

# OPPORTUNITIES AND CHALLENGES IN ALGAE BIOFUELS PRODUCTION

# A Position Paper by Dr. John R. Benemann in line with Algae World 2008



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# ALGAE BIOFUELS - AN INTRODUCTION

Summary: The cultivation of microalgae for biofuels in general and oil production in particular is not yet a commercial reality and, outside some niche, but significant, applications in wastewater treatment, still requires relatively long-term R&D, with emphasis currently more on the R rather than the D. This is due in part to the high costs of even simple algae production systems (e.g. open, unlined ponds), and in even larger part to the undeveloped nature of the required algal mass culture technology, from the selection and maintenance of algal strains in the cultivation systems, to achievement of high productivities of biomass with a high content of vegetable oils, or other biofuel precursors.

#### CURRENT COMMERCIAL TECHNOLOGY

icroalgae are currently cultivated commercially for human nutritional products around the world in several dozen small- to medium-scale production systems, producing a few tens to a several hundreds of tons of biomass annually. The main algae genera currently cultivated photosynthetically (e.g. with light energy)

for various nutritional products are Spirulina, Chlorella, Dunaliella and Haematococcus (Figure 1). Total world production of dry algal biomass for these algae is estimated at about 10,000 tons per year. About half of this produced takes place in mainland China, with most of the rest in Japan, Taiwan, U.S.A., Australia and India, and a few small producers in some other countries.

Figure 2 provides examples and description of some of these commercial production systems. Microalgae biomass is also produced for live aquaculture feeds in systems that individually produce from a few kilograms to a few tons of biomass annually. Microalgae flourish in municipal wastewater treatment ponds, where they perform a waste

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purifying function (Figure A), but harvesting of the algal biomass is generally not practiced, and where it is the chemical flocculants used to remove the algal cells limit further uses of the algal biomass, even for biofuels (e.g. anaerobic digestion for methane generation).

Finally, production of microalgae for nutritional products is also carried out commercially by dark fermentations (using

starch or sugar, -rather than light energy and CO<sub>2</sub>) as in photosynthesis with a few thousand tons of algal biomass with a high content of valuablee omega-3 oils, used mainly in infant formulas, produced by this route. This approach has also been proposed by at least one company as a near-term route for biodiesel production. However, here we emphasize photosynthetic processes and such fermentation systems are not discussed further.

#### PONDS AND PHOTOBIOREACTORS

icroalgae cultivation using sunlight energy can be carried out in open or covered ponds or closed photobioreactors, based on tubular, flat plate or other designs. Closed systems are much more expensive than ponds, and present significant operating challenges (overheating, fouling), and due to gas exchange limitations, among others, cannot be scaled-up much beyond about a hundred square meters for an individual growth unit.

For large-scale biofuels production, which would require systems of hundreds of hectares in scale, this would mean require deploying tens of thousands such repeating units, at great capital and operating cost. Open ponds, specifically mixed raceway ponds (Figure 2B) are much cheaper to build and operate, can be scaled up to several hectares for individual ponds and are the method of choice for commercial microalgae production. However, such open ponds also suffer from various limitations, including more rapid (than closed systems) biological invasions by other algae, algae grazers, fungi and amoeba, etc., and temperature limitations in colder or hot humid climates.

The hydraulics (e.g. dispersion and mass transfer coefficients) of large ponds are also uncertain. Nevertheless, about 98% of commercial algae biomass production is currently with open ponds, even for high value nutritional products, which sell for prices over a hundred- and even a thousand-fold higher that allowable for biofuels. It must be noted that almost no information is available on the detailed designs, operations, yields, and other important aspects of commercial algal production, "Open ponds, specifically mixed raceway ponds (Figure 2B) are much cheaper to build and operate, can be scaled up to several hectares for individual ponds and are the method of choice for commercial microalgae production."



contrasting to the hundreds of publications from academic laboratories and others on algae cultivation with small-scale closed photobioreactors. This has led to a perception that the latter are the better and more promising production systems.

#### **ALGAE BIOFUELS**

Algae for biofuels have been studied for many years for production of hydrogen, methane, vegetable oils (triglycerides, for biodiesel), hydrocarbons and ethanol.

Algal hydrogen production has been extensively researched

for over three decades, but no mechanism that could plausibly be even conceptually scaled-up has not yet been demonstrated, even in the laboratory, and is, thus, not further addressed. This experience is a salutatory example that not all research leads to favorable outcomes, and, further, that research approaches that are not successful must be abandoned when their limitations are recognized. Of course, such recognition is often difficult for those who have invested a lifetime in such research.

Methane was the focus of most of the early work in microalgae biofuels production, when microalgae were considered mainly for their applications in wastewater treatment. Anaerobic digestion of algal

biomass remains an option, but the higher value of liquid transportation fuels, from microalgae, has been the focused of most attention on algae oil, specifically biodiesel production since the 1980s, after the first oil shocks. "The concept of having the algae

> few researchers have also studied, and some ventures are now promoting, the concept of ethanol production with algae, including one small company that implausibly claims to have received commitments for almost a billion dollars from a Mexican conglomerate. In any event, ethanol production by or from microalgae has many inherent limitations. The

possibilities are to either have the algae themselves directly produce ethanol by photosynthesis or, alternatively, to accumulate large amounts of starch and then metabolize this to ethanol. In either case, the ethanol would need to be excreted into the growth medium at very high levels, to allow its recovery. These would be daunting challenges for even advanced genetic engineering techniques. "The concept of having the algae themselves produce would require that the algae accumulate large amounts of starch by photosynthesis and then metabolize this to ethanol excreted into the media at very high levels, to allow its recovery."

More simply would be the production of starch by microalgae and its subsequent fermentation by yeasts, as practiced with cane sugar and corn starch in fuel ethanol production. Such an approach, however, would compete with very low-cost sugar and starch produced by higher plants. It is, however, not all that different in concept from the production of vegetable oils, triglycerides specifically, which is the focus of almost all the current interest in algae biofuels.

#### ALGAE HARVESTING AND STRAINS

The basic concept of algal oil production is to use relatively small (in total area) photobioreactors to produce a modest amount of "inoculum" culture (about 1-2 % of the total biomass produced) to

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seed much larger, totaling several hundred hectares, open ponds. Between 20 and 40% of the pond volume would be harvested on a daily basis (depending on season and other factors). The biomass would need to be concentrated by an initial factor of at least about thirty-fold, requiring very low-cost harvesting processes, such as



"bioflocculation", a spontaneous flocculation-sedimentation of the algal cells, using no, or at most very little, flocculation chemicals. Such low-cost harvesting processes must be developed and demonstrated for each algal species and even strain. At present there are no low-cost harvesting technologies available. The algal strains to be cultivated would be selected based on many criteria, of which oil content, productivity, and harvestability would be primary, but also resistance to contamination, tolerance of high oxygen levels and temperature extremes, and adaptation to the local water chemistry and other local conditions experienced by the algal cells in the growth ponds.



fter harvesting, further concentration and oil extraction is required, for which various processes are proposed, including cell breakage and solvent extraction, possibly using a three phase centrifugation. The residual biomass could be either sold as animal feed or, more plausibly at present, converted to biogas, for use in on-site power production, with the residual nutrients (and carbon) recycled back to the growth ponds.

#### POWER PLANT CO2 UTILIZATION

Central to the concept of algal biofuels production is the use of power plant flue gas or a similar

nearby available, enriched source of  $CO_2$ . However, contrary to what is often stated,  $CO_2$  capture by algal cultures is not a  $CO_2$  sequestration or greenhouse gas abatement process. That can only come from converting the algal biomass to biofuels and their use in replacing fossil fuels. And, of course, any fossil, and even non-fossil, energy expended by the process must be accounted for. Thus, in terms of greenhouse gas reductions, algal biofuels are fundamentally no different than other biofuels derived from higher plants, or other renewable energy sources.

#### **ECONOMICS**

The critical issue, after technical feasibility, that is the actual ability to reliably cultivate algal strains that can produce oil at reasonably high productivities, is the overall capital and operating cost of these production systems. Currently the plant gate production cost (e.g. not including costs such as marketing) for the lowest cost algal biomass produced for the nutritional market, *Spirulina* can be estimated at about \$5,000 per metric ton. Although this alga does not make oil, and has relatively low

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productivity, assuming that oil containing algae could be produced for a similar cost, and that the algal biomass had content of 25% oil, this would translate to \$20,000/ton of oil, or over 20-fold higher than



current vegetable or crude oil prices.

Of course it can be rightly argued that current commercial algae production is very small scale and inefficient, and that the

economies of scale possible for biofuel production, as well as foreseeable advances in the technology, could reasonably overcome this gap. Even assuming that high biomass and oil productivities are possible and stable cultivation achievable, the major problem is likely the irreducible minimal costs of large-scale cultivation systems, including the needed infrastructure, processing, waste treatment, water supply and other support systems required.

Prior economic-engineering feasibility analyses have conclude that even the simplest open pond systems, including harvesting and algal biomass processing equipment, would cost at least \$100,000 per hectare, and possibly significantly more. To this would need to be added operating costs. And algae production requires a site with favorable climate, available water (which can be saline, brackish or wastewater), a ready and essentially free source of  $CO_2$ , nearly flat land, and with a clay soil or liner, as plastic liners would be too expensive.

In brief, this represents the current reality, opportunity and challenges of microalgae oil and biofuels production. Because of the very high costs of closed photobioreactors, these would not be applicable to algal oil production, asides their above discussed use in seed production. In any event, development of this technology will require long-term, high risk, R&D.

#### PRODUCTIVITY

A

ssuming a currently achievable yield of about 50 mt/ha-yr biomass with 25% oil content (as triglycerides useful for biodiesel), or a yield of about 14,000 liters of oil per hectare per year, even a \$1/liter, selling price, this would not be sufficient to cover the above estimated optismitic capital costs (depreciations, return on capital, other fixed costs),

let alone any operating costs. Clearly, this requires a major improvement in the productivity of such systems, with a doubling, or even tripling, in outputs of what is currently possible.

This rough comparison does, however, put into context the current situation, compared to higher plants. Which already are produced at costs competitive with presently high oil prices. However, using oil, starch, sugar or other crops for biofuels is limited by the need to feed the human population, and, in any event, would be severely limited in its ability to "The interest in microalgae, as for other alternative biofuel sources, is that there would, or could, be less competition with food and feed production and that large-scale production is possible."



produce more than a small fraction of the demand for transportation fuels. The interest in microalgae, as for other alternative, so called second generation biofuel sources, is that these would, or could, be



less competition with food and feed production and that large-scale production is possible.

#### **R&D NEEDS**

In brief, the objective of R&D in this field is to demonstrate that it is actually possible to mass culture algae for maximal oil productivity, and harvest them cheaply, which remains to be shown, and to reduce the cost of such algal biomass production to an acceptable level.

The main issue that must be addressed by the future R&D is how to bridge the gap between the current reality, exemplified by commercial production systems (Figure 2) and the goal of low-cost algae oil production, which requires much higher "One of the advan productivities and oil content than is currently achievable. "One of microalgae is the system of microalgae is the system of microalgae is the system of microalgae is the system."

A long litany of R&D needs and goals can be formulated, centered both on the organisms, the algae, and the engineering of, the cultivation system. There is a need to isolate screen, select, test (in outdoor ponds) and genetically improve algal strains, for both higher oil content and overall productivity (e.g. photosynthetic efficiency in mass culture), as well as for resistance to grazers, invasions, temperature and other environmental factors, etc.

"One of the advantages of microalgae is their short generation times, as little as one day in outdoor mass cultures ... and a few hours under laboratory and even outdoors after inoculation."



ne of the advantages of microalgae is their short generation times, as little as one day in outdoor mass cultures (e.g. at the 50% per day dilution, readily achievable under

favorable conditions) and a few hours in the laboratory, and even outdoors after inoculation before the culture achieves optimal density for maximal productivity. This fast growth rate allows more rapid development of this technology than for

conventional crop plants, where a single lifecycle can be months to years.

Even with this advantage, the development of the algal strains and cultivation technologies to the level of productivity, efficiency, stability, and easy harvesting required for biofuels production will be very difficult and require years, assuming it proves to be actually feasible at all. Further, such developments in the "software", must be combined with the "hardware", the engineering design of the production system, including not only the large ponds, larger than anything operated thus far for intensive commercial cultivation, but also the algal processing, oil extraction, etc.

Again, there is no guarantee that a sufficiently low-cost process can actually be engineered. On the other hand, there are no clear "show-stoppers" that would suggest that either the biological or

engineering R&D required cannot be eventually successful.

### **RESOURCE POTENTIAL**

A final major issue is the resources potential for such systems. After

factoring in all the requirements for algal biomass and biofuels production, from climate, flat land, water and, most importantly, a local source of  $CO_2$ , among others, even a cursory analysis would suggest that the vision of enormous algae farms populating the deserts and producing large amounts of oil, from a small corner of the Southwest USA or the coastal Sahara, or wherever, is misguided. Algal biofuels are not likely to replace petroleum, as their most ardent promoters argue, but, on the other hand, certainly could, assuming the technology can be developed, become a worthwhile, perhaps even a significant, contribution to the goal of renewable energy production, in particular of transportation fuels. Again, the resource potential requires further study.

#### WASTEWATER TREATMENT

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ne short-cut to the goal of algae biofuels development would be to co-produce algal biofuels, specifically, vegetable oils, with higher value products, or in wastewater treatment. This pathway of development would allow this technology to develop and mature to the point where the algae biofuels could become an ever more important component of such processes, and eventually even the main outputs.

If these approaches the one that has the greatest opportunity for near-term applications is in wastewater treatment, and specifically municipal wastewater treatment. Microalgae are already used in wastewater treatment (Figure 2) where they provide  $O_2$  for bacterial breakdown of the organic component in the wastes. This technology is greatly limited by the lack of a reliable and low-cost algal harvesting process. A spontaneous flocculation and settling process ("bioflocculation") process is possible but remains to be demonstrated with a full-scale system.

Demonstrating such a low cost harvesting technology in municipal wastewater treatment would also open the way for nutrient removal from other wastewaters, allowing such processes to achieve a much higher level of treatment, at a much lower cost, and with biofuels production and greenhouse gas reduction, compared to conventional, energy intensive processes. Such a process development effort will require a cooperative and collaborative R&D approach which does not easily fit the paradigm and business model of true / most algal biofuel ventures.



# FIGURE 1. ALGAL STRAINS CURRENTLY MASS CULTURED



1. Spirulina (Arthrospira platensis)



3. Chlorella vulgaris



2. Dunaliella salina



4. Haematococcus pluvialis

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2 http://www.bpe.wur.nl/NR/rdonlyres/0DBAF32C-8B96-447B-937D-051AF2452101/48133/salinaorange1.jpg 3. http://io.uwinnipeg.ca/~simmons/16labman05/lb1pg7\_files/Chlorella2.jpg

#### FIGURE 2: EXAMPLES OF CURRENT COMMERCIAL ALGAL PRODUCTION SYSTEMS

# **A. Large open, unmixed ponds** for wastewater treatment and *Dunaliella salina* production. A.1. Wastewater treatment ponds, so-called "oxidation ponds" are not true algae production ponds, as algae productivity is not maximized and the biomass produced is rarely harvested and when harvested, by chemical flocculants the chemical flocculants interfere with utilization for biofuels. A handful of waste treatment ponds use the mixed raceway designs, discussed below, and these have great potential for application in a wastewater treatment process.

A.2. **Dunaliella salina** production in Australia uses very large saline evaporation ponds (>100 acres each), with these algae dominating naturally in >100 g/l of salt. However such open unmixed ponds result in their being produced at very low productivities (<5 ton/acre-yr). The algae is harvested by adsorption on polymers and their oil, very high in beta-carotene, extracted and sold.

**B.** Open, raceway, shallow, mixed ponds. These ponds are bout 15 to 35 cm in depth, are typically mixed with paddlewheels, are usually lined with plastic or cement, and are between 0.2 to 0.5 hectares in size. They are "high rate" ponds because their productivity is much higher (factor of ten almost) than the unmixed ponds just described. These high rate ponds are the main system currently used for commercial algae production of *Spirulina (Arthrospira platensis) Dunaliella salina, Chlorella vulgaris* and *Haematococcus pluvialis* (for astaxanthin) production. (Circular mixed ponds are also used for Chlorella production in the Far East). Two examples arer shown.

**C. Closed Photobioreactors** of many designs, with tubular reactors the dominant technology in commercial operations, both small diameter (~5 cm) rigid and larger diameter (>10 cm) flexible bag type reactors. Many other designs have been used in pilot scale production, including flat plate reactors, hanging bag reactors, hemispherical dome reactors, etc. These closed photobioreactors reactors currently produce *Haematococcus pluvialis* commercially in Hawaii (see Figure C1) and Israel (Figure C2).

**Figure A.1. Typical Oxidation Pond for Wastewater Treatment** (Napa, California, total about 140 hectares)



**Figure A.2. Dunaliella salina production ponds in Australia** (Each pond ~50 acres in size).



**Figure B.1. (Left) Spirulina production in open raceway paddle wheel mixed ponds** (Earthrise Nutraceuticals, LLC, California. Ponds in foreground appx. 0.5 hectares in size).



**Figure C1.** Examples of commercial closedphotobioreactors for production of astaxanthin with Haematococcus pluvialis. (Fuji Co., Hawaii) (diameter of each dome is a little over 1 meter). **Figure B.2. (Right) Open raceway paddle wheel mixed ponds at Cyanotech Corp.,** Kona, Hawaii, USA. Spirulina (blue-green ponds on to top of figure and Haematococcus pluvialis (red and green ponds, showing the two growth stages of this astaxanthin producing alga) on bottom.



**Figure C2.** Tubular Photobioreactors: (Algatech, Israel), each tube is about 6 cm in diameter and 100 m long.





## SOME RESOURCES AVAILABLE ON THE WEB FOR FURTHER INFORMATION

Benemann J.R. and W.J. Oswald. Final Report to US DOE NETL, 1996 "Systems and Economic analysis of microalgae ponds for conversion of CO2 to biomass" At: http://www.osti.gov/bridge/servlets/purl/493389-FXQyZ2/webviewable/493389.pdf

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# **ABOUT THE AUTHOR**



Dr. Benemann has worked in the area of biofuels, in particular microalgae biofuels, greenhouse gas abatement and environmental biotechnologies, for over 30 years. He was a participant in the US Dept. of Energy "Aquatic Species Program" and was a principal author of the final report of that program.

Among other activities, for the past six years he was a member of the US DOE-NETL (National Energy Technology Laboratory) "DOE Carbon Sequestration Project Review Committee" and also Manager of the "International Network on Biofixation of CO2 and Greenhouse Gas

Abatement with Microalgae" operating under the International Energy Agency "Greenhouse Gas R&D Programme."

He is a full time consultant and works for numerous companies and research organizations. He is also on the steering committee of the Algal Biomass Organization, an not-for-profit industry association.

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Algae World 2008 guarantees objective insights on Commercialization of Algae Biofuels, latest advances &

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