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Exergy efficiency of solar energy conversion to biomass of green macroalgae Ulva (Chlorophyta) in the photobioreactor

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ABSTRACT

Offshore production of macroalgae biomass, which was recently given the name seagriculture, is one of the important but least explored alternative energy resources. Unlike microalgae, macroalgae cultivation can be done offshore and therefore brings real news to the biofuel – food land agriculture conflict. A wide variety of small-scale laboratory experiments are done lately in order to deepen the knowledge and develop expertise in macroalgae cultivation and its downstream processing. For energy applications, it is common to evaluate the performance of an energy source or system in exergy efficiency terms. Another important parameter that is evaluated to determine the system's environmental impact is it's volumetric and areal footprint. The current work examines two exergy efficiency indexes, the Exergy Efficiency (EE), which takes into account all exergy inputs, and the Exergy Return On Investment (ExROI), that includes only fossil fuel exergy inputs, both on a green macroalgae Ulva grown in the macroalgae photobioreactor system (MPBR) incorporated into a building. Cultivation of macroalgae in the building embedded MPBR achieved maximal values of 0.012 and 0.22 for EE and ExROI, compared to a range of 0.05–8.34 and 0.013–0.327 found in published papers of microalgae systems. In addition, a modelled optimization of the initial biomass density leads to maximal values of about 0.035 for EE and 0.433 for ExROI, while further improvement may be achieved by optimization of nutrient addition and mixing methodology. This work demonstrates a tool to measure the performance of laboratory scale macroalgae biomass cultivation systems, followed by preliminary efficiency and environmental impact values, important for future upscaling.

1. Introduction

Rapidly growing energy consumption and consequential environmental effects have lead in recent years to a global realization of the urgent need to develop alternative renewable energy sources [1–3]. Offshore production of macroalgae biomass [4,5], which was recently given the name seagriculture [6], is one of the important but least explored alternative energy resources. Macroalgae produced in offshore farms is a potential feedstock for marine biorefineries, designed to process the biomass into fuel, food, chemicals and high-value products [7,8]. Therefore, this alternative offers also new capabilities to cope with the water-energy-land-food nexus [3,9].

Macroalgae relate to multicellular aquatic species from three groups: red, brown and green algae [10]. Till the 1950s macroalgae were mostly wild-harvested. Today, after the domestication of some species, macroalgae are cultivated globally, but still mostly in the Asian-Pacific region, where cultivation originated [11]. Most widely spread macroalgae cultivation industries include the edible red algae such as Japanise Nori (Pyropia), and the brown Kelp Wakame (*Undaria pinnatifida*) and Kombu (*Saccharina japonica*). A large demand exists also for the red algae hydrocolloids, carrageenan, which can be extracted from *Eucheuma* sp. and *Kappaphycus* sp., and agar, which can be extracted from agarophytes such as *Gelidium*, *Gracilaria*, *Pterocladia,* and *Gelidiella*. The success of these industries can be attributed to a combination of basic science and consumer demand [11].

Green macroalgae, although produced also as a food product, attract most research attention due to the nutrient uptake and fast-growing abilities of some species, such as the *Ulva* sp. The first enables utilizing *Ulva* for biofiltration of fishponds effluents [12,13]. The second, combined with high carbohydrate contents, places the *Ulva* sp. as a leading alternative for biorefinery and bioenergy feedstock [14,15]. Numerous studies have examined the different possibilities of extracting energy

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from *Ulva* and producing fuels in the form of biogas, bioethanol, biobutanol, and others [5,16–18]. However, energy stock seagriculture is still undeveloped. Increasing attention and research in this field requires suitable tools to evaluate the performance of macroalgae cultivation systems.

Energy and exergy analysis are common methodologies used to evaluate the performance of energy harvesting systems [1,19] and an often-applied impact category in life cycle assessments (LCA) [20–23]. Traditional fossil fuels such as coal, oil, and gas, although regarded as polluting and unsustainable, are still highly available and consist of high energetic densities and thus have a clear exergy and economic advantage in the short term. Alternative energy sources, before being applied in large scales, need to prove positive exergy efficiencies and an economic feasibility [24]. Energy conversion efficiencies are represented in different works by different indicators. Therefore, the applied indicators and scope of the analysis must be clearly defined and rationalized, including exact descriptions of calculation procedures [20].

Two important dimensionless performance efficiency indicators in the biofuel field are the Exergy Efficiency (EE) [25] and the Exergy Return On Investment (ExROI) [26– 32]. In the current work, EE considers all exergy inputs and outputs and is supposed to reflect the thermodynamic balance, accounting for the irreversibility of the conversion processes. The ExROI calculation excludes exergy inputs that do not derive from fossil fuels and thus is more useful for environmental impact evaluations. These definitions are presented mathematically in Eqs. (1) and (2), based on [33]. These equations are somewhat general, and thus the exact components of both parameters must be defined in each system according to its specific characteristics [20,33–37].

$$EE = \frac{\text{Total exergy output}}{\text{Total exergy input}} \tag{1}$$

$$ExROI = \frac{\text{Total exergy output}}{\text{Total fossil exergy input}} \tag{2}$$

Macroalgae photobioreactors (MPBR) [6], medium scale laboratory cultivation systems, can allow semi-open environments, thus enabling improved simulations of field conditions towards necessary future upscale. MPBRs were developed only recently, following the microalgae cultivation in photobioreactors (PBR) that has been performed for about a decade [38]. Consequently, no exergy efficiency values were yet published for MPBR systems. However, previous works have estimated exergetic performances of microalgae systems of different kinds, from the industrialized raceway ponds and tubular or flat-plate PBRs, to the building integrated façade PBRs [34–37,39–43]. These estimations usually focused on the input streams of energy consumed for mixing and thermal regulation of the system and on the energy content of the produced biomass as an output stream, ignoring other energy requirements for the construction of the system or for the processing of the biomass [34–36].

The current work suggests EE and ExROI formulas for the evaluation of these indicators for a closed MPBR system. This kind of energy budget analysis cannot be done in an offshore, uncontrolled, system. Furthermore, this work evaluates first MPBR exergetic efficiency values and compares them to other biomass production systems. In addition, occupational areal and volumetric productivity are evaluated and compared as an additional important evaluation parameter. Finally, a sensitivity analysis is performed, pointing out requested future system optimization steps for large-scale production on and off-shore.

2. MPBR exergetic efficiency models

The suggested models implement the EE and ExROI indicators on a closed MPBR, focusing on the main process exergy inputs and outputs. The MPBR EE includes direct exergy inputs in the form of solar energy (E_{sol}) and electrical energy (E_{elec}) and indirect exergy inputs, in the form of nutrients (E_{nut}) and biomass ($E_{bio\ initial}$). This part can also be called cumulative exergy demand [20]. It should be mentioned that the inclusion of solar energy input is not common in other exergy balance analysis, and may be of importance in intensive cultivations where irradiance can be controlled and manipulated [44–46]. The only relevant output parameter for the efficiency calculation is the produced biomass ($E_{produced\ bio}$), which is the accumulated biomass. Input and output exergy streams are illustrated in Fig. 1. Other exergy streams, related to labor, capital, waste and ecosystem services [47] are not taken into account as for the small scale of these systems. The second indicator, the ExROI, excludes from the calculation the exergy inputs that do not derive from fossil fuels, such as solar irradiance and biomass. EE is described in Eq. (3), and ExROI is described in Eq. (4). Mathematical representation and detailed calculation of each component are described in the methods chapter.

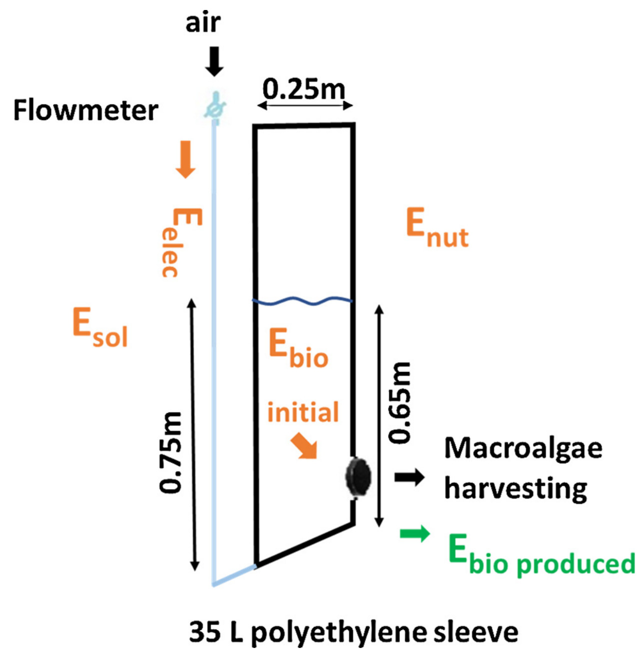

Fig. 1. System exergy input and output streams illustration. Input streams: solar energy (E_{sol}), electrical energy (E_{elec}) and energy embedded in initial biomass ($E_{bio\ initial}$) and in nutrients (E_{nut}). Output stream: energy embedded in produced biomass ($E_{bio\ produced}$).

$$EE = \frac{E_{produced\ bio}}{E_{sol} + E_{elec} + E_{nut} + E_{initial\ bio}} \tag{3}$$

$$ExROI = \frac{E_{produced\ bio}}{E_{elec} + E_{nut}} \tag{4}$$

3. Materials and methods

3.1. Marine macroalgae biomass

Green leafy macroalgae *Ulva* sp. (Fig. 2a) was collected from Haifa during spring 2016 and cultivated in a closed macroalgae photobioreactor system (MPBR) built for research purposes in the University of Tel Aviv [6] (Fig. 2b). During cultivation, nutrient concentrations in seawater were maintained at 6.4 mg l^{-1} of nitrogen and 0.97 mg l^{-1} of phosphorus by fertilizing with ammonium nitrate (NH_4NO_3, Haifa Chemicals Ltd, IS) and phosphoric acid (H_3PO_4, Haifa Chemicals Ltd, IS). CO_2 was supplied by bubbling air. A full description of this MPBR can be found in [6].