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Energy balance and environmental impact analysis of marine microalgal biomass production for biodiesel generation in a photobioreactor pilot plant

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ABSTRACT

A life cycle assessment (LCA) and an energy balance analysis of marine microalgal biomass production were conducted to determine the environmental impacts and the critical points of production for large scale planning. The artificial lighting and temperature conditions of an indoor bubble column photobioreactor (bcPBR) were compared to the natural conditions of an equivalent outdoor system. Marine microalgae, belonging to the dinoflagellate and raphidophyte groups, were cultured and the results were compared with published LCA data obtained from green microalgae (commonly freshwater algae). Among the species tested, *Alexandrium minutum* was chosen as the target marine microalgae for biomass production under outdoor conditions, although there were no substantial differences between any of the marine microalgae studied. Under indoor culture conditions, the total energy input for *A. minutum* was 923 MJ kg^{-1} vs. 139 MJ kg^{-1} for outdoor conditions. Therefore, a greater than 85% reduction in energy requirements was achieved using natural environmental conditions, demonstrating the feasibility of outdoor culture as an alternative method of bioenergy production from marine microalgae. The growth stage was identified as the principal source of energy consumption for all microalgae tested, due to the electricity requirements of the equipment, followed by the construction material of the bcPBR. The global warming category (GWP) was 6 times lower in outdoor than in indoor conditions. Although the energy balance was negative under both conditions, this study concludes with suggestions for improvements in the outdoor system that would allow up-scaling of this biomass production technology for outdoor conditions in the Mediterranean.

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1. Introduction

The next decade will be crucial in solving many of the environmental issues of our planet, especially those regarding the increase in greenhouse gases (GHG), water shortages, and the depletion of fossil fuels. Issues related to CO_2 emissions and fossil fuel depletion are linked, due to the large amounts of CO_2 released into the atmosphere from the industrial, transportation, and energy sectors [1]. To avoid further increases in GHG emissions and to increase the energy reserves of different countries, governments, policy stakeholders and research groups are investing in and developing projects related to the production of biofuels from terrestrial biomass feedstock, known as the "first generation" biodiesel, including corn, rapeseed, sunflowers, and sugarcane plants. There are advances in the production of "second generation" biodiesel, using residues from trees or lignocellulosic material as feedstock for bio-ethanol production. However, the use of these feedstocks for biodiesel production is controversial because the processing and commercialization of terrestrial plants are associated with several environmental and social problems, including a loss of biodiversity, increased freshwater consumption, higher prices of edible plants, and the resulting social inequalities [2–4]. Alternatively, one of the most promising feedstocks for the "third generation" of biodiesel production involve microalgae, due to their photosynthetic conversion efficiency, fast growth, sustainable biomass production, and high content of triacylglycerols (TAG), which is the oil that is commonly used as a raw material for biodiesel production [5,6]. To date, freshwater microalgae have been the main microalgal species researched for biomass and biodiesel production purposes. Of particular interest are the green algae, or Chlorophycean, including *Chlorella vulgaris, Chlorella protothecoides, Chlamydomonas reinhardtii,* and *Neochloris oleoabundans,* due to their high growth rates and their well-studied life cycle [7,8]. However, a drawback to their use is the permanent need for large quantities of freshwater in the continuous production of sufficient microalgal biomass, independent of the culture system. Use of sea/wastewater as the culture medium would significantly reduce the water footprint [9]. This implies the need to isolate seawater strains from the same place where they will later be grown. The efficient use of these strains requires that they have high TAG concentrations in addition to other energetically or commercially favorable cellular metabolites. Several advantages of the use of seawater as the medium for microalgae are that it leaves freshwater supplies free for other human and ecosystem uses, avoids ecological problems associated with the introduction of exotic microalgal species, maintains the system without any alteration to the local ecology, and avoids the loss of biodiversity [10,11]. The use of seawater microalgae strains allows the installation and operation of industrial scale plants in coastal countries, use non-arable land, and avoids or at least reduces freshwater consumption.

Based on these considerations, our group has explored the growth rates, lipid profiles, and TAG concentrations of various marine microalgal species and involved culturing the strains of interest in enclosed systems and improving these cultures for energetic purposes [12,13]. Most of the microalgae evaluated by our group in previous studies belong to the dinoflagellates and raphidophytes classes [12]. Dinoflagellates are well known because of their extensive bloom-forming proliferations in natural marine environments throughout the world [14,15]; in terms of the production of biomass for bioenergy, this harmful trait becomes an opportunity and an advantage. Previous studies [16,17] determined that dinoflagellates and raphidophytes readily adapt to growth in enclosed systems and that their natural capacity of proliferation can be exploited to establish long-term biomass culture facilities in various coastal countries [17,18]. The strains used in this study are present globally and can be considered strategic species because they can be isolated readily from local seawater spots around the world [14]. *Alexandrium minutum* is a tecate dinoflagellate with a high cell biovolume (>2800 μm^3) with a high biomass and lipid productivity. The dinoflagellate *Karlodinium veneficum* and the raphidophyte *Heterosigma akashiwo* are atecate cells and are advantageous in terms of lipid extraction by the ease of breaking the cells and avoidance of a higher energy input for the extraction of the lipids [13].

The biotechnology used for biomass production from microalgae principally involves two types of culture configuration: open and enclosed systems. Open systems, including raceways or open ponds, have a low initial cost of construction and maintenance, with a relatively low volumetric productivity, and parameters including temperature, evaporation, and contamination cannot be totally controlled [5]. Enclosed systems, including horizontal photobioreactors, bubble columns, or flat panels, produce a higher volumetric biomass (13-fold greater than raceways or ponds), allow the growth of a single microalgal cell type (monoculture), and have fewer contamination problems than open systems. However, the initial cost of construction is higher for enclosed systems than for open systems [5]. The energy cost of microalgal biomass production in enclosed systems suffers from the current need for materials and procedures that require high amounts of energy, including the different plastics used in the construction of the photobioreactor in bubble column photobioreactors and the concrete needed for open pond systems. Electricity consumption during the microalgal growth stage (water, air pumping, CO_2 injection, etc.) or in the filtration systems used to extract the biomass from the seawater in the dewatering stage is also high. Both open and enclosed systems are used to grow microalgae under autotrophic conditions, with sunlight as the energy source, nutrients obtained from a liquid medium, and inorganic carbon, as CO_2, provided in pure form or as injected air with atmospheric CO_2 concentrations. With these inputs, chemical energy is formed via photosynthesis [19]. Presently, most of the studies that use microalgae for biofuel purposes have been implemented in the lab or pilot scale, pending industrial scaling to demonstrate the production feasibility [7,8].

In this study, an enclosed system was chosen to achieve high marine microalgae biomass production because it allows the control of abiotic parameters and its biomass production per volumetric area is higher than in open systems. Additional considerations in establishing open system facilities