Why microalgal biofuels won't save the internal combustion machine

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Abstract: Proponents of microalgae biofuel technologies often claim that the world demand of liquid fuels, about 5 trillion liters per year, could be supplied by microalgae cultivated on only a few tens of millions of hectares. This perspective reviews this subject and points out that such projections are greatly exaggerated, because (1) the productivities achieved in large-scale commercial microalgae production systems, operated year-round, do not surpass those of irrigated tropical crops; (2) cultivating, harvesting and processing microalgae solely for the production of biofuels is simply too expensive using current or prospective technology; and (3) currently available (limited) data suggest that the energy balance of algal biofuels is very poor. Thus, microalgal biofuels are no panacea for depleting oil or global warming, and are unlikely to save the internal combustion machine. © 2009 Society of Chemical Industry and John Wiley & Sons, Ltd

Introduction

Resource constraints and the realization that climate change requires drastic and immediate measures combine to greatly improve the economic, political and societal viability of renewable (bio)-fuels and materials. However, first-generation biofuels, ethanol and biodiesel produced from sugar/starch and oil crops, respectively, have fallen into disfavor due to rising food prices, pressures on water, land and ecosystems, as well as poor or even unfavorable greenhouse gas (GHG) and energy balances. So-called second-generation biofuels – for example, ethanol from cellulosic biomass – are now the focus of extensive research, just as they were after the oil crises 25–30 years ago, when

many alternative energy sources of interest today were last subject to intensive investigation. However, the cultivation of dedicated energy crops leads to changes in land use, which shed doubt on the predicted positive GHG balance of such fuels.[1,2]

Microalgae currently stand in the spotlight because they have a reputation for very high productivities, some strains may contain over 70% of their weight in the form of triglycerides or hydrocarbons, and they can be grown using waste, saline, or brackish water and land resources, thus not interfere with food crop production.[3] Proponents of microalgal oil production claim yields that range from about 6000 to over 250 000 L oil ha^{-1} y^{-1}.[4–8] As world crude oil consumption is about 5 trillion liters per year, an area of 20–400 million ha

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(corresponding to 2–40% of the United States land area) would be required to substitute all crude oil products currently used in the world. Consequently, industrial ventures and academic groups are able to raise considerable funds to develop algal biofuels.[9]

Both commercial and research efforts tend to focus on closed photobioreactor (PBR) systems, with only a handful proposing use of open ponds.[10,11] Annual productivities are assumed that typically exceed those of existing commercial and experimental systems by far, while some even breach the theoretical limits of photosynthesis.[12–14] Unfortunately, few peer-reviewed research papers and reviews[4,15] address the validity of these claims, although critical 'grey literature' reports, such as blogs and other non-scientific forums, point out the fallacies of these projections.[12,16] Also, detailed cost- and energy-balance analyses, which will ultimately determine whether algal biofuels are commercially viable without distorting subsidies, are lacking.[15,17,18] Here we review current activities and conclude that most of the projections made for microalgal biofuels production are based on excessively optimistic assumptions regarding the achievable productivities, the feasibility of scale up, the economics of these systems, the energy balance, and available resources such as land and water (Table 1).

Current commercial production

Current commercial microalgae production is focused on a few high-value products used mainly for human nutritional supplements, include whole algal biomass, such as of *Spirulina* (*Arthrospira*) and *Chlorella*, and some extracted products, including β-carotene, astaxanthin, and docosahexanoic acid (DHA). Microalgae are also used as live feeds in aquaculture, and in waste-water treatment systems.[19]

Only about 10 000 metric tons (t) of microalgal biomass (dry matter basis) is produced annually in commercial operations, with a typical selling price of from $5000 to over $100 000 per dry t of biomass. When formulated into finished consumer products, this biomass generates a turnover of several billion dollars per year.[19,20]

Over 90% of the world's commercial microalgae production uses shallow, open, paddle wheel mixed, raceway type ponds. The two other systems in use are open circular ponds for *Chlorella* production in the Far East, and large (100 ha) unmixed ponds for *Dunaliella salina* production in Australia. Closed PBRs represent only about 1% of total commercial microalgae production, mainly for *Chlorella* (in Germany) and *Haematoccocus* production (in Israel and some other countries). In contrast, most academic research groups and many start-up companies for algae biofuels production continue to focus on closed PBRs, in part because these systems are easier to control and operate for research purposes, and in part because of the expected higher productivities.

Production systems

The main production systems for microalgae are raceway mixed ponds and PBRs. Other options, such as unmixed ponds and circular ponds, are not applicable to biofuels production because they are clearly less productive than raceway ponds. Dark fermentation of algae inevitably causes significant conversion losses of biomass-derived feedstocks from conventional agriculture or forestry.

Raceway ponds

In current commercial operations, raceway ponds are shallow with a typical operating depth of 20–30 cm, and the channels have a width to length ratio from 5 to over 10, covering an area of up to about 3000 m^2. The water is kept in motion by one paddle wheel per pond, with water velocity typically at 30 cm/sec (much higher velocities require excessive amounts of mixing energy). Flow guides provide proper flow around the distant end from the paddle wheel, preventing a mixing shadow where algae would settle. Nutrients are provided from agricultural fertilizers, although waste nutrients can also be utilized. Indeed, using such algae ponds for waste-water treatment would be an initial application of such systems in biofuels production.[21] One of the first large commercial microalgae production plants using raceway ponds is located in California, with 30 production ponds, each somewhat over 6000 m^2, with a total pond area of about 20 ha (Earthrise Farms, www.earthrise.com). The plant grows *Arthrospira* for human consumption, with production estimated at over 500 t/year. Production is mainly limited by the cold, nighttime temperatures that reduce the growing season for this warm-loving species to between seven and eight months a year.[19] Some even larger

Table 1 Issues

Issues	Present situation	Bottlenecks	Solutions	Perspectives	Comments	Refs.
Yield (see Table 2)	5–60 t ha⁻¹ y⁻¹ Comparable to tropical agriculture (including test plots) <1–2% of sunlight converted to chemical energy	Biological limitations	Reduced antenna size	Possible, but effects limited by raceway ponds	Are transgenic algae acceptable in open systems?	3,29,58
			Oil content	No simple trigger for oil production Oil-overproducing transgenic algae are feasible	Are transgenic algae acceptable in open systems? Easily outcompeted in open systems?	
		Cultivation methods	Limited for raceway ponds	Gradual small improvements	Learning curve not evident	
Cost (see Table 3)	$5000 – $15 000 t⁻¹ Factor 100 more expensive than biomass from agriculture or forestry	Cultivation	Use of waste water, optimize costs (investments, labor, energy, chemicals, etc.)	Raceway pond construction and operation cannot be improved radically Gradual improvements to $1000 t⁻¹ may be possible	Costs for pond construction, equipment, electricity and fertilizers are strongly increasing Learning curve not evident	17,20,40
		Harvesting	Use filamentous or sedimenting algae, avoid centrifugation and drying			
Energy balance	Presently <1–2? Very limited data on EROI (energy return on energy invested)	Cultivation	Limited options	Gradual improvements	Estimated 22–60% of product energy content	5,40,50,51,58
		Harvesting	Avoid centrifugation and drying	Gradual improvements	Estimated 3–9% of product energy content	
		Processing	Methods must be compared (processes not established, limited data)	Liquefaction, gasification or combined heat-power vs. extraction of lipids	Estimated 15–30% of product energy content	
Alternative technology path: Solar energy	10–30% of sunlight converted to electricity or heat	Price	New technologies (thin films, anti-reflective coatings, energy storage) Benefits from economy of scale	Yearly growth rate >30% Installed PV capacity end of 2008 was 15 GW (peak power)	Limited inputs after deployment Requires >10 times less surface area than microalgae Clear learning curve	15

plants have now been established in China, and one of these plants (China Evergreen, www.evergreen-eni.com) claims an annual production of over 4000 t/year.

Raceway ponds are easily contaminated by microbes of all types, other algae, rotifers, and other grazers. A common strategy to maintain monocultures in open ponds is to use extreme culture conditions such as high salinity for *Dunaliella salina* or high alkalinity for *Arthrospira.* However, the first alga mass cultured in open ponds, starting in the 1960s, was *Chlorella vulgaris*, which does not provide a selective chemical environment, but is simply a very fast grower. Here, mass culture is achieved by high inoculations and short-term batch cultures, not allowing contaminants to take over the culture. Recently, the production of *Haematococcus pluvialis*, a source of the high-value astaxanthin pigment, has been achieved commercially in open ponds as well, both in Hawaii and India, following a similar strategy (Mera Pharmaceuticals, www.merapharma.com; IGG Co., Mumbai, India). Also the Eustigmatophyceae *Nannochloropsis* sp., has been mass cultured in open ponds in Israel for (dietary) oil production and maintains itself as a pure culture (Seambiotic, www.seambiotic.com). Long-term mass culture of some diatoms in relatively large 100 m^2 paddle-wheel mixed ponds has also been reported, and commercial production of diatoms is being considered by several companies.[22] The close-out report of the Aquatic Species Program (ASP), a major US Department of Energy (DoE) R&D program, managed by the National Renewable Energy Laboratory (NREL), from 1978 to 1996, at a cost of nearly $25 000 000 (well over twice that, corrected for inflation), provides a good overview of the experimental work on raceway ponds for mass culture of microalgae, which suggests that mass culture of many algal species in such systems is quite feasible, though each species and strain will require considerable study and development work.[3]

Photobioreactors

PBRs are closed systems in which water, nutrients and CO_2 are provided in a controlled way, while oxygen is removed, either internally or in a separate degassing chamber.[23] The microalgae receive sunlight through the transparent container walls (tubes or flat plates) or in some designs via light fibers that channel light from sunlight collectors. Critical issues include cooling, pH-changes due to consumption of CO_2, inhibition by high oxygen concentrations, which can rapidly reach over 400% saturation, fouling of surfaces, the small unit sizes of such systems (typically < 100 m^2) and the high capital and running costs. Recent reviews cover the extensive developmental work to optimize different PBR systems.[24,25] The Japanese Government spent over $250 000 000 on such systems during the 1990s, essentially without tangible results, while Germany and France have also funded significant research and development programs. One of the results of this work is a commercial plant for production of *Chlorella*, in Klötze, Germany (www.algomed.de), which has a working volume of 700 m^3 inside a 1.2 ha greenhouse,[19] and produces Chlorella at a selling price of about €50 kg^{-1}. Other commercial operations are located in Israel (Alga Technologies, www.algatech.com), with over one hectare of tubular reactors producing *Haematococcus*, and Hawaii where Mera Pharmaceuticals (www.merapharma.com) grows *Haematococcus pluvialis* to produce astaxanthin. Smaller commercial PBRs produce up to 15 t of biomass per year for the production of carotenoids. Several other – sometimes large – industrial ventures failed soon after start up due to poor performance, high costs, and severe operating problems.[23] In general, PBR plants often report significant operating problems, including contamination, requiring frequent shutdowns and cleaning.

Yield

The yield of microalgal cultivations is a controversially discussed topic critical to the commercial potential of microalgal biofuels. Table 2 lists some yield data from publications, reports, and commercial enterprises.

Algae use incident light with about the same photosynthetic efficiency as land plants. However, because microalgae do not produce roots, stems, or other structures, and are continuously cropped, the actual productivity of algal cultures in short-duration experiments can be significantly higher than conventional agriculture. Thus, they can come closer to the maximum photosynthetic efficiency, which is calculated to be about 9–10% of total incident solar energy (about 20–22% of PAR, photosynthetically active radiation, essentially the visible part of the solar spectrum), being converted into biomass. If extrapolated, yields in the order

Table 2. Yield

Plant system	Productivity[1] (g m^{-2} day^{-1})	Productivity[2] (t ha^{-1} y^{-1})	Comment	Reference
C3 land plants		10–18 up to 24	Sugarbeet (temperate) Sugarbeet (tropical)	59
C4 land plants		10–30 up to 80 10–20 up to 50 30–61	Sugarcane commercial Sugarcane on test plots Sorghum commercial Sorghum on test plots *Miscanthus* on test plots	32,33,60,61
Microalgae	20 (48)	Up to 60	Raceway ponds	
Chlorella, Arthrospira, Dunaliella sp.	8 (20)	10–30	Commercial raceway ponds	31
Various species	15 (40)	30–50	Experimental raceway ponds. Summary of ABP 1978–1996	3,17
P. carterae	20 (33)	60	1 m^2, 13 months (Table 3 of [38] lists similar experiments)	38
Arthrospira	8 (15)	30	450 m^2, 10 months	62
S. obliquus	48 (3 months in summer)	Not applicable	20 m^2, unpublished results cited	63
Microalgae			**Photobioreactors**	
C. vulgaris	No data	130 claimed 25–50 reported in news items	700 m^3 PBR in a 1.2 ha greenhouse	30,41
Arthrospira (Spirulina)	7–25	33	Tubular PBR, 250 m, 4 m^3, 7 months, central Italy	37
H. pluvialis	10 –15	20–30		6
T. suecica	20 60 –70	Not applicable	Duration <1 month Single day result	64
P. tricornutum	61–73 (PBR size) 14–17 (total area)	Not applicable	PBR with optimized dilution rates, extrapolated yields	65
Arthrospira	5.44	Not applicable	Helical bioreactor, artificial light	66

[1]Productivities in g m^{-2} day^{-1} are only given when reported in the quoted source. The average annual productivity, with maximum productivity in summer between brackets. [2]Productivities in t ha^{-1}y^{-1} are only given when reported in the quoted source.

of 300 t ha^{-1} y^{-1} are possible – in principle.[17] Lower numbers are given in a recent review by Zhu *et al.* who calculated that the maximum conversion efficiencies of solar radiation into biomass are 4.6% for C3 and 6.0% for C4 plants at 30°C. Calculated on basis of a full growing season and solar radiation intercepted by the leaf canopy, the highest reported numbers are 2.4% for C3 and 3.7% for C4 crops.[26]

Short-duration, small-scale experiments under carefully controlled laboratory conditions demonstrate that algae can indeed achieve very high photon conversion efficiencies. However, this is only possible under low light conditions, typically one-tenth that of full sunlight. As light intensifies, the increase in photosynthesis rates slows down, due to the so-called light saturation effect. At full sunlight intensity, productivity is only about 20–25% that which

would be expected from the low-light measurements.[27] This is because the antenna chlorophyll molecules absorb more photons than the photosynthetic apparatus can actually use. The cure could be to genetically reduce the amount of these antenna chlorophylls, which are so numerous due to evolutionary reasons (algal cells compete with each other for photons and must harvest low light that filters through the water column).[28] It since has been a subject of some research efforts,[25,29] but no mutant has yet been developed that exhibits higher productivities in outdoor cultures.

Biomass yields in experimental raceway ponds reach 30–60 t ha^{-1} y^{-1}, as demonstrated in the Aquatic Biomass Program and elsewhere.[3,6,30] However, typical biomass yields of commercial systems are in the range of 10–30 t ha^{-1} y^{-1},[31] similar to conventional tropical agriculture,

where dry biomass yields of 20–25 t ha^{-1} y^{-1} for crops such as sugarbeet, maize, sorghum, and sugarcane are routinely obtained. On test plots, sorghum can yield up to 50 t ha^{-1} y^{-1}, while *Miscanthus* harvests have reached 61 t ha^{-1} y^{-1}, and sugarcane 72–80 t ha^{-1} y^{-1},[32,33] clearly higher than measured annual yields of algal biomass in experimental systems. Higher values for algae are always extrapolations. Similarly, extrapolated algal biodiesel productivities of up to 100 000 L ha^{-1} y^{-1} are compared with real palm oil yields of 4000–6000 L ha^{-1} y^{-1}.[8,18,34,35]

It is often assumed that PBRs would have higher productivities than open ponds. The large PBR in Klötze, Germany, mentioned earlier, was launched with claims that it would be able to produce 130–150 t of *Chlorella* ha^{-1} y^{-1}, but production was reported to be in the same range as the best raceway ponds; between 25 and 50 t ha^{-1} y^{-1}. Theoretically, there is no reason for PBRs to be of higher productivity, and side-by-side comparisons demonstrated that both have the same productivity if subject to the same environmental conditions.[36] However, temperature and light-intensity control can certainly improve the productivity of closed systems,[37] as heavy rain or cold weather can severely disturb open systems.[38]

Cost

Closed systems

The DoE Aquatic Species Program (ASP) initially focused on a closed PBR design, but this was soon abandoned when it became clear that such systems were neither practical nor economical.[3] This is so because the capital costs for PBRs and associated equipment are more than $100 m^{-2}, which is at least 10 times higher than for open pond systems.[39] Given the amount of material and equipment required, large-scale PBRs can be expected to remain at least as expensive as greenhouses with hydroponics systems, which have capital costs between $50 m^{-2} and $250 m^{-2}, and are only used for high-value produce such as vegetables, fruit and flowers. Also, the energy input in construction, operation and maintenance of the PBRs and associated equipment is significant and could easily result in a negative energy balance.[14]

Cost estimates of algal biomass grown in PBRs typically range from $30 000–$70 000 t^{-1},[40-42] which is roughly three orders of magnitude higher than the cost of waste biomass

from conventional agriculture or forestry (typically around $50 t^{-1}) (Table 3), and also at least an order of magnitude higher than fruit and vegetables produced in greenhouses. Much lower cost estimates of $2850–$3000 t^{-1},[4,18] are based on the assumption that economies of scale will reduce costs significantly. This, however, is quite debatable as many of the cost components (PBRs, tubing, pumps, electrical installations, buildings, maintenance, cleaning, and other labor) are not very sensitive to the scale of the operation, also because the scale of PBRs is limited to at most a few hundred square meters, about a hundred times smaller than open ponds.[17,40,43] Thus, it appears that PBRs can be ruled out for the production of algal biofuels because of cost, and most likely also energy inputs.

Open systems

Based on discussions with commercial producers, a price range of $8000–$15,000 t^{-1} has been reported for algal biomass produced in raceway ponds.[17,22,43] Current US delivered prices from China for 20 t container shipments are $5000 t^{-1} for *Arthrospira* and $10 000 t^{-1} for *Chlorella*, and *projected* production prices are as low as $2000–$5000 t^{-1},[44] about 10 times less than PBR-grown algae, but still almost two orders of magnitude more expensive than waste or energy crop biomass.[45,46]

Few detailed calculations on the cost components of producing algal biomass in large-scale raceway ponds are available. However, investments per ha of raceway ponds (> $100 000) are clearly higher than investments for new land plant cultivation (< $10 000).[17,20] To illustrate this, the individual cost items for a raceway pond are shown in Table 4 (from Table 3 in Benemann and Oswald[17]). For the same scenario, operating costs of $21 300 ha^{-1} were calculated, assuming yields of 30 g m^{-2} day^{-1} (110 t ha^{-1} y^{-1}) or even 60 g m^{-2} day^{-1} (220 t ha^{-1} y^{-1}). The resulting cost for algal biomass was calculated to be as low as $240 t^{-1}. However, according to John Benemann (personal communication), and as shown in Table 2, these productivities are no longer seen as realistic. Assuming an upper range of productivity in large-scale multiyear cultivations of 50 t ha^{-1} y^{-1}, the production cost of algal biomass in this scenario should be raised to at least $720 t^{-1} (corrected for inflation, and assuming that other costs such as for fossil fuel inputs, processing, fertilizers, and other cost items, have not changed).

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Table 3. Costs

System	Operating costs ($ kg^{-1})	Capital costs ($ ha^{-1})	Total costs ($ kg^{-1})	Remarks	Source or reference
Agriculture			0.04	Wheatstraw (Germany 2007)	
Forestry			0.04 – 0.055	Firewood (Germany 2007)	
Raceway ponds					
Commercial raceway ponds		100 000	5–15	Based on discussions with producers, John Benemann, personal communication	17,22,44
50 000 m^2 raceway pond	7–10	300 000	>8–11[1]	Costs at production sites in Thailand & USA	43
Raceway ponds	Not specified	Not specified	3.8	No calculations available	18
Raceway ponds	0.14	100 000	0.24	Projected cost based on a yield of 110 t ha^{-1} y^{-1}	17
Raceway ponds	€0.07	100 000	€0.21	Projected cost based on a yield of 100 t ha^{-1} y^{-1}	20
Photobioreactors					
PBR (Chlorella)	Not specified	Not specified	75 (selling price)	1.2 ha PBR in Klötze, Germany	41
PBR (Haematococcus)	Not specified	Not specified	>30[2]	Minimum price to compete with synthetic astaxanthin	42
PBR (cost analysis)	19.4	12.6 (capital costs 11% per y)	32	Manpower 13% Raw materials 17% Overall capital charge 34%	40
PBR (cost analysis)	Not specified	Not specified	2.95	Based on[40], with assumptions on scale-up benefits	18

Note: Numbers not corrected for inflation. [1]Total costs were not given; here a capital charge factor of 15% was used to obtain approximate total costs, which could be considered an annual charge for mature technology required to pay off the facility in 20 years[17]. [2] To produce astaxanthin at the price of synthetic astaxanthin ($2500 kg^{-1}), the algal biomass must be available for less than $30 kg^{-1} [42]. Natural astaxanthin now sells for $7000 kg^{-1}. http://www.israel21c.org/bin/en.jsp?enZone=Health&enDisplay=view&enPage=BlankPage&enDispWhat=object&enDispWho=Articl es%5El986 and www.algatech.com.

A similar cost estimate of €210 t^{-1} (about $300 t^{-1}) appeared in the report *Micro-algae biofixation processes: applications and potential contributions to greenhouse gas mitigation options.*[20] Here the authors specifically state that 'even with the most favorable assumptions about algae production costs (€210 t^{-1}) and revenues for biofuels (€120 t^{-1} algae) and GHG abatement (€50 t^{-1} algae), the process would still not be economically feasible. Thus, fuel-only algal systems are not plausible, at least not in the foreseeable future and additional revenues are required, either from waste-water treatment or higher value coproducts.' Again, this scenario was based on a highly optimistic yield of 100 t ha^{-1} y^{-1}, and costs per ton of algal biomass should be corrected accordingly, reinforcing the pessimistic conclusion. Another modeling study also put doubt on the economic feasibility:[47] 'To achieve the target CO_2 mitigation price of $30 t^{-1} CO_2 at 40% biological conversion efficiency, the allowable net cost should be less than $2.52 m^{-2} yr^{-1} at low-light intensity (average US location).'

This is significantly lower than currently feasible for raceway ponds, let alone closed systems.

Harvesting and processing

Depending on species, cell density, and culture conditions, harvesting algal biomass has been estimated to contribute 20–30% to the production cost.[48] This is because microalgae are usually small with a diameter of 3–30 μm, and culture broths are often quite dilute at less than 0.5 g l^{-1}. Typically between 20 and 40% of the culture must be harvested daily, and, thus, large volumes must be processed and the algal cells concentrated over 100-fold. This is less of a problem for the filamentous *Spirulina* which can be captured with wide mesh screens, or the rapidly settling *Haematococcus* algae. However, it is a significant issue for other algae, with *Chlorella* and *Dunaliella* harvested by centrifugation and chemical flocculation, methods requiring expensive equipment and substantial chemicals or energy inputs.[40]

Table 4. Capital costs of raceway ponds for a productivity of 30 g^{-1} m^{-2} day^{-1} (based on Table 8.3 in Benemann[17])

Item	Remarks	Cost $ ha^{-1}
Land preparation, grading, compaction	Percolation control by natural sealing	2500
Building of pond walls and levees		3500
Paddle wheels for mixing		5000
CO_2 transfer sumps and carbonation		5000
CO_2 supply (pipelines and scrubbers)	Assuming flue gas as source	5000
Harvesting and processing equipment	Settling Flocculation Centrifugation and extraction	7000 2000 12 500
Anaerobic digestion and nutrient recycling	Lagoon	3250
Other capital costs	Water and nutrient supply Waste treatment Building, roads, drainage Electricity supply & distribution Instrumentation & machinery	5200 1000 2000 2000 500
Item	**Remarks**	**Cost $ ha^{-1}**
Subtotals of above		59 450
Engineering, contingencies	15% above	8900
Total direct capital		68 350
Land costs		2000
Working capital	25% operating cost	3800
Total capital investment		74 150
Inflation corrected	2.5% inflation, 12 years	99 700

The only methods that are likely to be cost effective for algal biofuels are spontaneous gravity sedimentation and flotation – perhaps aided by some minimal chemical flocculant addition. However, for most cases such processes remain to be demonstrated in practice. Once the concentration of the algal biomass has been increased from a few hundred mg l^{-1} to a few g l^{-1} by such a process, centrifugation to achieve a high-density cell paste (e.g., 15–20% solids) becomes affordable.[40]

It is usually proposed to extract oil from the algal biomass with solvents. This is standard technology with oilseeds, but it is not certain how economical this will be with microalgae biomass. Drying the algae, which would greatly facilitate extraction, would be cost prohibitive (spray drying reportedly costs > $1000 t^{-1}),[40] unless waste heat or solar drying was used, and even these methods are not cheap. A three-phase centrifuge that combines biomass concentration with oil extraction has been proposed, but again, this remains to be demonstrated on a large scale.[49] Alternatively, the algal

biomass can be processed by thermochemical liquefaction or gasification,[50,51] converted to biogas,[52] or co-fired in combined heat-power plants. A recently announced Exxon Mobil–Synthetic Genomics venture aims to create oil-excreting photosynthetic organisms, which would greatly simplify this issue, but raises the question of whether such organisms can be grown in open systems in view of safety and contamination issues.

Algae-derived biofuels

A detailed discussion on the cost of algal biodiesel or other biofuels derived from – or produced by – algal biomass is beyond the scope of this perspective, also because the technology for producing these biofuels has not yet been established. However, a simple calculation based on biomass cost, oil content, and expected processing losses and costs will provide a rough measure of the lower cost boundaries. Assuming an oil content of 30%, biomass costs of $2000 t^{-1}, processing losses of 10%, and processing costs for drying,

extraction and chemical conversion of $1000 t^{-1}, algal oil would already cost $11 100 t^{-1}, which is 15 times more expensive than palm oil (and similar to the production cost in the best scenario (100 000 L^{-1} ha^{-1}) proposed by Pienkos and Darzins[8]). The assumptions are probably too optimistic, as algae only produce large amounts of lipids or hydrocarbons under nutrient stress conditions such as nitrogen limitation, which strongly reduces the total biomass yield.[3] Although it is theoretically possible to engineer algae to produce large amounts of lipids or hydrocarbons during exponential growth, wild-type algae or less productive mutants would easily crowd out such engineered algae, especially in commercial long-term operations using open systems. Moreover, large-scale cultivation of transgenic algae in open systems is not likely to be acceptable to regulatory bodies, as wind-blown foam, transport by birds, leakage or spillage are simply unavoidable.

Benefits

To determine whether algal biofuels really contribute to solving energy and environmental problems, several questions must be addressed in addition to cost and yield issues. First and foremost, the energy output of algae cultivations should exceed the energy inputs,[5,14,15,53,54] preferably by a large factor close to 10, as is claimed for the production of bioethanol from sugarcane.[55] Lower numbers would obviously have significant impacts on costs, net biofuel yield per ha, and relative environmental impacts. Unfortunately, only a few authors have attempted to calculate or determine the energy requirements of producing algal biofuels,[56] and these studies lead to the conclusion that – at best – the energy output exceed the inputs by a factor of two.[5,50,51,54] Wijffels *et al.* concluded that flat-plate PBRs would lead to a negative energy balance, with tubular bioreactors performing even worse.[14] Reductions in GHG emissions have not been studied in sufficient detail to be covered here. However, the lesson from first-generation biofuels is that the overall GHG balance is generally much less favorable than the energy balance, and constitutes a risk to commercial development.

Regarding land use, it is often claimed that the production of algal biomass does not replace agricultural land because unproductive wasteland can be used. This land, however, must still be relatively flat to allow construction,

maintenance and operation of raceway ponds. Also, it should not be located in wetlands or other coastal natural resources. More importantly, an abundant water supply is required, as the open ponds suffer from evaporation as much as rice paddies. The US southwest, which is often suggested as a possible site, is already at risk of severe water shortages. If brackish or salt water is used, evaporation will concentrate the salts and necessitate regular dilution with fresh water, and/or treatment and disposal of highly saline waste water.

If CO_2 mitigation and treatment of flue gas is the primary goal, the raceway ponds must be sited near power plants, which are typically located in or close to population centers. There, the required flat and sunny surface area is neither cheap nor easily available, because competing land uses such as housing and agriculture are financially much more attractive. As an example, the cash flow and net profit per m^2 from greenhouse-grown vegetables, which can also be fed with CO_2 from flue gas, is several orders of magnitude higher than for biofuels.[12]

Biofuels as a byproduct

Only if the algal biomass is a byproduct of waste-water treatment systems, or of the production of high-value compounds such as astaxanthin or β-carotene, commercially viable energy production from algal biomass might be feasible.[20] However, the amount of microalgal biomass available for energy production and GHG abatement is obviously limited to that obtained from profitable applications. This amount may be roughly estimated from current and expected production levels of microalgal products. Astaxanthin has an annual market size of $250 Mio or roughly 100 t, which could be produced from 10 000 t of algae (presently, most astaxanthin is chemically synthesized). The worldwide annual demand for eicosapentaenoic acid (now mainly obtained from fish) is claimed to be about 300 t.[57] Thus, production from *Phaeodactylum cornutum*, which contains about 2% eicosapentaenoic acid would require 15 000 t of algal biomass. Docosahexaenoic acid is produced by Martek (http://www.martekbio.com) and has a similar market size. For colorants, a market size of 800 t and an average content of 5% of dry weight have been proposed, requiring a scale of 16 000 t. Thus the total algal biomass available from these four high-value applications (if realized) is less than 100 000 t, nowhere near the 1600 Miot

of natural oil used per annum. Similarly, algal biomass from waste-water treatment systems was estimated to potentially contribute at most a fraction of 1% of US energy needs.[3] Completely replacing fish oil (annual sales 1–1.5 Mio t) by algal products would require an annual production of 2.5–3.5 Mio t of algae, which would be a highly significant boost to the microalgae industry.[44] However, most of this biomass would probably be used directly in aquaculture to obtain fish with the desired ω-3 fatty acid content, leaving no biomass to convert to energy products.

Alternative technology paths

Grown in raceway ponds algae convert at most 1–2% of incident light to chemical energy in the form of biomass, like land plants grown under optimal conditions. Current solar energy technologies, such as concentrating solar power (thermal) and photovoltaics, convert up to 30% of the incident light to electricity, thus requiring a total area 10–30 times less than algae. Estimates of current levelized costs of solar energy in regions also considered for the cultivation of microalgae range from $0.15 to $0.36 kWh^{-1}, clearly less than (hypothetical) electricity from algal biomass, which would cost at least $1.88 kWh^{-1} (1 kg dry algal biomass – at a present cost $5000 t^{-1} – contains about 19 MJ of energy, which could yield 2.64 kWh of electricity, assuming 50% efficiency). Solar electricity is already competitive in off-grid applications and/or during peak hours in sunny locations such as Hawaii and Italy, and, as it is expanding at a rate of over 30% per year from a current base of over 15 GW installed capacity (peak power photovoltaics, end of 2008), it strongly benefits from the learning curve. Further, after deployment, solar energy technology can be placed in deserts or on rooftops, requires little maintenance and labor, and does not use valuable resources such as fertilizers (nitrogen and phosphorous) and extraction solvents. Also, the infrastructure for electricity-based mobility is already present (railroads, light rail, trolley-buses, charging stations for recreational vehicles), or can be built at reasonable costs (e.g., charging and battery exchange stations for cars and bikes). If liquid fuels are required, for example for aviation or heavy equipment, algal fuels still have to compete with fossil fuels, bioethanol, biobutanol or fuels generated from (cheaper) biomass from forestry or agriculture by gasification and Fischer-Tropsch synthesis.

It should be clear though that our society must reduce its dangerous dependence on fossil fuels not only by developing new renewables, but also by a radically more efficient use of resources, as well as a strong drive towards sufficiency.

Conclusions

Yield and cost analyses show that the cultivation of algal biomass solely for the production of biofuels is not cost-competitive compared to other biomass sources by almost two orders of magnitude, while the energy balance appears to be poor. As it is difficult to identify breakthrough opportunities for significant yield increases and costs savings, algal biofuels are not likely to be competitive in the foreseeable future, also because competing alternative technologies are making significant (and faster) progress. Current high-value products from algae or waste-water treatment would not support sufficient quantities to underpin large-scale development of algae for biofuels production or CO_2-mitigation. Therefore, the current large investments in the production of algal biofuels are highly premature, and divert funds from more beneficial and urgently needed technologies. It goes without saying that microalgae can be put to beneficial uses such as the production of chemicals, feed, food additives, and wastewater treatment.

Acknowledgements

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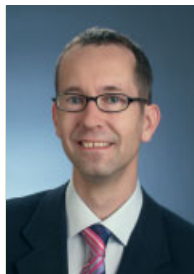
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