# MICROALGAL BIOFUELS: A BRIEF INTRODUCTION

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**Summary.**

The cultivation of microalgae for biofuels in general, and oil production in particular, is not a near-term commercial prospect. Aside from some niche, but significant, applications in waste-water treatment, this technology still requires considerable, long-term R&D. This is due in part to the high costs of even the simplest of algal production systems (unlined, open, paddle wheel-mixed, raceway-type ponds), in even larger part due to the presently undeveloped nature of algal mass culture technologies, from the selection of algal strains that can be stably maintained in the open ponds to their low-cost harvesting, and, most importantly, due to the need to achieve very high productivities of algal biomass with a high content of vegetable oils or other biofuel precursors, required by the high capital and operating costs of algae production. However, R&D to achieve these goals is justified by the potential to produce biofuels at very high productivities using saline water, land and other resources not useful in food production.

## Current Commercial Algae Biomass Production Technologies.

Microalgae are currently cultivated commercially for human nutritional products around the world in several dozen small- to medium-scale production systems, each producing a few tens to several hundred tons of biomass annually. I estimate total world commercial microalgal biomass production at about 10,000 tons per year. The main algae currently cultivated photosynthetically (i.e. with sunlight) for nutritional products are *Spirulina*, *Chlorella*, *Dunaliella* and *Haematococcus* (Figure 1). About half of the microalgae production takes place in mainland China, with most of the rest in Japan, Taiwan, USA, India and Australia, with smaller producers in other countries. Almost all (~99%) commercial production is carried out with open ponds. (See Figure 2 for examples of commercial production systems).

Microalgae also flourish in municipal wastewater treatment ponds (Figure 2.A.1.), where they help to purify the wastes. However, harvesting of algal biomass is generally not practiced in such systems, and where it is, the chemical flocculants required both greatly increase costs and limit utilization of the algal biomass, even for conversion to biofuels (i.e. methane by anaerobic digestion, as such waste-grown algae contain little if any oil. See below for further discussion).

Microalgae are also grown for live aquaculture feeds in hundreds of systems around the world that individually produce from a few kilos to at most a few tons of biomass annually and in these systems small-scale, enclosed cultivation systems (photobioreactors) are often used.

Finally, microalgae are produced commercially by dark fermentations (using starch or sugar), with a few thousand tons of algal biomass produced by this route mainly in the Far East for *Chlorella* used as a nutritional supplement, and, mainly in the US, for oil (triglycerides) high in the omega-3 fatty acid DHA, mainly used as an infant formula ingredient. This approach has also been proposed for algae oil production for biofuels, though current production technology requires rather expensive fermentation systems. This is approach is not further discussed herein. The potential of biofuels from seaweeds (macroalgae), will be covered in a future piece.

**Ponds and Photobioreactors.**

Microalgae cultivation using sunlight energy can be carried out in open or covered ponds, or in closed photobioreactors, including tubular, bag and flat plate designs. Closed systems (Figures 2.C.) are much more expensive than ponds, and present major design and operating challenges (overheating, fouling, gas exchange limitations, etc.). Most importantly, they cannot be scaled-up for individual growth units above about a thousand square feet (~100 $m^2$), often less. For biofuels production, which requires systems of hundreds of acres, this would mean thousands of such units, at high capital and even greater operating costs.

Open ponds, specifically shallow, mixed, raceway ponds (Figure 2B), are much cheaper to build and operate, can be scaled to several acres for an individual growth pond (though the maximal size is presently uncertain), and are the method of choice for commercial microalgae production around the world (Figures 2.B). Engineering designs of open ponds, including mixing systems (typically paddlewheels) and $CO_2$ supply and transfer, is rather well understood. Thus the main focus of future research must be on the biology of algae mass culture, rather than the engineering. Open pond cultures suffer from various limitations, including more rapid (compared to closed systems) invasions by other algae and algae grazers, fungi, amoeba, etc. Closed systems have advantages in colder climates, though, on the other hand, they would require cooling most days, with water spray the only practical cooling method, at high water use.

Almost all commercial algal biomass production is currently produced with open ponds, even for high value nutritional products selling for over a hundred dollars a kilogram, when for biofuels allowable costs are less than a dollar a kg. Almost no information is available on the design, operation, yields, and other important aspects of commercial algal production systems. In contrast, hundreds of publications from academic and government laboratories describe algae cultivation with small-scale closed photobioreactors. This has led to a widespread, but incorrect, perception that the latter are the better and more promising production systems for algal biofuels.

**Microalgae Biofuels.**

Microalgae have been studied for many years for production of hydrogen, ($H_2$), methane, oils (triglycerides and hydrocarbons, for biodiesel, jet fuels, etc.), and bioethanol.

Algal $H_2$ fuel production has been extensively studied for over thirty years, but no mechanism that could be plausibly scaled-up has as yet been described or demonstrated, even in the laboratory. Thus, algal $H_2$ production is not further addressed. However, this is a salutatory example that not all research leads to favorable outcomes, and that unsuccessful research approaches 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 (biogas) production by anaerobic digestion of algae biomass was the focus of most of the early work on biofuels from microalgae, when these were considered mainly for applications in wastewater treatment. However, the higher value of liquid transportation fuels - ethanol and oils - focused more attention on these biofuels after the 1970s oil price shocks, for example by the U.S. Dept. of Energy Aquatic Species Program (See Sheehan et al., 1998).

For ethanol production, algal cells would have to accumulate sugars or starches and then ferment these to produce ethanol at rather high levels (> 6% by volume) to allow for its economic recovery; daunting challenges even for advanced genetic engineering techniques. More simply would be the accumulation of starch by microalgae, their release from the cells and subsequent yeast ethanol fermentations, as in corn starch ethanol production. Such a process would need to compete with the very low-cost starch or sugar produced by crop plants. The production of ethanol by a pathway coupled directly to photosynthesis would not be practical, despite some seeming assertions for such a process by some commercial producers.

The main focus of most current interest in algae biofuels is the production of algae oils, e.g. triglycerides. In brief, some microalgae accumulate large amounts of oil, in particular triglycerides, when subjected to stress conditions (in particular nitrogen limitation for green algae and silicate limitation for diatoms). The key issue is not only accumulation of oil to high levels but also achieving high productivity, with a target of one barrel of oil per hectare per day, on average. Achievement of this goal remains to be demonstrated. One species, *Botryococcus braunii*, can contain about 50% of its dry weight as hydrocarbons, even under normal growth conditions. However, it grows very slowly and its large-scale cultivation remains a challenge.

Oils or hydrocarbons from microalgae can be converted through catalytic hydrogenation to hydrocarbons ("green diesel" or bio-jet fuel) with technology developed for other vegetable oils. Dried microalgae biomass can be converted to a relatively low quality oil via pyrolysis, but this technology is not unique to algae. Wet algae biomass can also be converted to "syngas" (a mixture of CO and $H_2$) by hydrothermal gasification processes, a more promising approach.

Recent proposals are to produce algae hydrocarbons by genetic engineering, for a higher quality, more directly useable ("drop-in") fuel than biodiesel. A favored scheme is for short-chain hydrocarbons synthesized and excreted by the algal cells, which thus act as a continuous oil production factory. The oil would be skimmed off the algae growth unit, or extracted into a non-polar phase. Although rather futuristic, and fraught with practical problems (for one example only: how to prevent bacteria from consuming the excreted hydrocarbons), this concept has recently garnered a great deal of attention and even large venture and corporate investments.

The real challenge, of course, is how to produce algal oils, cheaply. Scale is important, with a typical production system from several hundred to a few thousand acres. But scale alone is not sufficient: to produce cheap biofuels superior strains must be cultivated in low cost ponds.

## Algal Strains, Cultivation, Harvesting, Processing.

The basic concept for producing oils or other biofuels with microalgae is to use relatively small (in total area) enclosed photobioreactors to produce a starter ("inoculum") culture, at most 1-2% of the total biomass produced, to seed larger open ponds. Each day 20 to 50% of the pond volume must be harvested (depending on season and other factors). The biomass (a few hundred milligrams /liter) must be concentrated initially by about thirty-fold with a very low-cost harvesting process. Chemical flocculation, membrane separations, or centrifugation, the currently available options available, are much too expensive for biofuels. "Bioflocculation", the spontaneous flocculation-sedimentation of algal cells, using little or no flocculation chemicals, has been proposed as one promising approach for such initial harvesting, but still must be demonstrated to be reliable for even one system, and would need to be developed for each algal species, even strain and cultivation process.

The algal strains cultivated need to be selected based on many criteria, including oil content, productivity, and harvestability. Other essential attributes for strains to be grown in open ponds are resistance to contamination and grazers, tolerance of high $O_2$ and light levels, good growth under fluctuating temperatures, adaptation to the local water chemistry, among others.

After initial cell concentration, e.g. harvesting, further concentration and oil extraction is required. Cell breakage followed by solvent emulsification and recovery with a three phase centrifuge has been proposed (Benemann and Oswald, 1996). Cell rupture methods (e.g. heating, pressure, sonication, enzymatic lysis, etc., or a combination thereof) will need to be tested for each case. Other methods for oil extraction are also possible and this is an active area of R&D. Converting the algal oil to biofuels (biodiesel, green diesel, jet fuel) may be the lesser challenge.

The residual biomass could be either dried and sold as animal feed, similar to the "distiller dried grains" co-produced with corn ethanol, or equally plausibly, converted to biogas by anaerobic digestion for on-site power generation, with the residual nutrients and carbon recycled to the ponds. This option could cover all parasitic energy needs, and, indeed, generate surplus power, making algae oils not only "carbon neutral", but even potentially "carbon negative", to the extent that the surplus power replaces fossil fuel generated electricity.

Clearly, much R&D remains to be done, most importantly in how to actually stably and routinely cultivate the algae in large open ponds and, perhaps most importantly, how to achieve high productivities (see below). Fundamentally, algae biofuels technology will be based on the algae strains, still to be selected and improved, and whose mass cultivation must be mastered.

## **Power Plant $CO_2$ Utilization and Greenhouse Gas Abatement.**

Central to the concept of microalgal biofuels production is the use of power plant flue gases or of similar, nearby available, enriched sources of $CO_2$. Unlike higher plants, microalgae ponds or photobioreactors cannot achieve high productivities using atmospheric $CO_2$. Thus, all schemes for algae biofuels production rely on supplying the cultures with an enriched source of $CO_2$, from power plants, industrial sources, or smaller sources such as ethanol or anaerobic digestion plants.

However, contrary to common belief, $CO_2$ use by algal cultures is not $CO_2$ sequestration or a greenhouse gas abatement process by itself. That only comes from using the algal biofuels to replace fossil fuels, same as all other biofuels are thought to replace fossil fuels and thereby reduce greenhouse gas emissions and mitigate global warming. Algae biofuels produced using fossil fuel flue gas $CO_2$ are, actually, less desirable for greenhouse gas abatement than other biofuels, as by depending on the consumption of fossil fuels they actually add to the atmospheric load. (Indeed, whether it is actually the case that the fossil fuels replaced by biofuels will remain, for the long-term, in the ground, unused, is a question not satisfactorily answered, perhaps not even sufficiently asked, for any biofuels, or even for renewable energy in general. Although a topic that deserves further consideration, this is beyond the scope of the present piece).

The need for enriched sources of $CO_2$, e.g. power plant flue gases, adds to production cost and limits the location of algae biofuel production systems. Capturing any significant fraction of the $CO_2$ from large fossil fuel (e.g. coal) power plants will require tens of thousands of acres of algae ponds in close proximity to these plants, as flue gas transport for any distance is impractical. Suitable land and water resources are not available adjacent to most large power plants. $CO_2$ capture from flue could allow longer-distance transport, but is very expensive.

Further, it must be recognized that due to diurnal (algae do not use $CO_2$ at night) and seasonal variations in productivity and thus $CO_2$ utilization, the actual amount of $CO_2$ that can be captured from a power plant and then converted to oil is only a small fraction of that emitted by a typical power plant or other sources, at most about one-third, and even that requires recycling any waste $CO_2$ generated (e.g. from the biogas produced from the residues after oil extraction). Indeed, a more plausible approach is to co-locate algal production with smaller-scale $CO_2$ sources, such as small power plants, ethanol plants, or anaerobic digesters, rather than with large power plants or major industrial sources (cement plants, refineries, etc.), as is usually proposed.

Any fossil energy expended during the algae oil production process would reduce any greenhouse gas, that is $CO_2$, mitigation credits that may be imputed to such a process. As noted above, the production of algae oil combined with anaerobic digestion of the residues could generate methane that could be used to generate sufficient power to cover all the needs of the process with a surplus that could be exported for additional greenhouse gas mitigation credits.

In conclusion on this topic, the use of power plant and similar sources of $CO_2$ by algae oil production systems is not a benefit, as commonly, but wrongly, stated by most proponents of algae biofuels, but a necessity. Algae biofuels are, in this regard, no different in terms of greenhouse gas mitigation than other biofuels, which capture $CO_2$ from air. Indeed, it can even be argued that algae biofuels grown on fossil $CO_2$ emissions are less desirable than conventional biofuels. In any event, $CO_2$ supply is by no means cost-free. Which introduces the next topic.

## Economics.

After technical feasibility economics is the critical issue: the algal production systems must have very low capital and operating costs to compete with other crops and alternative energy sources. Most important is the reliable cultivation of algal strains in simple open ponds, producing oil at high productivities with a low-cost harvesting process. The lowest likely plant-gate production cost (e.g. not including costs such as marketing, overheads, R&D, etc.) for commercial algae biomass production in the US is about $5,000 per ton dry biomass for the *Spirulina* (belonging to the "cyanobacteria", which actually do not produce oil). Assuming that an algal biomass with 33% oil could be cultivated and the oil extracted at a similar cost, this would translate to $50/ gallon of oil, or over 20-fold higher than current oil prices.

Of course it can be rightly argued that economies of scale for large-scale biofuels production, improved productivities, and even modest advances in the technology could largely overcome this gap. However, even assuming that high biomass and oil productivities and stable cultivation are achievable, the major problem is likely the irreducible minimal costs of large-scale cultivation systems, including needed infrastructure, harvesting, processing, waste treatment, water supply, and other support systems required. Prior economic-engineering feasibility analyses concluded that for even the simplest open pond, overall system capital costs would be at least $40,000 per acre ($100,000/ ha), and possibly, probably, significantly higher (Benemann et al., 1982; Benemann and Oswald, 1996). To this must be added operating costs, which are site dependent. Furthermore, locations are required with favorable climate, readily available water (saline, brackish or wastewater), a nearby and essentially free source of $CO_2$, nearly flat land, and clay soils (plastic liners would be too expensive, but could perhaps be used for 10-20% of the ponds, which could be considered as part of the inoculum production system).

Assuming a simple capital charge of 20% per year (return on capital, depreciation, fixed capital costs), and projecting an optimistic 100 mt/ha-yr productivity with a 33% oil content this amounts to 233 barrels of oil per hectare-year. The above estimated $100,000/ha capital cost thus translates to almost $90/barrel and operating costs would bring this to well over $100/barrel, to which refining costs would be added. Clearly, such a combination of low capital costs and high productivities is needed for algae biofuels to compete with even very high future oil prices.

This represents the current vision, opportunity and challenges of microalgal biofuels production. Again, because of very high costs, at least ten-fold those of open ponds, and limits to scale-up, closed photobioreactors are not practical for biofuel production, aside for small-scale seed culture production. In brief, this technology still requires considerable R&D, with the major, but not the only, challenge being the achievement of very high productivities, required to justify the unavoidably high capital and operating costs.

**Productivity.**

Achievable biomass and oil productivity, using natural strains and technology at a climatically and otherwise favorable site, can be, optimistically, projected at most about half of the above stated rate of 100 mt/ha-yr with a 33% extractable oil content. As the above capital costs are already the lowest plausible that can be projected, a major improvement, at least a doubling, in productivity from the current expected levels is required for algae biofuels to become an economically feasible source of renewable fuels. This is the major goal in this field.

One promising approach to higher productivities is to genetically develop algal strains with a reduced level of chlorophyll and other light-absorbing pigments: the normally high content of such pigments in algal cells results in their mutual shading and inefficient light utilization at high light intensities, reducing overall productivity. These and other genetic improvements, such as linking photosynthesis to oil biosynthesis, may eventually boost algae oil production to the desired level and, possibly, in the long-term, to even a maximum of nearly 1 barrel of oil/ha –day (almost 60,000 l/ha-yr or about 6000 gallon/acre-yr). Any higher productivity claims, such as are being made by many promoters in this field, are clearly unobtainable; some even violate theoretical limits.

Indeed, even achieving the productivities projected with currently available strains and technology will require a major R&D effort. The higher productivities discussed above will, if achievable at all, require genetically modified organisms (GMOs, perhaps they should be called genetically modified algae, GMA), a somewhat controversial topic, discussed further below.

**R&D Needs.**

The central objective of R&D in this field must be to first develop strains that can be stably mass cultured in open ponds, and harvested, and do so at a considerably lower cost and with higher productivity (including oil) than current technology. A long list of R&D needs can be formulated (Benemann, 2002), for both the organisms and the cultivation system. The need is to isolate, screen, select, and test, both in the laboratory and outdoors, algal strains for properties that include, perhaps most importantly, high productivity (including high oil or starch content) and stable cultivation, which means resistance to invasion by other algae, grazers and other biotic challenges. Further, the strains used must be able to handle the pond temperature extremes at the specific location, be adapted to the cultivation medium (e.g. the local water source), and be easily harvested by a low cost process, such as bioflocculation. And, of course, the strains cultivated must be able to tolerate the rather high $O_2$ concentrations in the ponds. Clearly, the research needs to develop such strains and processes are rather extensive and interactive.

A major advantage of microalgae is their very fast growth rates; they can double in numbers in outdoor mass cultures in a day, or, after inoculation, even several times per day. Although fast growth is not synonymous with high productivity (a common error), short generation times do allow much faster development of this technology compared to conventional crop plants, where a single lifecycle can be months or, for trees, even years. For algae, a week is equivalent to a season for higher plants. Even with this advantage, the development of algal strains and cultivation technologies to achieve the high productivities, long-term stability, and low-cost harvesting required for biofuels production will require some years, assuming of course that it actually proves to be technically and economically feasible.

Advances in the organisms, the "software", must be combined with advances in the "hardware", the engineering design of the production system. In particular the ponds, larger than anything operated thus far in commercial cultivation, and the algal harvesting, oil extraction, processing, waste recycling, $CO_2$ supply and other system components need to be developed almost from scratch. Still, the engineering of the algal production systems is fairly well known and no major hurdles or uncertainties are apparent although, of course, there is still some uncertainty that a sufficiently low-cost process can actually be designed, built and operated. There are no clear "show-stoppers" to suggest that either the biological or engineering R&D cannot eventually succeed. As noted, the fast growth of microalgae suggests that progress, and applications, could be faster for microalgae than for biofuels derived from higher plants. Still, at best, it will take some years to establish the feasibility of large-scale algal biofuels production and the many uncertainties and unknowns in the development of the cultivation process provide ample opportunities for unsuspected or unknown hurdles and difficulties.

An important issue is that although genetically modified algae, GMA, will likely not be required for some years yet, R&D work must be initiated now, as it will take some time to develop the high yielding strains that will eventually be needed. Also, work must be carried out to demonstrate that GMA do not pose, indeed cannot pose, any environmental threat or danger, a logical proposition but must still be demonstrated, preferably by independent scientists and agencies. Public reaction to any premature release of GMA before these issues are addressed could become an impediment to algae biofuels, as seen from prior history with GMOs.

**Resource Potential.**

A major issue is the ultimate production potential for microalgae biofuels. After factoring in all the requirements for algae production, from suitable climate, to flat land and clay soils, to available water and $CO_2$ resources, even a cursory analysis would suggest that visions of enormous algae farms populating the deserts of the U.S. Southwest or Sahara are misguided.

Counter-intuitively, less water is used by algae grown in open ponds than by conventional crops (or even closed photobioreactors, which need to be cooled with water spray systems). Also brackish or saline inland water sources not useful for agriculture can be used by algae. Perhaps the most promising water resource is seawater. Although this requires locations not too far from the sea, allowable pumping energy input may allow use of land even several miles inland, depending on elevation. Still, for climatically favorable locations, water will be the limiting factor in many, even most, locations, perhaps even more than $CO_2$ availability.

The juxtaposition of all the requirements for algae mass cultivation – climate, land, water and $CO_2$ – to name just the main ones, will greatly restrict both the U.S. and global potential of this technology. Without detailed, highly site specific, studies, it is difficult to estimate any large-scale resource potential, but is likely that sufficient resources would be available, such that algal biofuels could, if the R&D is successful, make a plausibly significant contribution to the global goal of renewable energy production. However, even more likely, they will not, and cannot, replace more than a modest fraction, a small percentage, of current petroleum supplies.

The current interest in microalgae, and other so-called "next-gen" biofuels, is that would not compete with food-feed crops, while allowing for large-scale and low-cost production at much higher productivities than conventional crops. The use of oil, starch, sugar or other crops for biofuels is limited by the need to feed the human population, and, in any case, conventional agriculture can produce but a small fraction of current transportation fuel demands. It must, however, be recognized that next-gen biofuels are no panacea, in terms of their environmental footprints and are still far from demonstrated to be practical, let alone economically or socially acceptable. Microalgae biofuels are perhaps the least developed of such options, but because of their very fast growth rates that would allow for more rapid research and development. Although currently the only commercial use of microalgae biomass is as foods and feeds, algae production for fuel or feeds is new production that does not compete with conventional agriculture.

**High Value Co-Products and Wastewater Treatment.**

A short-cut to algal biofuels development, is to develop niche markets where there is little competition between biofuels and food/feed production. One approach is to co-produce algal biofuels with other, higher value co-products, such as, for examples, carotenoids or omega-3 fatty acids, with total markets exceeding a billion dollars. The biomass residue remaining after extraction of such products could be converted to biofuels. Such a development pathway would allow this technology to advance and mature, to the point where the biofuels could become an ever more important, and eventually the main, output. It is likely that at least some of the current companies in the algae biofuels field will sooner or later (perhaps soon) move towards this business model, as they realize that stand-alone algae biofuels production is too long-term a goal.

However, such schemes, though of interest to individual companies, will not be of great import, as high value co-products have limited markets (on a biomass basis), of tens of thousand, not millions, of tons. Co-production of commodity animal feeds along with biofuels is the other often proposed option for algae biofuels. Although, of course, animal feeds have very large markets, this approach suffers from the fact that the value of such feeds is not all that different from that biofuels, and, thus, does not fundamentally alter the requirement for high productivities and very low cost algae biomass production, or the resource limitations faced by such technologies. Indeed, it may be just as well to use the entire biomass for feed rather than fuel.

The nearest-term opportunity for practical development and applications of algae biofuels is in wastewater treatment, in particular municipal wastewater treatment. Large microalgae ponds are already used in such applications (Figure 2), and there algae provide $O_2$ for bacterial breakdown of waste organic matter, and in turn use the liberated $CO_2$ and other nutrients for growth. However, this low-cost, low energy consumption technology is currently limited by the lack of a reliable, low-cost algal harvesting process. The bioflocculation- settling process mentioned above was first developed for this application (Benemann et al., 1982) and appears promising, but remains to be perfected and demonstrated with full-scale systems. This would, however, require a complete change in the current technology of large, relatively deep (typically 1 -2 meters), unmixed ponds, to the shallow, raceway, paddle wheel (or otherwise) mixed ponds used in commercial algae production and already used at some wastewater treatment plants.

By adding supplemental $CO_2$ to such wastewater treatment ponds it would be possible to use the process to remove all nutrients (nitrogen, phosphates), and achieve a much higher level of treatment, while generating more biomass, possibly with a high oil content, and also reducing greenhouse gas emissions, compared to conventional, energy intensive, wastewater treatment processes. Recycling waste nutrients as fertilizers, would achieve another major environmental goal with potential economic benefits. Globally, such an approach has significant potential.

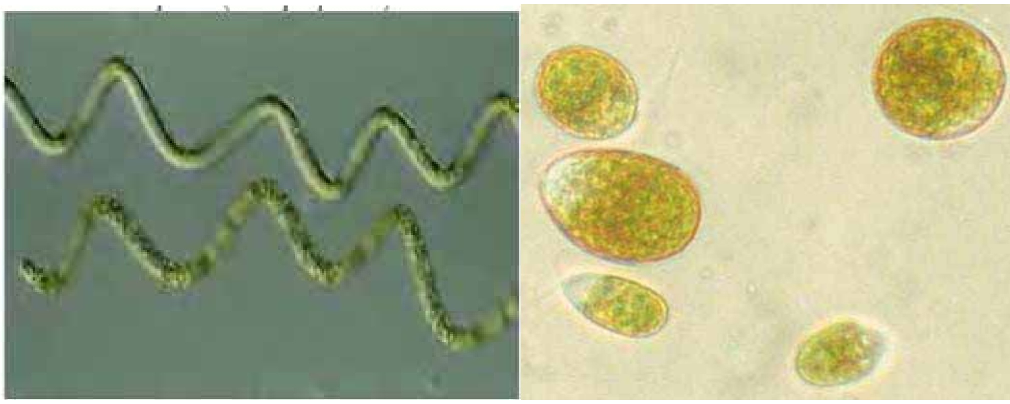
**Conclusions.**

Although algal biofuels still require a great deal of R&D, the prospect of a highly productive process, able to use land and water resources not suitable for conventional crops, justifies a continuing investment into this technology. Even if some current projections and proponents are excessively optimistic, and near-term achievements prove disappointing, these should not detract from the long-term potential of this technology and the need to carry out the required R&D. Potential applications in wastewater treatment alone would justify such efforts.

On January 7, 2009, a Continental Airliner Boeing 727 carried out at test flight of bio-jet fuel, that included 2.5% derived from algae oil, procured by Sapphire Co. from Cyanotech Co. in Hawaii (Fig. 2B1), and converted to bio-jet fuel by the UOP Corp. This test proved the technical feasibility of advanced algal biofuels. Practical and economic algal biofuels production processes must now be developed. The recent entry of, among many others, ExxonMobil Co., into this field, with an over $600 million investment, along with an enormous increase in US Federal and other funding for microalgae biofuels, may help achieve this long-term goal. However, this will only be possible if the R&D is focused of practical goals, rather than fanciful, approaches such as closed photobioreactors, miraculous GMA, and fantastic productivities, to name but a few such.

**FIGURE 1. MICROGRAPHS OF COMMERCIALLY CULTIVATED ALGAL SPECIES**
**Spirulina is a *cyanobacteria*, the other three are green algae (*chlorophyceae*)**

**A. *Spirulina* (*Arthrospira platensis*)** **B. *Dunaliella salina***



**C. *Chlorella vulgaris*** **D. *Haematococcus pluvialis***

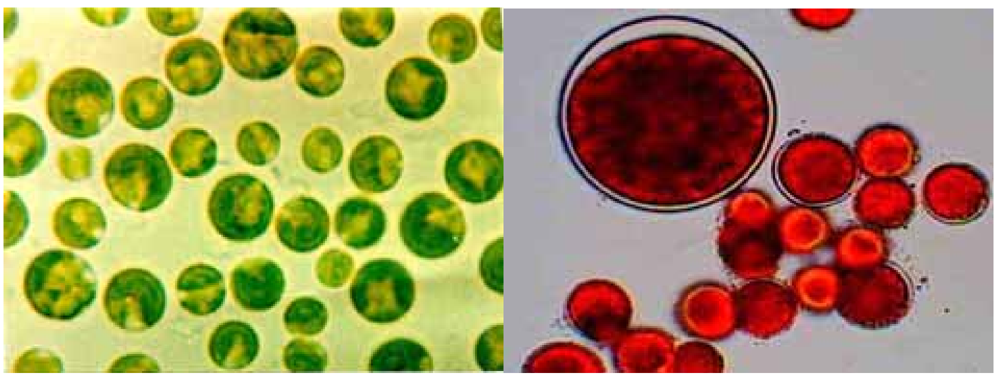


**FIGURE 2. EXAMPLES OF COMMERCIAL MICROALGAL PRODUCTION SYSTEMS**

**2.A. <u>Large open, unmixed ponds</u>**, for wastewater treatment and *Dunaliella salina* production.

2.A.1. Wastewater treatment ponds - so-called "oxidation ponds" - are not true algae production ponds because algae productivity is not maximized and the biomass produced is rarely harvested, and, when harvested, the chemical flocculants interfere with conversion of the biomass to biofuels. A few waste treatment ponds use mixed, raceway designs, see Figure 2B, which have great potential for application in combined wastewater treatment-biofuels production processes.

2.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 produce biomass at very low productivities (<5 ton/ac-yr). The algae biomass is harvested by adsorption on polymers and their oil, very high in beta-carotene, extracted and sold, mainly as a human food supplement (for its pro-vitamin A activity and antioxidant properties).

**Figure 2.A.1. Oxidation Pond for Wastewater Treatment** (Napa, California, total ~300 acres) Note: ponds on top are salt evaporation ponds.

**Figure 2. A.2.** ***Dunaliella salina*** **ponds in Australia** (Cognis-Betatene ponds in S. Australia. Each pond ~100 acres in size).

**2.B. <u>Open, raceway, shallow, mixed ponds</u>.** The raceway ponds are typically 6 to 16 inches (15 to 40 cm) liquid depth, mixed with paddlewheels, lined with plastic or cement, and up to about 0.5 hectares in size. The productivity of such mixed ponds is much higher (up to ten-fold) than the unmixed ponds in Figure 2A. These raceway 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 (bottom left also Fig 2.C.) Circular ponds, Fig 2.B.2, right, are used for *Chlorella* production in Japan and the Far East (Note: circular ponds do not scale above about 1,000 $m^2$, or a quarter acre, for individual ponds). All these microalgae products are sold mainly for human nutritional supplements.

**Fig. 2.B.1. Commercial microalgae production in open raceway paddle-wheel mixed ponds**.
A. Left; Earthrise Nutritionals, LLC, California. Production of Spirulina, Ponds ~ 1 acre.
B. Right: Cyanotech Co., Hawaii, producing *Haematococcus pluvialis* (red ponds) and Spirulina.

**Fig 2.B.2. Additional examples of commercial open pond production systems.**
**A.** Left *H. pluvialis* production in raceway paddle wheel mixed ponds (Parry Nutraceuticals, India). B. Right: *Chlorella* production in circular ponds (Chlorella Industries, Japan).

**2.C. Closed Photobioreactors** of many designs, with tubular reactors the dominant technology in commercial operations, both small diameter (~5 cm) rigid (see Figure 2.C.right.) and larger diameter (>10 cm) flexible bag type reactors. Many other designs have been used in pilot scale production, including various types of flat plate reactors, hanging bag reactors, hemispherical dome reactors (these also used in one commercial plant, see Figure 2.C.2 left), and other types.

**Figure 2.C. Left: *Haematococcus pluvialis* production, hemispherical photobioreactors** (Fuji Co., Hawaii) (dome ~1 meter diameter). **Right: *Haematococcus pluvialis* production, tubular photobioreactors** (each tube is about 100 m long, 5 cm diameter (Algatech Co., Israel).

**QUOTED REPORTS BY THE AUTHOR AVAILABLE ON THE WEB**

Benemann, J.R. ; Goebel, R.P. ; Weissman, J.C. ; Augenstein, D.C. 1982. "Microalgae as a source of liquid fuels". Final technical report USDOE –OER *http://www.osti.gov/bridge/product.biblio.jsp?query_id=0&page=0&osti_id=6374113*

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*

Benemann, J.R., 2002 "A Technology Roadmap for Greenhouse Gas Abatement with Microalgae". Report to the U.S. Department of Energy, National Energy Technology Laboratory, and the International Energy Agency Greenhouse Gas Abatement Programme, *http://www.co2captureandstorage.info/networks/Biofixation.htm*

Sheehan, J., Dunahay, T., Benemann, J., Roessler, P., Weissman, J. 1998. "Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae; Close-Out Report". NREL Report No. TP-580-24190 *http://www.nrel.gov/docs/legosti/fy98/24190.pdf*

**SOME PRESENTATIONS AVAILABLE ON THE WEB**

Benemann, J., "Open ponds and Closed Photobioreactors – Comparative Economics" 5th Annual World Congress on Industrial Biotechnology & Bioprocessing, April 30, 2008 Chicago, Illinois. *www.bio.org/ind/wc/08/breakout_pdfs/20080430/Track1_ContinentalA/Session9_230p400pm/Benemann_Continental_A_Wed.pdf*

Benemann, J., "Overview: Algae Oil to Biofuels", NREL-AFOSR Workshop, Algae Oil for Jet Fuel Production, Arlington, VA, February 19, 2008, *www.nrel.gov/biomass/pdfs/benemann.pdf*

Lundquist, T., and J. Benemann, Using CO2 and Algae to Treat Wastewater and Produce Biofuel Feedstock March 23 2007 First Western Forum on Water and Energy Sustainability, U.C. Santa Barbara *www2.bren.ucsb.edu/~keller/energy-water/4-2%20Tryg%20Lundquist.pdf*

Benemann, J., "Microalgae Biofuels", EECA Biofuels Conf., April 24, 2007, Wellington, New Zealand *www.eeca.govt.nz/eeca-library/renewable-energy/biofuels/summary/**john-benemann**.pdf*

Benemann, J., "Photosynthesis, Algae, CO2 and Bio-Hydrogen", GCEP Energy Workshop April 27, 2004, Stanford Univ. *http://gcep.stanford.edu/events/workshops_biomass_04_04.html*

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