Letters Response

Response to Reijnders: Do biofuels from microalgae beat biofuels from terrestrial plants?

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Reijnders [1] claims that microalgae are inferior to terrestrial oil crops as net producers of renewable energy. Algae-derived fuels are claimed to provide barely as much energy as the fossil energy that is consumed in producing them [1]. This claim is based exclusively on two simplistic analyses by Hirano *et al.* [2] and Sawayama *et al.* [3]. However, both these studies show little understanding of large-scale algae culture and grossly overestimate the fossil energy required in producing algal biofuels.

Hirano *et al.* [2] estimated the total energy requirements for *Spirulina* biomass production in raceway ponds. Biomass recovery was assumed to occur by a two-step process involving gravity sedimentation followed by centrifugation. The latter is an energy-intensive operation that is entirely impractical for recovering large quantities of biomass inexpensively, particularly if the product being produced is of a low value, such as biodiesel.

Sawayama *et al.* [3] based their analysis on raceway production of an alga with 20.5% (w/w) oil. The assumed biomass productivity was 15 000 kg ha^{-1} $year^{-1}$, which amounts to ~16% of the average annual productivity that is commonly attained in raceway ponds operated in the tropics [4–6]. Furthermore, the assumed biomass concentration in the broth was 0.5 kg m^{-3}, or only ~50% of the typical concentration in a well-operated raceway [7]. This assumption alone was sufficient to double the cost of harvesting the algal biomass compared with a more typical case. In addition, harvesting was assumed to occur via a two-step sedimentation–centrifugation process, which is in practice an unrealistic choice, as pointed out above. Oil was recovered by an energy-intensive thermochemical liquefaction of the biomass. Based on these questionable assumptions, Sawayama *et al.* [3] and Hirano *et al.* [2] concluded that microalgae were unsatisfactory for producing biofuels. In contrast with this, I and others have argued that microalgae are better than the other existing options for sustainably providing biofuels such as biodiesel [8,9].

In view of extensive past experience with microalgal culture [10–15], the data in Table 1 can be estimated for raceway production of microalgal biomass with 20% (w/w) oil, a biomass productivity of 0.025 kg m^{-2} d^{-1} [4–7,16] and concentration of 1 kg m^{-3} in the ponds. The energy ratio (i.e. the renewable energy produced per unit of fossil energy input) for the case in Table 1 is 2.8. The total energy yield for this case is 1,444 GJ ha^{-1} $year^{-1}$, assuming a 90% operational factor for the production facility (Box 1). The case in Table 1 is conservative in assuming a relatively low oil content in the algal biomass. The oil content of microalgae often exceeds 50% (w/w) [9,17].

For sugarcane, the total energy yield (ethanol and bagasse) is 218.5×10^{-2} GJ per tonne of cane [18]. Assuming a cane productivity of ~75 tonnes ha^{-1} [8], the total energy output is 163.9 GJ ha^{-1} $year^{-1}$, or merely 11% of the total energy output from algae. The energy ratio for bioethanol from sugarcane is ~8 [8]. Using the respective energy ratios and total energy yields, the net energy yields for microalgae (Table 1) and sugarcane are 928 GJ ha^{-1} $year^{-1}$ and 143 GJ ha^{-1} $year^{-1}$, respectively (Box 1). Clearly, with an oil content of only 20% and an average annual biomass productivity that has been demonstrated in the field, microalgae are far superior to bioethanol as a source of renewable fuels. Depending on the oil content of algal biomass and the quality of the biogas obtained from the spent biomass, the total energy yield from algae could be higher than 2300 GJ ha^{-1} $year^{-1}$ and the energy ratio can exceed 7 (Box 1).

Nearly 45% of all fossil energy input listed in Table 1 is linked to fertilizers. Considering that most of the added fertilizers re-emerge in the liquid effluent of the anaerobic digesters [8] and will be reused in agriculture, the actual input of fertilizer energy is only about two-thirds of the value given in Table 1. This alone would increase the energy ratio of algal oil from 2.8 as noted above to 3.3.

Assuming a net energy yield of 928 GJ ha^{-1} $year^{-1}$ and the annual liquid fuel energy requirement for transport in

Table 1. Energy account of algal oil production

Input/output	Energy (MJ kg^{-1} oil)
Energy in fertilizers[a]	14.12
Energy for cultivation	8.77
Energy for harvesting[b]	0.30
Energy for oil recovery[c]	3.17
Energy for biogas production	0.88
Energy for construction (entire facility including maintenance)[d]	4.00
Energy embodied in equipment (including maintenance)[e]	62.8×10^{-6}
Energy in algal oil[f]	37.90
Energy in biogas from residual biomass[g]	50.00

[a] Estimated as 22.85 MJ kg^{-1} of urea and 2.94 MJ kg^{-1} of diammonium phosphate.

[b] Using sedimentation followed by continuous vacuum belt filters.

[c] Approximate only in view of the developmental nature of algal oil recovery processes.

[d] Estimated as 80.4 MJ m^{-2} of facility area divided by a 20 year working life and the mass of oil produced annually.

[e] Estimated as fossil energy requirement of 27.2 MJ t^{-1} of machinery [18] (including equipment for biogas production) divided by the 20 year working life of equipment and the mass of oil produced annually.

[f] Assuming the same energy content in algal oil as in rapeseed oil, or 37.9 MJ kg^{-1}.

[g] Assuming a biogas yield and energy content of 0.5 m^3 kg^{-1} of spent biomass and 25 MJ m^{-3} of biogas [8], respectively.

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Box 1. Energy calculations

Total annual energy yield

The total annual energy yield (Y_E, GJ ha^{-1} $year^{-1}$) is calculated as follows:

$$Y_E = E_{oil}P_{oil} + E_{biogas}P_{biogas} \qquad \text{[Equation 1]}$$

where E_{oil}, E_{biogas}, P_{oil} and P_{biogas} are the energy content of algal oil, energy content of biogas, areal productivity of the oil and areal productivity of the biogas, respectively. E_{oil} is assumed to be the same as for rapeseed oil, or 37.9×10^{-3} GJ kg^{-1}. E_{biogas} value has been taken to be 25×10^{-3} GJ m^{-3} of biogas [8]. P_{biogas} (m^3 ha^{-1} $year^{-1}$) has been calculated as follows:

$$P_{biogas} = (1 - x_{oil})P_{biomass}Y_{biogas} \qquad \text{[Equation 2]}$$

where x_{oil} is the weight fraction of oil in the biomass (i.e. 0.2), $P_{biomass}$ is the annual areal productivity of biomass and Y_{biogas} is the yield of biogas from spent biomass. Y_{biogas} has been assumed to be 0.5 m^3 kg^{-1} of spent biomass. $P_{biomass}$ (kg ha^{-1} $year^{-1}$) has been calculated as follows:

$$P_{biomass} = 0.025\frac{kg}{m^2 d} \times 10^4\frac{m^2}{ha} \times 365\frac{d}{year} \times f \qquad \text{[Equation 3]}$$

where f is the operational factor (i.e. 0.9) for the production facility. The oil productivity (kg ha^{-1} $year^{-1}$) has been calculated as follows:

$$P_{oil} = x_{oil}P_{biomass} \qquad \text{[Equation 4]}$$

Net energy yield

The net energy yield (Y_N, GJ ha^{-1} $year^{-1}$) has been calculated as follows:

$$Y_N = Y_E\left(1 - \frac{1}{R}\right) \qquad \text{[Equation 5]}$$

where R is the energy ratio.

Effect of oil content of algal biomass and the biogas quality on total energy yield

If the oil content in the algal biomass is assumed to be 50% (w/w), the areal productivity of the biomass remains at 0.025 kg m^{-2} d^{-1}, the biogas yield from the residual biomass is raised to a plausible 0.65 m^3 kg^{-1} of spent biomass [8], the biogas quality is raised to a feasible value of 30.6×10^{-3} GJ m^{-3} of biogas [8], the total energy yield rises to 2,373 GJ ha^{-1} $year^{-1}$ and the energy ratio becomes 5.5. If this energy ratio is corrected for the fact that much of the fertilizer reappears in the effluent from the anaerobic digesters, the true energy ratio becomes 7.5.

Transport energy demand

The transport fuel needs of the United States have been referenced as 5.3×10^8 m^3 of biodiesel equivalent [8]. Therefore, the current annual transport energy demand in the US is as follows:

$$Trans\,port\ energy\ demand\,(GJ) = 5.3 \times 10^8 \rho_{biodiesel}E_{biodiesel} \qquad \text{[Equation 6]}$$

where $\rho_{biodiesel}$ is the density of biodiesel (i.e. 880 kg m^{-3}) and $E_{biodiesel}$ is its energy content (i.e. 37.8×10^{-3} GJ kg^{-1}).

the United States to be ~17.6×10^9 GJ (Box 1), all US transport fuel needs could be met by growing algae on less than 11% of the cropping land available in the country. By contrast, producing the requisite amount of energy from sugarcane bioethanol, with its energy ratio of 8 and the earlier specified net energy yield, will require 70% of the US cropping area. This assumes that algal oil can be used directly in transport. In practice, the oil will need to be converted to biodiesel and this will require about as much energy as is needed in converting an equal amount of palm oil to biodiesel, for example. In conclusion, despite a significantly lower energy ratio than sugarcane-derived bioethanol, microalgal oil could realistically meet all the transport fuel needs of the US, whereas bioethanol could not.

On the issue of photovoltaics, I do not see these as a meaningful alternative to biofuels. Biofuels have been shown to successfully power buses, trains and aircrafts. Even if photovoltaics were able to capture the entire 1 kW m^{-2} peak insolation with 100% efficiency, they would still not be able to power a small vehicle that typically uses a 60 kW motor. To produce this amount of power, a motorcar would need a photovoltaic surface of at least 60 m^2!

In conclusion, microalgal biofuels have the potential to be far superior to biofuels derived from terrestrial plants and have the potential to be produced sustainably.

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