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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 become inhibitory for growth, but for low salinity waters, such as municipal wastewater, organic inhibitors and biotic stressors are more likely to be the factor limiting the extent of water recycling.

There are many and diverse options for cultivating microalgae and maximizing the recovery of bioenergy products in a conversion process. One type of pathway for conversion is referred to as fractionation to major biochemical constituents – lipids, carbohydrates and proteins. This pathway presents opportunities to process different algal biomass components separately using a biorefinery approach, i.e., to develop specific biofuels or alternative products from each component stream of the fractionated algal biomass in an integrated manner. This approach can potentially increase algae-based product yields to well above those possible only using the lipid fraction [20,5]. Total biofuels yields from whole algal biomass using a biorefinery approach can, even with conservative assumptions, exceed the yields typically achieved using terrestrial feedstocks [21]. It is noteworthy that all of the process options discussed in the report to exploit such an approach rely on coproduction of biogas (primarily comprised of methane) by anaerobic digestion (AD) of residual algal cell mass to help power the plant. In addition the report also discussion opportunities to generate biogas from whole algae as a means to contribute and feed bio-derived methane to the natural gas supply [22]. In particular, incorporating AD appears critical to both the economics and sustainability of the conversion process, since AD also provides the main route for recycling nutrients to the cultivation process [23].

An alternative conversion technology for algae is based on Hydrothermal Liquefaction (HTL) and is receiving attention as a way to scale up production of an algae-based biocrude oil. A number of research groups are actively evaluating HTL and several companies are pushing its commercialization [24]. Results reported to date suggest that HTL provides a robust approach for algal biomass upgrading to a liquid biocrude intermediate product, which can then be upgraded catalytically to a renewable diesel blendstock. It has been reported that algal species and cell mass biochemical composition exhibit only minimal impact on fuel/product yields. However, HTL-based upgrading for algal biomass is currently at a relatively early stage of development and additional testing in continuous flow systems is needed as well as more characterization of the biocrude product composition and quality and especially the effectiveness for hydrotreating of the biocrude to a fuel blendstock.

Whichever process for fuel or energy production is pursued, the isolation of co-products can provide critical additional revenue necessary to reduce the net cost of producing an algae-based biofuel. As such, a biorefinery approach appears essential to realize the full value of algal biomass, i.e., wherein each component of the biomass is used for its most profitable application to maximize the biorefinery's overall economic performance [5,4]. This integration of different components will only be feasible when products and their respective market applications are commensurate. The highly complex and specific nature of multiple product separations will need to be prioritized as research topics to provide the maximum value to on-going and future work. For each of the major algal biomass biochemical fractions (i.e., lipids, carbohydrates and proteins), there are a subset of products and pathways to experimentally demonstrate the valorization approaches discussed in the report. The high value product area closest to being experimentally demonstrated and deployed at scales compatible with those of fuels is the production of oleochemical products (e.g. surfactants, lubricants, additives and bio-polymers) from algal oils.

TEA continues to be the main tool used to understand the market viability of algae-based systems for producing biofuels, bioenergy or other bio-based products. Literature TEAs for various algae-based production scenarios continue to report large variances in estimated process economics, making it difficult to draw definitive conclusions about "*true*" or "*most likely*" production costs. Beyond differences in financial modelling assumptions, the wide variability in projected algal biomass costs reported for a given algae-based production pathway is primarily attributed to differences in assumptions about growth characteristics and cultivation productivity. Furthermore, most TEA and LCA studies are based on data extrapolated from smaller scale pilot and lab-scale experiments, and larger and more extended demonstration scale data for algae cultivation and upgrading remains a key need. In general, the reliability of TEAs and LCAs of prospective algae-based production pathways suffers from their need to extrapolate large-scale production performance from more idealized laboratory- or pilot-scale data. For LCA, like TEA, the lack of a consistent reference framework makes side-by-side comparison of sustainability metrics for different approaches very difficult. Nonetheless, LCA remains the de facto standard approach being used to compare the sustainability attributes of different processing scenarios, including differences in assumptions about how co-product credits and system boundaries are handled. Because of this, where parameter uncertainty persists, it is recommended that this uncertainty be incorporated in assessments in order to increase the robustness and transparency of model projections and better guide research towards reducing overall uncertainty. Better standardization of LCA methodologies within the sector is needed before meaningful comparisons between disparate algae-based production systems can be made.

The development of less energy-intensive technologies for microalgae cultivation and harvesting steps is critical to further reduce the life cycle GHG emissions of microalgae-based biofuels production. Nevertheless, microalgae biofuel production systems are a recent development and improved production technologies are continuously coming onto the scene. It is recommended that future TEA and LCA studies be performed for envisioned commercial systems, both to better support and justify the selection of a particular production pathway as the optimum option for a given geography as well as to confirm previous results based on lab- or pilot-scale experiments.

3. State of technology of macroalgae bioenergy

In addition to microalgae, there are also a myriad of macroalgae species (seaweeds) that can be grown as biomass feedstocks as well as many potential pathways to produce bioenergy or other bio-based products from seaweeds. Conversion of seaweeds to biogas using AD technologies is among the most investigated approaches and is discussed in depth in the report. However, AD-based approaches for macroalgae may prove to be problematic in the longer term due to the potential for high salinity and sand accumulation over time. It is also unlikely that cast seaweed can be harvested at a scale sufficient to provide significant quantities of transportation fuel or on a consistent enough basis to meet the continuous supply needs for a biofuel-focused biorefinery. However, colocation of conversion plants where terrestrial biomass could also be sourced and used may provide a means of achieving continuous production from an intermittent supply of macroalgae feedstock. In addition, methane obtained from AD could be cleaned up, compressed and injected into the existing gas grid to bolster the gaseous bioenergy supply. The more likely scenario is new cultivation of seaweeds being established, more than likely associated with aquaculture. Seaweed-based production for bioenergy products (as opposed to higher value food, nutritional and chemical products, which is already commercialized to a significant extent) is at an early stage of development. It is not yet known which species will be best suited for such bioenergy production. Numerous parameters, including the method of cultivation, species of seaweed, seaweed yield per hectare, time of harvest, method of harvest, suitability of seaweed to ensiling, gross and net energy yields of biogas, carbon balance, cost of the harvested seaweed, cost of the produced biofuel, etc. have not yet been adequately assessed. Much additional research is required to understand the potential for macroalgae-based production.

4. Opportunities and outlook

At least until oil prices return to near their pre-August 2014 levels, or carbon emissions reductions are rewarded through higher carbon pricing in a global climate disruption mitigation policy, primary strategies for bioenergy production from algae will need to rely on a multi-product biorefinery approach. One of the products in the biorefinery would be fuels produced alongside higher value bioproducts to support the economical feasibility of the refinery. The basic promise of algae-based bioenergy applications is still valid; there does not need to be competition with existing food and feed supply since algae have the potential to be grown on non-arable land and there is also the potential to use wastewater as a cultivation medium and to recover nutrients at each step of an integrated process to minimize the pressure on limited available resources. However, the other side of the coin of potential is that there are significant barriers currently impeding commercialization and economic production of algae for relatively low value energy and fuel markets, in particular in supporting the resource demands for large-scale deployment. The barriers discussed in the report range from incomplete knowledge of algae biology to challenges associated with economical integration of technologies at demonstration scale. Even though many algae-based technologies have been demonstrated at the laboratory scale, this most often has been done focusing on specific unit operations or aspects of the technology such that the challenge remains to fully integrate algae-based processes and prove them out through extended multi-season operation. Progress in minimizing and primarily reducing energy, water and land use footprints of integrated algae-based operations needs to be a primary objective of future larger scale demonstrations.

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