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Article

Microalgal and Terrestrial Transport Biofuels to Displace Fossil Fuels

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Abstract: Terrestrial transport biofuels differ in their ability to replace fossil fuels. When both the conversion of solar energy into biomass and the life cycle inputs of fossil fuels are considered, ethanol from sugarcane and biodiesel from palm oil do relatively well, if compared with ethanol from corn, sugar beet or wheat and biodiesel from rapeseed. When terrestrial biofuels are to replace mineral oil-derived transport fuels, large areas of good agricultural land are needed: about $5x10^8$ ha in the case of biofuels from sugarcane or oil palm, and at least $1.8\text{-}3.6x10^9$ ha in the case of ethanol from wheat, corn or sugar beet, as produced in industrialized countries. Biofuels from microalgae which are commercially produced with current technologies do not appear to outperform terrestrial plants such as sugarcane in their ability to displace fossil fuels. Whether they will able to do so on a commercial scale in the future, is uncertain.

Keywords: Transport biofuel, terrestrial plants, microalgae, fossil fuels

Introduction

Biofuels are promoted to displace fossil fuels. 'Energy security' by the displacement of fossil fuels, has been a main driver in the expansion of transport biofuel production from terrestrial crops [1]. Especially the increase of bioethanol production from Brazilian sugarcane and US corn can be traced back to energy security concerns [1]. The question has been raised whether terrestrial biofuels offer the best way to reduce energy security concerns. Chisti [2] has argued that, in displacing fossil fuels, per

hectare (ha) microalgae are about a factor of 9 better than terrestrial crops such as sugarcane. The view that algal biofuels are superior to terrestrial biofuels in the displacement of fossil fuels has wider support [3-8].

Here, for the purpose of analyzing the performance of microalgal and terrestrial transport biofuels in displacing fossil fuels, both the conversion of solar energy into biofuel and the life cycle inputs of fossil fuel into biofuel production will be considered. This will be done on the basis of energy content (expressed as Joules). The efficiency of converting solar energy into biomass is obtained by dividing the lower heating value of biomass by the input of solar radiation during cultivation. The input of fossil fuels into the biofuel life cycle will be used to correct the solar-energy-to-biofuel conversion efficiency. This includes energy input necessary for infrastructure (such as machinery and equipment) and refers to the current fossil fuel input. If, for instance, the current life cycle fossil fuel input equals 20% of the energy content of the biofuel, the solar-energy-to-biofuel conversion efficiency will be reduced by this percentage to establish an overall solar energy conversion efficiency. The higher the overall solar energy conversion efficiency, the better a biofuel will be able to displace fossil fuels given a specified solar irradiation. The ability to displace fossil fuels can also be expressed in terms of net energy yields ha^{-1}. These net energy yields are calculated by subtracting the lower heating value of cumulative fossil fuel input from the lower heating value of the biofuel produced from a hectare of land. In the following, both overall solar energy conversion efficiencies and net energy yields ha^{-1} will be referred to.

It may be noted that the impact on energy security is not the only matter relevant to decisions about biofuel production. Impacts on food prices, soil quality and biodiversity, the consumption of natural resources such as water and the emissions of greenhouse gases and a variety of other substances are also topical [1]. However, here only the ability to displace fossil fuels will be considered. In doing so, no distinction will be made between the three major types of fossil fuels: mineral oil, natural gas and coal. The reasons therefore are: substantial variability in the relative use of these three types of fossil fuels in the production of specific biofuels (e.g. ethanol from corn) [1], large between-country variations in import dependency for specific fossil fuels and the possibility to convert natural gas and coal (the latter after gasification) into liquid fossil fuels via the Fischer-Tropsch reaction [1].

Biofuels from terrestrial plants

Most studies agree that the ‘seed-to-wheel’ cumulative demand for fossil fuels associated with transport biofuels from terrestrial plants is lower than the ‘well-to-wheel’ demand of (an energetically equivalent amount of) fossil transport fuels [1,9-30]. However, Patzek and Pimentel [31-34] have presented calculations for cornstarch-derived ethanol and soybean- and sunflower-derived biodiesel which suggest a higher cumulative fossil fuel demand for biofuels than for fossil fuels. The difference in outcome with respect to other studies is partly caused by differences in allocation of fossil energy inputs to (co)products, partly by higher estimates of fossil fuel input in specified yields from agriculture and in industrial processing, and partly by differences in taking account of the energy demand of the infrastructure, labour and seed production needed for transport biofuel production [1,35].

Overall, it seems safe to state that, when allocation based on (partially subsidized) prices of transport biofuel and co-products, in western industrialized countries the cumulative fossil energy demand for transport biofuels made from starch, sugar and edible oils may be quite high. For ethanol from US corn or European wheat or rye, it would seem unlikely that, when allocated on the basis of prices, the 'seed-to-wheel' cumulative fossil energy demand would be lower than 80% of the energy content of ethanol [1,10,17,24,29]. In the case of biodiesel from rapeseed and soybean, qualitatively good estimates suggest that, when allocated on the basis of prices, the cumulative fossil energy demand may well be in the order of 60-80% of the energy content of biodiesel [1,10]. Such high cumulative fossil fuel demands lead to relatively low overall solar energy conversion efficiencies. For ethanol from European wheat the overall solar energy conversion efficiency has been estimated at 0.024-0.03% and for biodiesel from rapeseed at ~ 0.034% [1].

The cumulative fossil energy demand for transport biofuels may be relatively low if biofuels are based on high yielding crops from developing counties, such as oil palm and sugarcane and if lignocellulosic biomass is used for powering processing facilities [1,9]. If the latter applies, for instance the cumulative fossil fuel demand for producing bio-ethanol from sugarcane may energetically be lower than 10% of the bioethanol output [9]. In case of ethanol from sugarcane, the overall solar energy conversion energy efficiency is currently ~ 0.16% [29] and in case of biodiesel from palm oil ~ 0.15% [1]. The latter percentages are much higher than those for transport biofuels from European wheat and rapeseed [1]. Overall solar energy conversion efficiency determines net energy yield ha^{-1} and this in turn determines land requirements for fossil fuel displacement.

Table 1 presents for good quality land net energy yields ha^{-1} for biodiesel from palm oil, ethanol from sugarcane, ethanol from US and European starch crops and ethanol from Japanese sugar beet.

Table 1. Net energy yields in Giga Joules ($GJ=10^9J$) per hectare for selected biofuels and photovoltaic modules.

Crop	**Location**	**Product**	**Net energy yield in GJ ha^{-1} $year^{-1}$**	**Source**
Sugarcane	Brazil	Ethanol	160-175	[9]
Oil palm	Malaysia	Palm oil biodiesel	140-180	[1]
Starch crops	USA, Europe	Ethanol	< 35-50	[14,24]
Sugarbeet	Japan	Ethanol	25	[27]

The total input of transport fuels derived from mineral oil in the world economy is ~ 90 EJ (= $90x10^{18}$ J) [1]. The data in Table 1 allow for making an estimate of good quality land requirements for a hypothetical complete substitution of 90 EJ mineral oil-derived transport fuels by biofuels. In case of ethanol from sugarcane and biodiesel from palm oil this would require about $5.\ 10^8$ ha, and in case of ethanol from starch crops and sugar beet at least: $1.8\text{-}3.6x10^9$ ha. For comparison, current worldwide cropland is ~ $1.8x10^9$ ha [36], and the area considered fit for additional cropland is between $4x10^8$ and $1.2x10^9$ ha [1].

It has been argued that it would be preferable to use marginal or abandoned land rather than good quality land for the production of terrestrial biofuels. This would mitigate, if not eliminate, the upward effect of biofuel production on food prices [1]. And to the extent that marginal or abandoned land is

used that currently sequesters little carbon, the contribution of using biofuels to climate change may be reduced [12]. However, under market conditions there is a strong pressure to use good quality land for biofuel production, because the use of marginal land is less profitable [1]. If one goes beyond the market mechanism, use of marginal land is a distinct possibility. Because crop yields from marginal land tend to be lower than from good quality land, in the latter case, the areas needed for 90 EJ transport fuel production would increase over the values derived from Table 1 [1].

Microalgal biofuels from ponds and bioreactors

Data about the ability of microalgal biofuels to displace fossil fuels are much more patchy than those for terrestrial biofuels. Indeed, it is a remarkable aspect of several recent publications strongly advocating microalgal biofuels that fossil fuel inputs in the algal biofuel life cycle are not considered [2-8,37]

In natural ecosystems, the presence of specific microalgae is limited by competition of other algae, by zooplankton ('grazers') and viral lysis [38,39]. To suppress competing algae and zooplankton, the culture of specific microalgae is currently restricted to open ponds with extreme conditions such as very high salinity and/or a high pH [40,41] and bioreactors, usually flat plate or tubular reactors [3,42].

Open ponds used for growing microalgae are mostly 'raceway ponds'. These are man-made structures (made from e.g. plastic or concrete) with 10-20 cm water that are subjected to circulation and mixing [2]. Sustained open pond production has been successful for a limited number of microalgae such as *Spirulina*, *Chlorella* and *Dunaliella*. The yields of *Spirulina* tend to be relatively high, if compared with *Chlorella* and *Dunaliella* [1]. Maximum productivities of these microalgae are achieved under tropical or subtropical conditions [43]. The extreme conditions in the raceway ponds are not favourable to maximizing yield. Yields of *Spirulina* currently obtained in commercial facilities located in tropical and subtropical regions range from 10 to 30 Mega grams (Mg = 10^6g) dry biomass ha^{-1} $year^{-1}$ [43], corresponding with a solar-energy-to-biomass conversion efficiency in the 0.25%-0.75% range. Lower yields of e.g. *Spirulina* may occur due to phage infections and rainfall conducive to the growth of unfavourable organisms [44]. Li and Qui [45] reported that 80 Chinese *Spirulina* production plants had a dry weight production of on average 3.5 Mg $ha^{-1}year^{-1}$, corresponding with a solar energy-to-biomass conversion efficiency of ~ 0.1%.

To estimate the overall solar energy conversion efficiency, as pointed out in the Introduction, the photosynthetic yield has to be corrected for fossil energy inputs in growing and processing microalgae (both in infrastructure and operation). Two less recent studies are available that addressed energy inputs and outputs of producing biofuels from microalgae that can be grown commercially in open ponds. These studies did not take all energy inputs into account. For instance, fuel inputs into handling and clean up of discharges from ponds (which will probably be required in view of high pH and/or salt concentrations and high nutrient levels) were not addressed by either of these studies. Sawayama et al. [46] studied operational life cycle fossil energy inputs in growing and processing (by thermal liquefaction) Dunaliella tertiolecta, to supply bio-oil. Energetic inputs exceeded the energetic output by 56%, when dry weight microalgal yield was 15 Mg ha^{-1} $year^{-1}$. Hirano *et al*. [47] studied Spirulina production and processing to supply methanol (via synthesis gas). Here the assumed biomass yield was ~110 Mg ha^{-1} $year^{-1}$ (dry weight). Both fossil fuel inputs in infrastructure and in operation were

considered. The energetic output exceeded the life cycle fossil fuel input by 10%, which corresponds with an overall solar energy conversion efficiency of about 0.12% [1]. At more realistic estimates of *Spirulina* yield, which would be in the order of 10-30 Mg dry weight $year^{-1}$ ha^{-1} [43], fossil fuel inputs would have exceeded energetic outputs. Chisti [48] has argued that the estimates of fossil fuel inputs by Sawayama *et al*. [46] and Hirano *et al*. [47] are gross overestimates, and has suggested a lower estimate of fossil fuel input into growing microalgae in open ponds. However the latter estimate is energetically roughly similar to the upper end of the yield range achieved in commercial growing of *Spirulina* [43]. Chisti suggests on the basis of experiments that yields of more than 80 Mg dry weight ha^{-1} $year^{-1}$ can be achieved in open ponds [48]. However in open systems there tend to be large differences in yield between experiments and commercial production [1]. With current technology, 30 Mg biomass (dry weight) ha^{-1} $year^{-1}$ from currently commercially cultivated microalgae would seem a very good commercial yield from open ponds. So, in current open pond systems microalgae which are currently produced commercially do not outperform sugarcane as a source of transport biofuels.

It may be that in the future microalgal yields from raceway ponds may be increased over current levels. One way to do so is improving photosynthetic activity by re-engineering light harvesting antennae [49, 50]. However, even at the lowest estimate of fossil fuel input [47] a massive increase in yield, if compared with current commercial algal production [43], is necessary to outperform sugarcane. It is uncertain whether this can be achieved in commercial production using re-engineered microalgae.

Another way to increase yields may be growing micro-algae in water that has been saturated in CO_2 derived from power plants [29,51,52]. Yearly yields from ponds much exceeding 30 Mg dry weight $ha^{-1}year^{-1}$ have been claimed for this approach [29]. An efficiency of algal CO_2 capture in open ponds of 30% has been claimed [51, 53]. However, actual yields in open ponds have proved disappointing and maintaining desired algal cultures in such ponds has turned out to be difficult [54]. The value claimed to be achievable in ponds for algal capture of CO_2 is moreover well below the value for CO_2 capture and sequestration (CCS) in aquifers or depleted oil and gas fields. The latter would be able to reduce the emission of power plants with an efficiency of about 90% [55]. On the other hand: resources for CCS in aquifers or abandoned oil and gas fields are limited by natural geology, and there may be cases where a pond for algal capture of CO_2 is feasible, whereas aquifers and depleted oil and gas fields suitable for CO_2 storage are not available. Whether the application of CO_2 capture by microalgae will be important in the future would seem to depend to a large extent on the emission requirements for power plants and the solution of the problems that have made algal CO_2 capture so far disappointing. All in all, whether in open ponds the high yields necessary for outperforming terrestrial plants in overall solar energy conversion efficiency can be achieved commercially seems uncertain.

It has been shown that high microalgal yields may be achieved in bioreactors subjected to solar irradiation [42]. For the production of algal oil a value of about 16 Mg ha^{-1} $year^{-1}$, has been suggested as ‘possible with state of the art technology’ in closed systems [42]. This is somewhat over a factor of 3 better than palm oil [42]. However, achieving high algal yields in bioreactors requires large inputs of energy for building the reactors and for operational activities. It has been estimated that this could lead to a negative energy balance for flat panel bioreactors and an even more negative energy balance for tubular bioreactors [42].

Claims have been made for ultrahigh bioproductivity from algae in thin channel ultradense culture bioreactors that are indirectly supplied with solar irradiation [56]. In this case, the cultures are irradiated with pulsed light emitting diodes, powered by photovoltaic cells. However, the overall efficiency of converting solar radiation into biomass is probably below 0.2% [1], even when not corrected for the large fossil energy inputs in the bioreactor [42] and its irradiation system.

Just as in the case of open ponds, it may be possible to increase productivity in bioreactors by the use of CO_2 inputs. The use of photobioreactors has been proposed for algal capture of CO_2 from power plants [57] and a CO_2 capture efficiency of 40% has been suggested for algae in such reactors [58]. Again, this is well below the efficiency for CO_2 capture and sequestration (CCS) in aquifers or abandoned oil and gas fields which is about 90% [55]. The development of bioreactors for algal capture of CO_2 is in its very early stages and as yet does not allow for firm conclusions about its commercial performance, including its overall solar energy conversion efficiency. Thus, the ability of microalgal biofuels produced in this way to outperform terrestrial biofuels is uncertain.

However, the development of algal production has so far largely focused on applications in the food sector. Research into growing microalgae for biofuel production is limited. It may well be that further research can lead to substantial improvements in algal biofuel production, including in net energy yields.

Conclusions

Currently, microalgae do not appear to outperform terrestrial plants such as sugarcane in their ability to displace fossil fuels, when both the conversion of solar energy into biomass and the life cycle inputs of fossil fuels are considered. Whether they may be able to do so in the future on a commercial scale, is uncertain. In displacing fossil fuels, ethanol from sugarcane and biodiesel from palm oil outperform biodiesel from rapeseed and ethanol from sugar beet and starch crops produced in Europe, USA and Japan.

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