CATF WHITE PAPER:

THE STATUS OF ALGAL BIOFUEL DEVELOPMENT

CLEAN AIR TASK FORCE

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CONTENTS

INTRODUCTION

Algal biofuels continue to be a topic of great possibility and great controversy. While viewed as one of the most promising next-generation sustainable biofuels, algae have garnered a good deal of criticism as well when comprehensive analyses are undertaken to understand potential environmental and economic impacts. The National Research Council (NRC) 2012 report, "Sustainable Development of Algal Biofuels in the United States," places the uncertainty of the field in context, stating, "[Life-cycle assessment] results for net [greenhouse gas] emissions for algae biofuel production vary from a net negative value (that is, a carbon sink) to positive values substantially higher than petroleum gasoline" (p. 151). This substantial range is dependent on a number of factors, and can likely only be narrowed to the negative end of the spectrum through algal biofuel production that optimizes co-locations for generation, coproduct cultivation, and energy, land, nutrient, and water reuse possibilities. The past year's literature and research on algal biofuel development focuses on these issues as the most promising paths to generate biofuel that are both economically and environmentally sensible while emphasizing that sustainable large-scale commercialization, if achievable, is still years away.

This paper will aim to review the current state of algal biofuel research and production with particular regard to potential co-location, coproduct, and reuse synergies to cultivate algal biofuel as a viable substitute for petroleum-based transportation fuels. The paper will attempt to provide an overview of the current state of thinking on the energy return on investment (EROI) of algal biofuel, combined wastewater treatment and algal biofuel production, coproduct generation, the feasibility of marine algae for biofuel, and the environmental complications of algal biofuels. First, it will present some data on present capacity and near-term predictions for the industry.

PRESENT CAPACITY AND NEAR-TERM FORECASTS

American and Canadian advanced biofuel generation capacity experienced a 57% increase from 2011 to 2012 (Solecki, Dougherty & Epstein, 2012, p. 3). Yet, large-scale commercial algal biofuel production is still several years away, or even decades away, according to Exxon Mobil Corporation (Alic, 2013a). The considerable time scale for potential commercial viability has even led Exxon to restructure its partnership with Synthetic Genomics (SGI). Exxon invested hundreds of millions of dollars in 2009 in SGI to develop biofuels from naturally occurring or conventionally modified algae, as opposed to synthetic strains, seeking near-term profitability. The apparent lack of success to date has compelled the companies to sign a new agreement in the spring of 2013 that focuses more on long-term basic research and less on commercial development (Elgin & Waldman, 2013; Alic, 2013b; Synthetic Genomics, 2013). Handler et al. (2012) suggest that, even once the right strains of algae are identified, consistent operation of algal biofuel production will need to occur for five to fifteen years before true commercialization can be realized (p. 84).

Once the right strains of algae are identified, consistent operation of algal biofuel production will likely need to occur for five to fifteen years before true commercialization can be realized.

Some others in the field remain more optimistic about algal biofuel's near-term prospects. The Algae Biomass Organization (ABO) surveyed 471 respondents throughout the industry in January 2013. Of these respondents, more than 25% worked in commercial algae production, and more than 20% in a university setting, with the remainder comprised of equipment, materials, and support companies, government agencies, service suppliers, and end users, among others (ABO, 2013, Slide 2). 91% of total respondents expected that algal biofuels would be cost competitive by 2020 (ibid., Slide 4), and 37% anticipated that they would fall below $5 per gallon by that same year (ibid., Slide 5). Quinn, Catton, Wagner, and Bradley (2012), however, contend that the majority of studies overestimate feasible microalgae productivity in the near-term. Most yields, as defined by growth rate, cell density, and lipid content, represent theoretical or modeled results in the literature. Each prediction is inherently contingent on the factors applied within a given model. The National Research Council (2012) reminds us further that long-term, commercially-scaled results do not yet exist to match many of the maximum yield prospects projected.

The predictions and projections are nevertheless helpful in understanding the scale of potential supplies and scope of research in progress. Rawat, Kumar, Mutanda, and Bux (2013) predict a broad theoretical maximum yield ranging from 47,000 to 308,000 liters of algal biofuel per hectare (ha) per year, compared to current oil palm production capacity of 5,950 liters of biodiesel per ha per year (p. 446). Current yields of approximately 13,580 to

20,370 liters, or 12 to 18 tonnes,[1] of algal biodiesel per ha per year are reported in the NRC report (2012), with conservative projections of 33,960 liters per ha per year (p. 29). Quinn et al. (2012) assert that algal biofuel production could scale to exceed the 1992 Energy Policy Act's goal of replacing 30% of U.S. transportation fuels, or 1 billion barrels, with biofuels by 2030 (p. 55). The study screened the results using land use, slope, and weather data, and assumed that photobioreactors would grow the algae, as these consume much less land area than do open ponds. The most conservative estimates modeled–selecting only barren land for instance–indicate that producing 2.56 billion barrels, or 407 billion liters (108 billion gallons), of algal biofuel would require approximately 11.5 million ha of land, or about 1.2% of total U.S. land area (p. 56). (As a point of reference, the United States consumed 507 billion liters (134 billion gallons) of gasoline and 197 billion liters (52 billion gallons) of diesel in 2012.)

One study described in the NRC report (2012) extrapolates the data for photobioreactors and, using a similar methodology to Quinn et al. (2012), comes to a comparable conclusion whereby 151.4 billion liters (40 billion gallons) of biofuel, or 19.3% of annual U.S. transportation fuel demand, could be produced on 0.45% of U.S. land area (NRC, 2012, p. 123). Likewise, Chanakya, Mahapatra, Sarada, and Abitha (2013) identify studies whereby less than 0.5% of U.S. land area could be required if algae were cultivated on wastelands and brackish water so as not to interfere with soil and water suitable for agriculture (p. 114). Georgianna and Mayfield (2012) contend that a conservative yield of algal biofuel grown in photobioreactors could conceptually replace all of the United States' consumption of petroleum transportation fuels using only 30 million ha, or 3% of total U.S. land area, an area roughly equivalent to that currently utilized in the U.S. for soya planting (p. 329).

While potentially more land-efficient, the industrial production of algae in photobioreactors is considerably more expensive than is agricultural production in open pond systems (i.e. Georgianna and Mayfield, 2012; Chanakya et al., 2013; Soratana, Harper & Landis, 2012; Menetrez, 2012; Borowitzka & Moheimani, 2013). One of the studies reviewed in the NRC report (2012) focuses on large-scale open-pond algae systems and finds, not surprisingly, that more land area would be utilized. The researchers claim that 5.5% of the land in the continental U.S. would be required to generate 220 billion liters (58 billion gallons) of algal biofuel annually, or 28% of the 784 billion liters (207 billion gallons) consumed by U.S. transportation in 2010 (ibid., p. 123). Moreover, land area is only one of many sustainability concerns. In considering the demands on water, energy, and nutrients in scaling up algal biofuels, the NRC report (2012) finds that meeting even 5% of U.S. transportation fuel requirements, equal to approximately 39 billion liters (10 billion gallons) annually, would be unsustainable with current biological and engineering technology and expertise (p. 133).

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[1] Tonnes rather than liters are used as the unit of measure in the NRC report (2012). 1 tonne of biodiesel is equal to 1132 liters (Charles & Wooders, 2012, p. 8). Meanwhile, the volumetric requirements in the federal Renewable Fuel Standard are denoted in gallons.

Water demand for the cultivation of freshwater algae in open pond systems alone varies greatly due to not only minimal data and uncertainty regarding the paths to commercialization, but also factors such as rainfall, humidity, and temperature (ibid.). The NRC report (2012) refers to studies that offer a range of 32 to 3,650 liters of water per liter of algal biofuel generated from algae cultivated in open pond systems, as compared to 1.9 to 6.6 liters of water per liter of petroleum-based gasoline from oil sands or crude oil and 5 to 2,140 liters of water per liter of corn-based ethanol (p. 103). Moreover, even if water use can be recycled in a closed system, saline, nutrient levels, or other compounds will eventually accumulate and necessitate replacement (Borowitzka & Moheimani, 2013). Brackish to saline water and wastewater can potentially serve to mitigate many of these challenges (i.e. Handler et al., 2012; Beal et al., 2012; Rawat et al., 2013; Chanakya et al., 2013). Further advances will be needed to advance the design technology, however, as most production methods at present accumulate contamination to the extent that water must ultimately be replaced (Slade & Bauen, 2013). Currently, even brackish open pond systems consume vast amounts of freshwater, comparable to that used in petroleum-based fuel generation, according to Vasudevan et al. (2012). The myriad sustainability issues associated with nutrient requirements will be discussed later in the paper.

Cost as a major barrier for all algal biofuel production systems – both in terms of upfront expenditures and overall economic viability – has yet to be overcome. A plant that consistently produces at least one million gallons of algal biofuel annually will enable a much more realistic cost projection (Menetrez, 2012, p. 7078). Algal biofuel producer Solazyme has generated the product in the thousands of gallons range, and currently the price per gallon, as sold to the U.S. Navy in 2010, averaged $67 per gallon (ibid.). Economies of scale and further innovation are obviously expected to bring this price down throughout the industry. New technology from Sandia National Laboratories and the Arizona Center for Algae Technology and Innovation, for instance, are making strides in exposing and treating algal pond crashes. These are typically caused by invading predators such as fungi, bacteria, and viruses, and greatly reduce algal biomass productivity and cost-effectiveness (Lane, 2013). More generally, coproduct manufacturing, co-locations, and resource reuse are anticipated to serve as important drivers in the reduction of costs (NRC, 2012), perhaps even propelling algal biodiesel prices as low as a very comparable $4 per gallon in the perceivable future (Menetrez, 2012, p. 7079). 23% of ABO Survey respondents predicted a price of less than $3 per gallon by 2020 while 39% were uncertain (ABO, 2013, Slide 5).

WELL-TO-WHEEL INSIGHTS

If algal biofuels are to become part of the next generation of alternative transportation fuels, they will need to be less energy and carbon intensive than conventional transportation fuels are. That claim cannot be upheld today. With current technologies and methodologies in place, algal biofuel is not presently an improvement over conventional fossil-based transportation fuels economically or as a means to mitigate climate change

(Georgianna & Mayfield, 2012). Without accounting for the environmental externalities through a quantity or price policy mechanism like a carbon tax, the price per gallon of an algal biofuel is still substantially more than that of conventional gasoline or diesel. Even more challenging, the energy return on investment of algal biofuel remains too low – a good 5 to 10 times less than that of gasoline at the pump (Beal et al., 2012, p. 693) – at the present time to make it sustainable (NRC, 2012). In other words, the energy input that a system requires to produce biofuel from algae is often more than the energy that it in return can generate.

The current technologies and methodologies for producing algal biofuel do not offer an improvement over conventional fossil-based transportation fuels economically or as a means to mitigate climate change.

Lifecycle analyses (LCAs) of the greenhouse gas (GHG) emissions emitted in the production of algal biofuels are less than encouraging as well. They tend to range significantly, depending on the study, but can be an order of magnitude greater than those from other sources. One review of twenty-four LCAs of algal biofuel produced in open raceway ponds found that the process emitted between 0.1 and 4.4 kg CO_2e/kg of algae whereas the high end of emissions given for biofuels produced by corn, soybeans, and camelina was 0.4, 0.5, and 0.3 kg CO_2e/kg, respectively (Handler et al., 2012, p.89). While only three of the twenty-four LCAs resulted in emissions of more than 1 kg CO_2e/kg of algae, the results demonstrate the potentially negative environmental impacts due to fossil energy, freshwater, and fertilizer use in algae cultivation. For instance, the LCA study that exhibited emissions of 4.4 kg CO_2e/kg of algae assumed the addition of potassium nitrate, deemed by Handler et al. (2012) as the "the worst-performing N fertilizer in all three of our chosen environmental metrics" (p. 90). This assumption, among many others, generated lifecycle emissions of more than twice those of any other study that Handler et al. analyzed.

Similarly striking, Soratana et al.'s (2012) LCA of four conditions of microalgal biodiesel cultivated in photobioreactors, encompassing high and low levels of synthetic and natural or waste resources, calculated a well-to-wheel global warming potential (GWP) of at least 8 times that of conventional diesel production (p. 509). This finding was largely substantiated in the work of Lam and Lee (2012). Admittedly, neither incorporated coproducts nor many other synergistic opportunities in their analyses. Slade and Bauen's (2013) examination of seven recent LCA studies, normalized for comparative purposes, also found a low net energy ratio (NER) for photobioreactors, particularly due to the embedded energy in their construction, while showing that open ponds may have better results. In order to improve algal biofuel's EROI, production methods will need to optimize co-locations, co-uses, and coproducts.

Algal biofuel production requires a number of intensive inputs, from water and light to nutrients to help it grow. Similarly to conventional agriculture, the nutrients involved are namely high levels of nitrogen, phosphorus, and potassium as well as CO_2 and, in some cases, sugar. Energy is also needed to power the infrastructure, cultivation, harvesting, transport, and processing of algal biofuel production. Therefore, a systems-based process that, for instance, reuses nutrients from wastewater and generates energy needed to run the plant will have a much better chance of producing an algal biofuel that can serve as a viable, climate-beneficial alternative (Slade & Bauen, 2013). For instance, Chowdhury, Viamajala, and Gerlach (2012) cite an integrated microalgal biodiesel production system in which the energy from the algal biomass not used for fuel could be recovered to help heat the biorefinery. Residuals from algal biomass could also be utilized to generate electricity, typically via anaerobic digestion (Rawat et al., 2013; Georgianna & Mayfield, 2012; NRC, 2012).[2] While no such integrations exist currently at commercial scale, the algal biofuel field does seem to be moving in this direction, albeit slowly. Lam and Lee (2012) report that up through this past year, only about 30% of the published research on microalgae cultivation described wastewater as a source of the nutrients whereas the remainder of the studies referenced chemical fertilizers as the source (p. 676).

WASTEWATER TREATMENT AND ALGAE

Algae can already be utilized in wastewater treatment (WWT) to decompose bacteria in sewage and decontaminate wastewater so that it can be returned to water bodies. According to Lundquist, Woertz, Quinn, and Benemann's assessment published in 2010 (as cited in NRC, 2012), several thousand algal pond systems of less than 10 ha and a few larger than 100 ha are currently in operation in the U.S. for municipal WWT.[3] Studies have looked at microalgae in wastewater for decades (Cai, Park & Li, 2013; Chanakya et al., 2013), and within the last few years, they have begun to show the wisdom of combining this technique with energy production (Trent, Wiley, Tozzi, McKuin & Reinsch, 2012). Some WWT plants are currently performing anaerobic digestion to process sludge into biogas and methane, which produces CO_2 that could be used to aid algal growth[4] (Beal et al., 2012; Bai et al., 2012). Another coproduct, the digested solids left from anaerobic digestion, could be used or sold for fertilizer (Beal et al., 2012).

Beal et al. (2012) investigate the full EROI potential of a coupled wastewater treatment and algal biofuels production system. The yield produced by algae cultivated in WWT is roughly equivalent to that gained in traditional open-pond systems (Beal at al., 2012). Much less

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[2] Though electricity could also be produced via cogeneration during wastewater treatment (WWT), a more limited output would be available in a combined WWT and algal biofuel system than in a WWT plant alone due to the elimination of secondary sludge available for anaerobic digestion (Beal et al., 2012).

[3] In the U.S., more than 16,000 municipal WWT plants have been constructed since the passage of the Clean Water Act in 1972. Plants can also be privately owned, and range from facilities that service small housing developments to large industrial facilities.

[4] Supplemental carbon dioxide is often used to amplify algal biomass growth rates, and can be inserted into open pond systems via the dissolution of bicarbonate in water, injection of CO_2 gas through porous PVC pipes or stones, or use of a floating CO_2 injector (NRC, 2012).

freshwater is used to cultivate the algae, even on a LCA basis, and if the electricity can be co-utilized and produced on site, the EROI rises to 1.44 (ibid., p. 702). Since WWT plants operate under a public health and environmental mission, moreover, the EROI is generally less important. It can certainly be boosted, however, when costs are reduced and energy is generated within a coupled system. In this system, nutrients and CO_2 would be provided to algae in open ponds from the WWT plant rather than from chemical fertilizers. Chemical fertilizers are costly, require substantial fossil-fuel inputs, and, in the case of phosphorus, are scarce resources (Chanakya et al. 2013; Georgianna & Mayfield, 2012).

Rawat et al. (2013) describe that approximately 6 to 8 tons of nitrates per hectare are necessitated by microalgae cultivation, which is more than 50 times that required by plant crops (p. 447) and even substantially more than other energy crops, including oil palm and jatropha, require (Lam & Lee, 2012). As such, algae cultivation would increase nitrogen and potassium manufacturing and compete for scarce phosphorus with conventional food production (Borowitzka & Moheimani, 2013). WWT effluent reuse provides an opportunity to recycle these resources, limits chances for eutrophication, and lowers the expense of WWT nutrient removal. The latter could potentially result in close to $50,000 of savings per ha per year solely in avoided nitrogen removal (Rawat et al., 2013, p. 453). While these scenarios are optimistic and large-scale attempts will be needed to judge the capital costs of integration, the effect of pathogens on algal growth in wastewater, and the impacts of other factors (Cai et al., 2013), more efficient WWT coupled with sustainable fuel production could make for a worthwhile partnership.

Cultivating algae in wastewater can achieve yields roughly equivalent to those in open-pond systems, while using much less freshwater.

WWT in general is greatly needed in developing countries such as India to handle the amount of sewage produced by the population and left untreated. Recovering agricultural nutrients while generating biofuel and treating sewage could be a highly appealing combination (Chanakya et al., 2013). Algae as a means of decontamination in this manner could be particularly helpful and efficient in nations with a dearth of clean drinking water and problems with eutrophication (Mahapatra, Chanakya, & Ramachandra, 2013). Mahapatra et al. (2013) suggest that converting sewage into algal biomass such as *Euglena sp*., with similar properties to the vegetable oil feedstock used to generate biodiesel, could function as a win-win-win, solving wastewater, eutrophication, and transportation sector challenges. Researchers caution, however, that wastewater is vulnerable to bacteria and viruses, a factor that could lead to contamination and would likely increase the costs of system cleaning and monitoring (Lam & Lee, 2012). More studies must be undertaken.

INDUSTRIAL FLUE GAS, COPRODUCTS, AND CO-CROPPING

Flue gas CO_2 from power plants and wastewater from WWT plants could together provide an even greater synergy in the cultivation of algal biofuels (Dalrymple et al., 2013). The flow chart in Figure 1 exhibits a possible illustration of this process.

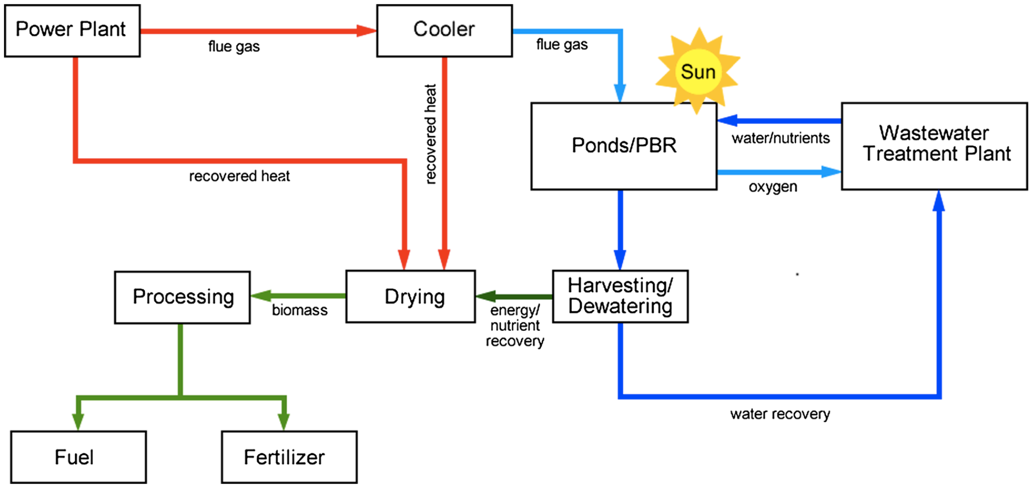

Figure 1: Flow chart depicts potential system for combined algal biofuel production with wastewater treatment (Dalrymple et al., 2013, p. 9)

Some algal biofuel research not only recommends co-location with industrial enterprises, such as coal-fired power plants or ammonia factories, in order to exploit the flue gas for CO_2, but also suggests this as a means of capturing carbon and mitigating climate change (Chanakya et al., 2013). As the algal biofuel will ultimately be combusted, the carbon will be released eventually. However, it would replace the additional carbon that would have been emitted from gasoline or diesel combustion. In addition, the reuse of the industrially emitted CO_2 reduces the cost and pollution of transporting another source of CO_2 to the algal biomass production site and could be especially appealing to a power plant constrained by a price on carbon. Even without an explicit carbon pricing policy, the capacity of algal biomass production systems to sequester CO_2 could theoretically facilitate the acceleration of carbon capture and sequestration (CCS) technology deployment by fostering a near-term market for industrial CO_2. According to Rawat et al. (2013), open pond systems located near industrial areas are potentially more proficient as CO_2 sinks than are photobioreactors, though the technology is still at an early stage.

Algal biomass production systems could sequester CO_2 and facilitate the acceleration of carbon capture and sequestration technology deployment by fostering a near-term market for industrial CO_2.

Chanakya et al. (2013) discusses the potential in India to co-locate open algal ponds on flooded paddy lands and to grow the algae in the time between harvests in a method referred to as “multi-tier, multi-cyclic cropping” (p. 132). The nutrients, land, and water are ideally recycled among the different crops. This operation could preserve land and money, offer additional income to farmers, and mitigate GHG emissions (Chanakya et al., 2013). The illustrative diagram in Figure 2 depicts how both biodiesel and biogas could be produced in an optimal system.

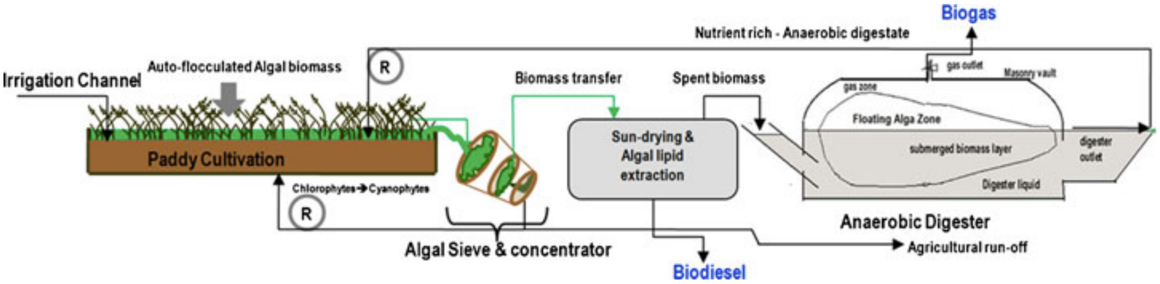

Figure 2: Schematic diagram of potential biogas and biodiesel production from algae cultivation in flooded paddies (Chanakya et al., 2013, p.129).

Even more land would be avoided by cultivating algae in floating photobioreactors offshore that utilize wastewater, as in the two-year OMEGA feasibility study funded by NASA[5] and the California Energy Commission (Trent et al., 2012). As OMEGA stands for offshore membrane enclosures for growing algae, these enclosures are envisioned as a means of exploiting the space in coastal saltwater bays already used for wastewater discharge and in close proximity to flue gas release in order to grow freshwater algae that treats the wastewater and produces fuel. In addition to saving space onshore, the algae would be saline intolerant, so little danger for escape or cross-contamination would exist.

Back on land, Mitra, van Leeuwen, and Lamsal (2012) highlight some of the limits of coupled production for biofuel. The use of agricultural co-products, such as corn thin stillage and soy whey, can be used to create strong conditions for growing algae while also providing an outlet for agro waste. The potential to produce high-value nutraceuticals such as omega 3 and 6 fatty acids, animal feed, and proteins from the algal biomass grown using agro-industrial co-product streams, however, may outweigh the value possible from biofuel production at the present time (ibid.). Studies examining methods to exploit agricultural waste, including pig and poultry manure and dairy dirty water (Fenton & Ó hUallacháin, 2012), for algal biofuel production are more promising. Bai et al. (2012) demonstrate that filtered pig sludge can produce a high yield of *C. vulgaris* algae biomass growth, a strain that could be advantageous for biofuel production.

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[5] NASA scientists received inspiration for OMEGA from the closed life support systems employed on the International Space Station. They applied how that technology maximizes resources and minimizes waste to innovate OMEGA as a means of converting waste into a valuable product in a closed system. The reported goals have been to reduce risk for the private sector in undertaking this type of system on a large scale and to demonstrate the floating system’s viability for treating wastewater while generating sustainable aviation biofuel (NASA, 2012).

MARINE MICRO AND MACROALGAE DEVELOPMENTS

The freshwater requirements of non-marine algae are so intensive in a freshwater-constrained world that some researchers are coming to the environmental and economic conclusion that freshwater algal biofuel development may simply be unsustainable (NRC, 2012; Borowitzka & Moheimani, 2013; Kraan, 2013). The terrestrial areas most suitable to algae cultivation are those with significant sunlight, warm temperatures, and relatively flat slopes (Quinn et al. 2012), which tend to be located in geographic regions that lack substantial freshwater resources and water recharge capabilities (NRC, 2012). Not surprisingly, the benefits of marine algae are beginning to gain more notice. Some research findings highlight that open ocean marine algae cultivation is not dependent on freshwater and could avoid both land use and fertilizer due to the nitrates and phosphates that are inherently tossed about in seawater currents (Kraan, 2013). However, the NRC report (2012) posited that the freshwater constraints of algal biofuel production could curb the future potential of the entire field since the feasibility of engineered marine algae had yet to be substantiated in a published research study (NRC, 2012). Laboratory results from Georgianna et al. (2013) that support the realistic conversion of marine algae into biofuel may offer the substantiation heretofore absent.

While some researchers doubt that freshwater algal biofuels can be produced in an economically and environmental sustainable manner, marine algae offers more commercial promise—particularly if molecular engineering can transform marine species into viable biofuel production strains.

By successfully transforming the chloroplasts of the marine microalgae, *Dunaliella tertiolecta*, via molecular engineering techniques, Georgianna et al. (2013) demonstrate the achievability of recombinant protein production in marine algae. They assert that molecular engineering will be key in transforming marine algae species into viable biofuel production strains. *D. tertiolecta* is viewed as a strong candidate for biofuel production since it has been used in wastewater remediation, has a relatively high lipid content, and can sustain relatively high growth rates in environments with varying salinity and acidity (ibid.). In the study, Georgianna et al. (2013) produced five recombinant enzymes that could both support biofuel production and generate and enrich valuable coproducts, particularly animal feed additives, to make the economics of algal biofuels more readily approachable. The strategy is conceivably applicable to many other marine algae species as well, creating a plausible pathway to a broader algal biofuel supply chain.

As large-scale seaweed farming currently occurs throughout Asia for food, cosmetics, industrial additives, and other uses, macroalgae cultivation is well understood and could supply a piece of the biofuel puzzle going forward as well (Kraan, 2013; Ruiz, Rodríguez-

Jasso, Fernandes, Vicente & Teixeira, 2013; Cai et al., 2013). Cai et al. (2013) suggest that the modern farming methods already in existence for macroalgae make the harvesting step of the process easier and less expensive, an important point as algae harvesting is typically very energy intensive. The absence of lignins in macroalgae facilitates processing as well (Kraan, 2013). As macroalgae additionally lack lipids, however, little potential exists to convert it into traditional biodiesel, likely restricting biofuel production to ethanol or biogas routes (Cai et al., 2013). Due to the relatively high water content of seaweed, microbial conversion appears to be a better production pathway than either thermochemical conversion or direct combustion (Kraan, 2013). Hydrothermal treatment to generate bio-crude oil (Ruiz et al., 2013) or decarboxylation/hydrogenation reactions to produce green diesel (Borowitzka & Moheimani, 2013) are also possibilities.

Kraan (2013) highlights the advantages of brown algae, also known as kelp, which is comprised of more than 50% carbohydrates and farmed in very large quantities in Asia. Kelp could not only mitigate excess nutrients in run-off and wastewater releases, but could also help to protect fishery resources in coastal areas. SINTEF Norway and other public and private endeavors are presently exploring the potential for macroalgae-to-biofuel conversion on a large scale (Kraan, 2013). On a smaller scale, coccolithophorid algae are also being examined as an interesting alternative to the standard marine microalgae species. Coccolithophorid algae fix carbon via photosynthesis into $CaCO_3$ plates, potentially enabling the carbon to be buried and thus sequestered relatively easily (Moheimani et al., 2012).

ENVIRONMENTAL IMPACTS

Water, land, energy, GHG emissions, and fertilizer issues have been referenced throughout this paper, and are challenges that have not yet been addressed suitably for large-scale commercialization of algal biofuel development. While ideas proffered in this text and beyond suggest routes to address the challenges in part, additional impacts currently in practice or forecasted are also concerning. Cross-contamination from algae cultivated in open ponds, a common and relatively economical cultivation method, is one such concern. At this time, no genetically modified (GM) algae have been approved for cultivation in open air ponds, while federal regulations do not currently cover those developed in enclosed systems, such as photobioreactors (Henley et al., 2012).

Researchers seem to accept that algae in open pond systems – and even those in enclosed systems – will almost certainly escape into the larger environment, even with strict regulations in place (Henley et al., 2012; Handler et al., 2012; Slade & Bauen, 2013). The subsequent impacts are unknown, though competition would likely benefit wild algae over their domesticated or genetically modified counterparts (Henley et al., 2012). Wild algae, for instance, have evolved light harvesting antennae larger than is efficient in order to shade out competitors (Perrine, Negi & Sayre, 2012). Consequently, photosynthetic losses are high. Perrine et al. (2012) demonstrate in the lab that, while wild algae can lose up to

75% of the energy they absorb to heat or fluorescence, green algae with transgenically-modified antennae size can double photosynthetic efficiency and enhance the organism's growth by 30%. This study may have important implications for algal biofuel production, while also highlighting one competitive disadvantage of modified algae for biofuel when compared to those in the wild.

Ecosystems could still be affected, however, to a greater or lesser extent than they currently are when exposed to algal blooms and eutrophication. These pose dangers to society, including the risk of contact with toxins that can lead to endocrine disruption and liver failure in humans (Menetrez, 2012). Conversely, little research has been conducted on the threats to farmed algae from pathogens like bacteria and viruses (Georgianna & Mayfield, 2012). Researchers further caution that algae are capable of horizontal gene transfer[6] with other algae as well as occasionally with beings higher up the chain, such as phytoplankton (Henley et al., 2012) and sea slugs (Snow & Smith, 2012). The potential for horizontal gene transfer complicates the process of modifying existing algal species.

According to Henley et al. (2012), the US Environmental Protection Agency and US Department of Agriculture are in the process of determining whether the alteration of "an existing functional gene" or "an existing regulatory sequence" in the cultivation of eukaryotic algal biofuels should be regulated and, if so, how (p. 71). These agencies already regulate transgenic GM in which a gene or regulatory sequence from one organism is inserted into a different one (Henley et al., 2012). Monsanto, one of the largest agricultural companies in the world and an entity most known for breeding high-yield crops, is partnering with Sapphire Energy to facilitate the latter's attempt to commercialize algal biofuel (Snow & Smith, 2012). Though higher profile than most, Monsanto's collaboration is just one of many such efforts underway. Yet, the current system of GM agriculture and the associated regulatory structure in the United States is far from uncontroversial. Menetrez (2012) further cautions that GM organisms have the potential to infiltrate drinking water supplies, as more frequent or intense algal blooms would mean increased opportunities for the toxins they generate to pass into drinking water resources. The impacts on those who might ingest the toxins remain relatively unknown (ibid.).

There is a growing sense among researchers that ecologists should become more involved in the development, regulation, and monitoring of algal biofuel.

Many researchers call for ecologists to become more involved in the development, regulation, and monitoring of algal biofuel, whether it

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[6] Horizontal gene transfer (HGT) is the exchange of genes from one organism to another, excluding traditional reproduction. The risk from genetically modified (GM) algae to wild species involves the HGT of a modified or selected trait from released GM algae to another organism. HGT to a wild alga could provide it a competitive advantage over other algae in its habitat, impacting ecosystem function, or could release toxins that endanger plant, animal, or human health (Henley et al., 2013).

encompasses simple scale-up or substantial genetic modification. Henley et al. (2012) call for GM that is “ecologically-minded” as guided by the Ecological Society of America (p. 74). The Society urges “sterility, reduced fitness, inducible rather than constitutive gene expression, and the absence of undesirable selectable markers” (as cited in Henley et al., 2012, p. 74). Handler et al. (2012) advise that ecologists and others gain basic access to more of the information involved in studies, as much of this is currently protected as proprietary or confidential. Dana, Kuiken, Rejeski, and Snow (2012) recommend an eco-risk research agenda and are crafting one in conjunction with the Synthetic Biology Project at the Woodrow Wilson International Center for Scholars. Ecological and biological expertise could prove very useful in the sustainable development of this field.

CONCLUDING THOUGHTS

It is clear that, while many opportunities exist for algal biofuel to evolve into a sustainable replacement for petroleum-based transportation fuels, the field is not there yet and many ecological, environmental, economic, and technical questions remain. Innovation has the potential to provide some of these answers. The Algae Research Laboratory and Microbial Environmental and Chemical Engineering Laboratory (MECEL) at the Masdar Institute in the United Arab Emirates (UAE), for instance, has been researching the UAE’s unique desert algae that can endure both widely varying temperatures and high salinity (Masdar Institute, 2013). In collaboration with the Massachusetts Institute of Technology, Masdar has committed to cultivating algae that requires little-to-no freshwater or arable land for aviation biofuels. Many miles away in Brazil (Wald, 2012), SEE Algae Technology is constructing a biofuels plant adjacent to a sugar refinery in order to utilize the CO_2 from the sugar cane waste that is burned for electricity, and in Scotland, a new European Union (EU) research consortium named AccliPhot has been established to cultivate marine algae in photobioreactors (Casey, 2013).

These ventures are emblematic of the innovative strategies evolving to address many of the remaining challenges that will be necessary to overcome. As the industry continues to progress more toward sustainably integrated co-locations, coproduct generation, and resource re-use, the potential of algal biofuels grows more tangible. Until the EROIs, LCAs, and eco risks are balanced, however, large-scale commercialization awaits.

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