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The Forefront of Low-cost and High-volume Open Microalgae Biofuel Production

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Abstract
This review summarises the status of seven selected companies at the cutting edge of liquid fuel production from microalgae cultured in open systems. Open microalgae production technologies and companies have fostered commercial collaborations and technological progress towards producing low-cost, high-volume microalgae biofuels, although significant large scale-demonstration is required. This work provides a concise summary of each respective company’s technology, background, and where available, productivity and economics. Based on the review findings, an unprecedented level of collaboration between entities is needed across the production chain to achieve cost-competitive production systems to displace current liquid fuels. In addition to microalgae mass production and culturing challenges, there are also notable challenges surrounding harvesting/dewatering, extraction, and conversion to a final product. The microalgae biofuel industry will thus require a ‘cross-pollination’ of industries historically unrelated to biological production systems, and there is likely to be a consolidation of current microalgal biofuel capability and expertise.

Introduction
The two fundamental microalgae biomass production technologies aiming to supply the global demand for renewable biofuels are known as ‘open’ ponds and ‘closed’ bioreactor/fermentor systems (Borowitzka 1999, Ugwu et al. 2008, Vasudevan and Briggs 2008, McHenry 2010). Whilst many microalgae species must be cultured in highly controlled conditions, species that exhibit a selective advantage in particular environments are able to be cultured in open-air systems such as ponds (Borowitzka 1999). The majority of microalgae biofuel companies are designing commercial production systems based on open cultivation of particular species/cultivars due to the advantages of relatively lower capital and production costs of open systems compared to the currently available closed systems, and a historically proven record of production (Borowitzka 1999, Spolaore et al. 2006). At present, the most common open system designs include the use of natural water bodies, constructed ponds of a variety of shapes, depths, and sizes, and also tanks (Ugwu et al. 2008). Each system exhibits unique advantages and disadvantages. For example, while commonly used raceway ponds improve yields and reliability relative to simple shallow ponds, they can be an expensive design to construct and operate (Borowitzka 1992, Kunjapur and Eldridge 2010).

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There are numerous technical components to this analysis, including biological, engineering, economic, and environmental challenges. While open systems may exhibit relatively low capital requirements compared to closed systems (Huntley and Redalje 2006, Chisti 2007), the microalgae yield is often decreased with relatively poor water body mixing, contamination, and microalgal predatory organism issues (Huntley and Redalje 2006, Chisti 2007, Ugwu et al. 2008). Further production limitations can include low solar resource utilisation, low atmospheric CO2 diffusion, and high land and water demands (Ugwu et al. 2008, Clarens et al. 2010, Borines et al. 2011b, McHenry 2012, Moheimani et al. in press), and extreme events such as high rainfalls or low temperatures can lead to total pond culture losses (Moheimani and Borowitzka 2006, Amin 2009, Borowitzka and Moheimani 2010). Therefore, industrial-scale microalgae developments will likely occur in dry to arid regions with good solar resources on land unsuitable for conventional agriculture (Gross 2007, Hankamer et al. 2007, Borowitzka and Moheimani 2010, McHenry 2010). However, the use of arid regions may present problems related to suitable water access and availability to replace the extremely large evaporative losses from open ponds in such areas (Chisti 2007, Clarens et al. 2010). Further water-related challenges involve the resultant wastewater treatment. Hence, significant collaborative research and development is required to reduce microalgae production demand for freshwater, output effluent wastewater issues, and also relatively high energy demands, which all require significant cross-disciplinary investment (Wyman and Goodman 1993, Xiong et al. 2008, Charcosset 2009, Borowitzka and Moheimani 2010, Clarens et al. 2010).

Highly productive microalgal industrial developments in nonagricultural areas may reduce arable land competition between conventional biofuel and agricultural food production (Sheehan et al. 1998, Huntley and Redalje 2006, Chisti 2007, Gross 2007, Hankamer et al. 2007, Cantrell et al. 2008, Borowitzka and Moheimani 2010). However, cost-effective microalgal biofuel production will reflect conventional biology-based primary industries, and remain fundamentally tied to total factor productivity of biological systems. Thus, industrial-scale commercial production will be dependent on microalgae biology, the climate, and inputs costs such as energy, water, land, capital, labour, transport, and nutrients (Borowitzka 1999, Kunjapur and Eldridge 2010). As such, productive regions and production systems will be selected according to technological, economic, infrastructure, and environmental conditions suitable for particular species and strains (Borowitzka 1992, Kunjapur and Eldridge 2010). While microalgal biomass production in open ponds may seem a relatively trivial technical challenge, the complexity of downstream biofuel processing imposes additional production costs that will make it difficult for the final fuel to compete with existing energy supply prices (Lee 2001, Borowitzka and Moheimani 2010). For microalgae producers to achieve and sustain a competitive advantage will require capital, culturing operations, harvesting, drying and processing equipment costs to all remain low, whilst achieving a sustained high-level productivity over the entire year (Borowitzka 1999).

This review’s primary focus is the technical research and development challenge to open pond production, specifically in terms of existing partnerships and capabilities of each company, and the development needs of the industry as a whole. This review companies primarily using open systems, (in reverse-alphabetical order): Synthetic Genomics Inc.; Seambiotic; Sapphire Energy Inc.; Muradel Pty. Ltd.; General Atomics; Aquaflow Bionomic Corporation, and; Aurora Algae Inc. Due to the limited peer-reviewed literature available on the forefront of commercial microalgal production, the authors contacted each company to update the publically available information presented in this review. The authors have made every attempt to provide only facts and
commentary, without undue criticism of strategies or opinions on commercialisation potential. However, this review aims to collate and clarify the often rudimentary unqualified information publicly available regarding microalgae biofuel production developments, and also facilitate sustained progress in the expansion of the microalgae industrial endeavour.

**Synthetic Genomics Inc. www.syntheticgenomics.com**

Synthetic Genomics Inc. (SGI) is a privately owned company based in La Jolla, California, USA, with co-founders Craig Venter (as the Chairman, CEO, and Co-Chief Scientific Officer), and Hamilton O. Smith (Co-Chief Scientific Officer). The company focuses on commercialising genomics and policy research capability at the J. Craig Venter Institute. SGI development scope encompasses biochemistry, bioinformatics, climate change, environmental genomics, genome engineering, microbiology, plant genomics, and synthetic biology.

SGI partnerships encompass a range of sectors and companies, including the Asiatic Centre for Genome Technology, Biotechonomy LLC, BP, Draper Fisher Jurvetson, Exxon Mobil, Meteor Group, and Plenus. In 2009, Exxon Mobil agreed to provide up to USD300 million to SGI for research and development and production of biofuels from photosynthetic microalgae on a milestone basis. SGI’s broad scope includes developing metabolic pathways for producing biochemicals and biofuels from a number of feedstocks, microbial methods to increase conversion and recovery of subsurface hydrocarbons, and the development of novel plant feedstocks and microbial agents for agriculture.

**SGI’s Technology Review**

SGI have planned to develop a 4 ha test site incorporating both ponds and photobioreactors, although are not expected to become a major fuel producer in their own right. SGI’s wide research and development scope is focussing on primary and enabling technology, including harvesting microalgae, increasing strain lipid contents, agricultural organism GM for disease resistance, vaccine development, and gene synthesis. SGI is well known for being the first to synthesise a genome using oligomers, and using polymerase cycle assembly, and SGI have developed cultivation and monitoring technology to assess as yet undiscovered wild microorganisms with novel genes for commercial biofuel production. SGI aim to produce commercial products from these new organisms, and are developing methods to engineer organisms to increase productivity.

**SGI Summary**

Currently there are no publicised production claims for SGI relating to large-scale production facilities. Synthetic Genomics’ commercial scope, technology, and capability remain at relatively primary stages of development, and in terms of microorganisms, or modification, seem to be resisting convergence into technology types, or specific commercial markets. At this stage it is unclear if SGI will specialise into modification for fuel producing organisms, or organisms that produce refining precursors. A large uncertainty for the microalgae industry at present is the regulation and standards required for GM technology applied at the industrial scale. Nonetheless, the staged Exxon Mobil funding will add enormous capability to SGI, and the considerable intellectual property
available to SGI promise to generate much innovation,¹ and progress towards developing low-cost, high-volume, sustainable biofuels.

**Seambiotic www.seambiotic.com**

Seambiotic was the first company to utilise flue gas from coal burning power stations for microalgae cultivation. In 2003, Seambiotic was founded as a private company in Ashkelon, Israel, with an objective to grow and process marine microalgae to produce biofuel and food additives (primarily omega-3 fatty acids). Seambiotic with their major partner, Nature Beta Technologies Ltd. (NBT), a subsidiary of Nikken Sohonsha, currently operate a 10 ha plant in Eilat, Israel, culturing a low-lipid, high-carbohydrate *Dunaliella* strain for beta-carotene production in salty water pumped from the Red Sea. NBT is an Eilat-based nutraceutical-grade microalgae company producing since 1988, and Seambiotic’s Chief Advisor, Ami Ben-Amotz, a scientific director of NBT, initiated the biofuel focus. Seambiotic have several partnerships, including with Seattle-based Inventure Chemical. Seambiotic supply microalgae paste for Inventure’s thermochemical process where catalysts convert the paste into biodiesel, a sugar solution, and a protein solution. Seambiotic and Rosetta Green, a company specialising in unique gene identification in plants, announced collaborations in 2010 for strain improvement aimed at improving contamination resistance and oil yield. Seambiotic also have a non-commercial computational collaboration with the US National Aeronautics and Space Administration (NASA) to optimise microalgae-based aviation biofuel feedstock. Seambiotic signed a licence agreement and a joint venture with Yantai Hairong Electricity Technology Ltd. and Penglai Weiyuan Science & Trading Ltd for construction of a 10 ha, USD10 million facility in Penglai power station China, owned by China Guodian Corporation, China’s fifth largest power company.

**Seambiotic Review**

Seambiotic’s research and development pilot study over the last five years has occurred at the Ashkelon Rutenberg coal-fi red flue gas desulphurisation (FGD) power station of the Israeli Electric Corporation in Ashkelon. The following algae have been grown in Seambiotic’s 0.1 ha open raceway pond pilot plant: Amphora sp.; *Dunaliella* sp.; Chlorococcum sp.; Nannochloris sp.; Nannochloropsis sp.; Navicula sp.; Phaeodactylum tricornutum; Skeletonema sp.; Tetraselmis sp. (etc.). Seambiotic’s impressive productivity results in their 0.15 cm deep raceway ponds include both seasonal and annual studies over several years (2005–2007, and ongoing). Average yearly productivities of 20 g m⁻² day⁻¹ (~700 t ha⁻¹ yr⁻¹) using *Nannochloropsis* ‘fed’ with FGD inputs, in addition to conventional inputs. In contrast to many microalgae companies, Seambiotic’s production parameters and results are often publically available (see Table 1).

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¹WO2010068821, WO2009048971, WO2009076559, WO2009064910, O2009144192, and WO2009140701. In addition to SGI intellectual property, the company has access to the considerable intellectual property and capabilities of the hundreds of researchers at the J. Craig Venter Institute.
Seambiotic were the first microalgal company to successfully grow microalgae outdoors at a medium scale for several years, and the company possess gas transfer, cleaning, and various other production control technologies.\(^2\) In terms of economics, Seambiotic’s own microalgal oil cost estimates are around USD50 L\(^{-1}\), based on 25% lipid content and 0.8 kg L\(^{-1}\) of dry microalgae. As the company uniquely holds a high resolution commercial understanding of current microalgae production system costs, these costs estimates have high reliability. Seambiotic aim to produce microalgal oil at USD0.34 kg\(^{-1}\), equivalent to approximately USD2.25 L\(^{-1}\) of biodiesel assuming a 12% microalgae lipid content. The authors note that this estimate is simply based on the Dunaliella facility costs in Eliat.

**Seambiotic Summary**

Seambiotic’s successful history of commercial microalgae production and demonstration of the full production chain is unique among microalgae companies focussing on biofuels. Furthermore, Seambiotic are one of very few microalgae companies that are able to produce both biodiesel and bioethanol from their own product. The transition from a high-cost, high return model of Dunaliella production into high-volumetric production at low-cost will require significant innovation, partnerships, investment, and likely new algal strains. Therefore the company’s biofuel productivity data will change with the culturing of other microalgae other than Dunaliella. Nonetheless, Seambiotic believe that high value co-production can subsidise biofuels production to successfully compete with mineral oil, a distinct difference from simply a low-cost, high-volume model.

**Sapphire Energy Inc. www.sapphireenergy.com**

Sapphire is a privately owned company operating a pilot facility (40 ha) in Las Cruces, New Mexico, and an integrated microalgal bio refinery (using hydro processing) and production facility (120 ha of ponds) in Columbus, New Mexico, designed to produce biofuels. Sapphire Energy is supported by ARCH Venture Partners, Cascade Investment LLC, the Wellcome Trust, and Venrock Partners. This impressive list of partners have provided around USD100 million. Sapphire received a further USD104 million through the US Department of Energy (DoE), and a loan guarantee from the US Department of Agriculture for the integrated microalgal biorefinery in Columbus. Sapphire’s large number of collaborators also include: Amec; Amex Geomatrix; Brown and Caldwell; the DoE’s Joint Genome Institute; Deutsche Bank; Dynamic Fuels; Harris Group; New Mexico State University; San Diego Center for Algal Biotechnology; Sandia National Laboratories; Scandia National Institute; the Scripps Research Institute; Shaw; Square 1 Bank; Praxair; University of California; University of Kentucky; and the University of Tulsa.

\(^2\)WO2008107896 Method for growing photosynthetic organisms.
Sapphire Review
The company uses GM microalgae to achieve high productivity, by creating strains through both selective breeding and synthetic biology. Sapphire Energy is looking at the entire microalgae production value chain, and the company states it has over 230 patents or applications spanning the entire microalgae-to-fuel process, including systems for cultivation, CO₂ utilisation, refining, and harvesting (reportedly having used ultrasonic, microwave, and dissolved air flotation harvesting technology).

Sapphire’s estimates the Columbus integrated microalgal biorefinery project’s productivity at around 25 g m⁻² day⁻¹, the equivalent of 30 t day⁻¹ total area output. The expanded Columbus facility is expected to produce 100 BPD of microalgal oil, yielding a minimum of 60 BPD of fuels, including jet fuel, petrol, and diesel. The inputs include 35,000 t yr⁻¹ of CO₂ for microalgal culture, and 210 t yr⁻¹ of H₂ for the refining process, in addition to conventional inputs, such as water, nutrient, energy, etc. The logistical challenge for on-site delivery of these input gases will necessitate careful site selection, and will require large reticulation systems to maintain high productivity over the entire facility area. Sapphire’s expansion plans include a 1,200 ha plant in New Mexico, proposed to be completed in 2013, supplying around 400 ML of microalgal oil by 2018. A simple calculation finds the company’s stated expected output of around 100 BPD at the 120 ha facility is roughly 6.5 ML of microalgal oil, or roughly 54,000 L ha⁻¹ yr⁻¹. In the authors’ opinions, this is an optimistic scenario.

Nonetheless, Sapphire has demonstrated it has the capability to produce infrastructure-compliant ASTM (American Society of Testing and Materials) certified fuels. In 2008, Sapphire produced 91-octane petrol from microalgae that met ASTM standards, and in 2009, Sapphire supplied microalgal jet fuel to a Boeing 737–800 twin-engine test flight with Continental and JAL airlines. The jet fuel trial reduced fuel consumption by around 4% due to higher energy density of the microalgal fuel. In 2009, Sapphire partnered with Algaeus, FUEL, and The Veggie Van Organisation to demonstrate an unmodified plugin-hybrid Toyota Prius consuming microalgae-based fuels. Sapphire provided 190 L for the Prius trial. The authors note that much of the microalgal biomass to produce Sapphire’s fuels in these trials were not produced by Sapphire, and were sourced from other microalgal biomass suppliers. In terms of economics, Sapphire’s goal is to be able to produce microalgal oil at between USD60 to USD80 per barrel by 2025. Additional costs of refining to meet ASTM standards are estimated by the authors at between 5–12 US cents L⁻¹ (using hydrogenation), which is likely to decrease with the investment from Sapphire’s biorefinery project.

Sapphire Energy Summary

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3 The authors were able to locate only the following patents: WO2010042138 System for capturing and modifying large pieces of genomic DNA and constructing organisms with synthetic chloroplasts; WO2010051489 Animal feedstock comprising genetically modified algae; WO2010019813 Production of fatty acids by genetically modified photosynthetic organisms; WO2009158658 Induction of flocculation in photosynthetic organisms; WO2009036067 Molecule production by photosynthetic organisms; WO2009136087 Methods of producing organic products with photosynthetic organisms and products and compositions thereof; US200902246766 High throughput screening of genetically modified photosynthetic organisms; US200900123977; System for capturing and modifying large pieces of genomic DNA and constructing organisms with synthetic chloroplasts; US20090126260 Methods of refining hydrocarbon feedstocks; US20090087890 Methods of producing organic products with photosynthetic organisms and products and compositions thereof; WO2008321074 Production of Fc-fusion polypeptides in eukaryotic algae; CN101544918; M15-M85 vehicle alcohol ether fuel and preparation method thereof; GB2464264 Vector comprising chloroplast replicating sequence, and; GB2460351 Vectors comprising essential chloroplast genes.
The combination of the high profile vehicle and jet trials, impressive intellectual property, alongside the noteworthy group of partners and investors give Sapphire an extremely competitive commercial advantage over many microalgae biofuel producers in progressing towards low-cost, high-volume biofuels. However, at present Sapphire are yet to demonstrate their capability for medium-scale primary microalgae production. The authors are aware that Sapphire representatives approached both Seambiotic in Israel, and Cognis (a Dunaliella salina microalgae production company based in Western Australia), to purchase microalgal biomass for their fuel trials. In the author’s opinions, Sapphire aim at maintaining productivities of around 25 g m\(^{-2}\) day\(^{-1}\) over an entire year is relatively optimistic for open pond systems, but is potentially feasible. Maintaining these productivity values over large areas is dependent of the species characteristics and the production system design, which will in turn determine the final cost per barrel of microalgae oil. The authors are unaware of the microalgae species/cultivars used by Sapphire, and the company’s open pond designs and cultivation trials are still in the early stages. In terms of the productivity and use of Sapphires GM strains, the author’s suspect no GM microalgae will be used in the open pond trials in the near future due to significant regulatory barriers.

**Muradel Pty Ltd. muradel.com**

Muradel was established to commercialise Murdoch University’s and University of Adelaide’s microalgal technology intellectual property developed over a 30 year period. The in-house intellectual property incorporates the full microalgal production chain, including species selection, culture management, harvesting, oil extraction, media recycling, biomass disposal/reuse, and culture system design, construction, and operation. Muradel possesses extensive experience in commercial microalgae production and engineering, most notably through the work of Prof. Borowitzka from Murdoch University, who played a vital role in the development of the worlds’ largest microalgae production facility of around 750 ha of ponds producing Dunaliella salina for commercial beta-carotene production in Hutt Lagoon, Western Australia, operated by Cognis.

Murdoch University and the University of Adelaide have received over AUD2 million from REDGTF (Renewable Energy and Distributed Generation Task Force) to develop a small pilot plant (one 20 m\(^2\) and four 200 m\(^2\) raceway ponds) at Karratha. Murdoch University and the University of Adelaide have also received $1.89 million funding from the Commonwealth Government of Australia as part of the Asia-Pacific Partnership on Clean Development and Climate to develop a commercial biodiesel and aviation fuel feedstock production process. Muradel project investors and partners include Rio Tinto, Laing O’Rourke, Parry Nutraceuticals, South China University of Technology, and Z-Filter. Muradel’s proprietary microalgal strains isolated in Western Australia will be used to produce biodiesel and aviation fuel feedstock. The operational locations of Muradel include Perth and Karratha in Western Australia, and Adelaide in South Australia.

**Muradel Review**

Murdoch University in Perth specialise in microalgae species and cultivar selection, culture optimisation, process design, and economic modelling, while University of Adelaide specialise in culture dewatering, microalgae extraction, conversion and process design. Laboratory-scale low-cost, high efficiency harvesting for the microalgal strains are undertaken in Adelaide, while laboratory-scale extraction optimisation for the strains occur at both Perth and Adelaide. Continuous small-scale outdoor laboratory trials (using 1 m\(^2\) raceway ponds) in Perth and Adelaide were used to determine productive strains, average productivities, and effective
monitoring and management protocols. The long-term (greater than 3 years) continuous trial results from Perth found reliable average microalgal biomass productivities of greater than 20 g m\(^{-2}\) day\(^{-1}\) with an average lipid content of at least 30\% (equivalent to around 36 t of microalgal oil ha\(^{-1}\) yr\(^{-1}\)). Based on the Perth results, Muradel expect that the Karratha site will be able to fix 60 tCO\(_2\)-e ha\(^{-1}\) yr\(^{-1}\), although the productivity results transferability will be determined in the pilot plant raceway ponds located at the Rio Tinto Yurralyi Maya Power Station in Karratha, while the harvested microalgae will be sent to Adelaide for analysis, lipid extraction, and biofuel production. Muradel is the only company known to the authors that is using a strain of microalgae that can tolerate salinity levels from seawater to around three-times seawater concentration. This strain reduces the flushing, or ‘blow-down’ requirement of ponds, decreasing effluent and contamination risks, and in combination with a unique harvesting and dewatering technology, as well as lipid extraction methods optimised for the unique strains. In terms of economics, Muradel state that their cost of production of microalgal biomass contracted from AUD12 kg\(^{-1}\) in 2008 to below AUD3 kg\(^{-1}\) in 2010, with the pilot plant aiming to reduce costs to less than AUD1 kg\(^{-1}\) for final biofuels.

**Muradel Summary**

With several decades of experience in microalgae isolation, culture optimisation, and commercial-scale experience, Muradel are a unique entity in the microalgal biofuels space. The two universities are using proven production systems (raceway ponds), and are focussing on capital expenditure minimisation and supply chain logistics to achieve high volume, low-cost, high-reliability culture systems for production of biodiesel and aviation fuel feedstock. If the Karratha pilot plant research maintains reasonable productivities, a 20 ha demonstration plant by 2012 at Karratha will require an investment of between AUD10–15 million, a significant barrier to achieving commercial production.

**General Atomics www.ga.com**

General Atomics (GA), based in San Diego, has a 50-year history, and since 1986 has been owned by Neal Blue and Linden Blue. GA has a long history in environmental, energy, and defence contracts, and affiliated companies include GA Aeronautical Systems, Inc., which manufactures the Predator\(^{\text{®}}\) unmanned aircraft. In 2009 GA won a staged USD43 million Defence Advanced Research Projects Agency (DARPA) contract to develop cost-effective scalable microalgae production for Jet A biofuel production. GA microalgae partnerships include: Center of Excellence for Hazardous Materials Management (CEHMM), New Mexico State University, the State of New Mexico, Algaeventure Systems Inc., Beach Energy Ltd, Carlsbad City, and AgriLife Research. GA’s microalgae operational facilities include the Pecos Valley at New Mexico State University’s Agriculture Science Centre, and also potential site near Moomba, in the Cooper basin, South Australia.

**General Atomics Review**

The 3 year DARPA contract focuses on identifying key cost drivers for increasing productivity and reducing capital and operating expenditures, including strain selection, water, CO\(_2\), and nutrient supply, harvesting, extraction, and conversion, etc. The AgriLife Research partnership received USD4 million from the Texas Emerging Technology Fund (matched with DARPA funds), for high-oil strain evaluation, the development and testing of both open pond production systems and microalgal oil separation systems. (<1 ha) open pond production, increasing to a commercial-scales (20–45 ha) in the final stages. Also under the DARPA program,
GA’s partnership with Algaeventure Systems from Maysville, Ohio, includes a purchase order and evaluation of Algaeventure’s microalgae “Harvesting, Dewatering, and Drying” technology (AVS HDD) which reportedly reduces dewatering costs considerably using unique centrifugal technology. Algaeventure Systems, Inc. is a spinoff company from Univenture, Inc., an environmentally conscious plastics packaging manufacturer, which may be a future higher value output stream which subsidises biofuel production.

GA’s joint partnership with CEHMM, New Mexico State University, the State of New Mexico, and the city of Carlsbad, focuses on reducing hazardous wastes from open pond microalgae production. The partnership aims to culture microalgae in high temperature, high saline open pond systems on unused non-arable lands in the southwest of New Mexico. Two small (95 kL) capacity ponds have been constructed with a high density polyethylene liner to prevent groundwater contamination, and at least two years of data has been recorded. Since these initial ponds were built, at least three additional ponds under 1 ha and processing facilities have been constructed, with a solvent-based extraction plant. In early 2010, CEHMM became the world’s first fully integrated microalgal biomass biorefinery with a full capacity of 3,800 L day$^{-1}$ of microalgal oil. CEHMM’s Executive Director, Doug Lynn, states that the current system has the potential to produce 47,000 L of oil ha$^{-1}$ yr$^{-1}$, although no specific productivity data has been released to confirm this extremely high productivity. Nonetheless, the joint partnership is now in a unique position of being able to follow the production chain from cultivation to extraction at the New Mexico State University Agriculture Science Centre. New Mexico State University was awarded USD2.36 million by the US Air Force for jet fuel production and refining research with the University of Central Florida.

In 2010, Beach Energy Ltd., an Australian oil and gas company, and GA announced a joint project researching production of biofuels in the Cooper Basin, South Australia. On June 30, 2009, Beach Energy’s estimated oil and gas reserves were 66 million barrels of oil equivalent, with production in the 2008/09 financial year of 9.6 million barrels of oil equivalent. The project aims to culture microalgae using effluent and CO$_2$ emissions from gas and oil production sites. The preliminary project scope includes microalgal biofuels market demand, input power, transport, and other required infrastructure evaluations, in addition to water, land, solar, and CO$_2$ resource assessments. Depending on the outcomes of preliminary work, between 1,000 and 2,000 ha open ponds could be constructed in the Cooper Basin around 2015.

**General Atomic Summary**

The leveraged DARPA funding and the existing infrastructure and intellectual property$^4$ from culture to refining, alongside unique applications in the oil and gas industry, launch GA’s considerable technical capability into a strong position in microalgae biofuels sector. The authors are unable to verify the reliability or productivity of the very high productivity claims (especially without microalgae strain/species information), and recommend prudence as the DARPA funded program is at the strain selection and system testing phase. Similarly, the small-scale biorefinery and production ponds, while a significant development, will require larger systems to

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$^4$ WO2008070281 Photosynthetic oil production with high carbon dioxide utilisation, WO2008070280 Photosynthetic carbon dioxide sequestration and pollution abatement, and WO2008048861 Photosynthetic oil production in a two-stage reactor.
determine the economics of the production systems. Nonetheless, the formidable technical capability of GA may be able to overcome many of these cost challenges, and the authors would suggest that GA’s economic and microalgal strain selection data would add significant value to this review of their potential progress towards supplying low-cost, high-volume sustainable biofuels.

**Aquaflow Bionomic Corporation www.aquaflowgroup.com**

Aquaflow, based in Marlborough, Blenheim District, in New Zealand was established in 2005. The private company has uniquely specialised in harvesting wild microalgae from municipal sewage ponds, agricultural effluents, and even rivers. Aquaflow has an estimated 100 million shares held by mostly New Zealand investors, with Pure Power having an 18% stake in the company. Aquaflow Bionomics expected to raise an estimated AUD10–15 million to develop continuous flow microalgae production technology with parallel water remediation, fuel production, and high-value co-product capabilities. In 2008 Aquaflow partnered with Honeywell UOP (a world leading fuel refining technology company) to provide microalgal oil to optimise the refining of micrargae oil from Aquaflow’s wild microalgae. The agreement gives Aquaflow access to UOP/Eni Ecofining™ processes to produce Honeywell Green Diesel™ and Honeywell Green Jet™ fuels, which uses catalysts and thermal energy for output separation. The cooperative agreement project between Aquaflow and Honeywell’s UOP have received USD1.5 million from the U.S. DoE to demonstrate exhaust stack CO₂ microalgal capture with Honeywell’s automated control systems. In 2010 a USD3.1 million co-funded collaboration between Aquaflow and the US Gas Technology Institute (GTI), funded in part by the U.S. DoE onmicroalgal biomass conversion technology aimed to develop hydrolysis and hydroconversion technology to produce gasoline and diesel directly from microalgae. The Illinois-based GTI has over 65 years of environmental expertise resulting in around 750 licenses and 1,200 patents.

Aquaflow is also collaborating with Impulse Devices Inc. (IDI) from California specialising in acoustic inertial confinement nuclear fusion using high frequency sound waves to create cavitation in liquids. In terms of microalgae research, IDI’s acoustic cavitation technology is able to control algal growth and modify water characteristics without the use of chemicals. Aquaflow has also partnered with Solray Energy, which is a joint venture between Solvent Rescue (a solvent recovery company), and Rayners (a heating equipment manufacturer). Other Aquaflow partners include NZ Capital Strategies, Milestone Capital (Rutherford Fund) and collaborations with New Zealand Trade and Enterprise.

**Aquaflow Bionomic Corporation Review**

Aquaflow currently operate with around 60 ha of open sewage oxidation ponds. Aquaflow’s pilot plant operates in Nelson, New Zealand, with wild microalgae harvested using dissolved air flotation and flocculation, followed by a belt press for extraction of solids (8 to 10% microalgae by volume, the rest is primarily water). This method is commonly used in wastewater treatment, although uniquely, the Aquaflow harvesting technology has been in operation at the Blenheim Municipal Wastewater site for more than 2 years harvesting microalgae. Aquaflow’s continuous harvester processes 35 m³ of water each hour, and achieves between 70 and 90% recovery of microalgae with minimal human oversight. Each harvester is built inside a 40 ft sea container, enabling modular networks, built with standard components, exhibiting low electricity consumption. The company’s approach is unique as it avoids challenges of most other microalgae biofuel system strategies based around microalgal
monocultures, ponds, or bioreactor technologies. Aquaflow’s 60 ha of open oxidation ponds serves a population of 27,000, with a mix of sewage, municipal, and agro-industrial waste, with a water flow of 5 GL yr\(^{-1}\). Aquaflow claim that whilst wild microalgae populations change seasonally, an average equilibrium of the total population remains suitable for biofuel production. Despite the relative oil fractions of each species varying considerably, the company utilises an integrated Pyrolysis and hydrogenation process using the total microalgae biomass. Therefore, the process is not reliant on direct oil extract from the microalgae.

The economics of the biofuel conversion processes are unavailable to the authors at this stage. However, the company omit sales of microalgae biofuels and potential carbon sequestration value from their business model, and state that they solely rely on water remediation and equipment sales. Aquaflow would be able to sell refined microalgae biofuel feedstock and have also recently focussed on high value co-products, but may also receive water processing royalties. In addition, as wastewater oxidation ponds culture microalgae as a by-product of the process, the focus on productivity is somewhat depreciated, as long as sufficient biomass is available over the majority of the year.

**Aquaflow Bionomic Corporation Summary**

Aquaflow’s commercial advantage in producing microalgae biofuels by the use of existing sewage oxidation ponds is likely to produce a relatively inexpensive source of microalgae biofuel feedstock. To the extent that this option is reproducible will depend on oxidation sewage pond designs, associated inflow rates, and environmental conditions suitable for microalgal cultures. Therefore, the availability of suitable sites will determine the maximum output of macroalgae biofuels using Aquaflow commercial model. Unfortunately, little data are available to verify the seasonal variance of productivity in the existing pilot plant ponds in Blenheim. However, the notable interest of Aquaflow partners suggests that annual average microalgae production and associated downstream processing economics are attractive. As a comparison with productivity figures from dedicated microalgae ponds, the average annual productivity from wild microalgae is around 5 g m\(^{-2}\) day\(^{-1}\), or the equivalent of 18.25 t ha\(^{-1}\) yr\(^{-1}\). For example, if the 70–90% efficient harvester used in the 60 ha pilot facility ponds, the annual microalgal biomass collected would be around 766–985 t yr\(^{-1}\). This relatively small annual primary biomass production illustrates why Aquaflow’s commercial focus remains water remediation, and cost-effective sustainable biofuels, carbon sequestration, and other co-production streams to create an additional benefit, rather than simply a low-cost, high-volume model.

**Aurora Algae Inc. www.aurorainc.com**

Aurora Algae (formerly Aurora Biofuels) was founded in December 2006 in Alameda, California as an owner-operated biofuel company. The company specialises in open pond microalgae culturing developed by Prof. Tasios Melis at Berkeley University, and conversion technology based on transesterification of microalgae oils. Aurora’s operational facilities are in Vero Beach, Florida, USA (<1 ha), and Karratha in Western Australia (~2.5 ha), the site of the “Algae Biofuel Demonstration Facility”. Aurora Algae has attracted several investors, including Gabriel Venture Partners® (based in Silicon Valley with over USD260 million in ventures under management), Noventi Ventures (also from Silicon Valley with past investments including Bitfone, EasyMarket, Sygate and M7), and Oak Investment Partners (over USD8 billion in committed capital with more than 481
companies. Aurora Biofuels has raised over USD40 million to fund construction of demonstration open pond systems.

**Aurora Algae Review**

Aurora completed an 18 month pilot project in early 2009 at the Vero Beach pilot facility. Whilst the capacity of the facility is less than 3,500 L microalgal biofuel yr⁻¹, the company states that it has produced biodiesel to the American Society of Testing and Materials (ASTM) standard. Aurora aims to improve pond productivity primarily through enhanced genetics, and is using proprietary non-transgenic methods to develop unique strains (directed mutagenesis).³ Aurora is focussing on low-cost production systems and use CO₂ injection to both provide mixing and deliver gas to eliminate the need for conventional aeration components. The company uses flotation technology to harvest, and state they achieve a relatively high microalgae-to-water concentration (20%). Wet extraction of microalgal oil is used, which reduces energy consumption and cost by avoiding the drying process entirely. Aurora states their production process is able to produce fuels other than biodiesel, although little detail is available.

Aurora Algae is in the process of building 20 ha “Algae Biofuel Demonstration Facility” in Karratha, Western Australia, which is expected to use industrial CO₂ emissions for culturing photosynthetic microalgae to produce biodiesel, protein-rich feed for fish and human consumption, including omega-3 oils. This small facility is expected to be the forerunner to a commercial production facility, and produces between 12–15 tonnes of algal biomass per month (Aurora Algae 2012). In terms of economics, Aurora expect to produce biofuel at USD0.5 L⁻¹ by 2012, assuming average productivities of around 33,000 L ha⁻¹ yr⁻¹ (around 9 g m⁻² day⁻¹ of fuel) with microalgal biomass sold at USD300 t⁻¹, all produced in an 800 ha production facility. This also assumes a zero-cost CO₂ source. In terms of yield, most company’s best average productivity is around 20 g of microalgal biomass m⁻² day⁻¹, and oil fractions of oil species are generally between 40 and 60%, excluding associated conversion losses. Therefore Aurora’s productivity estimates are reasonable, in the opinion of the authors, and is based on actual production at the small scale. However, CO₂ extraction, pumping, and reticulation is not in reality ‘free CO₂’, and it appears that Aurora are using biomass sales to effectively subsidise biofuel production, and further processing may be required on site. For example, the biomass will exhibit excessive salt concentrations for use as an animal fodder without washing. There is also limited availability of basic cost data for Aurora’s Karratha facility including conversion processes, energy inputs, fertiliser requirements, capital and operating costs, etc. Based on the knowledge of the authors of the area, we believe the actual cost of fuel production at this location is likely to be at least 25% higher than the USD0.5 L⁻¹ value. In the author’s opinions, while good progress is being made, the USD0.5 L⁻¹ value is optimistic and speculative, as the full 20 ha facility in Karratha remains unbuilt and the final microalgae strains are being developed.

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⁵Patents of Aurora include, WO2010011335 Glyphosate applications in aquaculture, WO2010008490 The use of 2-hydroxy-5-oxoproline in conjunction with algae, WO2009149470 VCP-based vectors for algal cell transformation, WO2009082696 Methods for concentrating microalgae, and WO2008060571 Methods and compositions for production and purification of biofuel from plants and microalgae.
Aurora Algae Summary

Aurora's relative competitiveness is hinged on their production technology, microalgae productivity, and processing capability. In general, the microalgal concentrating and wet extraction technology, alongside any potential multiple output production makes Aurora an attractive commercial competitor in microalgae low-cost, high-volume biofuel space, although future developments will provide more information of yields and associated costs. Aurora's non-transgenic GM microalga strain development may be extremely successful in terms of high productivity. However, there will be concerns over the high-yielding non-transgenic strains resilience to competition, and questions of selective propagation in open ponds over time. The completed 18 month project is likely to have produced data on the magnitude of the oil yield decline, although this information is unavailable to the authors.

Harvesting, Dewatering, Extraction, & Conversion Considerations

All seven companies considered in this chapter aim to produce large quantities of microalgae biomass using open cultivation systems, and have chosen or will have to choose a process to convert this biomass into saleable products. The focus of many of these companies is biofuel, although some are focussing on alternative value chains such as nutraceuticals, chemicals, or remediation approaches. Figure 1 outlines that cultivation of microalgae is only the first step in a multistage system required to convert microalgae to fuels. Although the focus of this review is on the current commercial status of open systems for microalgae cultivation, it is fundamental that the growth system is considered in the context of the entire process, including harvesting/dewatering, extraction, and conversion.
The concentration of microalgae in open pond systems are typically between 0.5 and 2 g L\(^{-1}\) (Fon Sing et al. 2011) which is up to 10 times less than the cell density in closed (photobioreactor) systems. This low density requires moving and harvesting massive quantities of water in multiple stages as demonstrated in Fig. 2. Primary dewatering is typically achieved through flocculation, and once flocculated, the concentrated algae solution is separated from the water via settling or flotation (e.g., dissolved air flotation). Various methods of flocculation can be used with some algae naturally flocculating while other species requiring the addition of chemicals or flocculants like chitosan to induce the agglomeration of cells (In addition to these methods, some companies such as Origin Oil and Diversified Technology have used pulsed electric fields with great success to enhance flocculation and lyse the microalgae cells).
Secondary dewatering or mechanical drying is typically achieved through physical separation of the water and the algae on the basis of mass difference via centrifuges or decanters. These machines are energy intensive, however, recent developments by Evodos have seen the power consumption drop significantly (Evodos 2011). In addition, a membrane recently developed by Pall Corporation is able to separate microalgae from water, requiring much lower energy consumption than standard centrifuges. After mechanical drying, the microalgae solution resembles toothpaste or a thick sludge. Removing the remaining water is undertaken by drying with heat. Although a range of dryer technologies exist, the fundamental need to vaporise the water results in a very high energy burden. Consideration of the required downstream harvesting and dewatering operations indicates the need for large microalgae developments to optimise upstream strain selection, water/nutrient recycling, and other downstream processes to be competitive. The wide range of methods proposed for converting microalgae to fuel can be categorised into one of two groups:

- Processing the whole algae for conversion into fuel or other products;
- Extraction of oil or other components from algae for conversion into fuel or other products.

Within these two groupings, there are methods that require dried microalgae biomass and methods that are effective in the presence of water, and Fig. 3 provides a useful guide to characterising the wide range of methods under research or being pursued in commercial application (deBoer et al. 2012). It is also possible for microalgae to produce fuel via direct secretion, like the ethanol producing microalgae cultivated by Algenol, and the hydrocarbon secreting chlorophyte Botryococcus braunii (Metzger and Largeau 2005). Despite this potential, most companies pursuing large scale open pond cultivation are considering conversion methods that fit in to the two categories listed above.
Although energetically feasible, relatively simple and proven anaerobic digestion yields a low value product, methane, and is typically not pursued commercially except as a means of converting byproducts to energy. Out of the three thermochemical methods, liquefaction is the most promising as it produces a crude oil replacement from microalgae in the presence of water at relatively mild conditions (Biller and Ross 2011). Furthermore, this process was shown to be the most energetically feasible process in a comparison of the four most promising methods available for conversion of microalgae into fuel (de Boer et al. 2012). Instead of processing the whole microalgae cell, it is possible to extract components of interest (e.g., lipids) and convert these compounds to desired fuel products. The most familiar method is some form of solvent extraction (e.g.: soxhelet) to remove the oil from the dried biomass followed by transesterification (Lardon et al. 2009). Although technically feasible, this method is economically impractical due to the very high energy burden associated with drying and solvent extraction. In response, methods to convert compounds like lipids in situ have been developed resulting in simultaneous extraction and conversion of the compounds of interest from the microalgae. The most feasible method in this category involves mixing the dried and disrupted biomass with methanol and a strong acid to produce fatty acid methyl esters (Wahlen et al. 2011). Although effective, this method still results in a high energy burden and associated cost due to the need for drying and evaporation of large excess volumes of methanol (de Boer et al. 2012). To overcome the problems associated with drying, further methods have been developed to convert the lipids directly to fuel products in-situ in wet microalgae biomass. One recent method showing promise in this category is the supercritical ethanolysis and subsequent esterification proposed by
Levine et al. (2010). Despite being effective this method still results in the need to purify (evaporate) large volumes of ethanol ultimately resulting in a high energy burden. Unfortunately, it is at present not possible to say that any of the numerous methods in development will become commercial viable at the industrial scale, with very few of them energetically viable (producing more energy than they consume) (Borines et al. 2011a, de Boer et al. 2012, McHenry 2012). With these challenges in mind, it is necessary that companies pursuing high-volumetric production of fuels, chemicals, or other compounds of interest from microalgae carefully consider the effect their cultivation system has on the entire process.

Conclusion
Historically, commercial open microalgae production has been limited to relatively small-scale volumetric production of high-value products (Pulz and Gross 2004). Irrespective of the current range of competing companies using open systems, industrial-scale microalgae production of cost-competitive biofuels will require detailed biotechnical and system control capability to achieve production reliability, and aim to lower production costs (Jamers et al. 2009, Kovacevic and Wesseler 2010). In the recent past, in an attempt to produce high-volumetric microalgal energy products, the industry has witnessed collectively recurring issues associated with biological system unpredictability, variable photosynthetic efficiencies, technological challenges with poor CO2 addition, high energy inputs, and fundamental difficulties in microalgae harvesting and extraction (Brennan and Owende 2010, Clarens et al. 2010, Borines et al. 2011a). These issues are fundamental to progressing towards sustainable supplies of low-cost and high-volume algal biofuels.

This review suggests that the current suite of open pond microalgae technical developments are progressing towards a low-cost, high-volume sustainable supply of liquid fuel, yet is highly conditional on the sum of the technical resources and commercial strategies of each major player. Competing in low-cost, high-volume energy markets against conventional fuels will require enormous further technological development to achieve commercially viable and sustainable microalgal biofuel production systems (Brennan and Owende 2010, Kovacevic and Wesseler 2010). The authors would like emphasise that these challenges are not insurmountable, but will likely require an unprecedented level of collaboration between several industries historically unrelated with biotechnology or the biological sciences generally, and long-term support from both governments and non-government institutions.

References


