Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae

John Benemann[1], Angela Manancourt[2], Paola Maria Pedroni[3]

[1]Manager, International Network on Biofiaxation of CO_2 and Greenhouse Gas Abatement, 3434 Tice Creek Drive, No. 1, Walnut Creek, California, 94595 USA (jbenemann@aol.com)
[2]IEA Greenhouse Gas R&D Programme, Cheltenham, Great Britain
[3]EniTecnologie S.p.A., San Donato Milanese, Milan, Italy

Introduction.

Microalgae cultures have been studied for production of commodities - foods, feeds, fuels, and fertilizers – for several decades, starting with an international R&D collaboration that aimed at producing food for an exponentially growing world population (Burlew, 1953). At the time the only practical use of microalgae was in wastewater treatment, using large, unmixed, "oxidation ponds". Even at that early stage, two distinct concepts for algal mass cultures emerged:
1. Closed photobioreactors, such as long transparent plastic bags or narrower tubes, containing the liquid culture and fed CO_2 (described in Burlew, 1953), for production of human foods; and
2. Open mixed ponds for wastewater treatment and co-production of feeds (Oswald et al., 1953).

These alternative microalgae production processes, open ponds and closed photobioreactors, have been the focus of both research and applications in microalgae mass culture for the past five decades. The technical difficulties of closed photobioreactors, from overheating to high costs, discouraged their initial development, but this research revived in the 1970's and over the past two decades has been the main focus in this field. Several large (> 0.5 ha) plants for production of high value products were built, with one, using horizontal tubes, still operating in Germany.

The use of circular, mechanically mixed, open ponds for microalgae, specifically *Chlorella*, production was developed in Japan during the 1950's by Tamiya and associates, and these designs are still used today in Japan and Taiwan for *Chlorella* production. Open ponds of a raceway designs were first developed by Oswald and colleagues in California to grow algae on municipal wastewaters, with the algae producing the dissolved O_2 required by bacteria to oxidize the wastes. During the 1960's a raceway pond design was developed in Germany that used paddle wheel mixing, and this was introduced in the U.S., initially for wastewater treatment (Benemann et al., 1980). However, applications of such mixed raceway ponds in wastewater treatment have been limited, and typically algal biomass is not harvested from such systems. The paddle wheel mixed raceway pond design is of relatively low cost and can be scaled-up from a few square meters to several hectares. It is now widely used for the production of microalgae for nutritional products, in particular *Spirulina*, with a world production of this species at about 2,000-3,000 metric tons, with production costs of $5,000 to $10,000/metric ton, dry basis.

Production of large volume commodities, such as feeds or fuels, at one-tenth these costs or less, remains a goal for the future, despite research programs with open ponds in the U.S. (Sheehan et al., 1998) and closed photobioreactors in Japan (Usi and Ikenushi, 1996). This presentation highlights the R&D needed to achieve the goal of high productivity microalgae processes cost competitive with higher plant agriculture, as envisioned by the pioneers in this field, and the applications of such technologies to renewable fuels production and greenhouse gas abatement.

Low-Cost Microalgae Production R&D Needs.

The goal of producing microalgae biomass at costs that are competitive with agricultural crops requires major advances in microalgae production technology, from the fundamentals of solar energy conversion efficiency by photosynthesis to the engineering of large-scale pond systems. Other key issues are how to cultivate selected and improved strains of algae in open ponds, how to harvest these microscopic organisms, how to provide the required nutrients, in particular CO_2, and how to process the wet biomass harvested from the ponds to yield the desired products. Each of these topics presents major R&D challenges that must be resolved before microalgae production can make a significant contribution to human welfare and environment. As the focus here is on large-scale, low-cost commodities, only open ponds, and specifically the paddle wheel mixed reactors, are considered. Closed photobioreactors are used to speed the build-up of the inoculum for such systems. Here the research challenges in this field are briefly addressed.

Productivity. Maximizing the metric tons of organic dry weight (and energy content/ton) produced per hectare of pond area per year (mt/ha/yr) is the most important goal for R&D in this field. Among the many factors limiting productivity, light saturation and photoinhibition are perhaps the major ones. A key strategy to overcome these limitations is to reduce the number of light harvesting pigments per reaction center in photosynthesis (Polle et al., 2001; 2004). This could be achieved using modern tools of biotechnology and molecular genetics, and would, if successful, increase microalgae culture productivities several-fold. The ultimate productivity potential of microalgae mass cultures will need to be established through long-term R&D, but should be over 200 mt/ha/yr in favorable locations, with half this achievable in the near-term.

Algal Strains and Mass Cultures. Achieving high productivities will require the mass culture of selected and genetically improved microalgal strains in open ponds. In the current commercial production of microalgae, *Spirulina* and *Dunaliella* are mass cultured by employing selective media while *Chlorella,* and *Haematococcus* require large amounts of inoculum production and frequent culture re-starts. The former suffers from relatively low productivities, the latter from high costs of inoculum production. For large-scale, low-cost algal mass cultures, the inoculum approach will need to be used, but made much more efficient. An inoculum production system using a progression of closed photobioreactors will be required, and methods found to minimize zooplankton grazing, amoeba and fungal infections, and invasions by other algae, to name a few.

Biomass Composition, Harvesting and Processing. Concentration of dilute suspensions of microscopic algae has been a major R&D challenge. Settling by spontaneous bioflocculation is a low-cost process, the issue is how to induce such bioflocculation behavior in algal cells. Processing the harvested biomass, at a few percent solids, is a further challenge. Drying is generally prohibitive, sun drying can degrade the biomass, fermentations need to cope with the tough cell walls of many algal species and the algal biomass must have a suitable composition. For example, a high content of fermentable carbohydrates is required for fermentations. And can be achieved by limiting the nitrogen supply. These issues still require considerable R&D.

Engineering Designs. The design and operation of large systems (> 1 ha), in particular of low-cost unlined ponds, remains to be demonstrated, as is the efficient distribution, transfer and utilization of CO2, possibly from power plants. The capital and operating costs of such processes must be reduced to allow large-scale (>100 ha) production of algal biomass at under $500/ton.

Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae

The recent focus on global warming brought renewed attention to microalgae, this time for their potential in greenhouse gas abatement. Superficially a major attraction of microalgae mass cultures is that they use, actually require, CO_2 from a concentrated source, as they cannot use atmospheric CO_2. The use of power plant flue gases for microalgae mass cultures for production of renewable fuels, thus avoiding greenhouse gas emissions from coal-fired power plants, was proposed some five decades ago and a conceptual process elaborated early-on (Oswald and Golueke, 1960). However, neither the source of the CO_2 nor the process of biofixation would result in greenhouse gas abatement. Rather it is the conversion of the algal biomass to a renewable fuel, which then substitutes for a fossil fuel, which reduces greenhouse gas emissions.

Greenhouse gas abatement can also come from the energy (e.g. fossil fuel) savings of using microalgae wastewater treatment ponds, compared to conventional wastewater treatment systems. Finally, greenhouse gas can be abated by avoiding methane or nitrous oxide emissions from wastes and by substituting energy intensive products, such as fertilizers, with microalgae-based products. Indeed, all these attributes - renewable energy production, energy conservation, mitigation of secondary greenhouse gases, and production of organic fertilizers - are combined in microalgal wastewater treatment processes. Thus, wastewater treatment, municipal, industrial and agricultural, is the most immediate and practical approach to renewable fuels production and greenhouse gas abatement with microalgae. In such processes, the ability of microalgae to recover nutrients is perhaps their most valuable attribute, as it allows for reuse of plant fertilizers.

However, wastewaters and related applications would not be sufficient to achieve a large impact on the immense problem of greenhouse gas emissions and abatement. An often used figure of merit is the abatement of 1 Gt (gigaton) of CO_2, or equivalent (e.g. other greenhouse gases). Although waste treatment could plausibly contribute substantially to such a goal, additional applications would be required, which means systems where renewable fuels production is the main, even only, process objective. Such processes have been studied for many years, for examples microalgal H_2 (Hallenbeck and Benemann, 2002) and oil/biodiesel production (Sheehan et al., 1998). However, these remain topics for long-term R&D. We estimate, very roughly, that achieving the goal of 1 Gt of CO_2 avoided will require about 6 million hectares of algal production ponds worldwide, depending on the fossil fuel replaced and many other factors.

Developing low cost production processes for microalgae, in particular for potential applications to renewable fuels production and greenhouse gas abatement, will require long-term R&D. This suggested the need for information exchange, coordination and integration of the work carried out in this field by organizations and laboratories around the world. To server such a role, and on the proposal by the U.S. Department of Energy and EniTecnologie (Pedroni et al., 2001), the IEA Greenhouse Gas R&D Programme established in June of 2002 the "International Network on Biofixation of CO_2 and Greenhouse Gas Abatement". The Network had nine members in the most recent concluded year, contributing to the support of meetings (six held thus far), technical advisers, management support and development of reports (including the "Technology Roadmap", Benemann, 2003). Ten research projects are being carried out or planned by member organizations and advisers, covering areas such as maximizing productivity, municipal and agricultural wastewater treatment, power plant flue gas utilization and biofertilizer production. Information on the Network can be obtained from the website (www.ieagreen.org.uk)

REFERENCES

Benemann JR, Koopman BL, Weissman JC, Eisenberg DE and Goebel RP (1980) Development of Microalgae Harvesting and High Rate Pond Technology. In Shelef G, and Soeder CJ, eds. –Algal Biomass, 457-499, Elsevier BioMedical Press

Benemann, J (2003) "Technology Roadmap - Biofixation of CO2 and Greenhouse Gas Abatement with Microalgae". Final Report to the U.S. Dept. of Energy, National Energy Technology Laboratory, Morgantown-Pittsburgh, January 14, 2003. Available at www.ieagreen.org.uk

Burlew D (1953) Algae Culture, From Laboratory to Pilot Plant. Carnegie Inst. of Washington.

Hallenbeck P, Benemann J (2002) Biological Hydrogen Production: Fundamentals and Limiting Processes. Int J. Hydrogen Energy 27: 1185 – 1193.

Oswald WJ and Golueke CG (1960) The Biological Conversion of Solar Energy. *Adv. Appl. Microbiol*., 11: 223 – 242 (1960).

Pedroni P, Davison J, Beckert H, Bergman P, and Benemann J (2001) A Proposal to Establish an International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae". Proceed. Dept. of Energy/NETL 1st National Conf. on C Sequestration. May 2001.

Polle J, Kanakagiri S, Benemann JR and Melis A (2001) Maximizing photosynthetic efficiencies and hydrogen production by microalgal cultures. In, *Biohydrogen II: An Approach to Environmentally Acceptable Technology* (J Miyake, T Matsunanga and A San Pietro, Eds.), pp. 111-130. Pergamon Press, Oxford, UK

Polle JEW, Aksoy M., Stauffer G, Benemann JR, Weissman JC. (2004) Genetic Improvements for Increasing Solar Energy Conversion Efficiency by Microalgae Cultures (International Photosynthesis Congress, Montreal, September 2004, in press)

Sheehan J, Dunahay T, Benemann J, Roessler P (1998). *A Look Back at the U.S. Department of Energy's Aquatic Species Program - Biodiesel from Algae*. National Renewable Energy Laboratory, Golden, CO, 80401 NERL/TP-580-24190.

Usui, N., and M. Ikenouchi M (1996) "The biological CO_2 fixation and utilization project by RITE (1) – highly effective photobioreactor systems". *Energy Conserv. Mgmt*. **38**: S487 – S492.