10. Macroalgae for Higher Value Products and Liquid Fuels

10.1. MACROALGAE POTENTIAL

With the world's oceans covering over 70% of the planet's surface and the need to develop more sustainable routes to fuels and chemicals increasing, it is anticipated that over the medium- to long-term ocean-grown biomass, especially macroalgae or seaweeds exhibiting areal growth productivities exceeding terrestrial crops (see **Chapter 9**), will become an ever larger contributor of renewable feedstock for the bio-based products industry. In 2014, 27.3 million tons wet weight of seaweed was produced globally[403] for use mainly in production of hydrocolloids, food and feed.[404] There is limited use of seaweeds for energy production; whole seaweed is generally not considered viable for producing energy alone due to its high feedstock price, but using seaweed processing side streams or by-products to produce energy or fuel coproducts in seaweed-based biorefineries may become viable in the future. Co-production of bioenergy products is seen as an interesting option for obtaining value from side-streams that don't have higher value uses. However, there are only a few stakeholders considering bioenergy products beyond biogas at this point. The main reason is the relatively high price of seaweed and the need to produce higher value products than energy from the seaweed biomass for production to be economically viable.

For liquid biofuels in particular, macroalgae is a biomass feedstock with great production potential but also considerable obstacles to being used, the main obstacle being its relatively high price for cultivation and conversion.[405] Currently the biorefinery concept, where smaller amounts of multiple higher value products are produced together with a few larger volume lower value bulk products like liquid biofuels, is seen as the way forward.[406–409] Depending on the streams available at a future biorefinery there are mainly two routes for energy production: biological conversion and hydrothermal processing. Thermochemical conversion by pyrolysis or gasification of macroalgae into biofuels is not energy efficient because of the high water content of the algal biomass.[410] At the time of report preparation, energy and chemicals via sugar routes remain the most researched and understood, although these routes are still not straightforward. However, hydrothermal processing, an area of active research that shows promise for algae feedstocks (see **Chapter 5**), may ultimately prove to be a better fit for macroalgae feedstocks than biological conversion. During biological processing, either the carbohydrate macromolecules of a high-carbohydrate containing seaweed species (such as *Saccharina latissima*) are broken down to sugar monomers and fermented to ethanol, butanol or other sugar-fermentation products similarly to land-based biomass processing, or the seaweed is digested anaerobically to produce biogas that can be used as is or upgraded to pipeline quality methane (see **Chapter 9**).

The many identified macroalgae projects described below are mostly focusing on improving cultivation efficiency and economics, not specifically on production of bioenergy, e.g., liquid or gaseous biofuels. Biofuel production processes from macroalgae are more or less similar to the routes used for terrestrial biomass feedstocks. The main concerns for the viability of the value chain are the feedstock production scale and price.

In addition to the current uses of whole seaweeds as foods and feeds and of macroalgal polysaccharides as hydrocolloids, macroalgae also contain a variety of compounds possessing a wide range of bioactive properties, such as anti-tumor, antiviral, anticoagulant, mucus protecting, LDL cholesterol reducing, prebiotic, anti-inflammatory and anti-hypertension effects.[411] One example is the sulphated polysaccharide fucoidan in brown seaweed, which has been extensively studied with respect to its potential pharmacological properties.[411] Industry based on marketing of extracted bioactives or other high market value compounds represents a new bio-economy opportunity. However, while bioactive compounds can command a high market price, they represent a relatively small percentage of seaweeds dry weight. In such cases, residues from seaweed processing will constitute the major part of the seaweed biomass and are expected to be available for production of additional products, potentially including bioenergy products like biofuels. An on-going challenge to achieve such coproduction of higher value speciality products and lower value bioenergy products remains the disparity in scales of markets and production volumes between speciality chemicals/bio-actives and commodity biofuels.

The majority of published literature, studies and projects on macroalgal cultivation and conversion available to the authors is coming out of Europe, especially from the countries in northern Europe and Scandinavia. Due to the great interest in the potential for algal biofuels and the increasing importance of cultivated macroalgae in certain regions of Europe, especially in northern Europe, there have been numerous projects financed at both European and national levels. As such, the balance of this chapter focuses on recent developments in Northern Europe, summarizing major projects and companies actively researching or commercializing seaweed biomass. The majority of projects are not focused on applications but rather simply on lowering the cost and improving macroalgae cultivation efficiency, rate, yield and biomass quality.

Due to the fact that seaweed cultivation is labor intensive, with mechanized and automated cultivation technologies still at the development phase, most of the seaweed currently being used in Europe is wild harvest.[404] The number of sites with dedicated seaweed cultivation is growing rapidly, although the total amount being produced is still quite small, at maximum a few hundred tons wet weight per year. Even though seaweed cultivation is becoming a large-scale business, in general the feedstock remains too pricey to be used solely for energy production. Examples of natural and cultivated seaweed farming are shown in **Figure 10-1**.

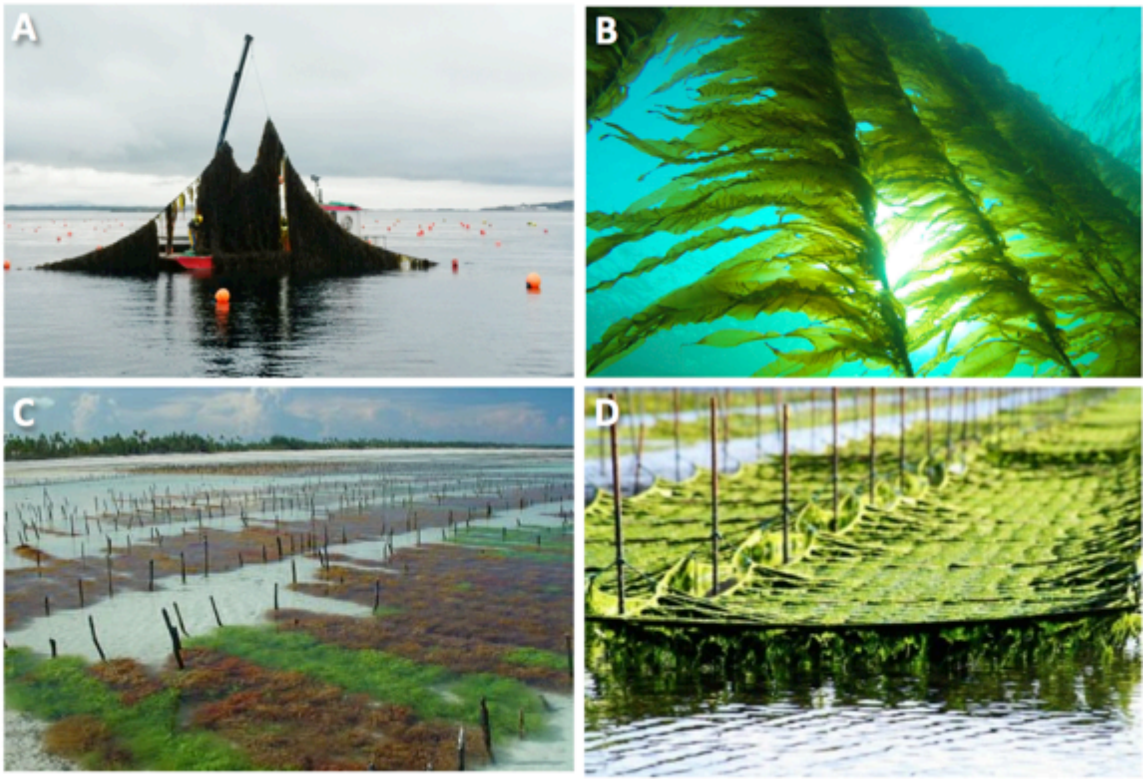

Figure 10-1: Seaweed farming (A-B) Cultivated seaweed harvesting by Seaweed Energy Solutions (SES), Norway (Photo: Judit Sandquist (A) and SES[412] (C) Seaweed farming in Zanzibar[413] (D) Nori farming in Japan[414]

New cultivation technologies for seaweed feedstocks are being developed in R&D-projects in

Scotland, Ireland, Norway, Denmark, Sweden, Faroe Island, the Netherlands, Spain and Portugal, aiming to improve macroalgal growth productivity and biomass quality, enhance the predictability and increase the degree of mechanization and automation, thereby lowering cultivation cost. Large sea areas are available for aquatic biomass production without the conflicts that characterize corresponding terrestrial biomass production (e.g., arable land, fresh water, fertilizers, pesticides, GMO, etc.). One driver of increasing importance in the Nordic region is Integrated Multitrophic Acquaculture (IMTA), in which seaweeds are used to alleviate the dissolved effluents from fish farms.[388] This development is expected to increase the availability of seaweed and conversely lower its price.

10.2. MAJOR EUROPEAN PROJECTS

The AT~SEA project, advanced textiles for open sea biomass cultivation, was an EU 7th framework research project started in 2012 and ended in July 2015.[415] This project targeted the development of advanced, 2D seaweed cultivation substrates in order to demonstrate the technical and economic feasibility of seaweed cultivation in Europe. The project homepage states that the project identified suitable textiles for open sea seaweed biomass cultivation. Furthermore, project members founded a start up company (AT~SEA Technologies) to help commercialize the project's developed technologies. Seaweed cultivation is the focus in this project. Applications for seaweed biomass are not addressed.

MERMAID was an EU 7th framework project started in 2012 and ended in 2015.[416] This project targeted the integration of seaweed cultivation sites with offshore energy production, such as wind and wave energy production. Seaweed application was not targeted specifically, but co-produced seaweed biomass was assumed to be a marketable product in the business cases.

EnAlgae (Energetic Algae, http://www.enalgae.eu/) was a collaboration project within the INTERREG IVB North West Europe (NWE) Programme carried out March 2011 to June 2015 focused mostly on the following:

- micro- and macroalgae production in European pilot facilities, demonstration of strain management and common data management.
- Identification of opportunities within political, economic, and technology sectors to promote the adoption of algal biomass for the European energy market
- development of new tools to support decision- and policy makers as well as investors.[417]

Its overall objective was to develop algal-based technologies to reduce net CO_2 emissions and dependency on unsustainable energy sources in North West Europe. Sustainable technologies for algal biomass production, bioenergy production and greenhouse gas (GHG) mitigation were developed in the project and taken from pilot facilities through to market-place products and services.

MacroFuels (http://www.macrofuels.eu/) is a newly started project in the EU Horizon2020 framework that aims to produce advanced biofuels from macroalgae. The targeted liquid and gaseous biofuels are ethanol, butanol, furanics and biogas.[418] The conversion routes applied will be enzymatic hydrolysis with subsequent fermentation to ethanol, anaerobic digestion to biogas and thermochemical conversion to furanics. The project participants have started to grow seaweed but no results are available yet.

10.3. NATIONAL COMPANIES AND PROJECTS

Denmark

MacroAlgaeBiorefinery - MAB3 was a four-year project focused on assessing the potential for macroalgal biorefineries to produce food, feed and fuel products.[419] The project vision was to ferment the carbohydrates to ethanol and use the protein rich residues as feed.

The subsequent MAB4 project also focuses on macroalgae-based biorefineries. This project includes activities on seaweed cultivation and chemical extraction of products from seaweed. The chemicals of interest are food, feed and cosmetics ingredients.[420]

DTU and Steeper Energy have been working on HTL conversion of algae, both microalgae and macroalgae, and have found this conversion method promising for both alga types.[421]

The Netherlands

Hortimare is a Netherlands-based company that operates in Norway and the Netherlands. They offer "Seaweed Genetics and Hatchery" where seaweed juveniles, bred for high contents and yields of marine proteins, mannitol, alginate and bio-active ingredients, are developed and sold to seaweed farmers. Hortimare also offers an "Integrated Aquaculture Service" supplying services to seaweed cultivation in the direct proximity of salmon farms. These seaweeds absorb significant amounts of the valuable nutrients released from aquaculture farms and are typically rich in proteins, mannitol and other ingredients, and according to Hortimare this type of integrated aquaculture also helps salmon farmers in maintaining and restoring marine ecosystems by improving bio-diversity and combatting sea lice.

In Hortimare's "Seaweed Bio-Refinery Plant," cultivated macroalgae is processed and refined into high quality protein for feed and food applications, feed for salmon being one of them. Other products are higher priced compounds for the global chemical-, pharma- and nutraceutical markets. There are probably side-streams from seaweed processing that can be utilized for fuel or energy production, although the issue of disparity in scales between higher value and commodity bioenergy products still needs to be overcome.

The Dutch Seaweed Biorefinery Program was a four-year project that ran between September 2009 and August 2013.[422] This project aimed to assess the concept of large-scale biorefinering of seaweeds to produce CO_2 neutral chemicals, third generation biofuels and bio-energy. The project investigated several seaweed types as well as conversion and application strategies in a cascading biorefinery concept. The authors concluded that technical feasibility was demonstrated, however, several challenges remain before such seaweed-based biorefineries will be economically viable.[423]

North-sea-weed-chain: This one-year project assessed two business cases with two seaweed species, *Saccharina latissima* for winter cultivation and *Ulva sp*. for summer cultivation. Among the products, sugars from the sugar kelp were identified as potential biofuel intermediates, but the project concluded that since seaweed will be an expensive feedstock, the highest possible value needs to be obtained from the products extracted from the marine feedstock.[424]

Norway

Seaweed Energy Solutions AS (SES) focuses on large-scale cultivation of seaweed primarily for feed and food purposes, but energy production from fractions and residuals is also part of the scope. SES operates Europe's probably largest seaweed farm in Mid-Norway with access to 70 hectare for cultivation of different seaweed species like the large biomass producing kelps sugar kelp *Saccharina latissima* and winged kelp *Alaria esculenta*. From their 300x300 m large pilot, SES produced 100 tons sugar kelp in 2015.[425] SES participates in various research projects focussed on finding innovative uses for cultivated seaweed and seaweed processing residues. Previously, in 2011-13, SES ran several projects with financial support from the Research Council of Norway (SeaBreed, SeaweedTech) and Eurostars (SeaweedStar), all focusing on macroalgae cultivation and conversion of macroalgal biomass to bioethanol.

There are several smaller Norwegian companies that produce seaweed-based food and feed products, e.g., Austevoll Seaweed Farm, Seaweed AS and Algea.[425] More recently established companies like Ocean Forest, Folla Alger, Frøya Tare and Alginor also aim to cultivate or process seaweed.[425] All of these companies have so far no waste streams that can be used for energy production but their knowledge can contribute to developing and improving commercial seaweed cultivation and processing, and some of them will probably be important participants in the rapidly growing seaweed industry in Europe.

SINTEF Fisheries and Aquaculture also conducts research to develop industrial scale macroalgae cultivation technology, as well as on integrated multi-trophic aquaculture (IMTA).[426] Of note, SINTEF also has a 4 year Priority Project to develop technology for the production of biofuels and chemicals from seaweed.[427]

Of on-going seaweed projects, the following three, all financed by The Research Council of Norway, are the largest ones: 1) PROMAC aims to develop energy efficient processing of cultivated macroalgae for use in food and feed-products;[428] 2) MACROSEA seeks to establish a knowledge platform for industrial macroalgae cultivation, focusing on understanding and overcoming biological, ecological and technological challenges[429] and 3) MARPOL is to apply enzyme technology to develop innovative biomaterials by modify and upgrading of macroalgae polysaccharides.[430]

Others

FMC Health and Nutrition, a producer of functional ingredients for foods and dry-tablet medications, harvests wild seaweed for alginate and other polysaccharides production. In their processing operations there are waste streams not being productively used today, which could potentially be used for additional bioproducts or bioenergy production.

France's Center of Studies and Valorization of Algae (CEVA) is well known for their competence on cultivation and processing of algal biomass into high value products.

Ireland's MaREI Centre at University College Cork performs significant research on biogas and biohydrogen production from seaweed.

There are several other universities and research institutions in Europe, which have research groups actively researching seaweed-based production. These include: Energy Research Centre of the Netherlands (ECN); Scottish Association for Marine Sciences (SAMS); National University of Ireland, Galway; Irish Seaweed Center, Harper-Adams University; Teagasc (Agricultural Technological Institute in Ireland); Queen's University, Belfast; Aarhus University; Danish Technological Institute; Technical University of Denmark (DTU); Chalmers University; Gøteborg Universitet; Linné Universitet; Scandinavian Biogas; and the University of Linköping.

Several of these institutions were partners in the recently completed EnAlgae project (INTERREG 2011-2015), which brought together 19 partners and 14 observers from across seven EU member states described previously.[417]

Another large on-going research project on bioenergy production from cultivated macroalgae is Sweden's SEAFARM, which is focused on developing techniques for cultivating seaweeds to be used as raw materials for future seaweed-based biorefineries producing food, feed, bio-based materials and bioenergy products.[431]

11. Conclusions and Recommendations

This report provides an overview of the state of technology of algae, both micro- and macroalgae, as feedstocks for bioenergy applications. Their photosynthetic efficiency far outpaces terrestrial feedstocks and it is generally accepted that there is a tremendous opportunity to exploit algae for bioenergy applications because of their high yielding biomass potential and favorable process energetics. However, there remain substantial technical, economical and sustainability barriers in place that slow down the successful commercial deployment of algae-based technologies for bioenergy applications. These barriers are discussed throughout the report and can be categorized as follows: 1) Biomass productivity needs to be optimized with respect to energy, water and nutrient balance, to ensure a sustainable overall value chain; 2) 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 algal biomass as a function of cultivation and production practices needs to be understood and integrated with the algae process operations; 4) Co-located inoculation, cultivation, primary harvest, concentration, and preprocessing systems need to be developed to aid economical viability; 5) Technologies for efficient on-site processing or fractionation of algal biomass into lipids, carbohydrates, and/or proteins needs to be developed at scales compatible with large-scale cultivation and farming; 6) Development and implementation of methods to maximize recycle of nitrogen and phosphorus compounds and other essential nutrients from residual materials need to be promoted to minimize fresh fertilizer and other nutritional input requirements.

Since the 2010 report was published, the economic and policy challenges have become more pronounced despite tremendous advances in understanding and manipulating algae biology, larger scale cultivation demonstration, and valorizing algal feedstocks for a variety of higher value product applications. In essence, it is understood that *high uncertainty still exists in how soon algae-based routes can become cost competitive for bioenergy, and how big algae for bioenergy ultimately can be*. This uncertainty stems from and extended period of low fossil fuel prices (in particular in comparison to 2010-2014), coupled with an on-going lack of clarity regarding future policy on carbon pricing. The cost targets for competitiveness in the market have become significantly more difficult to reach, despite the substantial improvements being achieved in the underlying core algal cultivation and upgrading technologies. As a consequence, companies that were leading commercial development of algae-based biofuels are increasingly redirecting their commercial focus towards production of higher value food, feed and specialty products. This report's comprehensive review of international commercial and research algae installations illustrates this shift in market focus.

Beside the economic challenges, there are additional concerns around the sustainability of large, commodity-scale algae cultivation. There could be unsustainable demands on nutrients if algae were grown at a level sufficient to replace 5% of U.S. transportation fuels. The nutrients available in wastewater (e.g., municipal or cellulosic biorefinery-derived) provide an opportunity to mitigate the cost of meeting the nutrient demand for algal growth while still allowing for the production of high quality algal biomass. Alternatively, the different bioenergy conversion options, e.g. lipid extraction, fractionation or biogas production processes, allow for different levels of nutrient recycling that will partially reduce an overall cultivation facility's net nutrient demand. The wide ranges of reported economic cost projections and algae process life cycle assessments illustrate the high level of complexity and uncertainty still facing the nascent algae production and refining industry.

This report provides a comprehensive overview of the recent progress in the fields of biotechnology for strain improvement of microalgae. In particular, the ability to manipulate the cell's biochemistry independent of the growth mechanism has been and remains one of the major challenges in algal (and other) strain improvement. Increasing the algal cell lipid content typically negatively affects growth rate and biomass productivity. With the advent of genomic information becoming readily availability and substantial advances in metabolic engineering over the past 5 years, tremendous improvements have been made in reconfiguring metabolic networks without impacting growth rates. Manipulation of the cell's metabolism upstream of lipid synthesis, e.g., by increasing the availability of pyruvate for production of acetyl-CoA as a substrate for the initial steps in lipid biosynthesis, has increased cellular lipid content without impacting growth rate. Similarly, improvements in photosynthetic efficiency to achieve actual efficiencies closer to the theoretically possible 8-12% have been carried out in model organisms. An increased rate of photosynthesis was observed after reducing the size of the light-harvesting complex, with a simultaneous reduction in respiration. This is an area that should continue to be investigated in future research. Translating learnings and advances demonstrated in model organisms to large-scale-relevant species should also become a future research priority. There is a highly dynamic relationship between algal oil content and algal biomass growth productivity, which depends on the integration of species and the physiological conditions it is exposed to. There are opportunities to improve the productivity of algae through minimizing losses occurring during photosynthesis while avoiding impairing algal cells' robustness for outdoor deployment. This overall issue represents both one of the greatest technical opportunities and challenges to advancing microalgae-for-bioenergy deployment, and should be a major emphasis area for future research.

Numerous new promising conversion approaches have been developed, at least to a preliminary level, since the 2010 report was published. Of these approaches, two have gained traction as distinct pathways to pursue for the production of algae-derived fuel and products. These pathways can be categorized in broad terms as: 1) pretreatment of algal biomass in the presence or absence of acid to fractionate whole algae cell biomass into lipid, carbohydrate and protein fractions; and 2) processing whole cell algae under high temperature and pressure conditions to an upgradable biocrude liquid using hydrothermal liquefaction (HTL). Both pathways include a route to fuel while at the same time allowing for nutrient recycling and thus gain ground in the area of achieving more sustainable operations. While the core technologies are very different, both pathways are being pursued in parallel as a means to increase biofuel yield from algae. The first, the fractionation pathway, thanks to its less destructive nature (compared with HTL), can be integrated with multiple routes to co-products to maximize the valorization of the algal biomass. As long as the on-gong challenge of achieving cost-competitive production of bioenergy products in the current low energy market price environment persists, greater industrial research emphasis is likely to be placed on identifying and developing new higher value co-products.

In terms of macroalgae (seaweeds), conversion to biogas using anaerobic digestion (AD) technologies is among the most investigated approaches, with many research studies on use of macroalgae as a renewable feedstock reported since the 2010 report was published. The promise of a macroalgal biomass to biogas approach for algal bioenergy production is that lower cost cast seaweed could be used and AD-derived biogas could be used directly or upgraded to pipeline quality methane for injection into the existing gas grid to bolster gaseous fuel supply. Such conversion and bioenergy generation is not necessarily dependent on a continuous supply of macroalgae feedstock, as at least in some locations it will also be possible to feed (or co-feed) terrestrially-sourced biomass to supplement intermittent supplies of cast seaweed. A mixed feedstock approach like this could also improve economic viability. Feedstock flexibility coupled with the ability to integrate with existing gaseous fueling infrastructure makes an AD-based bioenergy route attractive for further study and development. However, AD-based approaches for macroalgae are not yet fully proven and may be problematic in the longer term due to issues such as high salinity and accumulation of sand in the reactors. It is also unlikely that cast seaweed can be harvested at a scale sufficient to provide significant quantities of transport fuel or on a consistent enough basis to meet the continuous supply needs for a biofuel-focused biorefinery. The more likely scenarios are co-feeding of land-based biomass as well as new large scale 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 would be best suited for such a bioenergy application. Numerous parameters, including species, method of cultivation, harvest method, suitability of various feedstock storage methods, cost of the harvested seaweed, cost of the produced biofuel, etc., have not yet been adequately assessed and much additional research is required.

At least for the foreseeable future, primary strategies for liquid biofuels production from algae will need to rely on producing products from algae that will command a higher market value than liquid fuels. Alternatively, approaches that can valorize integration of algal production with wastewater treatment or carbon capture from high CO_2 emitters such as power plants or cement plants may aid the economical viability of algal biofuels production. In all cases, the production of algae for biomass and bioenergy applications will need to be integrated with existing markets and demand trends for products and fuels and will be guided by the quality and cost of the algal biomass.

For the algae bioenergy field to move forward and commercial operations to be able to begin to deploy at scale cost-competitive technologies for fuel-production from algae in the future, both improved policy support and well coordinated long-term and preferably highly international RD&D programs are needed. Despite wide-spread criticisms about the considerable demands that large scale cultivation of algae for bioenergy will place on nutrient, energy and water availability, these issues can be overcome with a long-term commitment to R&D and a focus on overcoming the major barriers that are limiting the realization of algae-based systems. In addition to meeting the economic targets mentioned above, it is imperative that algal-based processes meet sustainability goals, including having an overall positive return on expended energy, accompanied ultimately by a reduction in greenhouse gas emissions for the production of fuels or products. Furthermore, to support process and operation sustainability, there is a need to maximize the recycle of nitrogen, phosphorus, carbon and other nutrients from residual materials remaining after preprocessing and/or residual processing to minimize fresh fertilizer input requirements in upstream cultivation and reduce the demand on ever more constrained global nutrient resources.

As a final note, there have been challenges during the writing of this report in comparing the technical, economic and sustainability metrics across different technologies, as well as results being reported on similar systems by different laboratories, both nationally and internationally. This situation reflects the current lack of a transparent framework for describing and reporting on algal research and algae processing operations. In light of this, we want to close by emphasizing that there is a clear and urgent need for more open data sharing and harmonization of analytical approaches, spanning the full range of issues being investigated, from cultivation and processing of algae, to product isolation and marketing, to TEA and LCA modelling methodologies. A harmonization of methodologies in the international algal bioenergy community is imperative to increase the efficiency and pace of progress in the high priority areas of research needed to advance development and deployment of more sustainable algae-based bioenergy production.

Appendix A: Overview of Input Metrics for Describing Algae Bioenergy Operations

Table A-1: Overview of suggested harmonized inputs in measurements used for reporting on algae operations, compiled from tables in ABO's Industrial Algae Measurements document (IAM 7.0, http://algaebiomass.org/resource-center/technical-standards/IAM7.pdf) and Batan et al [112]

Metric	Unit	Notes
1. Cultivation: Continuous data - weather		
Precipitation	cm day^{-1}	Precipitation data (as available from weather events)
Air temperature	°C	Minimum hourly basis
Dew point temperature	°C	Hourly basis
Solar radiation/insolation	W m^{-2}	Hourly basis
Wind speed	m s^{-1}	Hourly basis
Air pressure	mm Hg	Hourly basis
2. Cultivation: Continuous data – culture		
Water salinity	mg L^{-1}	
Water pH	pH	
Water temperature	°C	
Dissolved oxygen	mg L^{-1}	
Oxidation reductive potential	mV	
Photosynthetically active radiation (PAR)	µmol m^{-2} sec	Hourly basis
3. Cultivation: Installation/logistics		
Land use/cost		Upon installation
Polyethylene consumption	m^3 ha^{-1}	
Scale of production (pond/cultivation size)	ha	
Days of operation		Steady state/dynamic/culture crash ratio
Diesel Fuel Consumption	L ha^{-1}	[112]
Polyethylene consumption	m^3 ha^{-1}	
Natural Gas Consumption	MJ ha^{-1}	
Electricity Consumption	kWa ha^{-1}	
Photosynthetic Area per Facility Area	ha ha^{-1}	
Transportation Costs	L kg^{-1} biofuel	
4. Cultivation: Discrete data – culture		
Pond depth	cm day^{-1}	Daily basis
Make-up water (evaporation)	L	Volume of make-up water added to the pond (if applicable)
Make-up water (after harvest)	L	Volume of water added back after harvest (if applicable)
Nutrients – nitrogen	mg N L^{-1}	Daily basis, measured as ppm N
Nutrients – phosphorus	mg P L^{-1}	Daily basis, measured as ppm P
Optical density (OD)	absorbance	
CO_2 source (flue gas/purified CO_2)	Wt %	
Water supply		Fresh/saline/brackish water, stating source

Biomass concentration (ash free dry weight)	g L^{-1}	Measured according to standard procedure of total suspended solids
Contamination count	count (type) mL^{-1}	
Salt consumption	g kg^{-1} algae	
5. Cultivation/productivity and other calculated metrics		
Total productivity (ash free dry weight)	g	$\frac{AFDW_{t\ final}(g) - AFDW_{g\ initial}\,(g)}{pond\ volume\ (L)}$ represents total biomass produced during an experiment or batch
Average biomass areal productivity	g m^{-2} day^{-1}	$\frac{AFDW_{total}\,(g)}{pond\ area\ (m^2)} \times total\ days$
Daily Biomass areal or volumetric productivity	g m^{-2} day^{-1} or g L^{-1} day^{-1}	$\frac{AFDW_{t+n}\,(g) - AFDW_t\,(g)}{n}$ where n = number of days between measurements, allowing for n > 1, typical sampling plans are AFDW every other day and calculated on a m^2 or L basis
Average biomass volumetric productivity	g L^{-1} day^{-1}	$\frac{AFDW_{total}\,(g)}{pond\ volume\ (L)} \times total\ days$
Nitrogen depletion rate	mg L^{-1} day^{-1}	$\frac{nutrients\ N_t\,(mg) - nutrients\ N_{t+1}\,(mg)}{n}$ where n = number of days between measurements and nutrient N > 0
Phosphorus depletion rate	mg L^{-1} day^{-1}	$\frac{nutrients\ P_t\,(mg) - nutrients\ P_{t+1}\,(mg)}{n}$ where n = number of days between measurements and nutrient P > 0
6. Cultivation/strain specific parameters for productivity		
Light absorption coefficient		Needed for physics-based modeling of strain productivity
Light extinction coefficient		Needed for physics-based modeling of strain productivity
7. Cultivation/other LCA/TEA metrics		
Water evaporation rate	cm day^{-1}	$\frac{pond\ depth_{t+n}\,(cm) - pond\ depth_t\,(cm)}{n}$ where n = number of days between measurements
Pond downtime (unplanned)	% of month	% downtime due to unplanned events, crashes, contamination, emergency maintenance
Pond mixing energy	KWh day^{-1} m^{-3}	

	volume	
8. Cultivation: Biomass component analysis		
Moisture/Ash	% DW	Based on harvested, centrifuged material
Total lipids	% DW	Based on harvested, centrifuged material
Total protein	% DW	Based on harvested, centrifuged material
Total carbohydrates	% DW	Based on harvested, centrifuged material
C:N:P molar ratio		Based on harvested, centrifuged material
Biomass elemental composition (C, H, N, S, O, P)	Wt %	Based on harvested, centrifuged material
9. Harvesting and conversion		
Dewatered algal biomass concentration	g L^{-1}	
Harvesting efficiency	%	Specify at each stage of harvesting process
Processing	As applicable	As much detailed information on conversion process, heat supply and efficiency of conversion or extraction as possible
Natural gas consumption	MJ ha^{-1}	
Methanol Consumption	g kg^{-1} biofuel	
Sodium hydroxide Consumption	g kg^{-1} biofuel	
Sodium methoxide Consumption	g kg^{-1} biofuel	
Hydrochloric Acid Consumption	g kg^{-1} biofuel	
Spent biomass usage	As applicable	As much detailed information on processing of residual biomass as possible, including recycling nutrient and energy credits

Appendix B: Company and Research Group Overview

An overview of global installed commercial facilities with capacity and target products is included here. We first highlight a couple of commercial installations here, with no particular preference other than that these represent installed operations across the value chain; from biomass production, volatile fuel production (Algenol) to biochemical pretreatment and extract and heterotrophic fermentation of microalgae. Commercial seaweed operations are presented as well, to highlight the

11.1. EXAMPLES OF COMMERCIAL PHOTOTROPHIC ALGAE CULTIVATION OPERATIONS

There are many commercial algae cultivation companies currently in operation around the world. We will not summarize all companies here, but refer to the summarizing table of commercial operations, which is included as **Appendix B**. We selected a subset of the commercial operations here to highlight the different approaches that are currently undertaken as a viable approach to algae commercial deployment.

Sapphire has been developing the algae liquefaction technology since 2007 and has now moved to a pilot plant scale of operation. Sapphire has three facilities across California and New Mexico. Its headquarters and primary lab are in San Diego, California, there is a Research and Development Facility in Las Cruces, New Mexico. In 2010, the company began construction of the world's first commercial demonstration algae-to-energy farm in Columbus, New Mexico. Construction of Phase 1, constituting of the first 40 ha (100 acres) of ponds was completed in 2012. The company has the full technology pathway from algae growth to harvesting to conversion and fuels marketing. The algae growth system is an open pond design using non-potable water based on non-arable land. With the planned 120 ha (300 acres) of cultivation, the annual product yield is estimated to be around 3,780,000 L (1 million gallons) of transportation fuels.

Algenol uses a proprietary strain of cyanobacteria to produce an ethanol product, which is directly recovered from their photobioreactors.[432] The algae biomass is periodically harvested and processed by hydrothermal liquefaction to produce a biocrude. Algenol has an integrated biorefinery pilot plant in Fort Myers, Florida, with a capacity of 37,800 L (10,000 gal) per year of ethanol. In 2015, Algenol plans to announce their first commercial facility, to be located in the United States.

11.2. EXAMPLES OF INSTALLED OPERATIONS OF HYDROTHERMAL LIQUEFACTION OF ALGAE

Hydrothermal processing of algae to fuels is still primarily a subject of laboratory R&D. The bulk of the research is still performed in batch reactor systems and cannot even be considered actual process development.[229] However, there are a few examples of the technology coming out of the laboratory into the marketplace.

As part of their patent portfolio (over 300 patents and patent applications) **Sapphire** has a patented process for liquefaction which includes a hydrothermal step with biocrude treatment and recovery including acidification and solvent extraction.[433] They also have a patent application describing the upgrading of the biocrude product.[434] The Sapphire biocrude ("Green Crude Oil") has been tested in partnership with petroleum refiners, such as Tesoro, in coprocessing with petroleum streams in a range of applications including hydrotreating, catalytic cracking, and delayed coker.

Algal biomass collected following ethanol production at the **Algenol** plant provides the feedstock for the biomass-to-hydrocarbon fuels process. The biomass is dewatered before being fed into the HTL unit, which Algenol has developed in collaboration with PNNL. The HTL biocrude oil is upgraded in a hydrotreater unit to a hydrocarbon product that essentially contains a mixture of liquid hydrocarbons in the range of diesel, jet and gasoline fuels. The upgraded product contains none of the oxygen, nitrogen or sulfur present in the biocrude from HTL and can be distilled into diesel, jet fuel and gasoline fractions. On one wet acre of algal cultivation Algenol can produce around 30,200 L (8,000 gallons) of liquid fuels per year, mainly ethanol, with 1,890 L (500 gallons) of jet ultra-low sulfur diesel, 1,440 L (380 gallons) of gasoline and 1,190 L (315 gallons) of jet fuel. This makes Algenol's technology compare favorably to corn at 3,900 L/ha (420 gallons per acre) per year.

Genifuel Corporation and Reliance Industries, Ltd. were partners with Pacific Northwest National Laboratory (PNNL) and others in the National Association for Advanced Biofuels and Bioproducts (NAABB), which coordinated research on the fuels pathway of algae strain development, growth, harvesting, and conversion. Reliance has now contracted with Genifuel to fabricate a 1 ton per day pilot plant for hydrothermal processing of algae biomass to liquid and gaseous fuels. Construction of the pilot plant is complete and start-up is underway, with delivery to India planned for later in 2015. The hydrothermal processing technology is licensed by Genifuel from PNNL.[435]

Muradel has a hydrothermal liquefaction demonstration plant at Whyalla, Australia, which can produce 30,000 liters per year of biocrude. A planned commercial plant of 1000 hectare would produce 500,000 barrels of biocrude per year. Muradel uses marine algae grown in seawater on marginal land for their feedstock. They earlier decommissioned their 2-year old pilot plant near Karratha, NWA. The projected cost for biocrude were $9.90/L using the pilot plant data, but costs are expected at about 1$/L in the new plant.

A continuous-flow hydrothermal liquefaction pilot plant was designed and built at the University of Sydney in Australia. Although there is no commercial interest involved in this work, it is a significant element in the process development effort for HTL of algae. The design flow rate of the pilot plant is 15-90 L of algae slurry at 10 wt% dry solids per hour. The process design does not include a biocrude separation technology, but biocrude extraction by dichloromethane is handled batchwise off-line. Processing results for *Chlorella* and *Spirulina* have been published.[436]

11.3. EXAMPLES OF COMMERICAL HETEROTROPHIC ALGAE OPERATIONS

Solazyme, recently rebranded as **TerraVia**, is a San Francisco based corporation which cultivates *Chlorella*, a type of microalgae.[437] The microalgae are grown in fermentation tanks, and use the sugar derived from a variety of crop plants. Though previously a prominent producer of fuel derived from microalgae, they currently market food and nutrition products.[438,439]

DSM is a Dutch company that produces a variety of commodities pertaining to health and nutrition. It utilizes algae to produce some of its nutritional lipid products, primarily those which incorporate Omega-3.[440] In 2010, DSM acquired Martek, a company which produced DHA using *Schizochytrium*.[441,442] DSM also collaborates with other companies, such as Evonik Nutrition and Care GmbH and Sanofi to produce other algae related products.[443]

ADM, the **Archer Daniels Midland Company**, is a health and nutrition company. In 2014, ADM and Synthetic Genomics, Inc entered into a joint venture, which explored the use of microalgae to produce omega-3 fatty acids. [444] Synthetic Genomics works with a number of algal strains, including *Chlorella*, to create their products. [445]

Bunge is a global agribusiness, which produces food and fertilizer. The company partners with

Solazyme/TerraVia, and has a line of algae related products called algawise, which contain Omega-9 fatty acids.[446,447] It also operates several plants which produce ethanol from crops.[448]

Roquette is a French company which processes plant based raw materials, and their feedstocks include maize, wheat, potatoes, peas, and microalgae. They cultivate Chlorella, and have a microalgae brand called algohub, which relates to pharmaceuticals, cosmetics, animal nutrition, infant nutrition, and nutraceuticals.[449,450]