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Site selection for microalgae farming on an industrial scale in Chile

Cristián P. Bravo-Fritz [a,*], César A. Sáez-Navarrete [a], Leandro A. Herrera Zeppelin [b], Rosanna Ginocchio Cea [c,d]

[a] Departamento de Ingeniería Química y Bioprocesos, Facultad de Ingeniería, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Macul, 7820436 Santiago, Chile
[b] Departamento de Ingeniería Química y Biotecnología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Beauchef 851, 8370456 Santiago, Chile
[c] Departamento de Ecosistemas y Medio Ambiente, Facultad de Agronomía e Ingeniería Forestal, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Macul, 7820436 Santiago, Chile
[d] Center of Applied Ecology and Sustainability (CAPES), Pontificia Universidad Católica de Chile, Av. Libertador Bernardo O'Higgins 340, 8331150 Santiago, Chile

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ABSTRACT

Scientific research and commercial projects into the use of microalgae as a source of energy have increased markedly over the last decade. The economic feasibility and overall sustainability of operations based on farming of microalgae on an industrial scale will largely depend on their geographic location. Criteria concerning selection of sites from which diverse local resources can be optimized have to be also considered. The present study leads the analysis of relevant factors (i.e. natural resources, road infrastructure, geographic characteristics and industrial activities which generate greenhouse gas emissions) that support proper decision-making process for selecting potential areas of large-scale microalgae farming in Chile. Based on an eight-step methodology, ten potential sites were identified as meeting all necessary requisites for the industry across the country. Sites cover 103,600 ha, capable of producing an estimated volume of 1.5 Mm^3 per year of biodiesel, and replacing 17% of the annual diesel consumption in Chile.

1. Introduction

In terms of energy, Chile depends on the international fossil fuel market. Of the 285,400 Tcal consumed in 2012 [1,2], almost 60% is imported and 66% originates from fossil fuels, 31% of them being related to petroleum derivatives. Transport represents the largest consumer sector (56%) of fossil fuels [2]. Other percentage of hydrocarbons is used by the electric generation sector, where thermal power plants complete the national demand. Electricity is transmitted along the country via six independent systems, known as SING, SIC, SMLL, SMA, SMM and IP. Given the growing energy demand (30%) in the industrial and mining sectors (I&M) over the last decade, transmission alternatives are being evaluated which could have a significant impact on carbon footprints, prices and supply [2].

Projections from the Chilean Ministry of Energy estimate that energy consumption in the country will increase by 23% in 2020 [1,2]. Given the scale and urgency of this problem, specific policy guidelines on energy must be devised in the short term. This projection is of the same order as the estimate for the global primary energy demand for the same period, which foresees an increase of around 20% [3]. Regarding the most relevant issues, the energy policy should define the composition of the national power grid, design a new national system of electricity transmission, guarantee security of supply, establish energy efficiency requirements, determine guidelines on the sustainable location of new power plants and boost sources of non-conventional renewable energy (NCRE).

Faced with similar scenarios, other countries have begun safeguarding against their oil dependency, seeking alternative methods for producing liquid fuels capable of substituting, either completely or partially, petroleum derivatives. Examples include Germany, France and Argentina, which over the last decade have implemented political campaigns, economic subsidies, regulatory frameworks and the promotion of R&D initiatives into the production of biofuels made from seasonal crops, such as soybean, corn, sugar cane or rapeseed [4]. Another case is that of Brazil and the US, which are the largest producers of biofuels in the world, but unlike the examples above, they started the incentive and production before this last decade [5]. However, current global production of biofuels has ground to a halt, reaching approximately 60 MTOE [5].

Unlike other countries on the continent, Chile is only beginning to establish a regulatory framework regarding NCREs in general and biofuels in particular; so far, its production, distribution and consumption are voluntary. The country has a limited potential of biomass sources for production of traditional biofuels. Theoretically, Chile could meet 2% of its national gasoline demand with ethanol from corn, and 5% of its diesel demand from rapeseed [6]. These percentages are taken from a nationwide territorial analysis, which shows that just 21% of its surface is used for agriculture, of which just 8% is arable or cultivable (1,266,000 ha, equivalent to 1.7% of the national land area) [7].

Other studies have exposed a shortage of economic, energy and social results originating from traditional biofuel production, such as

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[*] Corresponding author.
E-mail address: ctbravo@uc.cl (C.P. Bravo-Fritz).

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corn ethanol or soy biodiesel [8–11]. This has led to research being conducted into low-intense sources of biofuel production (in terms of soil, water, energy and nutrients), which also allows for a more sustainable industry [12]. One such alternative to consider is the biomass obtained from microalgae. This alternative has also some other relevant advantages when compared with traditional biofuels such as its production does not directly compete with food [13,14] and avoid environmental (i.e. carbon balance) impacts related to land use change [15].

The first research into the use of microalgae as a source of energy dates back to 1850s, whereby researchers successfully cultivated different isolated species in the laboratory. Focus then switched to improving biomass production yields to achieve larger scale crops, in both open and closed systems. Towards the end of the 1970s, the US Department of Energy (USDOE) created a division called the Aquatic Species Program (ASP), to study the feasibility of producing bioenergy from algae. However, the low oil prices of 1980–2000 meant R&D into the so-called "microalgae farms" came to a standstill. In 1996, the ASP was discontinued and its findings were published in the 1998 book entitled, "A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae" [16,17].

Microalgae are ubiquitous, unicellular organisms of diverse metabolism (photoautotrophic, heterotrophic, mixotrophic or photoheterotrophic). Some species modify their metabolism in response to changes in environmental conditions. They are generally considered photoautotrophic, with the ability to convert inorganic carbon, CO_2, into complex organic material (for example lipids, glycosides and proteins) [8,16]. These microorganisms are interesting to the field of bioenergy because they constitute a sustainable and abundant raw material for the production of biodiesel, bioethanol, biohydrogen and biogas, among other products, in the context of a biorefinery [14]. Biodiesel is obtained from the transesterification of lipids; bioethanol, from the fermentation of glycosides; biohydrogen, from the modified metabolism of the microalgae; and biogas, from the anaerobic digestion of the biomass or from the organic residue they generate during the biorefining process [14]. However, strain development and process engineering are needed to make algal biofuels practical and economically viable [18].

At the global level, the US, Germany, China, Australia, Japan and Spain are at the cutting edge countries of R&D into bioenergetic or food-related microalgae projects. In Chile during 2010, CORFO (a state entity that supports the competitiveness and productive diversification of the country) allocated funds to three public–private business consortia, AlgaeFuels S.A., Desert Biofuels S.A. and BAL Biofuels S.A., for the development of technology and research into the production of biodiesel from microalgae (the first two listed) and ethanol from macroalgae (the latter). The geographical and environmental characteristics of Chile (topographical, extension and climate) represent a potential advantage for algae production with bioenergy purposes.

One of the most important aspects to consider in the production of microalgae on an industrial scale (the central theme of this study) is the strategic location of the culture farms. These microorganisms can be cultivated in both open (raceway ponds) and closed (photobioreactors or PBRs) systems. Nevertheless, given the high investment and operating costs of the PBRs, a mixed system is proposed in which PBRs are employed as the main technology in the permanent production of mass inoculum for larger scale raceway ponds (RWP), so that growth is faster to avoid contamination [19–21]. The use of PBRs is a key factor to the success of this industry [22]. For the use of RWP, extensive land surfaces are required that comply with numerous environmental standards and design constraints, in order to optimize industrial production. For a microalgae farm of regular conditions, capable of yielding 15 m^3/ha/year of biodiesel [8,23–25], the necessary surface areas required that have been documented [26] are listed in Table 1.

Table 1
Land sizes required for different scales of biodiesel production.

Biodiesel scale	Scale or size of plant	Surface area of microalgae farm
m^3/year	Name	ha
<8000	Pilot	<530
8000–40,000	Medium	530–2760
>40,000	Industrial	>2670

The value mentioned above for the surface productivity of microalgae biodiesel (15 m^3/ha/year), is obtained from operational data associated with the farming in RWP, simplifying and gathering a large number of variables which determine this productivity (for example, solar radiation, light incidence angle, environmental and farming temperature, nutrient concentrations, gas–liquid CO_2 transfer). For its estimation it is necessary to consider a maximum concentration of biomass of 0.5 g/L [8,24] before harvest ($C_{harvest}$), ten days farming ($d_{farming}$), ponds with 30 cm depth [24,27] ($Depth_{RWP}$) and 360 of annual operation ($d_{annual/op}$ resting maintenance). Operating these values and subjecting them to unit change (volume, mass and area) biomass productivity is obtained:

$$\begin{aligned}\mathrm{Prod}_{\mathrm{biomass}} &= \mathrm{C}_{\mathrm{harvest}} \cdot \mathrm{d}_{\mathrm{farming}}{}^{-1} \cdot \mathrm{Change}_{\mathrm{Vol}} \cdot \mathrm{Change}_{\mathrm{Mass}} \cdot \mathrm{Depth}_{\mathrm{RWP}} \\ &\quad \cdot \mathrm{Change}_{\mathrm{area}} \cdot \mathrm{d}_{\mathrm{annual/op}} \\ &= 54 \frac{\mathrm{ton}}{\mathrm{ha} \cdot \mathrm{year}}.\end{aligned}$$

Then, considering an average microalgae with 25% of lipids, a conversion 1:1 of lipids to biodiesel and a biodiesel density of 0.88 t/m^3($\rho_{biodiesel}$), the analyzed biodiesel surface productivity is obtained:

$$\mathrm{Prod} \cdot \mathrm{surf}_{\mathrm{biodiesel}} = \mathrm{Prod}_{\mathrm{biomass}} \cdot \%\mathrm{lipids} \cdot \rho_{\mathrm{biodiesel}}{}^{-1} = 15.3 \frac{\mathrm{m}^3}{\mathrm{ha} \cdot \mathrm{year}}.$$

The correct site selection for farming can help save natural and agricultural resources of the country, optimize biomass productivity, reduce the costs of transport and energy consumption, as well as improve public perception and acceptance of projects such as these. The first study or report found in this area was delivered by Maxwell and collaborators in 1985, from SERI, now NREL, covering the southwestern area of the US (Table 2). The authors compiled information according to three categories (climate, water and land) to identify potential production areas, in order to construct overlay/superposition maps [28].

The lack of studies between 1985 and 2010 relates to a dearth of research into microalgae in general, in line with the aforementioned international oil context during this period. However, since 2010 onwards, there has been extensive research into determining potential sites for microalgae production around the world (Table 2). In the same period, the USDOE published the "National algal biofuels technology roadmap", which includes an entire chapter on the evaluation of resources and potential sites [29].

In 2010, Milbrandt and Jarvis conducted an evaluation in India for the NREL. The authors conducted a survey of public and private information, culminating in a graphic of different potential sites using GIS (Geographic Information Systems) methodologies [30]. Similarly, research was conducted into potential resources in Canada and Australia in 2011 and 2012, respectively [31,32]. From this moment onwards, the use of GIS became recurrent, allowing researchers to modify, add or remove constraints and making the search for potential sites more objective in the process. These diverse studies share certain aspects, including land not being used for agriculture and areas presenting gentle slope, abundance of water resources, high levels of solar radiation and temperatures adequate for cultivating different microalgae species [33–36].