Available online at www.sciencedirect.com
ScienceDirect
Current Opinion in Biotechnology

# Novel approaches to microalgal and cyanobacterial cultivation for bioenergy and biofuel production

Kirsten Heimann

Growing demand for energy and food by the global population mandates finding water-efficient renewable resources. Microalgae/cyanobacteria have shown demonstrated capacity to contribute to global energy and food security. Yet, despite proven process technology and established net energy-effectiveness and cost-effectiveness through co-product generation, microalgal biofuels are not a reality. This review outlines novel biofilm cultivation strategies that are water-smart, the opportunity for direct energy conversion via anaerobic digestion of $N_2$-fixing cyanobacterial biomass and integrative strategies for microalgal biodiesel and/or biocrude production via supercritical methanol-direct transesterification and hydrothermal liquefaction, respectively. Additionally, fermentation of cyanobacterial biofilms could supply bioethanol to feed wet transesterification to biodiesel conversion for on-site use in remote locations.

**Address**
Centre for Sustainable Tropical Fisheries and Aquaculture, James Cook University, Townsville, QLD 4811, Australia

Corresponding author: Heimann, Kirsten (kirsten.heimann@jcu.edu.au)

**Current Opinion in Biotechnology** 2016, **38**:183–189

This review comes from a themed issue on **Energy biotechnology**

Edited by **Andrew S Ball** and **Jamie HD Cate**

http://dx.doi.org/10.1016/j.copbio.2016.02.024

## Introduction

As the world population increases to more than 9 billion people by 2050, food — , clean drinking water — and energy security, as well as climate instability are becoming pressing and interlinked problems with large socio-economic and environmental impacts [1,2]. Algae (micro and macroalgae and cyanobacteria (blue-green algae)) have been heralded as potential saviours, as they can be cultivated on non-arable land, in non-potable nutrient-rich water resources using waste $CO_2$ and light as key biomass production ingredients [3]. Yet to date, microalgal biofuels production has not transited into reality primarily due to economic competitiveness.

A detailed life-cycle based review focussing on the production potential of biodiesel from microalgae, identified high capital investment requirements, operational costs and biomass loss due to contamination, rather than technological hurdles, as the main reasons [4••]. While energy requirements for dewatering/harvesting are typically included, the large land and water requirements identified by Day *et al.* [5], particularly for open pond-based systems are, however, often not considered. High capital investment requirements can be combated by adopting a staged high value, low volume bio-product strategy with the aim to expand facilities, as capital is raised for actual biofuel production [6,7••]. Reviews by Wijffels *et al.* [8••], Savakis and Hellingwerf [6], and De Bhowmick *et al.* [9] provide detailed outlines of genetic engineering strategies for the enhancement of biofuel potential. Given the resistance to the use of genetically engineered organisms in many nations, particularly in outdoor (uncontrollable) locations, this will not be the focus of this review.

Another aspect receiving little attention, being rarely included even in recent life cycle analyses [10,11], are the fertilisation requirements of microalgae for optimal growth, because recycling of nutrient-rich waste waters from the downstream biomass to fuel processing pathways [7••] or collocation with nutrient-rich water resources, such as water treatment plants (e.g. [12,13] and other references in this volume) is envisaged. Typical industry process diagrams rarely align production fertilisation — with areal requirements, leading to process diagrams that may be implementable at pilot-scale or for on-site supplies only, but fail to deliver at product market scales.

Given the above, this review will briefly touch on microalgal strain selection, that is, biomass biochemical profile requirements, in light of extraction/fuel production technology and their impacts on biomass dewatering requirements. It will also discuss alternative production pathways, incorporating alternatives for energy production and fertiliser recycling.

## The bio-products trap — hindrance or facilitator for fuel production?

Microalgae and cyanobacteria have an undeniably high industrial potential for high value, low volume bio-product markets, as demonstrated by their contribution to the highly lucrative pigment and food supplement markets. The production potential for microalgal products has been reviewed in depth in recent years (e.g. [14–16]), most highlighting the need for process integration of waste recycling for economic production of biofuels [17••] and co-production of fine chemicals [18]. It is noteworthy though that, despite workable net energy and cost-effectiveness of this multiple co-product and by-product approach [17••], microalgal biofuels are still not being produced at any scale. This could be indicative of a catch 22 situation where high value products could drive the economics and investment at the expense of progressing to low-value biofuel production until markets are saturated. One aspect mentioned for targeted high value bio-product markets, but receiving little attention, is the necessity for cultivation of specific strains, which have the obligatory biochemical profile — yields and — productivities to meet required productivities [19]. This has flow on effects on the economics of such production facilities, due to either more cost-prohibitive system requirements (e.g. closed systems) and/or impacts of contamination (e.g. open raceway ponds). This review investigates the possibility of a direct biofuels approach by integrating waste recycling, energy generation and waste product-derived co-products.

## System considerations

To date, open raceway or hybrid system production of microalgal biomass appears to be the general consensus for economic biofuel generation [20], but, irrespective of system, the requirement for water movement to keep the biomass homogenously resuspended for light exposure and dewatering/harvesting of relatively dilute biomass (often <1 g dry weight (DW) $L^{-1}$) can increase the cost of the operation, both in terms of capital and energy expenditures, for example, 0.21 kWh $kg_{\mathrm{biomass}}{}^{-1}$ for raceway operation and 0.42 kWh $kg_{\mathrm{biomass}}{}^{-1}$ for centrifuge-based dewatering/harvesting [21]. In an interesting life cycle analysis, Handler *et al.* [21] investigated energy requirements for different systems (stirred tank secondary treated sewage and raceway) integrated with different biofuel processing pathways, fast pyrolysis (RTP™, Rapid Thermal Pyrolysis for the former) and oil extraction followed by hydro-processing for the latter cultivation approach and created a novel scenario where raceway cultivation of biomass was coupled with fast pyrolysis. Despite potential greenhouse gas emission savings of ∼85% compared to petroleum petrol production, switching dewatering from settling to dissolved air-floatation (DAF) eroded the greenhouse gas emission savings basis by more than 50%.

A novel and recently more investigated cultivation strategy is biofilm cultivation of microalgae [22,23••]. These systems have traditionally been used for remediation of waste waters, probably best known as algal turf scrubbers, but a serious link for the commercial production of microalgal biomass has been made only recently [22]. Microalgal biofilm cultivation avoids large energy expenditure for mixing and dewatering/harvesting (Table 1), as the biomass scraped of a cultivation surface yields a paste with a similar total solid content to that obtained by centrifugation. Furthermore, as the algal biofilm is separated from the air by only a thin layer of water, irrespective of system design (Figure 1) [22], carbon dioxide and light utilisation is much improved [24]. Algal species choice in these systems is positively correlated to the hydrophobicity of the cell surface, providing superior attachment to the cultivation substratum [23••]. Cultivation surface productivity of these systems typically range from 2 to 6 g DW $m^{-2}$ $day^{-1}$, while system footprint biomass can vary considerably based on design from 5–10 to 46–80 g DW $m^{-2}$ $day^{-1}$, with rotating and vertical systems showing the highest biomass productivities even in pilot-scale operation [23••]. Based on algal turf scrubber species analyses for waste water treatment, freshwater green microalgal species grow readily has biofilms [23••] and the successful cultivation of the nitrogen-fixing and self-settling cyanobacterium *Tolypothrix* sp. was also recently shown for outdoor cultivation in the semi-arid tropics [25]. The biofilm cultivation approach when integrated with biomass to fuel/energy conversion scenarios can yield novel theoretical strategies for biofuel/bioenergy using microalgae/cyanobacteria.

## Biofilm-integrated microalgal/cyanobacteria biofuel/bioenergy production

The various microalgal cultivation biofilm strategies are described in Box 1, where considerations of footprint, water loss and suitability for different applications are detailed.

Many microalgae are capable to grow as biofilms in a perfused biofilm cultivation system, providing environmental conditions are sufficiently humid [22]. A scenario for self-sufficient perfusion biofilm-generated microalgal

**Table 1**

**Comparison of energy and water requirements of open ponds (OP), vertical flat panel (VFP) and biofilm cultivation systems (BF) for biomass cultivation and dewatering/harvesting**

| Parameter | OP | VFP | BF |
|---|---|---|---|
| Biomass areal productivity [g $m^{-2}$ $d^{-1}$] | 48[a] | 68[a] | 2–80[b,c] |
| Energy for cultivation [kWh $bbl^{-1}$] | 333[a] | 294[a] | N/A |
| Water consumption [$m^3$ $bbl^{-1}$] | 312[a] | 34[a] | 178[d]<br>22[e] |
| Energy for harvesting/dewatering | | | |
| Centrifugation [kWh $bbl^{-1}$] | 1352[a] | – | – |
| Chitosan flocculation [kWh $bbl^{-1}$] | – | 135[a] | – |
| Chamber press filtration [kWh $bbl^{-1}$] | 1190[a] | – | – |

[a] Ref. [48•].

[b] Ref. [22].

[c] Ref. [23••].

[d] Based on [62] for a horizontal ATS.

[e] Based on [32•] for a vertical water troph-positioned rotating biofilm reactor; bbl: barrel of oil (159 L).