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Research review paper

Microalgal production — A close look at the economics

Niels-Henrik Norsker [a,*], Maria J. Barbosa [b], Marian H. Vermuë [a], René H. Wijffels [a]

[a] Bioprocess Engineering, Wageningen University, P.O. Box 8129, 6700 EV Wageningen, The Netherlands
[b] Food and Biobased Research, Bornse Weilanden 9, 6708 WG, Wageningen, The Netherlands

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ABSTRACT

Worldwide, microalgal biofuel production is being investigated. It is strongly debated which type of production technology is the most adequate. Microalgal biomass production costs were calculated for 3 different micro algal production systems operating at commercial scale today: open ponds, horizontal tubular photobioreactors and flat panel photobioreactors. For the 3 systems, resulting biomass production costs including dewatering, were 4.95, 4.15 and 5.96 € per kg, respectively. The important cost factors are irradiation conditions, mixing, photosynthetic efficiency of systems, medium- and carbon dioxide costs. Optimizing production with respect to these factors, a price of € 0.68 per kg resulted. At this cost level microalgae become a promising feedstock for biodiesel and bulk chemicals.

SUMMARY
Photobioreactors may become attractive for microalgal biofuel production.

Contents

1. Background

Microalgal biomass has been suggested as an energy source for a number of compelling reasons, including high area yields compared with other crops, high oil content in some strains, low water consumption and the possibility of production on arid lands and several oil companies, including Exxon, BP, Chevron, Shell and Neste Oil (BP, 2009; Mascarelli, 2009) are investing in research in microalgae for energy purposes. In a recent study, microalgal fuel production was concluded to be relatively close to being economically feasible, given expected developments in market conditions and production technology (Stephens et al., 2010). But the scientific community in the field is divided with respect to the question which of the microalgal production technology is the most promising for future developments and scale up? It has been claimed that photobioreactors are unsuited for biomass production at a cost compatible with biofuel production (Waltz, 2009) whereas open systems suffer from low biomass productivity and high costs of biomass harvesting because of low biomass densities, large land use, losses of carbon dioxide and poor contaminant control possibilities (Posten, 2009). Microalgae can conserve a maximum of 9–10% of solar the solar energy (photosynthetic efficiency) but microalgal outdoor production systems so-far rarely exceed 6% (Carvalho et al., 2006). However, new methods for genetic modification and metabolic flux modelling of microalgae are being developed and are believed to result in higher photosynthetic efficiency (Schenk et al., 2008; Beer et al., 2009; Wijffels et al., 2010). In continuously illuminated systems, microalgae can already now be cultivated at

* Corresponding author.
E-mail address: niels-henrik.norsker@wur.nl (N.-H. Norsker).

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high efficiency at light intensities similar to or higher than direct sunlight (Qiang et al., 1998; Cuaresma et al., 2009), but growth in the dynamic light environment in outdoor systems is still far from being well understood. In the last decade, there has been a private sector development of new, low cost photobioreactor systems that apply the *light dilution* principle which has been shown give high photosynthetic efficiency (Pulz and Scheibenbogen, 1998) and the development of biorefinery processes will contribute to the value chain (Wijffels et al., 2010). What is missing, however, is a conceptual model for assessment of the effect of enhancing photosynthetic efficiency on one side and increased operating costs on the other. The present work is attempting to fill that gap by assessing the performance of present day photobioreactors and analyzing the effect of optimizing key process parameters on biomass production costs.

2. Algal reactors

The cost of microalgal biomass production under Dutch climatic conditions was analyzed for the 3 main types of photobioreactor systems that are commercially applied today: open raceway ponds, tubular photobioreactors and flat panel photobioreactors. A short description of the main operational characteristics of the 3 reactors is given here but a full description of the process layout and energy cost analysis can be found in the Supplementary material: Design basis.pdf.

The raceway ponds are shallow, ring-channel systems, in which the depth for hydraulic reasons cannot be less than 0.2 m. This results in a low biomass density (0.3 g DW per liter). To provide mixing, the culture is circulated with a paddle wheel at a velocity of 0.25 m/s. The process requires significantly less energy for mixing than the two other reactor designs but due to low biomass density, high costs are incurred for harvesting. This type of reactor is extensively used in industrial microalgal production, for example to produce *Spirulina* and *Dunaliella* of which globally 5000 t and 1200 t, respectively, is produced per year (Spolaore et al., 2006).

In the *tubular reactor*, the algal culture is circulated in transparent tubes by a centrifugal pump and intermittently passes through a degasser — an air-sparged vessel where the accumulated oxygen is blown off. High oxygen concentrations reduce the algal productivity and optimizing the degassing is an important feature of the design process. A horizontal layer of soft, disposable polyethylene tubing with a one-year lifetime was considered, but there are many other possible configurations such as stacked layers of glass or acrylic tubing. Turbulent flow (0.5 m/s) is required to mix the cells between illuminated zones at the tube periphery and dark zones around the center. With the present configuration, a biomass density of 1.7 g DW per liter is obtained. Tubular reactors are used industrially for example for producing the valuable pigment, astaxanthin with alga *Haematococcus* and also for *Chlorella* and *Nannochloropsis* production.

The *flat panel reactor* is basically a flat, transparent vessel in which mixing is carried out directly in the reactor with air sparging. The normal aeration level for flat panel photobioreactors is 1 liter of air per liter reactor volume per minute (Sierra et al., 2008). The design examined here is the *closely spaced*, *vertical flat panel reactor*, in which light dilution is obtained by applying larger specific surface and self-shading of the panels. In this way, it is possible to achieve a higher photosynthetic efficiency, albeit at higher mixing and installation costs. The panels are assumed made of polyethylene film with a one-year lifetime. The polyethylene film is supported by a steel mesh casing. The reactor configuration results in a biomass concentration of 2.1 g DW per liter. Such a system has been demonstrated efficient for example for production of algal strains that accumulate lipid under nutrient limitation (Rodolfi et al., 2009).

3. Light and light absorption

Calculation of productivity was based on an assessment of attainable photosynthetic efficiency for the 3 reactor systems, obtained from literature data covering various sites, algal species and time of year. The results can be found in the Supplementary material, Photosynthetic efficiency.pdf. From the presented data, PE is independent of irradiation level but depending on photobioreactor type. Characteristic PE values for the three photobioreactor types were selected as indicated in Figs. 1–3 in the Supplementary material, Photosynthetic efficiency.pdf and the values are given here in Table 1. In Fig. 1, the daily horizontal irradiation for Eindhoven, the Netherlands is compared with the irradiation for Bonaire, the Dutch Antilles, which served as an example of a “near-ideal” algal cultivation site. Algal productivity was calculated for the 3 systems on a monthly basis from PE, algal biomass combustion enthalpy and irradiation and shown in Table 1.

4. Production cost

The distribution of biomass cost on individual items for the 3 reactor systems are presented in Table 2. System specific critical cost contributions are underlined – these are the costs that are relatively high for the given system. Details can be downloaded from the Supplementary material: Design basis.pdf. The calculation was carried out at plant scales 1 and 100 ha. These figures represent a *base case* in terms of productivity and unit operation costs.

The sum of the unit production costs is the total biomass production cost (produced as a wet paste). In the base case, the tubular photobioreactor is the most economic for production of biomass under Dutch conditions with a production cost of € 4.15 per kg DW.

Mixing and mass transfer (oxygen removal) costs are the sum of depreciation and energy consumption of paddle wheel, circulation- and aeration pumps. The 3 plants have very different operating economy with respect to mixing. For the raceway pond, mixing costs € 0.08 per kg DW. For the tubular reactor, € 1.27 and for the flat panel reactor, € 3.10 per kg DW.

In the tubular reactors, mixing is created by turbulence in the circulating algal suspension. But turbulence is expensive to produce in terms of energy input and depreciation of the pumps. If high velocities are applied “to be on the safe side”, the power requirement is also considerable as is evident from Fig. 1 in the Supplementary material, Design basis.pdf. In the base case, a velocity of 0.5 m/s was applied. Optimizing fluid velocity in the pipes is obviously important but can only be achieved by studying the direct effects of mixing on algal growth and unfortunately, little work has been carried out in this field.

Another important matter for the mixing economy in tubular reactors, is the shear stress experienced in the pump. Because of concern for shear stress damage, air-lift pumps have frequently been applied, but they are considerably less efficient than centrifugal pumps, and efficiency values as low as 2% have been recorded for tubular reactor studies (Hall et al., 2002) but unless very shear sensitive algae are produced, there is little point in applying air-lift pumps. The diatom, *Chaetoceros muelleri* which is widely used in aquaculture is

Table 1
Base case: microalgal biomass production in various photobioreactor types in the Netherlands.

	Open pond	Tubular bioreactor	Flat panel bioreactor
PE (solar)	1.5%	3%	5%
Productivity (ton DW) per ha	21	41	64