Biotechnology and Bioprocess Engineering **2003**, 8: 354-359 ©KSBB

Review of Advances in Biological CO_2 Mitigation Technology

Jin-Suk Lee* and Joon-Pyo Lee

Biomass Center, Korea Institute of Energy Research, Daejeon 305-343, Korea

Abstract CO_2 fixation by microalgae has emerged as a promising option for CO_2 mitigation. Intensive research work has been carried out to develop a feasible system for removing CO_2 from industrial exhaust gases. However, there are still several challenging points to overcome in order to make the process more practical. In this paper, recent research activities on three key technologies of biological CO_2 fixation, an identification of a suitable algal strain, development of high efficient photobioreactor and utilization of algal cells produced, are described. Finally the barriers, progress, and prospects of commercially developing a biological CO_2 fixation process are summarized.

Keywords: CO_2 mitigation, microalgae, photobioreactor, utilization of microalgae

INTRODUCTION

As the concerns over global warming are increasing, many research works on carbon sequestration have been carried out. However, the high cost of CO_2 disposal is a major barrier for dissemination. The cost of removing CO_2 from a conventional thermal power plant is estimated to be in the range of $128-967/ton of carbon (tC) [1]. The sequestration cost should be around $10/ tC for disposal to be economically feasible. It is very difficult to achieve the goal only by developing new large-scale sequestration technologies such as CO_2 separation and storage. If the utilization of CO_2 into high value added products is possible, the sequestration cost may be reduced. That is why intensive research work, including chemical and biological, has been carried out to convert CO_2 into useful chemical products.

Among various CO_2 utilization technologies, the biological methods, particularly the ones using microalgal photosynthesis, have several merits such as mild conditions for CO_2 fixation, no requirements for the further disposal of recovered CO_2, and direct CO_2 fixation from flue gases if a suitable microalga is available. The last advantage is quite important because the separation of CO_2 from flue gases takes a major portion (over 70%) of the total sequestration costs (Fig. 1). In addition to these advantages, carbon fixed by microalgae is incorporated into carbohydrates and lipids, so that energy, chemicals, or foods can be produced from algal biomass [2-6]. Because of the advantages mentioned before, many works have been carried out to incorporate the CO_2 fixation process by microalgae into practical uses [7-11].

The major research projects, which have been performed, are 1) the isolation of a suitable algal strain 2) the development of the photobioreactor having higher CO_2 fixation rates and its scale-up 3) the utilization of algal cells produced from the fixation process. 1) As mentioned above, direct CO_2 fixation from flue gases may reduce the sequestration cost significantly. However, the flue gases having high CO_2 concentrations (10~30%) and the toxic compounds like SO_x and NO_x, are extremely inhibitory to growth of most algal strains. 2) Like other biological processes, the CO_2 fixation rates by microalgae are very low. Therefore, the reactor sizes will become very large if the process applies to fix CO_2 emitted from the industrial sources. Light limitation will be a major problem for such large reactors, which are usually employed for the biological CO_2 fixation process. Therefore, the design of the large-scale photobioreactor minimizing its light limitation will be a critical issue. Finally 3) Utilization technology of algal cells into value added products may make the process commercially viable. This review will describe recent works done for the development of biological CO_2 fixation processes.

***Corresponding author**
Tel: +82-42-860-3553 Fax: +82-42-860-3739
e-mail: bmjslee@kier.re.kr

IDENTIFICATION OF SUITABLE MICROALGAE FOR CO_2 FIXATION

As it is known that the concentrations of CO_2 above 5% adversely influence growth of most microalgae [12, 13], the strains that may grow fast under high CO_2 concentrations (up to 20%) would be required. Extensive work has been carried out to find a suitable algal strain for the direct recovery of CO_2 from industrial sources [14-20]. The criteria used for the screening work were not only tolerances to high CO_2, temperature, and toxic compounds (NO_x and SO_x) but high growth rate and maximum cell densities.

Watanabe *et al.* [14] isolated a fresh-water green alga,

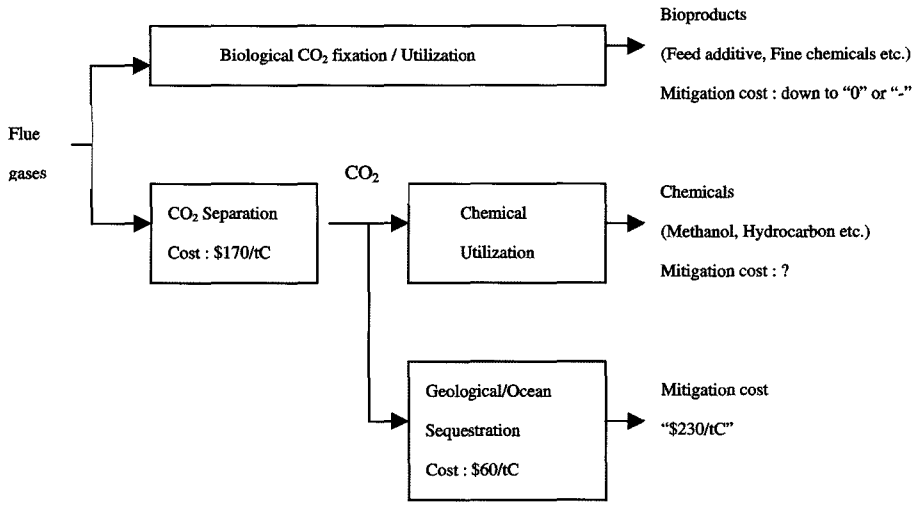

Fig. 1. General scheme of CO_2 mitigation by various technologies.

named *Chlorella* HA-1, from a paddy field. *Chlorella* HA-1 showed maximum growth at 5 and 10% CO_2 but the growth rate decreased remarkably with increasing concentration of CO_2 higher than 10%. They proposed that *Chlorella* HA-1 may be used to fixing CO_2 directly out of stack gas from LNG thermal power plants which contains about 10% CO_2 and a small amount of NO_x. The strain showed a broad range of responses with changes in pH and temperature. But the growth rate of the strain drastically decreased when CO_2 concentration was higher than 20% (v/v). Kodama *et al.* [15] reported that a new highly CO_2 tolerant marine microalga, *Chlorococcum littorale* suitable for high density cultures, has been isolated. Though the alga had an optimum growth rate in cultures with 5 and 10% CO_2, the algal growth rate with 20% CO_2 was comparable to the optimum. No growth was observed, however, at 70% CO_2. The strain may be applied to the power plants located at sea-shore.

If the hot flue gases from industrial sources are directly introduced into the algal cell cultures, the thermal stability of the cells will also be an important criterion in screening a suitable strain. Several studies have been reported the isolation of a strain having a high thermal stability [16-18]. Hanagata *et al.* [16] screened five freshwater green microalgae for tolerance to high CO_2 concentrations and reported that *Scenedesmus* and *Chlorella* species had high growth rates in up to 50% CO_2. The strains showed stable growth rates against high temperatures but no information about pH stability was given. Maeda *et al.* [17] isolated an algal strain, to be named *Chlorella* sp. T-1, which has the optimum temperature of 35°C for growth and maintains good growth up to 40°C. Sakai *et al.* [18] isolated very thermo-tolerant strains from various hot springs. The strains were identified to belong to the genus *Chlorella* and were named H-84 and A-2. Both strains exhibit the highest growth rate at 40°C and grow well up to 42°C. With regard to CO_2 tolerance, the strains could grow well up to 40%. Other works, such as mutation or adaptation studies, have been reported to enhance the tolerances of microalgae in high concentrations of CO_2 [21,22].

Other important inhibitory compounds for CO_2 fixation in algal cells are NO_x and SO_x. Flue gases emitted from industrial sources usually contain up to 200 ppm of NO_x and SO_x. Most highly CO_2 tolerant algal cells, however, may survive only under 50 ppm of NO_x and SO_x [14,23,24]. Therefore, the inhibition by the toxic compounds in the gases would be inevitable if the flue gas is directly introduced into the microalgal culture. To overcome the inhibition effects, several studies have been carried out [25-27]. Recently Sung *et al.* [19] isolated a highly CO_2 tolerant microalga and named it *Chlorella* KR-1. Growth of the strain was not inhibited in conditions up to 20% of CO_2, 100 ppm of NO_x and 50 ppm of SO_x [25]. Tolerances of *Chlorella* KR-1 to the toxic compounds could be increased by controlling pH of culturing medium and the cells could grow well up to 250 ppm of SO_x and 300ppm of NO_x [26]. However, controlling the pH was effective only for some specific microalgae. Several strains of microalgae, which are suitable for CO_2 fixation, have been listed (Table 1).

Cases of direct CO_2 fixation from actual flue gases have been also reported [17,25,32-35]. *Chlorella* KR-1 can fix CO_2 directly from the actual flue gas emitted from LNG boilers [25]. The growth rate of KR-1 cultured with the LNG flue gas was approximately equivalent to that obtained from 10% CO_2 gas mixtures. Hamasaki *et al.* [33] reported that the algal strains, *N. salina* and *P. tricornutum*, can fix CO_2 from flue gases emitted from a power plant. The flue gas contains about 10-15% CO_2 and 70~150 ppm of NO_x and SO_x, each. The biomass productivity was about 11 g m^{-2} day^{-1} in raceway reactors. At Cyanotech Corp., the algal production facility in Kona Hawaii, a small power plant was built to produce both power and allow the capture of the CO_2 required for algal production ponds. Two 180 kW generators produce the electricity required to operate the algal production ponds and other power production needs. The stack gas comes

Table 1. Growth characteristics of microalgal candidates for biofixation of carbon dioxide

Microalgae	CO_2, %	NO_x, ppm	SO_x, ppm	Growth rate in linear phase, g L^{-1} day^{-1}	Ref
C. littorale	70	50	30	0.47	[27]
Chlorella HA-1	20	100	50	0.51	[28]
Synechocystis sp.	100	600*	100*	-	[29]
C. caldarium	15	50	-	-	[23]
Chlorella KR-1	30	100	100	0.78	[30, 31]

*: NO_3^- and SO_3^- concentrations in aqueous phase.

Table 2. Aerial productivity of biomass grown outdoors in the different photobioreactors

Photobioreactor	Microalgal strains	Culture volume, L (light path, cm)	Highest productivity, g m^{-2} day^{-1}	Ref.
Raceway pond	*Chlorella* sp.	200 (20.0)	13.2	40
"	*Chlorophyta* sp.	" (")	8.2	"
Helical tubular	*Chlorella* sp.	30 (2.5)	28.1	41
Vertical flat-plate	*Synechocytis aquatilis*	24 (1.5)	31.0	42
" (Continuous)	*Nannochloropsis* sp.	1000 (10.0)	12.0	43
Tubular (in vertical arrangements)	*Chlorella sp.*	700,000 (5.0)	35.7	44
Tubular (Horizontal)	*Haematococcus pluvialis*	25,000 (41.0)	13.0	6
Tubular (Inclined)	*Chlorella pyrenoidosa*	50 (1.2)	130.0	45
Annular	*Nannochloropsis* sp.	140 (3.5)	52.5	46

out at 20 m^3/min and contains 8% CO_2 and is transferred to the microalgae culture systems for CO_2 fixation [34].

DEVELOPMENT OF PHOTOBIOREACTOR SYSTEMS

Although significant progress has been made in finding a suitable microalga, there are still several major problems to overcome in order to make the biological CO_2 fixation applicable. Since the CO_2 fixation rate is too low, a large capacity is required for the system to do a meaningful CO_2 sequestration. For example, a raceway pond, the most widely used photobioreactor for commercial production of microalgae, requires 1.5 km^2 to fix the CO_2 emitted from a 150 MW thermal power plant [7]. Thus, it is important to maximize both volumetric productivity and photosynthetic efficiency to reduce the capacity of the system. However, it is not an easy task because the two objectives are, in part, contradictory. In most cases, the high cell concentration may decrease the photosynthetic efficiency because of the shadowing effects by the cells themselves. Many photobioreactors with various configurations, which may introduce light energy efficiently into the dispersion of microalgae, have been developed.

As enclosed photobioreactors have many advantages over raceway ponds, such as higher productivity and possible application for various microalgae species, the application of the closed photobioreactor has been a focus of the R&D activities to develop microalgae greenhouse gas mitigation technologies. Thus, extensive work for the development of a highly efficient enclosed photobioreactor having a high aerial productivity and a low cost for construction has been done over the last few decades [35-39]. The aerial productivities of various photobioreactors have been compared in Table 2 [6,40-46].

Recently several technical approaches to improve the light utilization efficiency of the reactor with higher cell densities have been tried by using Fresenel lenses and optical fibers [47-49]. Takano *et al.* reported that they could obtain 4.44 g CO_2 L^{-1} day^{-1} with a cell concentration of 6.8 g/L [47]. The CO_2 removal rate is two or three times higher than that obtained at a small tubular reactor. However, the optical fiber reactor has not been in application because of the high capital cost. However, this principle seems to be applicable only for the aquaculture of certain species in the future. Among various photobioreactors, the enclosed photobioreactor has the highest productivity based on capital cost (Fig. 2). While many experimental photobioreactors have been designed, constructed and deemed successful, very few have been actually successful on the commercial scale [6,38,40,41].

Scaling up of the research photobioreactor to a com-

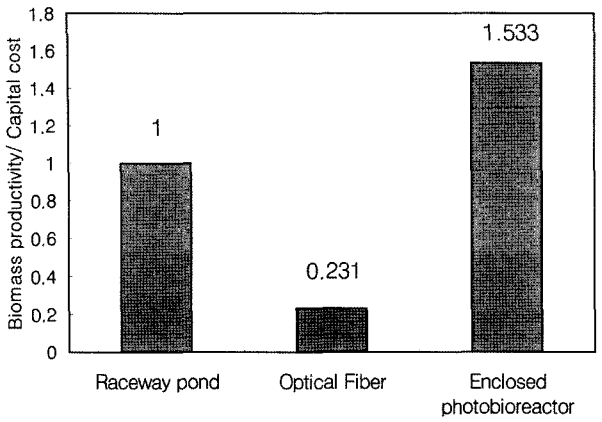

Fig. 2. Comparison of the photobioreactors [50].

mercial scale is not trivial. Problems related to the scale-up of the photobioreactor were reviewed by Tredici [36]. Currently only three commercial enclosed photobioreactors have been constructed and are under operation. IGV-GmbH developed a commercial scale photobioreactor system, which consists of compact and vertically-arranged, horizontally running glass tubes of a total length of 500,000 m and a total reactor volume of 700 m^3. The system takes 10,000 m^2 for installation and 260~300 tons of CO_2 which results in the annual production of 130~150 tons dry biomass. Because the length of photobioreactor is too long, shear stress should be high. Therefore, the reactor may not be used for the cultivation of shear sensitive algal cells. The system is used for culturing *Chlorella*. Mera Pharmaceuticals, Inc. (formerly Aquasearch Inc.) developed another horizontal enclosed photobioreactor suitable for the culturing of shear sensitive cells. The volume of the unit system is 25,000 L. The reactor is now used for the culturing of *Haematococcus pluvialis*. Dome-shaped photobioreactor has been developed and used for culturing *H. pluvialis* [51]. However, none of them are currently used for CO_2 mitigation.

Another important factor responsible for low productivity is the light saturation effect. Microalgae cultures can utilize only a fraction of the sun light to which they are exposed, typically one third or less. The reason for this is that the algal photosynthetic pigments capture more protons under full sunlight conditions than can be processed by photosynthesis. Recent research demonstrated that algal cultures and mutants with reduced antenna sizes can exhibit increased photosynthetic rates under high light intensities [52,53].

UTILIZATION OF MICROALGAE

As microalgae grown from CO_2 fixation contain various useful compounds, the strategy for utilizing algal cells obtained from CO_2 fixation is very important for the CO_2 fixation process to be economically viable. Since most actual flue gases may contain some toxic compounds, several studies were done for the utilization of microalgae into non-edible products. Frenz *et al.* [53] recovered hydrocarbon from *B. braunii* by solvent extraction and proposed the use of hydrocarbon as a fuel to replace diesel. Sawayama *et al.* [2] investigated the feasibility of producing liquid fuels from *B. braunii* by thermochemical liquefaction. However, those processes to utilize algal cells as fuels were reported to be not economically viable because the value of fuel was not high enough. If the algal cells are utilized as fuel, the CO_2 mitigation costs are predicted to be between \$150/tC and \$280/tC [54]. Zhong *et al.* [55] studied the use of microalgae as fillers in plastics. By mixing *Chlorella vulgaris* with polyvinylchloride (PVC) and forming them into molds, building materials have been produced. Because microalgae are in a chemically stable form, long-term storage of CO_2 may be possible. For long-term storage of CO_2 , gene manipulation technology has been applied to convert CO_2 into the high quality of cellulose by microalgae [56]. Hirano *et al.* [57] studied the process of methanol production by the gasification of algal cells and obtained 1.1 of energy balance which showed that the process was plausible as a process for energy production. They also reported that the energy balance could be even higher if the more efficient production of microalgal biomass was developed. When the processes mentioned above utilize algal cells in non-edible products, there will be no toxicity problems but the economic feasibility of the processes is very doubtful.

Therefore, several studies have been done to fix CO_2 from cleaner flue gases and utilize the biomass products in higher value products like feed additive or pigments. Lee *et al.* [3] reported that algal cells produced from CO_2 fixation using LNG flue gas were successfully used as a feed additive for chicks. They also reported that toxicity was not detected throughout the experiments. The demonstration work for the production of algal cells using CO_2 produced from a lime production plant and the utilization of the biomass in feed for chicks also has been reported [38]. Nakamura *et al.* [35] reports that they are working on a project involved in extracting high value products of \$100,000 per kg of C from microalgae produced from CO_2 fixation. When the project is completed, it is expected that the net CO_2 sequestration cost may be decreased to zero from \$100/tC.

One successful example for the practical biological CO_2 fixation system has been reported. Cyanotech Corp., located at Kona, Hawaii, constructed a small power plant to produce both power and fed flue gases that were emitted from the power plant to algal production ponds in order to recover CO_2 in flue gases. The company could expect an annual net income (credit) of almost \$300,000 from power and CO_2 savings from the operation of the system [34].

CONCLUSION

In this review, we have discussed the potential and applications of the biological CO_2 fixation technology for CO_2 mitigation. Although some progress has been made

in finding a suitable algal strain for CO_2 fixation and developing a photobioreactor, there are still too many problems to apply a biological CO_2 fixation process for CO_2 sequestration purposes. For example, the productivity of microalgae required for a meaningful CO_2 sequestration should be three orders higher in magnitude levels than the current system-a daunting goal. Thus, some short-term approaches to microalgae CO_2 fixation/ utilization are possible by combining CO_2 from the fossil fuel combustion system and nutrients in a photobioreactor where microalgae photosynthetically convert the CO_2 into high commercial value products, such as feed additive and pharmaceuticals. The approaches may contribute to reduce the CO_2 sequestration cost.

Acknowledgement This paper was performed for Carbon Dioxide for Reduction and Sequestration Center, one of 21st Century Frontier R&D Programs funded by Ministry of Science and Technology of Korea.

REFERENCES

[1] IEA (1998) Carbon dioxide capture from power stations. Available at http://www.ieagreen.org.uk.

[2] Sawayama, S., T. Minowa, and S. Yokoyama (1999) Possibility of renewable energy production and CO_2 mitigation by thermochemical liquefaction of microalgae. *Biomass Bioenergy* 17: 33-39.

[3] Lee, J. S., D. G. Kim, J. P. Lee, S. C. Park, J. H. Koh, and S. J. Ohh (2001) CO_2 fixation by *Chlorella* KR-1 using flue gas and its utilization as a feedstuff for chicks. *J. Microb. Biotechnol.* 11: 772-775.

[4] Becker, E. W. (1994) *Microalgae*. 1st ed., pp. 250-275. Cambridge University Press, Cambridge, UK.

[5] Metzger, P. and C. Largeau (1999) Chemicals of *Botryococcus braunii*. pp. 205-260. In: Z. Cohen (ed.). *Chemicals from Microalgae*. Taylor & Francis Ltd., London, UK.

[6] Olaizola, M. (2003) Commercial development of microalgal biotechnology: from the test tube to the marketplace. *Biomolecular Eng.* 20: 459-466.

[7] Karube, I., T. Takeuchi, and D. J. Barnes (1992) Biotechnology reduction of CO_2 emissions. *Adv. Biochem. Eng. Biotechnol.* 46: 63- 78.

[8] Usui, N. and M. Ikenouchi (1997) The biological CO_2 fixation and utilization project by RITE (1). *Energy Convers. Mgmt.*, 38: S487-S492.

[9] Otsuki, T. (2001) A study for the biological CO2 fixation and utilization system. *Sci. Total Environ.* 277: 21-25.

[10] Hughes, E. and J. Benemann (1997) Biological fossil CO_2 mitigation. *Energy Convers. Mgmt.* 38S: 467-473.

[11] Hall, D. O., S. A. Markov, Y. Watanabe, and K. K. Rao (1995) The potential application of cyanobacterial photosystnesis for clean technologies. *Photosyn. Res.* 46: 159-167.

[12] Silva, H. and S. J. Pirt (1984) Carbon dioxide inhibition of photosynthetic growth of *Chlorella*. *J. Gen. Microbiol.* 130: 2833-2838.

[13] Lee, Y. and H. S. Tay (1991) High CO_2 partial pressure depresses productivity and bioenergenetic growth yield of *Chlorella pyrenoidosa* culture. *Appl. Phycol.* 3: 95-101.

[14] Watanabe, Y., N. Ohmura, and H. Saiki (1992) Isolation and determination of cultural characteristics of microalgae which functions under CO_2 enriched atmosphere. *Energy Convers. Mgmt.* 33: 545-552.

[15] Kodama, M., H. Ikemoto, and S. Miyachi (1993) A new species of highly CO_2-tolerant fast growing marine microalga suitable for high density culture. *J. Mar. Biotechnol.* 1: 21-25.

[16] Hanagata, N., T. Takeuchi, Y. Fukuju, D. J. Barnes, and I. Karube (1992) Tolerance of microalgae to high CO_2 and high temperature. *Phytochem.* 31: 3345-3348.

[17] Maeda, K., M. Owada, N. Kimura, K. Omata, and I. Karube (1995) CO_2 fixation from flue gas on coal-fired thermal power plant by microalgae. *Energy Convers. Mgmt.* 36: 717-720.

[18] Sakai, N., Y. Sakamoto, N. Kishimoto, M. Chihara, and I. Karube (1995) *Chlorella* strains from hot springs tolerant to high temperature and high CO_2. *Energy Convers. Mgmt.*, 36: 693-696.

[19] Sung, K. D., J. S. Lee, C. S. Shin, and S. C. Park (1998) Isolation of a new highly CO_2 tolerant fresh-water microalga *Chlorella* KR-1. *Kor. J. ChE.* 15: 449-450.

[20] Murakami, M. and M. Ikenouchi (1997) The biological CO_2 fixation and utilization project by RITE: Screening and breeding of microalgae with high capability in fixing CO_2 . *Energy Convers. Mgmt.* 38: S493-S497.

[21] Price, G. D. and M. R. Badger (1989) Isolation and characterization of high CO_2 requiring- mutants of the Cyanobacterium *Synechococcus* PCC7942. *Plant Physiol.* 91: 514-525.

[22] Yun, Y. S., J. M. Park, and J. W. Yang (1996) Enhancement of CO_2 tolerances of *Chlorella vulgaris* by gradual increase of CO_2 concentration. *Biotechnol. Tech.* 10: 713-716.

[23] Hauck, J. T., G. J. Scierka, S. J. Perry, and M. M. Ataai (1996) Effects of simulated flue gas on growth of microalgae. *Proceedings of 212th ACS National Meeting*. August 25-30. Orlando, USA.

[24] Kurano, N. H. Ikemoto, H. Miyashita, H. Hasegawa, T. Hata, and S. Miyachi (1995) Fixation and utilization of carbon dioxide by microalgal photosynthesis. *Energy Convers. Mgmt.* 36: 689-692.

[25] Lee, J. S., D. G. Kim, J. P. Lee, S. C. Park, J. H. Koh, H. S. Cho, and S. W. Kim (2002) Effects of SO_2 and NO on growth of *Chlorella* sp. KR-1. *Biores. Technol.* 82: 1-4.

[26] Lee, J. N., J. S. Lee, C. S. Shin, S. C. Park, and S. W. Kim (2000) Methods to enhance tolerances of *Chlorella* KR-1 to toxic compounds in flue gas. *Appl. Biochem. Biotechnol.* 84/86: 329-342.

[27] Kurano, N. (1996) A new highly CO_2 tolerant microalga for CO_2 fixation. *Japan Patent* 8-9963.

[28] Watanabe, Y. (1993) A highly CO_2 tolerant microalga. *Japan Patent* 5-304945.

[29] Hirano, A. (1996) CO_2 fixation method using a new microalga, *Japan Patent* 8-56648.

[30] Sung, K. D., J. S. Lee, C. S. Shin, S. C. Park, and M. J. Choi (1999) CO_2 fixation by *Chlorella* KR-1 and its cultural characteristics. *Biores. Technol.* 68: 269-273.

[31] Lee, J. S., K. W. Lee, M. J. Choi, K. D. Sung, C. S Shin, and S. C. Park (2000) A highly CO_2 and SOx tolerant microalga and its utilization for CO_2 fixation. *Japan Patent* 3013990.

[32] Brown, L. M. (1996) Uptake of carbon dioxide from flue gas by microalgae. *Energy Convers. Mgmt.* 37: 1363-1367.

[33] Hamasaki, A., N. Shioji, Y. Ikuta, Y. Hukuda, T. Makita, K. Hirayama, H. Matuzaki, T. Tukamoto, and S. Sasaki (1994) Carbon dioxide fixation by microalgal photosynthesis using actual flue gas from a power plant. *Appl. Biochem. Biotechnol.* 45/46: 799-809.

[34] Pedroni, P., J. Davison, H. Beckert, P. Bergman, and J. Benemann (2001) A proposal to establish an international network on biofixation of CO_2 and greenhouse gas abatement with microalgae. *Proceedings of 1st National Conference on Carbon Sequestration*. May 2-6, Washington DC, USA.

[35] Borowitzka, M. A. (1994) Large-scale algal culture systems: The next generation. *Austral. Biotechnol.* 4: 212-215.

[36] Tredici M. R. (1999) Bioreactors, photo. pp. 395-419. In: M. C. Flickinger and S. W. Drew (eds.). *Encyclopedia of Bioprocess Technology: Fermentation, Biocatalysis and Bioseparation*, Vol. 1. Wiley Ltd., New York, USA.

[37] Lee, Y. K. (2001) Microalgal mass culture systems and methods: Their limitation and potential. *J. Appl. Phycol.* 13: 307-315.

[38] Pulz, O. (2001) Photobioreactors: Production systems for phototrophic microorganisms. *Appl. Microb. Biotechnol.* 57: 287-293.

[39] Bayless, D. J., G. G. Kremer, M. E. Prudich, B. J. Stuart, M. L. Chiasson, K. Cooksey, and J. Muhs (2001) Enhanced practical photosynthetic CO_2 mitigation. *Proceedings of 1st National Conference on Carbon Sequestration*. May 2-6, Washington DC, USA.

[40] Hase, R., H. Okigawa, C. Sasao, M. Morita, and Y. Watanabe (2000) Photosynthetic production of microalgal biomass in a raceway system under greenhouse conditions in Sendai city. *J. Biosci. Bioeng.* 89: 157-163

[41] Morita, M. and Y. Watanabe, and H. Saiki (1998) Investigation of a cone-shaped helical tubular photobioreactor design in terms of practical use. *Proceedings of 4th International Conference on Greenhouse Gas Control Technologies*. August 30-September 2. Interlaken, Switzerland.

[42] Zhang, K., S. Miyachi, and N. Kurano (2001) Photosynthetic performance of a cyanobacterium in a vertical flat-plate photobioreactor for outdoor microalgal production and fixation of CO_2. *Biotechnol. Lett.* 23: 21-26.

[43] Zhang, C. W., O. Zmora, R. Kopel, and A. Richimond (2001) An industrial-size flat plate glass reactor for mass production of *Nannochloropsis* sp. *Aquaculture* 195: 35-49.

[44] Pulz, O. (2001) Industrial microalgal production plant in Germany: Design and Scale-up. *Proceedings of Symposium on Microalgae and Seaweed Products in Plant/Soil-Systems*. June 20-22. Mosonmagyarovar, Hungary.

[45] Lee, Y. K. and C. S. Low (1991) Effect of photobioreactor inclination on the biomass productivity of an outdoor algal culture. *Biotechnol. Bioeng.* 38: 995-1000.

[46] Zittelli, G. C., R. Liliana, and M. Tredici (2003) Mass cultivation of *Nannochloropsis* sp. in annular reactors. *J. Appl. Phycol.* 15: 107-114.

[47] Takano, H., H. Takeyama, N. Nakamura, K. Sode, J. G. Burgess, E. Manabe, M. Hirano, and T. Matsunaga (1992) CO_2 removal by high-density culture of a marine cyanobacterium *Synechococcus* sp. using an improved photobioreactor employing light-diffusing optical fibers. *Appl. Biochem. Biotechnol.* 34/35: 449-458.

[48] Michiki, H. (1995) Biological CO_2 fixation and utilization project. *Energy Convers. Mgmt.* 36: 701-705.

[49] Nishikawa, N., K. Hon-Nami, K. Hirano, Y. Ikuta, H. Hukuda, M. Negoro, M. Kanebo, and M. Hada (1992) Reduction of carbon dioxide emission from flue gas with microalgae cultivation. *Energy Convers. Mgmt.* 33: 553-560.

[50] Tokyo Electric Power Company R&D Center (1997) Research on effective culture of microalgae. p. 16. R&D Report of Global Environment Group, Tokyo, Japan.

[51] http://www.microgaia.com

[51] Melis, A., J. Neidhardt, and J. R. Benemann (1999) *Dunaliella salina* (*Chlorophyta*) with small chlorophyll antenna sizes exhibit higher photosynthetic productivities and photon use efficiencies than normally pigmented cells. *J. Appl. Phycol.* 10: 515-525.

[52] Nakajima, Y. and R. Ueda (2000) The effect of reducing light-harvesting pigment on marine microalgal productivity. *J. Appl. Phycol.* 12: 285-290.

[53] Frenz, J., C. Largeau, E. Casadevall, F. Kollerup, and A. J. Daugulis (1989) Hydrocarbon recovery and biocompatibility of solvents for extraction from cultures of *Botryococcus braunii*. *Biotechnol. Bioeng.* 34: 755-782.

[54] Nakamura, T., M. Olaizola, and S. Masutani (2001) Capture and sequestration of CO_2 from stationary combustion systems by photosynthesis of microalgae. *Proceedings of 1st National Conference on Carbon Sequestration*. May 2-6. Washington DC, USA.

[55] Benemann, J. R. (1997) CO_2 mitigation with microalgae systems. *Energy Convers. Mgmt.* 38: S475-S479.

[56] Tokyo Electric Power Company R&D Center (2000) Research on Fixation and effective utilization of CO_2 using microalgae. R&D Report of Global Environment Group, 21-22.

[57] Hirano, A., K. Hon-Nami, S. Kunito, M. Hada, and Y. Ogushi (1998) Temperature effect on continuous gasification of microalgal biomass: Theoretical yield of methanol production and its balance. *Catalysis Today* 45: 399-404.

[Received September 29, 2003; accepted December 17, 2003]