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Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects

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ABSTRACT

Micro-algae have received considerable interest as a potential feedstock for producing sustainable transport fuels (biofuels). The perceived benefits provide the underpinning rationale for much of the public support directed towards micro-algae research. Here we examine three aspects of micro-algae production that will ultimately determine the future economic viability and environmental sustainability: the *energy and carbon balance*, *environmental impacts* and *production cost*. This analysis combines systematic review and meta-analysis with insights gained from expert workshops.

We find that achieving a positive energy balance will require technological advances and highly optimised production systems. Aspects that will need to be addressed in a viable commercial system include: energy required for pumping, the embodied energy required for construction, the embodied energy in fertilizer, and the energy required for drying and de-watering. The conceptual and often incomplete nature of algae production systems investigated within the existing literature, together with limited sources of primary data for process and scale-up assumptions, highlights future uncertainties around micro-algae biofuel production. Environmental impacts from water management, carbon dioxide handling, and nutrient supply could constrain system design and implementation options. Cost estimates need to be improved and this will require empirical data on the performance of systems designed specifically to produce biofuels. Significant (>50%) cost reductions may be achieved if CO_2, nutrients and water can be obtained at low cost. This is a very demanding requirement, however, and it could dramatically restrict the number of production locations available.

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1. Algae for biofuels

Micro-algae are a large and diverse group of aquatic organisms that lack the complex cell structures found in higher plants. They can be found in diverse environments, some species thriving in freshwater, others in saline conditions and sea water [1,2]. Most species are photoautotrophic, converting solar energy into chemical forms through photosynthesis.

Micro-algae have received considerable interest as a potential feedstock for biofuel production because, depending on the species and cultivation conditions, they can produce useful quantities of polysaccharides (sugars) and

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triacylglycerides (fats). These are the raw materials for producing bioethanol and biodiesel transport fuels. Micro-algae also produce proteins that could be used as a source of animal feed, and some species can produce commercially valuable compounds such as pigments and pharmaceuticals [1].

There are two main alternatives for cultivating photoautotrophic algae: raceway pond systems and photobioreactors (PBRs). A typical raceway pond comprises a closed loop oval channel, ~0.25–0.4 m deep, open to the air, and mixed with a paddle wheel to circulate the water and prevent sedimentation (Ponds are kept shallow as optical absorption and self-shading by the algal cells limits light penetration through the algal broth). In PBRs the culture medium is enclosed in a transparent array of tubes or plates and the micro-algal broth is circulated from a central reservoir. PBR systems allow for better control of the algae culture environment but tend to be more expensive than raceway ponds. Auxiliary energy demand may also be higher [2–5].

The perceived potential of micro-algae as a source of environmentally sustainable transport fuel is a strong driver behind their development and provides the underpinning rationale for much of the public support directed towards micro-algae R&D. It is important, therefore, that algae biofuel systems are able to clearly demonstrate their environmental and longer term economic credentials. Here we examine three aspects of micro algae production that will ultimately determine the future economic viability and environmental sustainability: the *energy and carbon balance*, *environmental impacts* and *production cost*. Examining each of these aspects in turn provides the structure for this paper. The analytical approach we adopt combines systematic review and meta-analysis with insights gained from expert workshops convened in 2010 and 2011 as part of a European FP7 research project: AquaFUELs [6].

2. The energy and carbon balance of micro-algae production

If micro-algae are to be a viable feedstock for biofuel production the overall energy (and carbon balance) must be favourable. There have been many attempts to estimate this for large scale micro-algae biofuels production using life cycle assessment (LCA) methods to describe and quantify inputs and emissions from the production process. Attempts have been hampered, however, by the fact that no industrial scale process designed specifically for biofuel production yet exists. Consequently, the data that underpins micro-algae LCA must be extrapolated from laboratory scale systems or from commercial schemes that have been designed to produce high value products such as pigments and heath food supplements. Despite this limitation, it is anticipated that LCA can still serve as a tool to assist with system design.

Here we review seven recent LCA studies (summarised in Table 1). These studies describe eleven production concepts, but comparison is impeded by the use of inconsistent boundaries, functional units and assumptions. To compare the results on a consistent basis a simple meta-model was developed. This model was used to standardise units and normalise the process description to a consistent system boundary comprising the *cultivation*, *harvesting* and *oil extraction* stages (a complete description of the modelling approach is provided in the electronic supplementary information).

Table 1 – Life cycle assessment studies on algae derived fuels.

Ref.	Lead author	Description
[7]	Kadam	Compares a conventional coal-fired power station with one in which coal is co-fired with algae cultivated using recycled flue gas as a source of CO_2. The system is located in the southern USA, where there is a high incidence of solar radiation
[8]	Jorquera	Compares the energetic balance of oil rich microalgae production. Three systems are described: raceway ponds, tubular horizontal PBR, and flat-plate PBRs. No specific location was assumed. The study only considers the cultivation stage and the system energy balance
[9]	Campbell	Examines the environmental impacts of growing algae in raceway ponds using seawater. Lipids are extracted using hexane, and then transesterified. The study is located in Australia, which has a high solar incidence, but limited fresh water supply
[10]	Sander	A well-to-pump study that aimed to determine the overall sustainability of algae biodiesel and identify energy and emission bottlenecks. The primary water source was treated wastewater, and was assumed to contain all the necessary nutrients except for carbon dioxide. Filtration and centrifugation were compared for harvesting. Lipids were extracted using hexane, and then transesterified
[11]	Stephenson	A well-to-pump analysis, including a sensitivity analysis on various operating parameters. Two systems were considered, a raceway pond and an air-lift tubular PBR. The location of the study is in the UK, which has lower solar radiation than the other studies
[12]	Lardon	Considers a hypothetical system consisting of an open pond raceway covering 100ha, and cultivating *Chlorella vulgaris*. Two operating regimes are considered: i) normal levels of nitrogen fertilisation; ii) low nitrogen fertilisation. The stated objective was to identify obstacles and limitations requiring further research
[13]	Clarens	Compares algae cultivation with corn, switch grass and canola (rape seed). The study was located in Virginia, Iowa and California, each of which has different levels of solar radiation and water availability. Five impact categories considered: energy consumption (MJ), water use (m^3), greenhouse gas emissions (kg CO_2 equivalent), land use (ha), and eutrophication (kg PO_4)

Production systems were compared in terms of the net energy ratio (NER) of biomass production. NER is defined here as the sum of the energy used for cultivation, harvesting and

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