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Letter to the editor

A perspective on renewable bioenergy from photosynthetic algae as feedstock for biofuels and bioproducts

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ABSTRACT

There has been substantial technical progress in developing algae-based bioenergy in recent years and a large part of industry and academic research and deployment projects have pivoted away from a pure biofuels strategy. This letter summarizes the findings of a recently completed, comprehensive report, that represents a collaborative effort of at least 20 co-authors, where we analyzed the prospects for using microalgae and macroalgae as feedstocks for biofuels and bioenergy production. The scope of this report includes a discussion of international activities advancing bioenergy and non-energy bioproducts from algae, progress on the use of macroalgae (both cast and cultivated seaweeds) for biogas applications, distinct biochemical and thermo-chemical conversion pathways, multi-product biorefining opportunities, as well as a thorough review of process economics and sustainability considerations. It is envisioned that a higher value algal biomass-based bioproducts industry will provide the additional revenue needed to reduce the net cost of producing algae-based biofuels. As such, a biorefinery approach that generates multiple high-value products from algae will be essential to fully valorize algal biomass and enable economically viable coproduction of bioenergy. To accelerate the implementation of algae-based production, minimizing energy, water, nutrients and land use footprints of integrated algae-based operations needs to be a primary objective of larger scale demonstrations and future research and development.

1. Introduction

In light of persisting low fossil fuel prices, the algae-based industry is forced to shift its focus from lower value commodity biofuels and bioenergy products to higher value (non-energy) products that can be profitable today. The International Energy Agency (IEA) Bioenergy Technology Collaboration Program (TCP) commissioned and published a report summarizing the state of technology of algae-based bioenergy [1]. This report is the result of a thorough literature review and a collaboration of at least 20 co-authors, with respective expertise in processing, biorefinery applications, macroalgae and overall techno-economics or sustainability considerations. The scope covers the international status and prospects for using microalgae and macroalgae as feedstocks for producing biofuels and bioenergy products and follows a prior IEA Bioenergy Task 39 report published in 2010 [2]. The scope of the report covers algae-based options for producing liquid and gaseous biofuels, and also algae-based bioenergy in the more general context of integrated biorefineries. Although significant opportunities exist to exploit the high photosynthetic efficiency of algae for bioenergy and biofuels production, inherent biological cellular constraints on strain production capacity are coupled to large differences in projections about production scenarios for both micro- and macroalgae. The report emphasizes the substantial challenges to extrapolating productivity reported in the literature to outdoor cultivation performance over the long term. There are also significant challenges to developing cost-competitive algae-based production. Mitigation of these challenges is driving development of combined biofuels and bioproducts pathways in a multi-product biorefinery context to maximize the valorization of algae. The analysis presented in the report is intended to help inform a deeper understanding and insight into the promises and challenges for algal biofuels and bioenergy technologies to be substantial contributors to future liquid and gaseous transportation fuel supplies.

Technical progress notwithstanding, the prospects for commercial algae-based bioenergy or biofuels production are significantly more challenging today than they were in 2010. This is primarily the result of the substantial decline in petroleum prices since August 2014. Much lower petroleum prices since then have greatly increased the economic challenge of bringing cost competitive algae-based biofuels to market. Companies that were leading commercial development of algae-based biofuels have been increasingly redirecting their commercial focus towards production of higher value food, feed and specialty products. At least until oil prices return to near their pre-August 2014 levels or reducing carbon emissions becomes sufficiently economically valued, primary strategies for liquid biofuels production from algae will need to rely on a biorefinery approach where coproduction of higher value products facilitates the economic viability of coproducing algal biofuels [3–6].

The structure of the report follows different areas of research and development (R & D) for algae bioenergy and bioproducts applications. The primary emphasis is on microalgae routes to biofuels and bioproducts, consistent with the much larger body of literature and research reports reflecting public and private funding compared to macroalgae. The state of macroalgae-based bioenergy production is also reviewed, and a key finding is that the prospective use of low-cost, cast seaweed for biogas production may be a potential near-term commercial bioenergy opportunity in some regions. The report's appendices also include a unique overview of commercialized technologies and a detailed list of R & D projects and

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commercially deployed algae-based production installations worldwide.

The energetic considerations of algae production provide a framework to consider the maximum limits for areal algae productivity and absolute biofuels/bioproducts production potential given physical and geographical constraints. As already highlighted, clear economic and sustainability challenges still exist to develop large-scale cost-competitive algal biomass-derived biofuels. While absolute economical considerations on algal biomass cultivation and biofuel production costs are a complex function of variables that vary with physical, geographic and socio-economic environments, there are opportunities to integrate production of algal biomass within a biorefinery approach to derive additional value from products coproduced along with gaseous or liquid biofuels. What follows is an abbreviated version of the report's executive summary.

2. State of technology of microalgae bioenergy

The single biggest and most critical barrier to market deployment of commercially viable algae-based production remains the high cost of cultivating and harvesting the biomass feedstocks relative to terrestrial plant biomass. Even though recent research findings and technology development have not changed the basic promise of using algae-based systems to produce renewable bioenergy as well as chemical and nutritional products, challenges remain to achieve both the targeted cost and sustainability metrics. Algae as a class of photosynthetic microorganisms exhibit tremendously large biological diversity and metabolic plasticity compared to terrestrial plants, i.e., they are able to more widely adapt their biochemical metabolic pathways and cellular composition in response to external conditions including physiological inputs. At least for some geographical locations, there need not be significant competition with land used to provide existing food and feed supplies thanks to the potential of growing algae on non-arable land. Moreover, the rapid growth and exceptionally high photosynthetic efficiency of algae feedstocks allows for higher areal biomass (and thus product) yields to be achieved compared with terrestrial crops. In this context, algae remain a promising renewable feedstock to research to address future energy and sustainability challenges.

Significant economic and sustainability barriers impede commercial production of algae feedstocks for relatively low value energy and fuel market applications. Future research and commercial implementation of algae as feedstocks should provide global, economical and sustainable solutions to currently identified barriers, which range from large biological diversity among species to integration of new conversion technologies at demonstration scale. Among these barriers, the inverse relationship between productivity and lipid content may prove to be an especially difficult challenge to overall process optimization and economic viability [7]. Even though many algae-based technologies have been demonstrated at laboratory scale, most often this has been done in isolation, and thus a challenge remains to fully validate the efficacy of the different technologies working effectively together in an integrated and efficient manner. Reducing energy, water and land use footprints of the integrated operation also must be one of the key objectives of future larger scale demonstrations [8]. Overall potential production yields and process challenges are intimately related to specific production strains and their cultivation characteristics including geographic location. Great care should be taken in interpreting yields reported in the literature if they have not been fully vetted in larger scale and longer term integrated demonstrations.

Challenges to realize increased future applications of algae-based systems can be categorized into the following barriers to cost effective and sustainable algae-bioenergy deployment: [7] 1) algal biomass productivity, energy, water, nutrient (fertilizer), greenhouse gas (GHG) emissions and land use of any algae operation must be sustainable across the entire value chain, and data needs to be collected in a consistent and scale-relevant manner to support reliable techno-economic assessments (TEA) and life cycle analyses (LCA); 2) further ecological, genetic and biochemical development of algae species is needed to improve productivity and robustness of algae strains against perturbations such as temperature, seasonality, predation, and competition; 3) physical, chemical, biological, and post-harvest physiological variations of produced algae strains need to be researched and understood and integrated with biorefinery operations; 4) integration of co-located inoculation, cultivation, primary harvest, concentration, and preprocessing systems needs to be developed to maximize economic viability; 5) full valorization of algal biomass by on-site processing of algal biomass into its lipid, carbohydrate, and/or protein fractions needs to be developed at scales compatible with large-scale cultivation and farming; 6) to support process and operations sustainability, recycling nitrogen, phosphorus, carbon and other nutrients from residual materials remaining after processing must be maximized to minimize the requirements for fresh fertilizer in cultivation.

One of the most challenging aspects for sustainable cultivation of algae for commercial production to supply commodity-scale markets is to mitigate the enormous amounts of water and nutrients required to grow and process algal feedstocks. Effective wastewater recycling is essential to minimize freshwater and chemical nutrients consumption [9,10]. Water usage requirements for algal biomass and biofuel production will vary depending on growth conditions and ultimately the lipid or biofuel yield from the biomass. For example, for a production system growing algae to a concentration of approximately 1 g/L, assuming 20% oil content of the harvested algal biomass to be used for biofuel applications, a total of ~5000 L of algae culture would need to be processed to generate 1 kg of biofuel (green/renewable diesel or bio-diesel). Algal biomass typically contains 45–50% C, 7.6% N and 1.4% P. While the specific elemental composition can vary dramatically based on growth conditions and species of algae used, on average the above approximation can be made, and this is consistent with the Redfield molar elemental ratio (106:16:1C:N:P) on a mass basis (40:7:1C:N:P). Thus, the nutrient requirements to support the same 1 kg of biofuel would be in the range of 0.38 kg N and 0.07 kg P equivalent (corresponding to 0.214 kg phosphate delivered). These approximate resource estimates for algal production are consistent with earlier reports in the literature, where water requirements of 3000 L of water per kg of microalgae-based biodiesel have been estimated [11], with associated nitrogen requirements of 0.18–0.33 kg nitrogen if freshwater without any recycling is used for open pond cultivation [12,13]. While closed photo-bioreactors can be used to reduce evaporative water losses [9], this imposes additional costs in installed capital equipment.

Higher efficiency water use and wastewater recycle may further reduce water consumption, with the direct use of wastewater potentially able to provide an inexpensive and effective nutrient source that also reduces freshwater use [14]. The integration of algal production with wastewater treatment (WWT) would allow both processes to achieve better economic performance as well as improved environmental sustainability. The two main approaches being examined are: 1) direct WWT via algal production, with the treated effluent discharged for offsite use (i.e., wastewater is only used once for algal production); and 2) use of treated or untreated wastewater as a cultivation medium for algae production, with the wastewater then re-treated and recycled. In the WWT application, the main products are reclaimed water (cleaned up wastewater), algae-based fertilizer, and biomass-derived products such as biofuels. However, at current prices, biofuels and fertilizers would not be economical products [15–18], and fees for WWT and sales of reclaimed water would provide most of the revenue. The dedicated production of algae-based biofuels using treated or untreated wastewaters has so far only been investigated at relatively small scales, and while this provides an economically appealing approach for lowering the cost of algal cultivation, much more needs to be done to demonstrate the viability of this approach for large-scale applications. For municipal wastewaters, the limiting nutrients for algae growth are typically (in sequence of limitation) inorganic carbon, nitrogen, possibly some trace metals, and phosphorus [14,19]. For cultivation systems using extensive water recycle, salts can build up to high enough concentrations to