



Algae farms require vast water surface areas to efficiently convert sunlight into an oil used as a biofuel.

ALGAE

The scum solution

The green slime that covers ponds is an efficient factory for turning sunlight into fuel, but growing it on an industrial scale will take ingenuity.

BY NEIL SAVAGE

When you imagine the crops that will provide biofuels, what is the first image that enters your mind? A field of corn or sugar cane? Maybe you should be picturing pond scum instead.

Algae, the organisms that cover ponds with a green film and turn tides red, are a promising source of biofuels. Researchers estimate that algae could yield 61,000 litres per hectare, compared with 200 litres to 450 litres from crops such as soya and canola. And, as the price of petroleum soars, that sort of yield is drawing interest from government and industry alike. Last year, the US Department of Energy gave US\$44 million to create a research consortium to advance the technology for turning algae into fuel.

Industry is also gearing up. Sapphire Energy, a renewable energy company headquartered in San Diego, California, has received more than US\$100 million in private investments to develop 'green crude', as well as another US\$104 million from the US federal government's 2009 stimulus package. The oil company Exxon Mobil gave a US\$300 million vote of confidence to algae by teaming up with the biotechnology company Synthetic Genomics in La Jolla, California. And aircraft maker Boeing helped establish the Algal Biomass

Organization to promote the creation of algal jet fuel.

That algae draws so much research attention is a testament to its compelling potential. The organisms can be grown in artificial ponds on land that's unsuitable for agriculture, so they don't have to compete with food crops for space. They can be cultivated on the surfaces of lakes or coastal waterways, or in vats on wasteland. Algae reproduce rapidly, spreading over a body of water within hours. And they can thrive on what would otherwise be considered a clean-up problem — the water from waste-treatment plants and the carbon dioxide spewed from industrial chimneys.

Most algae being explored for biofuel production are single-celled organisms that turn carbon dioxide, hydrogen and nitrogen into carbohydrates, lipids and proteins. Depriving the organisms of nutrients causes the photosynthetic mechanism to switch from growing more algae to producing lipids. After a few days, a centrifuge is used to separate the algae from the water they grow in. Breaking open the cells then allows the extraction of an oil that can be turned

into a hydrocarbon-based fuel. The alga's protein and carbohydrate remnants can be processed into pharmaceuticals or used as animal feed.

But what's simple to describe can be difficult to accomplish efficiently. Just ask GreenFuel Technologies, a company founded in 2001 by researchers at the Massachusetts Institute of Technology (MIT) in Cambridge. GreenFuel built a series of ever-larger pilot plants that used waste gases from power plants as a food source for oil-producing algae, and it signed a US\$92 million deal to build more plants in Spain. In 2009, the company shut down because of a lack of funds, having learned that harvesting algae was more expensive than it had anticipated. A recent study of algal biofuel production by the Energy Biosciences Institute at the University of California, Berkeley, which is funded by the oil company BP, found that much work remains before the struggle for economic viability can be won. According to Nigel Quinn, an agricultural engineer at Lawrence Berkeley National Laboratory who led the study, making fuel from algae using today's technology is a money-losing proposition, unless it's done in conjunction with another process, such as treating wastewater or producing valuable by-products.

To reach the big time, algal oil production must overcome several obstacles. For one thing, there's the question of space: for photosynthesis to work, light must reach the algae. If a layer of algae is more than a few centimetres thick, the organisms on the surface shade

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those underneath, blocking the sunlight. One alternative is to spread horizontally — and wide. Algae would need to cover an area of 9.25 million hectares — about the size of Portugal — to derive enough biodiesel to cover Europe's annual transport requirement of 370 billion litres, according to René Wijffels and Maria Barbosa, environmental technologists at Wageningen University's Food and Biobased Research centre in the Netherlands.

Realistically, only 5.5% of land in the United States is available to accommodate algae-growing ponds, estimates Mark Wigmosta, a hydrologist at the Pacific Northwest National Laboratory in Richland, Washington. With the current technology, that land could produce 220 billion litres of algal oil per year — equivalent to about half of the oil imported by the United States for transport each year. Furthermore, with current production processes, such a large-scale algae-growing enterprise would require roughly three times as much water as is devoted to all US agriculture, says Wigmosta. To assess whether water usage could be reduced, he looked at areas where the average levels of sunshine, precipitation and humidity would lead to more efficient algal growth: the Gulf Coast, the southeastern seaboard and the Great Lakes. He found enough land in these regions to replace about 17% of petroleum imports with biofuel, using only one-quarter of the water devoted to agriculture (roughly the same amount of water that bioethanol production requires). Wigmosta based this analysis on a system using open ponds of 30 centimetres depth and 4 hectares in area, assuming they are supplied by fresh water. Strains of algae that grow in salt water or waste water could make the equation more favourable.

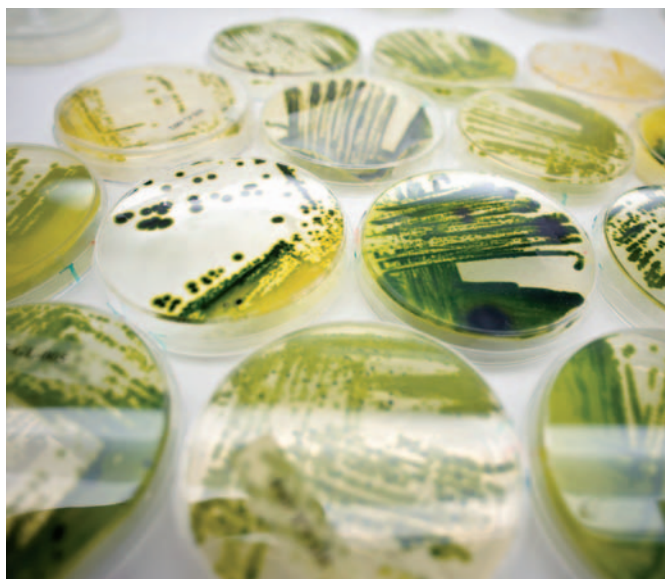
It might be possible to use less water by switching from open ponds, which lose water through evaporation, to closed photobioreactors. In a typical reactor, an array of glass tubes circulates CO₂ through a mixture of algae and water; the goal is to expose all organisms to enough sunlight. But such systems — which Wigmosta says are popular in China — present their own difficulties. For example, because the reactors soak up sunlight, they need to be cooled, which often means spraying them with water, possibly cancelling out the savings made by avoiding evaporative loss.

The other input that algae need, besides water, is CO₂ — but algal cells can't efficiently tap into atmospheric CO₂ to support the rapid growth needed for a commercial operation. So algal farms might need to be situated near artificial CO₂ sources, such as coal-burning

power plants. "If you have to pipe CO₂ four or five miles, the piping costs will eat you alive," Quinn says.

ADVANCED ALGAE

The renewable oils company Solazyme in South San Francisco, California, is trying to sidestep some of the problems with algal cultivation by exchanging photosynthesis for the same sort of fermentation used to produce ethanol. "The productivity is incredibly low when you grow algae in a direct photosynthesis process," says Solazyme president and chief technology officer Harrison Dillon. The company keeps its algae in the dark and feeds them sugar, which can be derived from any source. The organisms then convert the sugar into an oil. Dillon predicts that even without government subsidies, the company's biofuel will be priced competitively with petrol (gasoline).



Algae at Solazyme are kept in the dark and fed sugar to produce an oil.

line). Solazyme is converting old factories to demonstrate its technology and has a contract to deliver 570,000 litres of alga-derived fuel to the US Department of Defense this year. The company hopes to be selling algal oil to commercial refineries to produce a hydrocarbon-based fuel by the end of 2013.

James Liao, a chemical and biomolecular engineer at the University of California, Los Angeles, also wants to move away from traditional ways of using algae. The main issue with restricting nutrients to force the organisms to make oil is that it trades off growth for oil production. Liao, instead, adds more nutrients. The result is an artificial algal bloom, which yields little oil but a lot of protein. The algae then become a feedstock for another organism, such as *Escherichia coli*, which digests the algae and produces alcohols such as ethanol and butanol. Those, in turn, can be built up into hydrocarbon-based fuels by using standard chemical processes. One advantage of Liao's

proposal is its efficiency. "It's probably the fastest way to fix CO₂," Liao says. Another is that it avoids one potential problem of open ponds, the invasion of other organisms. Strains that have been genetically engineered to produce more oil may have trouble out-competing natural strains that enter the system. As a bonus, the conversion process produces ammonia as a by-product, and this nitrogen source can be used to fertilize the next round of growth.

Another possible fuel source is blue-green algae, which aren't strictly algae but bacteria of the genus *Cyanobacterium*. Whereas algal cells must be destroyed to extract their oil, cyanobacteria secrete their products. As a result, it's unnecessary to kill one batch and grow a new one, allowing continuous production. George Church, a geneticist at Harvard Medical School in Boston, Massachusetts, has engineered cyanobacteria to produce hydrocarbon molecules at the appropriate lengths for various fuels. "We're not making oils. We're making something much closer to petroleum," says Church, who cofounded Joule Unlimited in Cambridge, Massachusetts, to commercialize the technology. Moreover, Church says, tweaking the bacterium's genes will eventually make it possible for the organisms to soak up atmospheric CO₂ efficiently — an advance that would liberate fuel production from the need for an artificial source of CO₂. The company is testing its technology in a pilot plant near Austin, Texas, and expects to begin commercial production in 2012. The Joule team contends that its process will produce 140,000 litres per hectare per year.

There is plenty of room for progress. Current estimates are that biological photosynthesis can convert at most about 10% of the sunlight reaching the Earth's surface to chemical energy; Wigmosta says today's algae convert about 1.1%. Genetic engineering could create algae that produce more oil and are more efficient at converting solar energy to biomass. Engineers are working on improved designs for growth systems, such as structures that stack algae in layers for better sunlight exposure, and harvesting systems that could use microwaves or sound waves to extract the oil.

Quinn says it could easily take ten years of such research to make algal biofuels economically viable, but it's certainly possible to replace some proportion of the petroleum we use now. "We don't necessarily know what the path's going to be," he says. But "we're optimistic". ■

Neil Savage is a science writer based in Lowell, Massachusetts.