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REPORT IN BRIEF

Sustainable Development of Algal Biofuels in the United States

Biofuels made from algae are gaining attention as a domestic source of renewable fuel. However, with current technologies, scaling up production of algal biofuels to meet even 5 percent of U.S. transportation fuel needs could create unsustainable demands for energy, water, and nutrient resources, this report finds. Continued research and development could yield innovations to address these challenges, but determining if algal biofuel is a viable fuel alternative will involve comparing the environmental, economic and social impacts of algal biofuel production and use to those associated with petroleum-based fuels and other fuel sources.

As a potential source of renewable fuel, algae offer several advantages over land-based plants. Algae grow quickly, yield high amounts of biomass, and can grow in ponds or reactors located on non-farmable land. But cultivating algae and processing them to make fuel require significant inputs of freshwater, energy, and nutrients that may affect the competitiveness of algal biofuels with other types of fuels and biofuels.

This report, produced at the request of the Department of Energy, identifies potential sustainability concerns associated with producing algal biofuels in the United States. The report's authoring committee assessed resource needs and environmental concerns resulting from large-scale algal biofuel production and explored opportunities to mitigate these concerns. Although there are sustainability challenges with current algal biofuel production systems, innovative biological and engineering approaches could help develop new capabilities to make algal biofuel a viable alternative to petroleum-based fuels and other fuel sources.

Microalgae are single-celled organisms that use the sun's energy to create their own food. Some algae accumulate fats that can be converted to transportation fuels, such as biodiesel or jet fuel, while other algal species secrete compounds from which fuel is made, such as ethanol. Alternatively, whole algal cells can be processed into fuel. Algae complete their reproductive cycle in hours or a few days, and can be harvested for conversion into fuel on a daily or weekly basis. Image courtesy Sandia National Laboratories

Estimates of greenhouse gas emissions associated with algal biofuel production vary greatly, from a net negative value—that is, the process of making algal biofuel is a carbon sink—to positive values that are substantially higher than for petroleum gasoline. The amount of emissions depends on many factors including types of coproducts generated and the source of energy used during fuel production.

Sustainability Concerns

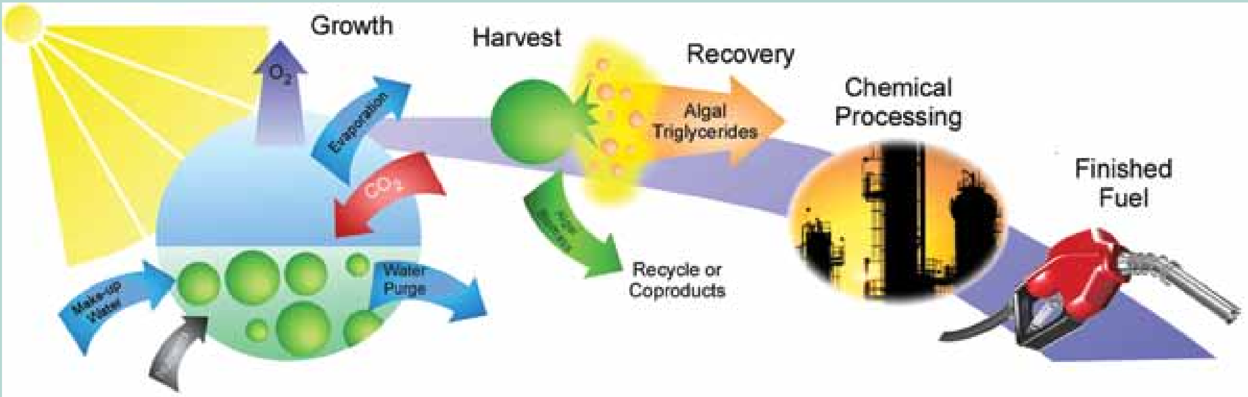
Producing any type of fuel requires resources. Algal biofuel production requires inputs of water, energy, and nutrients and land. If algal biofuel is to become a practical substitution for petroleum-based fuels, work will be needed to show that techniques used to generate small amounts of algal biofuel can be scaled up in an economically and environmentally sustainable manner.

Water

Water provides the physical environment in which algae grow and reproduce, acts to regulate temperature in cultivation systems, and provides

Box 1. Turning Algae into Fuel

A variety of production systems and processing options have been proposed for converting algae to biofuel, but they generally consist of the same basic steps.



Step 1: Growth: Algae are cultivated either in open ponds or in closed photobioreactor systems, which are transparent containers designed to allow light through to algal cells. Both systems must be agitated and circulated to prevent sedimentation, allow the even distribution of nutrients, and expose algae to light and carbon dioxide.
Step 2: Harvest: This step involves separating algae from their liquid growth media, for example, by filtering the water to remove algal cells or by separating algae and water with a centrifuge. Harvesting is not necessary for systems with algae or cyanobacteria that secrete compunds from which fuel are made into the culture medium.
Step 3: Recovery: This step involves extracting fatty liquids from algal cells or recovering fuel precursors from the culture medium. The residue left after lipids have been recovered can be recycled for nutrients, or may be useful as a coproduct.
Step 4: Processing: Algal lipids, biomass, or secreted products are processed into fuels.

a medium for delivering nutrients, such as carbon dioxide, nitrogen, and phosphorus. It's estimated that producing 1 liter of algal biofuel could use up between 3.15 and 3,650 liters of freshwater, depending on the growth and processing methods used. For comparison, between 5 and 2,140 liters of water is required to produce each liter of ethanol from corn, and about 1.9 to 6.6 liters of water are used to produce one liter of petroleum-based gasoline from crude oil or oil sands. However, assessments of water use for fuel production need to be considered in the context of regional water availability.

Nutrients

Algae require key nutrients to live and grow: carbon dioxide is essential for the photosynthetic production of biomass, and nitrogen and phosphorus are needed for the reactions involved in energy capture, release, and transfer. It's estimated that about 6 million to 15 million tonnes of nitrogen, and 1 million to 2 million tonnes of phosphorus would be needed to produce algal biofuel to meet 5 percent of U.S. transportation fuel need if the nutrients are not being recycled. That represents 44 to 107 percent of the total nitrogen use for agriculture in the United States and 20 to 51 percent of the total phosphorus use, demands that are likely unsustainable from the perspective of limited natural supplies.

Energy

Investments of energy are needed for various steps in producing algal biofuel, for example to agitate algae cultivation ponds to ensure that nutrients are distributed evenly. The balance of energy inputs during production to the amount of energy released when the fuel is combusted is measured using a ratio called the energy return on investment (EROI). The committee found that energy return on investment ratios for various algal biofuel production systems described in the published literature ranged from about 0.13 to 3.33. An energy return on investment of less than one indicates that the amount of energy needed to produce the fuel is greater than the energy contained in the fuel, a situation that is clearly unsustainable.

Sustainable fuel development, as defined by the United Nations, meets the needs of the present without compromising the ability of future generations to meet their own needs.

Box 2. The Need for Land

Algal biofuel production facilities can be located on non-farmable land—a significant advantage over biofuels made from land plants, which may compete with food crops for farm land. However, there are several important factors to consider when siting potential algal biofuel facilities, including topography, climate, and proximity to water and nutrient supplies. Finding large enough areas of suitable land could limit the expansion of algal biofuel production. A national assessment of land requirements for algae cultivation that takes into account climatic conditions; freshwater, inland and coastal saline water, and wastewater resources; sources of carbon dioxide; and land prices is needed to inform the potential amount of algal biofuels that could be produced economically in the United States.

Greenhouse Gas Emissions

Algae take up carbon dioxide via photosynthesis, helping offset a portion of the carbon dioxide and other greenhouse gases released during algal biofuel production and when the fuel is burned. To be a viable fuel alternative, algal biofuel would have to offer net greenhouse gas emission benefits during production and use relative to petroleum-based fuels.

The Potential for Innovation

The committee noted that none of the sustainability concerns is a definitive barrier to the development of algal biofuel as a fuel alternative. Biological and engineering innovations have the potential to mitigate the resource demands associated with algal biofuel, including research toward the following goals:

- ***Identify Algal Strains with Desired Characteristics***

A vast and diverse spectrum of algal species is available, but so far, only a narrow range of species has been considered for use in the commercial production of biofuels. Genomic analyses and physiological studies could help screen algal species for useful characteristics and expand the range of species used in algal biofuel production. For example, species with higher photosynthetic efficiencies would convert more available light into biomass, while other strains might produce more lipid per unit biomass.

- ***Develop Improved Algal Strains***

The same plant breeding and genetic engineering techniques that have advanced traditional agriculture could also be applied to algal strains, for example to develop algal strains that produce higher yields of lipids.

- ***Engineer Better Designs to Reduce Energy Inputs***

Improvements to algae cultivation and processing methods could reduce the energy requirements of algal biofuel production. For example, engineering innovations could develop harvesting methods that do not require as much energy input as current methods.

- ***Use of Alternative Sources of Water for Cultivating Algae***

Cultivating salt-tolerant algal strains would allow the use of brackish water, saltwater, or marine water for cultivating algae, decreasing the need for freshwater inputs.

Algal Biofuels: Future Potential

Systems for producing algal biofuel at commercial scales are still being developed. As the algal biofuel industry matures, the ability of different pathways for algal biofuel production to meet and balance yield with environmental, economic, and social sustainability goals will have to be assessed and compared to those of petroleum-based fuels, and other fuel alternatives (see Box 4). Current reports suggest that there are several resource use and environmental challenges to overcome in order to scale up algal biofuel production in a sustainable way. Innovations, research, and development in various aspects of the production pathway will help realize much of the potential for algal biofuels to improve energy security, reduce greenhouse gas emissions, and enhance environmental quality.

Box 3. Algae and Cyanobacteria as Recycling Systems

Laboratory experiments show that nitrogen and phosphorus inputs to algal biofuel systems could be gleaned from municipal, industrial, or agricultural wastewater. Feeding algae with nutrients from wastewater would help reduce reliance on nitrogen and phosphorus fertilizers that would otherwise be used for food production, and could also serve as the nutrient removal step in wastewater treatment. However, the feasibility of using wastewater for algal biofuel production has not yet been proven at commercial scale, and there might be few locations for algal biofuel facilities close to wastewater treatment plants.

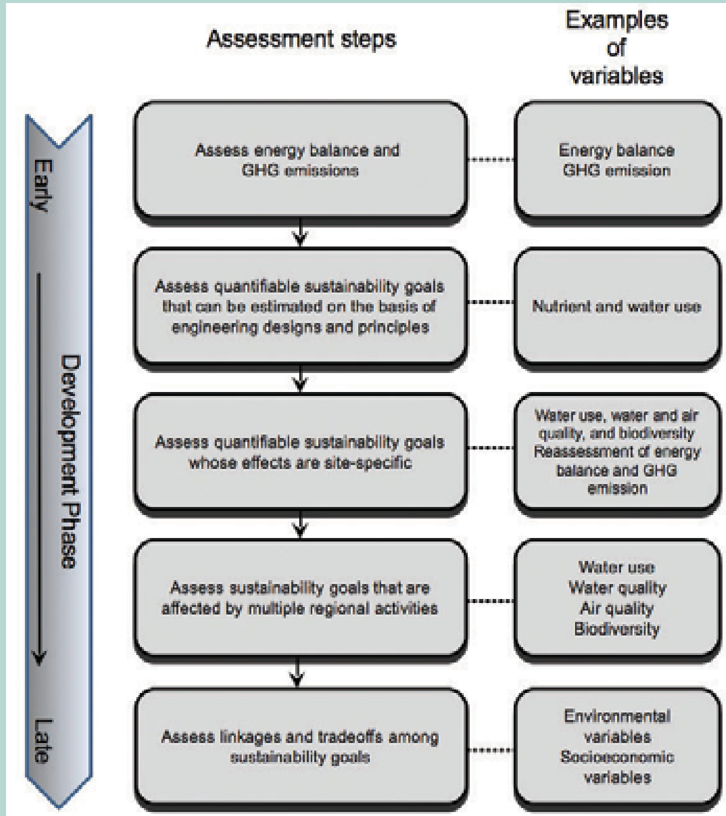
Box 4. A Framework to Assess the Sustainable Development of Algal Biofuels

The report's authoring committee proposed this decision framework to compare the sustainability of algal biofuel production with that of petroleum-based fuel and other fuel alternatives.

The framework starts with assessing two of the primary goals for developing alternative sources of fuel—improving energy security and reducing greenhouse gas emissions. To compete with other fuel sources, algal biofuel should have an energy return on investment that is at least comparable to other transportation fuels and generate less net greenhouse gas emissions, during both production and use, than fossil fuels.

Other criteria can be assessed based on the predicted inputs and outputs of the proposed system. For example, estimates of the resource requirements for a given system would help scientists avoid competition between food and fuel production for nitrogen, phosphorus, and freshwater supplies.

Furthermore, though some resource use or emissions can be estimated quantitatively without specifying the exact location of algal biofuel production facilities, other factors are highly location dependent. For example, environmental effects, such as biodiversity or the effect of water consumption, can only be assessed if the location of the algal biofuel system is known. Energy return on investment, greenhouse gas emissions, nutrient and freshwater requirements will likely need to be reassessed once the likely locations of deployment have been narrowed down.



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The National Academies appointed the above committee of experts to address the specific task requested by the Department of Energy. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report.

EXPERT CONSENSUS REPORT

For more information, contact the Board on Agriculture and Natural Resources at (202) 334-3062 or visit http://dels.nas.edu/banr. Copies of *Sustainable Development of Algal Biofuels in the United States* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu.