Biodiesel from microalgae beats bioethanol

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Renewable biofuels are needed to displace petroleum-derived transport fuels, which contribute to global warming and are of limited availability. Biodiesel and bioethanol are the two potential renewable fuels that have attracted the most attention. As demonstrated here, biodiesel and bioethanol produced from agricultural crops using existing methods cannot sustainably replace fossil-based transport fuels, but there is an alternative. Biodiesel from microalgae seems to be the only renewable biofuel that has the potential to completely displace petroleum-derived transport fuels without adversely affecting supply of food and other crop products. Most productive oil crops, such as oil palm, do not come close to microalgae in being able to sustainably provide the necessary amounts of biodiesel. Similarly, bioethanol from sugarcane is no match for microalgal biodiesel.

Crop-derived biodiesel and bioethanol are unsustainable

Carbon neutral renewable liquid fuels are needed to eventually totally displace petroleum-derived transport fuels that contribute to global warming. Biodiesel from oil crops and bioethanol from sugarcane are being produced in increasing amounts as renewable biofuels, but their production in large quantities is not sustainable. An alternative is offered by microalgae.

Microalgae are photosynthetic microorganisms that convert sunlight, water and carbon dioxide to algal biomass. Many microalgae are exceedingly rich in oil [1,2], which can be converted to biodiesel using existing technology. This article discusses the potential of microalgae for sustainably providing biodiesel for a complete displacement of petroleum-derived transport fuels, such as gasoline, jet fuel and diesel. In dramatic contrast with the best oil-producing crops, microalgal biodiesel has the potential to be able to completely displace petroleum-derived transport fuels without adversely impacting supplies of food and other agricultural products. It is further demonstrated that microalgal biodiesel is a better alternative than bioethanol from sugarcane, which is currently the most widely used transport biofuel [3].

Oil content of some microalgae exceeds 80% of the dry weight of algae biomass [1,2]. Agricultural oil crops, such as soybean and oil palm, are widely being used to produce biodiesel; however, they produce oils in amounts that are miniscule (e.g. less than 5% of total biomass basis) compared with microalgae [1]. As a consequence, oil crops can provide only small quantities of biodiesel for blending with petroleum diesel at a level of a few percent, but they are incapable of providing the large quantities of biodiesel that are necessary to eventually displace all petroleum-sourced transport fuels [1]. For example, oil palm, one of the most productive oil crops, yields only ~5950 liters of oil per hectare [1]. Biodiesel yield from a parent vegetable oil is ~80% of the oil yield per hectare. A country such as the United States requires nearly 0.53 billion m^3 of biodiesel annually [1] at the current rate of consumption, if all petroleum-derived transport fuel is to be replaced with biodiesel. To produce this quantity of biodiesel from palm oil, oil palm would need to be grown over an area of ~111 million (M) hectares. This is nearly 61% of all agricultural cropping land in the United States. Growing oil palm at this scale would, therefore, be unrealistic, because insufficient land would be left for producing food, fodder and other crops.

Based on these calculations, it is obvious that oil crops are not able to replace petroleum-derived liquid fuels in the foreseeable future. This scenario is, however, different if microalgae are used as a source of biodiesel.

An average annual productivity of microalgal biomass in a well designed production system located in a tropical zone can be in the region of 1.535 $kg\ m^{-3}\ d^{-1}$ [1,4]. At this level of biomass productivity, and if an average oil content of 30% dry weight in the biomass is assumed, oil yield per hectare of total land area is ~123 m^3 for 90% of the calendar year. (About 10% of the year is unproductive, because the production facility must be shut down for routine maintenance and cleaning.) This amounts to a microalgal biodiesel yield of 98.4 m^3 per hectare. Therefore, producing the 0.53 billion m^3 of biodiesel the U.S. needs as transport fuel, would require microalgae to be grown over an area of ~5.4 M hectares or only 3% of the U.S. cropping area. This is a feasible scenario even if the algal biomass contains only 15% oil by dry weight. No other potential sources of biodiesel come close to microalgae in being realistic production vehicles for biodiesel. Another important advantage of microalgae is that, unlike other oil crops, they grow extremely rapidly and commonly double their biomass within 24 h. In fact, the biomass doubling time for microalgae during exponential growth can be as short as 3.5 h [1], which is significantly quicker than the doubling time for oil crops.

An integrated oil-production process

A conceptual process for producing microalgal oils for making biodiesel is shown in Figure 1. The process consists

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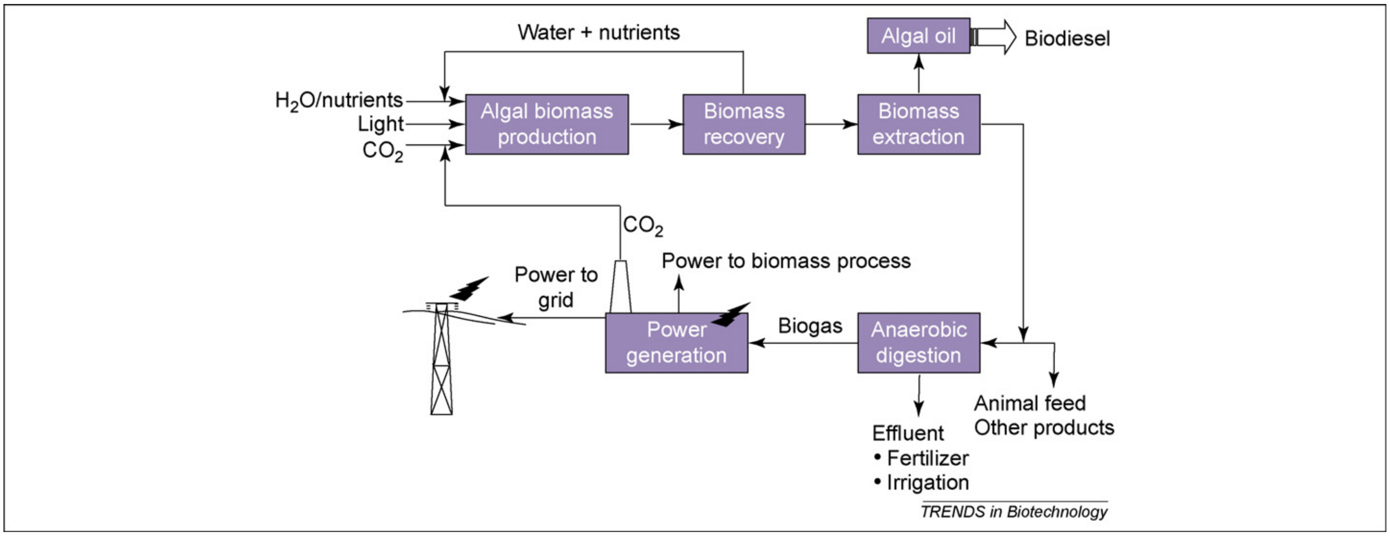

Figure 1. A conceptual process for producing microalgal oil for biodiesel. Water, inorganic nutrients, carbon dioxide and light are provided to microalgal culture during the biomass-production stage. In the biomass-recovery stage, the cells suspended in the broth are separated from the water and residual nutrients, which are then recycled to the biomass-production stage. The recovered biomass is used for extracting the algal oil that is further converted to biodiesel in a separate process. Some of the spent biomass can be used as animal feed and for recovering other possible high value products that might be present in the biomass. Most of the biomass undergoes anaerobic digestion, which produces biogas to generate electricity. Effluents from the anaerobic digester are used as a nutrient-rich fertilizer and as irrigation water. Most of the power generated from the biogas is consumed within the biomass-production process and any excess energy is sold to grid. Carbon dioxide emissions from the power generation stage are fed into the biomass production.

of a microalgal biomass production step that requires light, carbon dioxide, water and inorganic nutrients. The latter are mainly nitrates, phosphates, iron and some trace elements. Sea water supplemented with commercial nitrate and phosphate fertilizers, and a few other micronutrients, is commonly used for growing marine microalgae [5]. Fresh and brackish water from lakes, rivers and aquifers can be used. Growth media are generally inexpensive [1]. In a 100 tons annum^{-1} facility, cost of producing algal biomass has been estimated to be about \$3000 ton^{-1} [1], but cost per ton declines significantly as the scale of the production operation is increased.

Approximately half of the dry weight of the microalgal biomass is carbon [6], which is typically derived from carbon dioxide. Therefore, producing 100 tons of algal biomass fixes roughly 183 tons of carbon dioxide. This carbon dioxide must be fed continually during daylight hours. Microalgal biomass production can potentially make use of some of the carbon dioxide that is released in power plants by burning fossil fuels [7,8]. This carbon dioxide is often available at little or no cost.

The algal broth produced in the biomass production stage needs to be further processed to recover the biomass [9]. The water and residual nutrients recovered at this stage can be recycled to the biomass-cultivation stage (Figure 1). The concentrated biomass paste is extracted with a water-immiscible solvent to recover algal oil, which can then be converted to biodiesel using already existing methods [1]. The feasibility of oil extraction for microalgal biomass has been previously demonstrated [6,10]. The extraction solvent (e.g. hexane) is expected to be recovered and recycled.

The biomass residue that remains after extraction of oil could be used partly as high-protein animal feed and, possibly, as a source of small amounts of other high-value microalgal products [5,11,12]. In both scenarios, the revenue from selling the biomass residues could defray the cost of producing biodiesel. However, the majority of algal biomass residue from oil extraction is expected to undergo anaerobic digestion to produce biogas. This biogas will serve as the primary source of energy for most of the production and processing of the algal biomass. The generation of surplus energy is expected and this could be sold to grid to further improve the economics of the integrated process. Additional income could come from the sale of nutrient-rich fertilizer and irrigation water that would be produced during the anaerobic digestion stage (Figure 1).

The technology for anaerobic digestion of waste biomass exists and is well developed [13], and the technology for converting biogas to electrical/mechanical power is well established [14]. The carbon dioxide generated from combustion of biogas can be recycled directly for the production of the microalgae biomass (Figure 1).

Energy content of biogas produced through anaerobic digestion typically ranges from 16 200 kJ m^{-3} to 30 600 kJ m^{-3}[*] depending on the nature of the source biomass. Typically, the yield of biogas varies from 0.15 to 0.65 m^3 per kg of dry biomass*. Assuming average values of biogas energy content and yield, biogas production from microalgal solids, after their 30% oil content has been removed, could provide at least 9360 MJ of energy per metric ton. This is a substantial amount of energy and it should run the microalgal biomass production process.

Ideally, microalgal biodiesel can be carbon neutral, because all the power needed for producing and processing the algae could potentially come from biodiesel itself and from methane produced by anaerobic digestion of the biomass residue left behind after the oil has been extracted. Although microalgal biodiesel can be carbon neutral, it will not result in any net reduction in carbon

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[*] Recalculated from information given in a presentation by Wulf, S. (2005) First Summer School on Sustainable Agriculture, Bonn, Germany, August.

dioxide that has already accumulated as a consequence of burning of fossil fuels.

Production of microalgal biomass

Producing microalgal biodiesel requires large quantities of algal biomass. To minimize expense, the biomass must be produced using freely available sunlight and is thereby affected by fluctuations such as daily and seasonal variations in light levels. Microalgae can be grown on a large scale in photobioreactors [4,5,12,15–19]. Many different designs of photobioreactors have been developed, but a tubular photobioreactor seems to be most satisfactory for producing algal biomass on the scale needed for biofuel production (Figure 2).

A tubular photobioreactor consists of an array of straight transparent tubes that are usually made of plastic or glass. This tubular array, or the solar collector, captures the sunlight for photosynthesis (Figure 2). The solar collector tubes are generally less than 0.1 m in diameter to enable the light to penetrate into a significant volume of the suspended cells. Microalgal broth is circulated from a reservoir (such as the degassing column shown in Figure 2) to the solar collector and back to the reservoir [1]. A photobioreactor is typically operated as a continuous culture during daylight [1].

In a continuous culture, fresh culture medium is fed at a constant rate and the same quantity of microalgal broth is withdrawn continuously [5]. Feeding ceases during the night; however, the mixing of broth must continue to prevent settling of the biomass [5]. As much as 25% of the biomass produced during daylight might be consumed during the night to sustain the cells until sunrise [1,20,21]. The extent of this nightly loss depends on the light level under which the biomass was grown, the growth temperature and the temperature at night.

To maximize sunlight capture, the tubes in the solar collector are generally oriented North–South (Figure 2) [4,5]. By arranging the tubes in a fence-like arrangement, shown in Figure 2, the number of tubes that can be accommodated in a given area is maximized. The ground beneath the solar collector is either painted white or covered with white sheets of plastic [1,5,16] to increase reflectance or albedo, which will increase the total light received by the tubes.

Biomass sedimentation in the tubes is prevented by maintaining a highly turbulent flow. This flow is produced either using a mechanical pump (as shown in Figure 2) or a more gentle airlift pump, because mechanical pumps can damage the biomass [6,22–25]. Airlift pumps have been used commonly [5,12,26–28] because they are generally less expensive to install than mechanical pumps, cause less damage to biomass and do not have any moving parts that might fail; nevertheless, airlift pumps are less versatile than mechanical pumps and they can be difficult to design [28–30].

Photosynthesis generates oxygen. Under midday irradiance in most locations, the maximum rate of oxygen generation in a typical tubular photobioreactor can be as high as 10 g O_2 m^{-3} min^{-1}. Dissolved oxygen levels that are much greater than air saturation values will inhibit photosynthesis [27]. Furthermore, a high concentration of dissolved oxygen in combination with intense sunlight produces photooxidative damage to algal cells. To prevent photosynthesis inhibition and cell damage, the maximum tolerable dissolved oxygen level should not exceed 400% of air saturation value [27]. Because accumulated oxygen cannot be removed within a photobioreactor tube, the maximum length of a continuous tube run is limited. To remove oxygen, the culture is periodically returned to a degassing zone in which it is aerated to strip out the

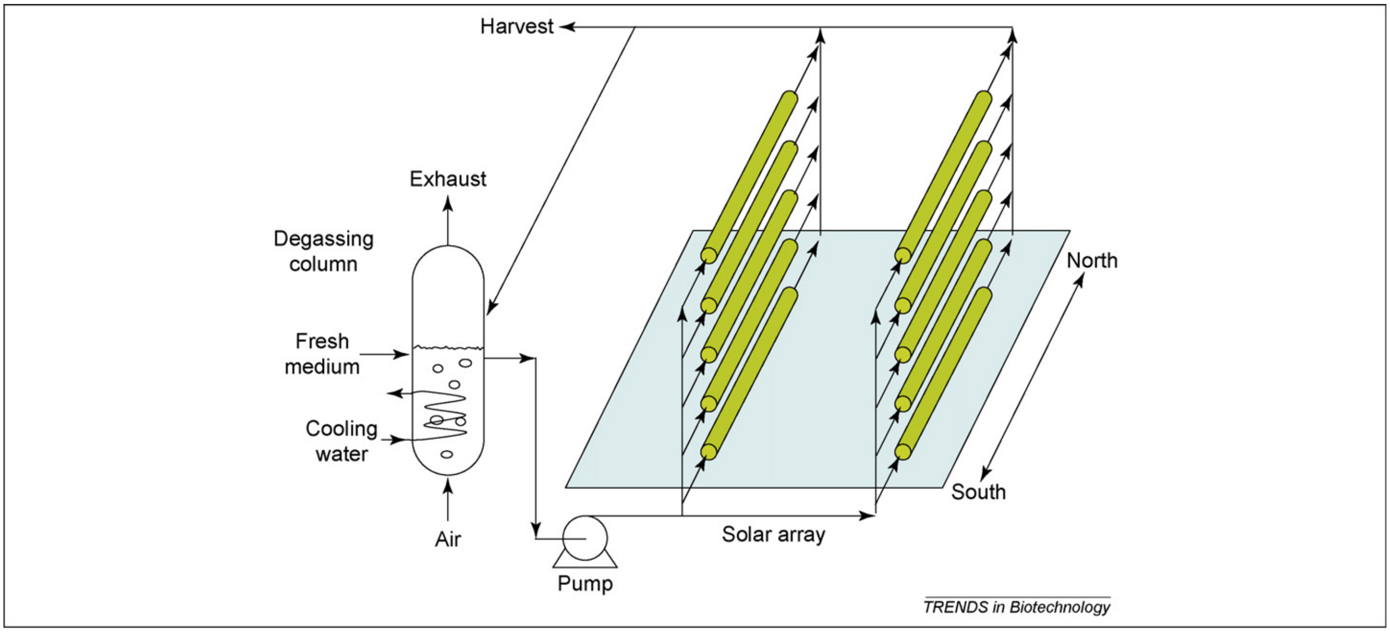

Figure 2. A tubular photobioreactor with fence-like solar collectors. Algal broth from the degassing column is continuously pumped through the solar array, where sunlight is absorbed, and back to the degassing column. Fresh culture medium is fed continuously to the degassing column during daylight and an equal quantity of the broth is harvested from the stream that returns to the degassing column. Cooling water pumped through a heat exchanger coil in the degassing column is used for temperature control. The degassing column is continuously aerated to remove the oxygen accumulated during photosynthesis and oxygen-rich exhaust gas is expelled from the degassing column.

accumulated oxygen (Figure 2) [1]. Typically, a continuous tube run does not exceed 80 m [27]; however, the possible tube length depends on several factors, including the concentration of the biomass, the light intensity, the flow rate and the concentration of oxygen at the entrance of the tube.

In addition to removing the accumulated dissolved oxygen, the degassing zone must disengage all the gas bubbles from the broth so that essentially bubble-free broth returns to the solar collector tubes. The presence of too many gas bubbles in the solar tubes will interfere with light absorption and reduce the flow of culture broth in the tubes. The design of potential gas–liquid separators that achieve complete disengagement of bubbles has been discussed [29,31]. A major requirement for a degassing zone is that its volume is kept small relative to the volume of the solar collector. This is owing to the fact that degassing zones are generally optically deep compared with the solar collector tubes and poorly illuminated, therefore negatively affecting microalgae growth.

Another factor that affects the performance of a photobioreactor is the pH of the culture. As the broth moves along a photobioreactor tube, its pH increases because of consumption of carbon dioxide [32]. To counteract this, carbon dioxide is fed in to the degassing zone in response to a pH controller. Furthermore, additional carbon dioxide injection points placed at intervals along the tubes can prevent carbon limitation and an excessive rise in pH [5].

Optimal temperature for growing many microalgae is between 20 and 30 °C. A temperature outside this range could kill or otherwise damage the cells. Algal broth in photobioreactor tubes exposed to sunlight will rapidly overheat, unless it is cooled. Cooling during daylight hours is essential. Furthermore, temperature control at night is also useful to prevent it from falling so low as to damage the cells. For example, the nightly loss of biomass owing to respiration can be reduced by lowering the temperature at night to a value that is a few degrees lower than the optimal growth temperature for a given alga. Outdoor tubular photobioreactors can be effectively and inexpensively cooled using heat exchangers, which can be placed in the degassing column, as shown in Figure 2, or in the tubular loop. Evaporative cooling, using water sprayed on tubes [16], can also be used and has proven successful in dry climates, for example in Israel.

At least once a year, a photobioreactor facility must be shut down for routine maintenance and cleaning. Cleaning and sanitization are required also in the event of failure of culture because of contamination with unwanted algae and parasites. A commercial photobioreactor must be capable of being cleaned rapidly to reduce downtime. Automated clean-in-place methods that do not require dismantling of the photobioreactor are generally used [33,34].

Better than bioethanol

It is useful to compare the potential of microalgal biodiesel with bioethanol from sugarcane, because on an equal energy basis, sugarcane bioethanol can be produced at a price comparable to that of gasoline [35]. Bioethanol is well established for use as a transport fuel [3] and sugarcane is the most productive source of bioethanol [35]. For example, in Brazil, the best bioethanol yield from sugarcane is 7.5 m^3 per hectare [35]. However, bioethanol has only ~64% of the energy content of biodiesel. Therefore, if all the energy associated with 0.53 billion m^3 of biodiesel that the U.S. needs annually [1] was to be provided by bioethanol, nearly 828 million m^3 of bioethanol would be needed. This would require planting sugarcane over an area of 111 M hectares or 61% of the total available cropping area of the United States.

Most of the energy needed for growing the cane and converting it to ethanol is gained from burning the cane crop waste or bagasse. For every unit of fossil energy that is consumed in producing cane ethanol, ~8 units of energy are recovered [35]. A similar level of energy recovery seems to be possible for microalgal biodiesel. This is because in terms of total dry matter (including sugar), sugarcane typically yields ~75 metric tons of biomass per hectare and this is much less than 158 tons per hectare for microalgal biomass. Under absolute best conditions, sugarcane biomass yield does not exceed ~100 metric tons per hectare. For similar levels of energy in total biomass, a higher biomass production per hectare effectively translates to a higher amount of stored solar energy per hectare.

Prospects of microalgal biodiesel

Impediments to large-scale culture of microalgae are mainly economic (Box 1). The economics of biodiesel production could be improved by advances in the production technology. Specific outstanding technological issues are efficient methods for recovering the algal biomass from the dilute broths produced in photobioreactors. Furthermore, extraction processes are needed that would enable the recovery of the algal oil from moist biomass pastes without the need for drying.

Algal biomass production capacity (i.e. the productivity) of a given photobioreactor facility depends on the geographical latitude where the facility is located. This is because the sunlight regimen varies with geographic location. For establishing the necessary size of the facility, the investment cost and operational expenses, anyone considering building an algal production facility needs to be able to calculate how much biomass and oil a facility will produce if it is located in a given region. Calculations such as this are not always reliable because of an insufficiently developed capability in photobioreactor engineering. Improved photobioreactor engineering will make predictions of productivity more reliable and enable design of photobioreactors that are more efficient.

A different and complimentary approach to increase productivity of microalgae is via genetic and metabolic engineering. Genetic and metabolic engineering are likely to have the greatest impact on improving the economics of production of microalgal diesel [1]. This has been recognized since the 1990s [36–38], but little progress seems to have been made and genetic engineering of algae lags well behind that of bacteria, fungi and higher eukaryotes. Producing stable transformants of microalgae has proved difficult [39,40], although strategies for efficient transformation are being developed [40]. Genetic and metabolic

Box 1. Economics of producing microalgal biodiesel

Microalgal biodiesel must be competitive with petroleum-sourced fuels that are, at present, the least expensive transport fuels. Whether biodiesel from microalgae is competitive will depend mainly on the cost of producing the algal biomass. One way to approach the competitiveness issue is to estimate the maximum price that could be reasonably paid for algal biomass with a given content of oil if crude petroleum can be purchased at a given price as a source of energy. This estimated price can then be compared with the current cost of producing the algal biomass.

The quantity of algal biomass (*M*, tons), which is the energy equivalent of a barrel of crude petroleum (i.e. has the same energy as a barrel of petroleum), can be estimated as follows:

$$M = \frac{E_{\text{petroleum}}}{q(1-w)E_{\text{biogas}} + ywE_{\text{biodiesel}}} \qquad \text{[Equation 1]}$$

where $E_{\text{petroleum}}$ (~6100 MJ) is the energy contained in a barrel of crude petroleum; q ($\text{m}^3\,\text{ton}^{-1}$) is biogas volume produced by anaerobic digestion of residual algal biomass; w is the oil content of the biomass in percent by weight; E_{biogas} (MJ m^{-3}) is the energy content of biogas; y is the yield of biodiesel from algal oil; and $E_{\text{biodiesel}}$ is the average energy content of biodiesel. Typically, y in Equation 1 is 80% by weight [1] and $E_{\text{biodiesel}}$ is ~37 800 MJ per ton. In keeping with average values for organic wastes, E_{biogas} and q are expected to be around 23.4 MJ m^{-3} and 400 $\text{m}^3\,\text{ton}^{-1}$, respectively[*]. Using these values in Equation 1, *M* can be calculated for any selected value of *w*.

Assuming that converting a barrel of crude oil to various useable transport energy products costs roughly the same as converting *M* tons of biomass to bioenergy, the maximum acceptable price that could be paid for the biomass would be the same as the price of a barrel of crude petroleum; thus:

$$\text{Acceptable price of biomass (\$/ton)} = \frac{\text{Price of a barrel of petroleum (\$)}}{M} \qquad \text{[Equation 2]}$$

The price of microalgal biomass, estimated using equations (1) and (2), for biomass that contains various levels of oil (15–55% by weight) is shown in Figure I for crude petroleum prices of up to \$1000 per barrel. At present the price of crude oil is about \$100 per barrel. At this price, microalgal biomass with an oil content of 55% will need to be produced at less than ~ \$340 ton^{-1} to be competitive with petroleum diesel. Literature suggests that, currently, microalgal biomass can be produced for around \$3000 ton^{-1} [1]. Therefore, the price of producing the biomass needs to decline by a factor of ~9, through advances in production technology and algal biology, to make biodiesel from microalgae a feasible option.

This analysis disregards possible income from biomass residues. In addition, converting *M* tons of algal biomass to biodiesel is likely to prove less expensive than converting a barrel of crude petroleum to various fuels. Nevertheless, the assessment given here provides an indication of what needs to be achieved for making algal biodiesel competitive with petrodiesel. A high threshold is placed on competitiveness of microalgal biodiesel by comparing it with petroleum diesel: none of the biodiesel being produced commercially from soybean oil in the U.S. and canola oil in Europe can compete with petroleum-derived diesel without the tax credits, carbon credits and other similar subsidies that it receives.

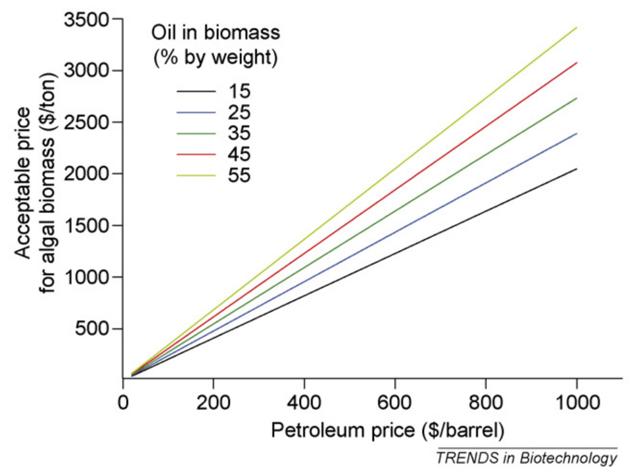

Figure I. Competitiveness of microalgal biomass depends on its oil content and the price of oil.

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[*] Recalculated from information given in a presentation by Wulf, S. (2005) First Summer School on Sustainable Agriculture, Bonn, Germany, August.

engineering in microalga has mostly focused on producing non-oil, high-value bioactive substances [41,42]. This situation is likely to change because of a strong reemerging interest in sustainably produced biofuels. For example, molecular level engineering can be used potentially to: (i) enhance the photosynthetic efficiency and increase biomass yield on light; (ii) increase biomass growth rate; (iii) elevate the oil content in biomass; and (iv) improve temperature tolerance of algae so that there is a reduced need for cooling, which is expensive.

Another important factor that could be addressed by metabolic engineering is photoinhibition. Like plants, microalgae experience photoinhibition at high daylight levels, in that photosynthesis slows down once the light intensity has exceeded a certain value. Engineered algae that are either not photoinhibited or have a higher inhibition light threshold would significantly improve biodiesel production.

Industrial processes require inherently stable engineered strains and understanding of the methods that can be used to keep an otherwise unstable strain from losing its engineered characteristics is important [43], but barely known for microalgae.

Concluding remarks

As discussed above, microalgal biodiesel is the only renewable biodiesel that has the potential to completely displace liquid transport fuels derived from petroleum. Existing demand for liquid transport fuels could be met sustainably with biodiesel from microalgae, but not with bioethanol from sugarcane. Algal biomass needed for production of large quantities of biodiesel could be grown in photobioreactors, but a rigorous assessment of the economics of production is necessary to establish competitiveness with petroleum-derived fuels. Achieving the capacity to inexpensively produce biodiesel from microalgae is of strategic significance to an environmentally sustainable society. Extensive efforts are already underway to achieve commercial-scale production of microalgal oil, but for the moment barely any biodiesel is being made from microalgae.

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