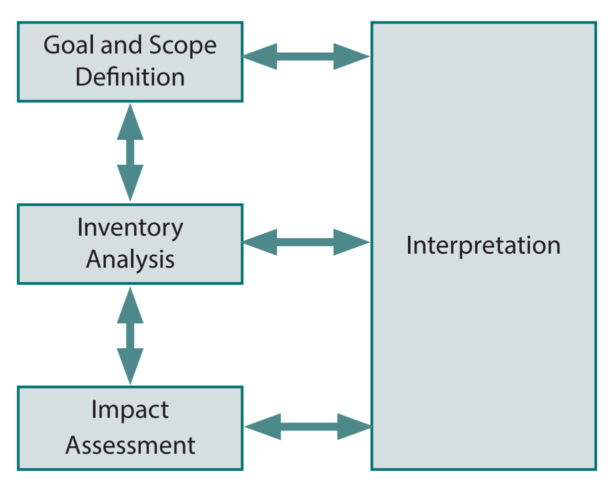

Figure 3. Life Cycle assessment process (Adapted from ISO 2006a)

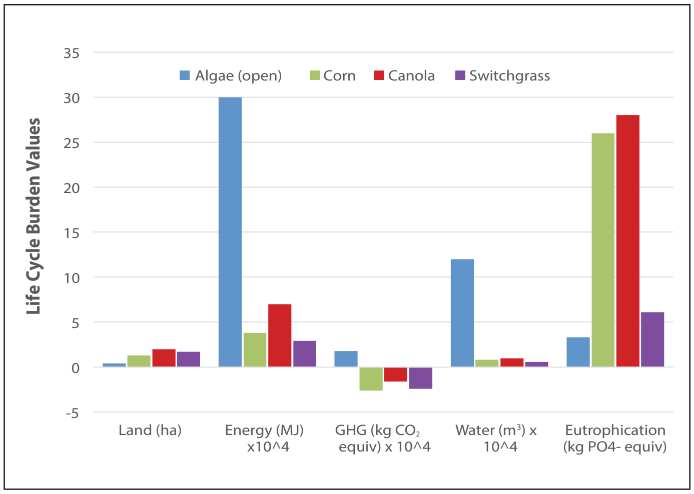

Figure 4. Life cycle burdens of various bioenergy crops, FU=317 GJ (Source: Clarens et al. 2010)

Algal Feedstock Production

The net energy ratio (ratio of total energy produced to the energy required from construction and materials through operations) of open systems is much higher than that of closed systems both for biomass and oil production from algae. Higher energy ratio values are better since they indicate a system is producing more energy than it requires to generate the energy. The magnitude of this ratio reflects the benefits of a system, so the higher the value the better. Ratios reported for open and closed production systems include: raceway (open) 8.34 biomass, 3.05 oil, flat-plate (closed) 4.51 biomass, 1.65 oil, and tubular (closed) 0.20 biomass, 0.07 oil. This large disparity in energy production in closed systems is related to the energy required for pump use, which is can be lower for a flat-plate system. In terms of energy usage for an open system compared to other bioenergy crops, algae systems use significantly more when taken to the point of feedstock production (Fig. 4). Figure 4 also shows that the algae system produces significantly higher CO_2 emissions compared to the other systems, which is directly related to the high energy requirement of cultivation.

Looking at a wide range of reaction vessels and scenarios for closed system production of algae, the use of HDPE is the most environmentally friendly material for construction (followed by PVC), most evident in acidification and smog formation results. HDPE is a petroleum derived thermoplastic whereas PVC is vinyl polymer, this construction means HDPE is more heat and abrasive resistant, harder, and able to absorb shock better than PVC. The use of flat glass is considered best for GHG emissions and carcinogenic/non-carcinogenic impacts. Eutrophication can be reduced through the use of wastewater in place of fertilizer for nutrients and GHG emission reductions are achieved through the use of flue gas.

Algae Renewable Energy Applications

Biodiesel is often one of the most preferred products that can be produced from algal oils. However, the implications of growing algae for biodiesel production seem to indicate it may have the greatest negative impact as a feedstock, from an environmental standpoint. Studies have shown that the harvest and separation methods used to extract oil significantly influence the life cycle analysis of algal biodiesel. For example, it has been found that the use of a centrifuge would be more energy intensive than a filter press to remove water and that an enzymatic process to breakdown algal cells in the ponds would help reduce the environmental burdens of algae production. Yet the harvest operations in general are problematic to the life cycle assessment. Additionally, if commercial fertilizers are used as a nutrient source, biodiesel production from algae was net energy negative. The main source of GHG emissions and energy use come from cultivation requiring electricity, with closed systems being significantly higher than open systems.

An analysis of a combined system, consisting of a closed system for algae growth followed by an open system for oil accumulation showed that the closed system portion used the most energy in the cultivation portion, but lipid extraction used by far the most energy in the total system. The lipid extraction portion alone makes the system energy negative. Sensitivity analysis indicates that even an increase in oil production by 20 percent would only reduce the total energy required by 5.6 percent.

Other uses for algae in conditions believed to have environmental improvement impacts have shown similar results as biodiesel production. Studies have shown that when algae is used as a CO_2 mitigation medium for flue gas and then used as a co-firing agent for electricity production, a reduction in total GHG and acidification is achieved, but there is an increase in natural resource depletion and eutrophication. The increase in natural resource depletion was a result of algae production practices requiring crude oil and natural gas resources which outweighed the benefits of algal displacement of coal during co-firing. Also, in using algae as a feedstock for methane production, the majority of environmental impacts are dominated by emissions produced from electricity production. These analyses reinforce the need to fully evaluate the energy and environmental impacts of the operations and combination of operations chosen to implement an algal production system.

Is Growing Microalgae for Feedstocks Right for You?—Questions to Ask

Assessing if microalgae are an appropriate aquacultural enterprise for a production system is a difficult decision. In order to make an informed decision from an economic and environmental standpoint, the following questions should be evaluated. These questions are critical for assessing the likelihood for success if a microalgae production enterprise is selected for an aquaculture facility.

1) *What is the estimated production cost?*
   Review numbers in this publication as well as other published literature to determine if the estimated production cost for the algae ($/ton) is in line with the numbers provided for the system being considered. Significant variations between published numbers and the system under consideration require additional explanation. For example: Is the production technology more efficient, if so how? Are the materials used in construction cheaper? Is less energy required to operate the system?
2) *How do the production system costs breakdown?*
   Understand what costs are associated with constructing the system versus those required to operate the system. How do those operating costs breakdown, and are all the costs considered? Electricity, water, water filtration, maintenance, labor, and algal nutrition are just a few costs that have to be considered. ***Unfortunately, just inoculating an open top tank with algae and expecting efficient growth yielding a valuable product with no input is unrealistic.***
3) *What is the cost of culture failure?*
   If some form of contamination were to enter the production system and the value of the algae under production was either lost or significantly devalued, what is the impact to the bottom line? Not only is there the loss of product revenue, but there may be additional costs to re-establish the system. If such a loss were to occur, would the production enterprise be able to withstand it? Also, an algae production system operator would need to know the resources and time required to sanitize the system and re-initiate the production cycle. Investigating the types of insurance available to cover such operations would be another worthwhile pursuit.

4) *What is the market for byproducts?*
   The plan for byproduct utilization (materials remaining after oil is extracted) is an important component of an algal enterprise. Having a plan to use the material will help avoid tipping fees at landfills and provide additional income. Make sure the potential market is both stable and large enough to handle tremendous amounts of biomass. Smaller niche markets for biomass would quickly become overwhelmed, and any new product market runs the risk of failure. Marketing biomass to larger, established industries, such as animal feed, would provide the greatest opportunity. Assessing synergistic relationships (nutrients from wastewater, carbon dioxide from flue gas, etc.) and determination of growth conditions may affect by-product composition, ultimately limiting available markets.
5) *What are the local impacts from this system?*
   This factsheet discussed numerous life cycle assessments for algae production systems, and while life cycle analysis often looks at a very big picture, it is possible to use it for smaller sites as well. Water quality and water supply impacts are probably the greatest concern for individual farms. Filling large tanks may be the initial concern, but there will also be wastewater handling considerations. Electrical power use and the need for back-up power (generators) as well as a fuel source for the back-up power is another impact that should be investigated.

Additional Resources

This list represents a truncated version of the references used in the development of this publication. This reduction was necessary to meet SRAC formatting requirements. A fully cited version of this publication is available from the authors.

Amer, L., B. Adhikari, and J. Pellegrino. 2011. Techno-economic analysis of five microalgae-biofuels processes of varying complexity. Bioresource Technology 102:9350-9359.

Chisti, Y. 2007. Biodiesel from microalgae. Biotechnology Advances 25:294-306.

Clarens, A.F., E.P. Resurreccion, M.A. White, and L.M. Colosi. 2010. Environmental life cycle comparison of algae to other bioenergy feedstocks. Environmental Science & Technology, 44(5):1813-1819.

Collet, P., A. Hélias, L. Lardon, M. Ras, R.A. Goy, and J.P. Steyer. 2011. Life-cycle assessment of microalgae culture coupled to biogas production. Bioresource Technology 102(1):207-214.

Huntley, M.E. and D.G. Redalje. 2007. CO_2 mitigation and renewable oil from photosynthetic microbes: a new appraisal. Mitigation and Adaptation Strategies for Global Change 12:573-608.

ISO. 2006a. 14040 Environmental management-life cycle assessment-principles and framework. London: British Standards Institution.

Jorquera, O., A. Kiperstok, E.A. Sales, M. Embiruçu, and M.L. Ghirardi. 2010. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. Bioresource Technology 101(4):1406-1413.

Lardon, L., A. Hélias, B. Sialve, J.P. Steyer, and O. Bernard. 2009. Life-cycle assessment of biodiesel production from microalgae. Environmental Science and Technology 43(17):6475-6481.

Pokoos-Aikins, G., A. Nadim, M.M. El-Halwagi, and V. Mahalec. 2010. Design and analysis of biodiesel production from algae grown through carbon sequestration. Clean Technologies and Environmental Policy 12:239-254.

Pulz, O., K. Scheibenbogen, and W. Gross. 2000. Biotechnology with cycanobacteria and microalgae. In: Rehm H-J, Reed G. (eds) Biotechnology 10 ed 2. Wiley-VCH, Weinheim, 105-136.

Pulz, O. and W. Gross. 2004. Valuable products from biotechnology of algae. Applied Microbiology and Biotechnology 65:635-648.

Richardson, J.W., M.D. Johnson, and J.L. Outlaw. 2012. Economic comparison of open pond raceways to photo bio-reactors for profitable production of algae for transportation fuels in the Southwest. Algal Research 1(1):93-100.

Sander, K. and G.S. Murthy. 2010. Life cycle analysis of algae biodiesel. The International Journal of Life Cycle Assessment 15(7):704-714.

Soratana, K. and A.E. Landis. 2011. Evaluating industrial symbiosis and algae cultivation from a life cycle perspective. Bioresource Technology 102(13):6892-6901.

Spoehr, H.A. and H.W. Milner. 1949. The chemical composition of Chlorella; effect of environmental conditions. Plant Physiology 24(1):120.

Stephenson, A.L., E. Kazamia,J.S. Dennis, C.J. Howe, S.A. Scott, and A.G. Smith. 2010. Biodiesel from algae: challenges and prospects. Energy Fuels 24:4062-4077.

Williams P.J. le B. and L.M.L. Laurens. 2010. Microalgae as biodiesel & biomass feedstocks: Review and analysis of the biochemistry, energetics & economics. Energy & Environmental Science 3:554-590.

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