A Techno-Economic Assessment Of Biofuels Production By Microalgae

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The present study regards the analysis of sustainability of biofuels production by autotrophic microalgae. The analysis has been based on approximated cost-estimation methods supported by data taken from the open literature and referred both to technical and economic aspects of the process. The objective functions used for process optimization have been estimated with reference to a plant based on 1 km^2 harvesting area. Possible scenarios for the industrial success of the process are presented.

1. Introduction

Current energetic and socio-economic concerns have greatly raised the interest for biofuels production from renewable sources. The main concerns regard: a) the continuous worldwide increase of liquid fuels consumption; b) the security of fuels supply as a consequence of internal/international political instabilities; c) the increase of the greenhouse gas emissions. The biotechnological route for fuels production stems out as an effective way to solve or at least to attenuate these concerns (Farrell et al., 2006; Chisti, 2007; Dale, 2008). In particular, biofuels production by microalgae appeared promising since the end of the last century.

Microalgae may be burned/gasified as crude dry matter in combustors/gasifiers or may be processed to produce liquid fuels. In the latter case the production processes require multiple steps: i) bio-oil production requires microalgae pressing and phase separation; ii) biodiesel production requires the transesterification of the oil. The industrial development of these routes to biofuel is still largely lacking as regards fundamental characterization of the underlying phenomena (Demain, 2009). The current pioneering efforts in the direction of industrialization of microalgae-to-biofuel processes have indicated the key aspects deserving further investigation (Chisti, 2007; Huntley and Redalje, 2007; Rodolfi et al., 2009). Relevant issues are the technological development and novel photobioreactors, the improvement of harvesting and pressing procedures, and the improvement of oil transesterification. Moreover, particular attention is to be paid to the selection of strains characterized by higher bio-oil productivity.

A rough assessment of techno-economic sustainability of biofuels production by microalgae is presented. The analysis has been based on approximated cost-estimation methods supported by techno-economic data taken from the open literature. The economical potential and the capital-intensity of an industrial plant have been estimated and discussed.

2. General Framework

Energetic considerations.

Under autotrophic conditions the microalgae growth is based solely on incident sunlight energy and on the CO_2 captured from the air. Therefore, the energetic content of a microalgae suspension is just a fraction of the sunlight irradiance (E_{SL}).

The overall efficiency (ε_{ov}) of the conversion of sunlight to chemical energy and microalgae production may be assessed as:

$$\varepsilon_{ov} = PAR\ \gamma \qquad (1)$$

where PAR is the Photosynthetically Active Radiation fraction, and γ the efficiency of conversion of PAR to chemical energy. The latter embodies the photosynthetic efficiency and the optical efficiency of the system.

The energy content of the microalgae (E_{DM}) may be assessed taking into account the energy content of the lipidic fraction (E_{oil}), that of the non-lipidic fraction (E_X) and the lipidic mass fraction of the microalgae (ω_{oil}):

$$E_{DM} = E_{oil}\ \omega_{oil} + E_X\ (1-\omega_{oil}) \qquad (2)$$

The ratio between the sunlight energy available and the E_{DM} yields the rate of microalgae production per unit of irradiated area ($F_{X,en}$), on a mass basis:

$$F_{X,en} = E_{SL}\ \varepsilon_{ov} / E_{DM} \qquad (3)$$

Table 1. Theoretical productivity of microalgae and oil: energy-based assessment

Global irradiation for surface inclined to South at 45°, Naples (E_{SL})	6’500 MJ/yr m^2 Suri et al., 2007
Photosynthetically active radiation (PAR)	43%
Efficiency of conversion of PAR to chemical energy (γ)	10%
Microalgae oil fraction (ω_{oil})	$25\%_W$
Energy content of lipids (E_{oil})	38 MJ/kg_{DM}
Energy content of no-lipid components (E_X)	17 MJ/kg_{DM}
Energy content of microalgae (E_{DM})	22 MJ/kg_{DM}
Theoretical productivity (based on energetic consideration)	
Microalgae ($F_{X,en}$)	13 kg_{DM}/yr m^2
oil fraction (F_{oil})	3.2 kg_{oil}/yr m^2

Table 1 reports data of microalgae and oil productivity assessed with reference to a irradiance typical of the southern countries of Italy. The data of γ, w_{oil}, E_{oil} and E_X reported in the table are average among values reported in the literature. The theoretical productivity (F_X and F_{oil}) should be considered the maximum value achievable with reference to the assumed conditions.

Microalgae culture considerations.

The rate of continuous microalgae production on a mass basis may be assessed on the basis of the mass balance on biomass extended to the photobioreactors. Assuming that the bioreactor conforms to a chemostat and an unstructured model may represent the biomass growth, the mass balance on microalgae reads:

$$D = \mu \qquad (4)$$

where D is the dilution rate (ratio between the liquid flow rate, Q, and the reactor volume, V), and μ the specific growth rate. For sake of simplicity, no distinction has been made between growth conditions and accumulation of lipidic compounds. Accordingly, μ represents the growth rate of the microalgae at a constant lipidic mass fraction (ω_{oil}). Taking X as the microalgae concentration in the photobioeractor, the mass production rate of microalgae per unit volume of the bioreactor (W_X) is:

$$W_X = D\ X \qquad (5)$$

The microalgae production rate per unit irradiated area (F_X) may be estimated taking into account the average depth of photobioreactors (δ_{pr}) (Chisti, 2007; Rodolfi et al., 2009):

$$F_X = \delta_{pr}\ D\ X \qquad (6)$$

Under autotrophic conditions and assuming δ_{pr}=0.04 m, μ=0.25 1/d, X=3 kg/m^3, eq. (6) yields F_X=0.03 kg/d m^2 (=11 kg/yr m^2). Accordingly, the volumetric flow rate of microalgae suspension produced is about q=0.010 m^3/(d m^2_{pr}). It should be noted that F_X is about the maximum productivity estimated based on energetic arguments ($F_{X,en}$).

3. Process Description

The main steps of the process to produce biofuels by microalgae are: a) intensive cultures of microalgae; b) harvesting of microalgae; c) separation of the lipidic fraction; d) transesterification of lipids; e) separation and concentration of the biodiesel. The lipidic fraction might directly be employed as bio-oil. A synoptic chart of the process is reported in fig. 1. Treatment processes for wastes and wastewaters are not included.

The process to exploit the non-lipidic fraction of microalgae is not included in fig. 1. The fate of this fraction will critically depend on the microalgae strain. The spectrum of possible paths to exploitation of this fraction is quite broad: gasification/combustion, food supplements, cosmetics, substrate for fermentations devoted to produce energetic carriers, etc.. In any case, the exploitation of this fraction asks for additional processes characterized by capital, costs and incomes that have not been included in the present analysis.

Microalgae cultivation system

The intensive cultivation of microalgae is typically carried out continuously in two system typologies: open ponds and photobioreactors. Open ponds are low-cost biomass growth sites, characterized by low biomass productivity. Photobioreactos are more expensive than open ponds, but they are characterized by high biomass productivity, thorough control of the operating conditions, better preservation of the native single-species cultures for prolonged times. The use of photobioreactors for the industrial scale cultivation of microalgae dedicated to biofuels production is generally encouraged in the published literature on the subject (Huntley and Redalje, 2007; Chisti, 2007).

Microalgae harvesting

The unit operations typically adopted for microalgae harvesting are based on mechanical separations where size and/or density difference drive the fractionation process. Typically, filtration, sedimentation, and centrifugation are used to harvest microalgae, the latter being the most expensive. The sizes of the harvesting units are controlled by the volumetric flow rate issuing from the photobioreactor.

Microalgae processing

The post-harvest processing depends on the fate of microalgae components. It should be pointed out that the sizes of the units adopted in the post-harvest processes are definitively smaller than the photobioreactor. In fact, the flow rates of the streams fed to the post-harvest units are typically at least one order of magnitude smaller than those of streams issuing from the photobioreactors. For the sake of simplicity the contribution of post-harvest processing has been ignored in the present analysis.

4. Cost Estimation

The cost estimation for the conceptual design of the flowsheet dedicated to the

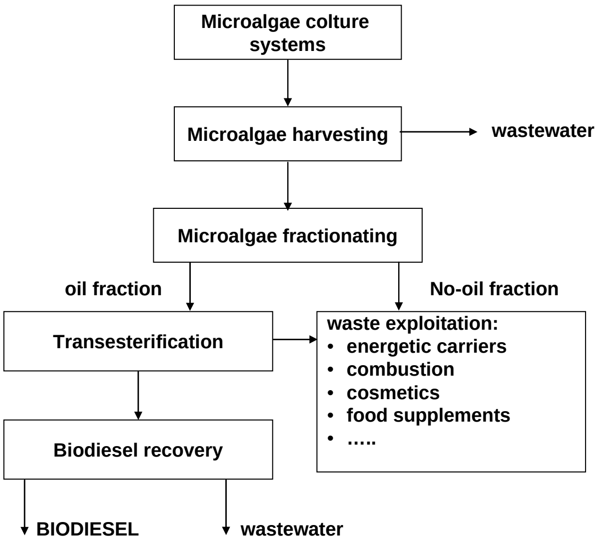

Fig. 1. Synoptic chart of biofuel production by microalgae

production of biofuels from microalgae has been carried out following the procedure proposed by Happel and Jordan (1975). In particular, the total capital requirement has been estimated considering the purchased cost of the main units and adopting the Lang factor (f_L) for ancillary apparatus and installation costs. Except for photobioreactors, purchased cost for the main units of the flowsheet has been estimated in agreement with correlations reported in Peters et al. (2003). The purchased cost of the photobiorecator has been estimated on the basis of the very limited data available in the literature (Molina Grima et al., 2003; Huntley and Redalje, 2007).

The peculiarity of the photobioreactor suggests that the purchased cost scales linearly with the exposed area. The present (2008) cost of an up-to-date photobioreactor – based on the plant cost index - is of about 120 €/m^2.

The filtration unit used to harvest the microalgae should be sized to filter the q stream at microalgae concentration of about 3 kg/m^3. The area of a vacuum continuous filter has been estimated assuming a pressure drop across the filter of 60 kPa and a specific cake resistance of 10^9 m/kg.

The economical sustainability of the process has been assessed in terms of economical potential (EP):

$$\text{EP} = \text{Product value} - \text{Raw Matl. Cost} \tag{6}$$

and of the yearly rate (L) of depreciation of the main fixed investment (I) required for the plant. L has been estimated as:

$$L = eI = ef_L I_F = ef_L \sum I_i \tag{7}$$

where e is [1/yr] the yearly fractional depreciation rate, I_F the fixed investment in complete system, and I_i the cost of the major processing equipment (Peters et al., 2003). The depreciation rate "e" has been assessed accordingly to the sinking fund method: e=i/[exp(in)-1], where n [yr] is the expected project life and i [1/yr] the rate of return of the firm. Tentative reference values of f_L=3, n=10, i=0.10 1/yr and e= 0.058 1/yr have been used for this preliminary economic assessment (Rudd and Watson, 1968).

Table 2 reports the input reference data used in the present analysis, which has been referred to a cultivation area of 1 km^2. As regards the major processing equipments, only the photobioreactor and the harvesting system have been taken into account. When estimating the EP, the cost of the raw materials (CO_2, nitrogen and phosphorous supplements, …..) have been neglected and the "Product value" is just the bio-oil cost (s_{oil}) for the yearly production rate (M_{oil}). It should be underlined that the cost of CO_2 would be a negative cost in eq. (6) in agreement with the current regulations on CO_2 sequestration.

The analysis of data reported in table 2 highlights that under the economical scenario adopted:

- the process is characterized by L larger that the EP;
- the capital investment related to the photobioreactor is the largest contribution to L.

Results suggest that one key to the development of economically sustainable bio-oil production is the development of inexpensive photobioreactors. In particular, the photobioreactor capital cost per unit area should be reduced by more than one order of magnitude. Moreover, studies aimed to increase the efficiency γ and the microalgae oil fraction will allow to improve the bio-oil productivity, then the process sustainability.

It should be pointed out that the present analysis is based on a very limited data base on photobioreactor pilot plants taken from the open literature. Additional data would be required to better support the assessment of photobioreactor costs and process performance. Moreover, the analysis should be complemented by the consideration of the economical benefits associated with exploitation of the non-lipidic fraction of the microalgae and by overall energy balance, CO_2 balance and process water demand.

Table 2. Selected input/output variables of the economic analysis.

Photobioreactor area	1 km^2
Bio-oil unit selling price on mass basis (s_{oil})	550 €/t
Volumetric flow rate of the microalgae suspension	0.12 m^3/s
Bio-oil productivity (M_{oil})	2’750 t/yr
EP	1’500 k€/yr
Photobioreactor cost	120’000 k€
Filter cost	170 k€
L	21’000 k€/yr

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