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International Network for Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae

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ABSTRACT

The utilization of concentrated CO_2 sources, such as power plant flue gases, by microalgae mass cultures to produce renewable fuels and fossil fuel-sparing products provides both near- and longer-term opportunities to mitigate greenhouse gas (GHG) emissions. Microalgae mass cultures, mostly using raceway-type open ponds, are currently used commercially to produce several thousand tons of food- and feed-grade algal biomass annually. Presently, costs are over an order of magnitude higher than acceptable for renewable fuels production and GHG mitigation. However, engineering cost analyses project sufficiently low costs if large (>100 hectare) open pond cultivation systems were deployed and higher algal biomass productivities (>100 tons/hectare/year) could be achieved. Achieving high productivities and low costs will require relatively long-term applied R&D into algal photosynthesis, large-scale cultivation, harvesting technologies and biomass processing to produce both fuels and higher value co-products. Microalgae mass cultures are currently also used in wastewater treatment and these environmental applications provide nearer-term opportunities for microalgae GHG abatement and renewable fuels production.

INTRODUCTION

Microalgae cultures have been investigated as a source of renewable fuels for several decades, starting with the pioneering research and process development work of Oswald and Golueke [1] at the University of California Berkeley. Their concept was to grow algae in municipal wastewaters to produce dissolved O_2, required for bacterial oxidation of wastes, then harvest the algal biomass and convert it to methane fuel by the process of anaerobic digestion. The methane was to be used to generate electricity and the CO_2 produced by the power plant, along with the nutrients recovered from the anaerobic digestion reactors, was to be used to grow additional algal biomass, expanding the potential scale of this process beyond the needs of wastewater treatment to several hundred hectares. The initial feasibility analysis appeared favorable. The energy crisis of the 1970's gave renewed impetus to R&D of this concept [2], with emphasis on the harvesting of the algal biomass from wastewater ponds through spontaneous flocculation and settling [3].
During the 1980's the emphasis in this R&D field shifted from methane production and waste treatment to biodiesel production and dedicated large-scale processes, where fuels were the only outputs. This “Aquatic Species Program” (ASP), was sponsored by the U.S. Department of Energy through the National Renewable Energy Laboratory, with the participation of many university groups and private companies [4]. Significant advances were made by the ASP, culminating in the operation of a 0.2 hectare pilot plant in Roswell, New Mexico, which demonstrated the ability to grow selected algal strains in large, potentially low cost, open ponds. However, the engineering analyses of such processes required very high biomass productivities, that

is solar conversion efficiencies, among many other favorable engineering and process assumptions, for economic feasibility [5].
During the 1990's extensive research on microalgae for utilization of power plant flue gas CO_2 for GHG abatement was carried out, mainly in Japan, sponsored by RITE (Research for Innovative Technologies of the Earth) and emphasizing the use of closed photobioreactors of various designs, with co-production of higher value products [6]. These R&D efforts were, however, discontinued by the end of the decade, in part because of the unfavorable economic projections for such approaches. Research along similar lines continues presently in the U.S., with the support of the Department of Energy.
In the mean-time a microalgae production industry has developed, starting in Japan during the 1960's for the production of *Chlorella* and then in Mexico, Thailand, U.S. and other countries for the production of *Spirulina*, both algae being used for human food supplements and some animal feed applications. During the 1980's, commercial production systems for *Dunaliella salina*, used as a source of beta-carotene, were developed in the U.S. and Australia. Recent commercial developments in microalgae biotechnology have achieved the cultivation of several novel algal species, in particular *Haematococcus pluvialis*, a source of the carotenoid astaxanthin, used in salmon aquaculture and also in food supplements. Many small-scale cultivation facilities produce microalgae for live aquaculture feeds. At present, about five thousand tons of microalgae biomass are produced annually at facilities around the world, mainly for the human food supplements market. Production costs are generally much higher than agricultural products, limiting current applications to specialty food and feed products. Production costs for *Spirulina*, the largest volume microalgae product at present, with some 2000 tons produced world-wide, are about U.S. $ 5,000 per ton.
A recent commercial success has been in the heterotrophic fermentation of microalgae, in the dark using sugars, for the production of polyunsaturated fatty acids, in particular DHA (docosahexaenoic acid), starting to be used in infant formulas and also animal feeds. However, microalgae are fundamentally photosynthetic organisms and their potential lies in the conversion of solar energy for useful purposes. Indeed, microalgae ponds are extensively used for wastewater treatment, although these are generally rather small systems (<10 hectares) and the algal biomass is seldom harvested or beneficially used.

THE INTERNATIONAL NETWORK FOR MICROALGAE BIOFIXATION

Despite several decades of R&D, applications of microalgae in fuels production and GHG abatement are yet to be realized in practice. One microalgae plant in Hawaii is using flue gas from a small power plant to supply the CO_2 required in microalgae production [7], demonstrating the practical feasibility of utilizing flue gas in microalgae cultures. A wastewater treatment plant in Sunnyvale, California, harvests microalgae biomass and converts it to methane fuel. However, few such applications can be pointed to and GHG mitigation with microalgae remains to be developed to a practical level.
To advance both the near- and long-term development and applications of microalgae for biofixation of CO_2 and GHG mitigation, the U.S. Department of Energy and EniTecnologie, the R&D arm of the Italian oil company ENI, with the assistance of the IEA Greenhouse Gas R&D Programme, have organized the "International Network for Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae". The Network, which became operative June 1, 2002, presently includes as members Arizona Public Services (a U.S. electric utility), Rio Tinto (an international mining company), ENEL Produzione Ricerca (the R&D arm of the Italian electric utility), EPRI (a U.S. R&D organization serving electric utilities) and the Gas Technology Institute (carrying out R&D in support of the gas industry). These companies and organizations, with an interest in promoting R&D and practical applications in this field, have joined together to more effectively use limited resources in a coordinated and cooperative R&D effort. The objective of the Network is to demonstrate the technical and economic feasibility of such technologies and initiate some practical demonstrations within this decade. The main task for the current year is to develop a R&D Roadmap detailing the most plausible processes and identifying specific research needs for accomplishing the technological objective.

THE MICROALGAE BIOFIXATION R&D ROADMAP

A Roadmap provides a structured R&D planning process by identifying the scientific and technological developments needed to achieve a specific strategic goal. The key tool is to characterize those processes that could be practically developed within a given time-frame and from these derive the specific R&D needs that have to be addressed to achieve the objective. Most importantly, the roadmapping effort involves consensus building among technical experts of the most plausible processes and the critical R&D needs that can meet the goal. The objective of the Network is to demonstrate the technical and economic feasibility of microalgae technologies in CO_2 biofixation and GHG abatement within five years and to achieve some initial practical applications of such processes within ten years. This time-frame constrains the possible processes and approaches which can be projected without the need to invoke major R&D breakthroughs.

The first event that laid the foundations for the development of the Network and represented the beginning of the roadmapping effort was a Workshop on microalgae technologies for CO_2 biofixation and GHG mitigation held in January 2001, in Monterotondo, Italy, with some three dozen participants representing a broad diversity of disciplines and organizations interested in this area of research [8]. Technical presentations and discussions covered the range of processes and R&D approaches in this field, from wastewater treatment to commercial algae production, from closed photobioreactors to large-scale open ponds, from algal genetics and physiology to conceptual processes for large-scale microalgae systems for energy production. A strong consensus developed that further R&D in microalgae applications for energy production and GHG mitigation was worthwhile, though the specific approaches to this end were not fully developed. A central issue of discussion was the feasibility of dedicated, stand-alone microalgae systems that would utilize flue gases CO_2 and produce renewable fuels as their sole outputs. This approach requires the achievement of very high productivities, near the theoretical maximum, as well as very large-scale cultivation systems, favorable locations and many other favorable assumptions to allow projection of economically viable processes [4]. The general consensus developed during these discussions was that although such approaches may be feasible in the long-term they cannot be considered for practical application in the near future. The preferred alternative is to develop microalgae biofixation systems as part of multipurpose processes, which provide additional services, such as wastewater treatment or higher value co-products, in addition to their GHG mitigation functions. Another major topic of discussion was the cultivation system to be used in such processes, in particular the applicability of closed photobioreactors. These were considered to be useful in the production of required algal inoculum, but only large open pond cultures could be of low enough cost to be applicable in microalgae GHG mitigation. The two major R&D issues identified were the need to develop techniques allowing the mass culture of selected microalgae species in large open ponds and the achievement of high productivities, of above 100 tons/hectare/year, even in multipurpose systems.

A meeting during which these issues were further discussed for the Roadmap development was held in Almeria, Spain, in May 2002, in conjunction with the Congress of Algal Biotechnology. The potential of microalgae in municipal wastewater treatment, their use in recovering nutrients from wastewaters generally, in particular agricultural drainage waters, the application of nitrogen-fixing microalgae for fertilizer production, and the co-production of microalgae fuels and higher value products, were addressed during this meeting [9]. Again, the consensus was that in the near- to mid-term GHG mitigation could be achieved by microalgae systems through the development of multipurpose processes, which not only fix CO_2 into renewable fuels but also avoid fossil energy inputs presently required by conventional processes, such as the production of synthetic fertilizers. Four general microalgae biofixation/GHG abatement processes were developed that encompass these potential near- to mid-term approaches in this field:

1. Municipal wastewater treatment using CO_2 for CH_4 production and with reduced energy consumption.
2. Recovery of nutrients from agricultural and other wastes with production of biofuels and fertilizers.
3. Use of nitrogen fixing microalgae and nutrient recycling for agricultural applications.
4. Co-production of biofuels and large volume/higher value products (biopolymers, animal feeds, etc.)

There is a considerable overlap among these conceptual processes. All require essentially similar production systems, i.e., open paddle wheel-mixed raceway ponds, all are based on using CO_2 from power plants or similar concentrated sources, all would produce renewable fuels and thus reduce GHG emissions, all would have additional GHG abatement functions, such as reduced fossil energy consumption compared to traditional processes, all are plausibly economically feasible, and all would be of sufficient scale, both as individual processes and in aggregate, in order to achieve significant GHG mitigation.

R&D ISSUES IN MICROALGE BIOFIXATON

These processes also have to address essentially similar basic and applied research issues, briefly summarized below:

Algal Strains. Mass culture of defined microalgal strains has been demonstrated in only a few cases (*Spirulina, Dunaliella*), with most algae, even *Chlorella*, mass cultured with difficulty. How to select and maintain algal strains that are competitive in outdoor pond cultures is a central R&D issue in this field.
Genetics and Molecular Biology. After selection of strains that can be mass cultured in open ponds, these will need to be further improved. Application of modern biotechnology tools is only in its infancy for use in microalgae.
Physiology. In outdoor pond cultures algae are exposed to highly variable and often extreme environments. How algal strains respond to these stresses requires a fundamental understanding of their physiology.
Culture stability. Algal cultures often succumb to invasions by competing algae, predation by zooplankton grazers, and crashes of unknown causes. Improving culture stability is a R&D challenge.
Inoculum production. When microalgae cultures fail they can be rapidly replaced. That requires the development of large-scale production of inoculum cultures, using, in part, closed photobioreactors.
Productivity. Maximizing productivity, that is solar conversion efficiencies, is the most important R&D objective in this field. Recent work on reducing algal pigments suggests approaches towards this goal.
Harvesting. Concentration of dilute suspensions of microscopic algae has been a major challenge in this field. Settling by spontaneous bioflocculation is a low-cost processes, but still requires considerable R&D.
Biomass conversion. Biofuels production is the main goal in GHG abatement and microalgae can be sources of CH_4, H_2, biodiesel, ethanol and hydrocarbons. These conversion processes all require R&D.
Co-Products and Co-Processes. Biofuels production is not enough to economically justify microalgae processes. Waste treatment and large volume co-products must be integrated with biofuels production.
Engineering Designs. Although large-scale open ponds can be of low cost, these, and the supporting systems (e.g. CO_2 injection) have yet to be demonstrated at the scale envisioned in the feasibility analysis.
Resources and GHG Mitigation Impact. Ultimately, the applicability of microalgae technologies for GHG mitigation will be decided not only by economics but also by their potential impacts: how many megatons of CO_2 abatement could microalgae processes provide, both regionally and globally. This will require an inventory of resources, from water to land, from wastes to CO_2, for the applicable processes.

CONCLUSIONS

R&D challenges in microalgae biofixation of CO_2 and GHG abatement require multidisciplinary skills and a critical mass to allow a broad coverage among the many R&D topics, as well as a diversity of approaches and projects which cannot be encompassed by any single organization. The Network provides the structure and the mechanism by which the required expertise are integrated, the critical mass reached and the research projects coordinated to help focus R&D efforts on most promising approaches towards the practical application. The Network has only now started operations and the process of formulating the Roadmap represents a key step for guiding future R&D activities by integrating in its broad vision the research projects carried out, either individually or in cooperation, by the Network participants.

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