Selection of optimal microalgae species for CO_2 sequestration

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INTRODUCTION

CO_2 fixation by photoautotrophic algal cultures has the potential to diminish the release of CO_2 into the atmosphere, helping alleviate the trend toward global warming. To realize workable biological CO_2 fixation systems, selection of optimal microalgae species is vital. The selection of optimal microalgae species depends on specific strategies employed for CO_2 sequestration. In this paper, the criteria used for selecting microalgae species for CO_2 sequestration systems will be discussed, as well as the characteristics of some species which have been tested for use in CO_2 mitigation.

COMMERCIAL VALUES

Some microalgae species, such as *Chlorella*, *Spirulina* and *Dunaliella* have commercial values. It is expected that commercial profit from biomass production will offset overall operational costs for CO_2 sequestration. *Chlorella* sp. has been studied for use in CO_2 sequestration. For example, Hanagata et al. (1992) reported that *Chlorella* sp. can be grown under 20% CO_2 conditions. The species has been used as a health food (Becker, 1994). CO_2 tolerance of *Dunaliella* sp. also has been examined and the species has been used in the industrial production of β-carotene (Graham and Wilcox, 2000).

Further potential applications of microalgal products are the utilization of secondary metabolite, fertilizer and biofuel production. In addition to CO_2 sequestration, another potential strategy to offset operational costs, is to develop multi-functional systems such as waste treatment and aquaculture farms, functions (Pedroni et al., 2001). Since economic feasibility is one of the major issues to realize biological mitigation systems, seeking additional value for the system is an important criterion.

CULTURAL SYSTEMS

Two distinctive cultural systems have been proposed for CO_2 sequestration with microalgae. One is the open pond system, and the other is the closed photobioreactor system. There is ongoing discussion regarding whether the open pond system or the closed photobioreactor system would be better for CO_2 sequestration (Benemann, 1997; Pedroni et al., 2001). Apparent advantages for utilizing the open pond system are low initial and operational costs. On the other hand, an advantage for the photobioreactor system has a higher potential productivity due to better environmental control and harvesting efficiency.

For an open pond system, the size of the area needed to assimilate significant amounts of CO_2 is being criticized. In fact, the typical size of open pond microalgae production systems range from 0.2 to 0.4 ha (Pedroni et al., 2001). However, there are already existing large-scale open pond systems. For example, the largest single algal production systems, developed by the Sosa Texcoco Co. near Mexico city is 900 ha (Becker, 1994).

The size of some recently constructed wetlands, which have been engineered for waste water treatment harnessing the ability of biological systems, is also suggestive. For example, the wetlands constructed for the Everglades Nutrient Removal Project in Florida occupies 1,406 ha (Arizona Department of Environmental Quality, 1995). The development of such constructed wetlands is increasingly popular, and wetlands have been built in a variety of locations, from the Sonoran desert in Arizona to the Everglades National Park in Florida (Arizona Department of Environmental Quality, 1995).

Another strategy, which has never been explored for CO_2 sequestration use, is to build moderately environmentally controlled systems. In such a system, microalgae is grown under a relatively controlled environment, such as a greenhouse and shade. This is an interesting idea since one can control environment inside a greenhouse while construction costs will not be as high as a photobioreactor with a solar collector system. In fact, a similar concept has been applied for wastewater treatment (Arizona Department of Environmental Quality, 1995; Bennett, 1998; Ono and Koshimizu, 2002).

The choice of the cultural systems is an important factor in selecting microalgae species. In the case of the open pond system, climate conditions over the open pond plays an important role.

In the case of the open raceway pond tested by Tohoku Electric Power CO. in Sendai, Japan, stable cultivation of *Tetraselmis* sp. was possible while other species, *Nannochloropsis salina* and *Phaeodactylum tricornutum* could not be cultivated continuously (Matsumoto et al., 1995). *Tetraselmis suecica* has been used in an outdoor culture experiment conducted at the Natural Energy Laboratory of Hawaii (NELH) in Kona on the island of Hawaii (Laws and Berning, 1991).

HIGH CO_2 TOLERANCE

Direct utilization of power plant flue gas has been considered for CO_2 sequestration systems (Benemann, 1993). The advantage of utilizing flue gas directly is the reduction of the cost of separating CO_2 gas. Since power plant flue gas contains a higher concentration of CO_2, identifying high CO_2 tolerant species is important. Although CO_2 concentrations vary depending on the flue gas source, 15-20% v/v is typically assumed.

Several species have been tested under CO_2 concentrations of over 15%. For example, *Chlorococcum littorale* could grow under 60% CO_2 using the stepwise adaptation technique (Kodama et al., 1994). Another high CO_2 tolerant species is *Euglena gracilis.* Growth of *Euglena gracilis* was enhanced under 5-45 % concentration of CO_2. The best growth was observed with 5% CO_2 concentration. However, the species did not grow under greater than 45% CO_2 (Nakano et al., 1996). Hirata et al. (1996a; 1996b) reported that *Chlorella* sp. UK001 could grow successfully under 10% CO_2 conditions. It is also reported that *Chlorella* sp. can be grown under 40% CO_2 conditions (Hanagata et al., 1992). Furthermore, Maeda et al (1995) found a strain of *Chlorella* sp. T-1 which could grow under 100% CO_2, although the maximum growth rate occurred under a 10% concentration. *Scenedesmus* sp. could grow under 80% CO_2 conditions but the maximum cell mass was observed in 10-20% CO_2 concentrations (Hanagata et al., 1992). *Cyanidium caldarium* (Seckbach et al., 1971) and some other species of *Cyanidium* can grow in pure CO_2 (Graham and Wilcox, 2000).

Table 1 summarizes the CO_2 tolerance of various species. Note that some species may tolerate even higher carbon dioxide concentrations than listed in the table.

Overall, a number of high CO_2 tolerant species have been identified.

Table 1. CO_2 tolerance of various species.

Species	Known Maximum CO_2 Concentration	References
Cyanidium caldarium	100%	Seckbach et al., 1971
Scenedesmus sp.	80%	Hanagata et al., 1992
Chlorococcum littorale	60%	Kodama et al., 1993
Synechococcus elongatus	60%	Miyairi, 1997
Euglena gracilis	45%	Nakano et al., 1996
Chlorella sp.	40%	Hanagata et al., 1992
Eudorina spp.	20%	Hanagata et al., 1992
Dunaliella tertiolecta	15%	Nagase et al., 1998
Nannochloris sp.	15%	Yoshihara et al., 1996
Chlamydomonas sp.	15%	Miura et al., 1993
Tetraselmis sp.	14%	Matsumoto et al., 1995

TOLERANCE ON TRACE ELEMENTS IN THE FLUE GAS

Some researchers considered the effect of trace acid gases on CO_2 sequestration by microalgae, such as NO_x and SO_2. As a source of trace elements, both model flue gas (Maeda et al., 1995; Nagase et al., 1998; Yoshihara et al., 1996) and actual flue gas (Matsumoto et al., 1995) have been used. It is reported that *Nannochloris* sp. could grow under 100 ppm of nitric oxide (NO) (Yoshihara et al., 1996). Under 1000 ppm of NO and15% CO_2 concentration, *Dunaliella tertiolecta* could remove 51 to 96% of nitric oxide depending on the growth condition (Nagase et al., 1998). *Tetraselmis* sp. could grow with actual flue gas with 185 ppm of SOx and 125 ppm of NOx in addition to 14.1% CO_2 (Matsumoto et al., 1995). Maeda et al (1995) examined the tolerance of a strain of *Chlorella* and found that the strain could grow under various combinations of trace elements and concentrations.

HIGH TEMPERATURE TOLERANCE

Since the temperature of waste gas from thermal power stations is around 120°C, the use of thermophilic, or high temperature tolerant species are also being considered (Bayless et al., 2001). Themophiles can grow in temperature ranging from 42-100°C. An obvious advantage of the use of thermophilies for CO_2 sequestration is reduced cooling costs. In addition, some thermophiles produce unique secondary metabolites (Edwards, 1990), which may reduce overall costs for CO_2 sequestration. A disadvantage is the increased loss of water due to evaporation. *Cyanidium caldarium*, which can grow under pure CO_2 is a thermophilic species (Seckbach et al., 1971). Miyairi (1995) examined the growth characteristics of *Synechococcus elongatus* under high CO_2 concentrations. The upper limit of CO_2, concentration and growth temperature for the species was 60% CO_2 and 60°C (Miyairi, 1995). Currently, an unidentified thermophilic species isolated from Yellowstone National Park has been examined by the group of researchers supported by the U.S. Department of Energy.

Although less tolerant than thermophiles, some mesophiles can still be productive under relatively high temperature (Edwards, 1990). Such species also can be candidate species for the direct use of flue injection.

MARINE MICROALGAE

The use of marine microalgae for biological CO_2 sequestration has been considered. One reason is that seawater could be used directly as a growing media so that maintenance costs of microalgae culture could be reduced. Many CO_2 sources, such as power plants, are located along the coastal area.

A number of marine algae species have been tested for CO_2 sequestration applications. Those marine algae species are, *Tetraselmis* sp. (Laws and Berning, 1991; Matsumoto et al., 1995), *Synechococcus* sp. (Takano et al., 1992), *Chlorococcum littorale* (Pesheva et al., 1994), *Chlamydomonas* sp. (Miura et al., 1993), *Nannochloropsis salina* (Matsumoto et al., 1995; Matsumoto et al., 1996) and *Phaeodactylum tricornutum* (Matsumoto et al., 1995).

CO_2 ASSIMILATION ABILITY

CO_2 assimilation ability is a pivotal criterion in selecting algae species. Since growth conditions vary from experiment to experiment, comparison is not straightforward.

A comparison of bubbling CO_2 gas versus adding carbonated water as a means of introducing CO_2 into the microalgal flumes was conducted. The bubbling CO_2 showed 96 ± 11% utilization efficiencies while adding carbonated water showed 81 ± 11% efficiencies. The difference in utilization efficiencies between two methods was statistically significant (Laws and Berning, 1991).

LIGHT CONDITION

Light condition, especially light intensity, is an important factor because the light energy drives photosynthesis. Typical light intensity requirements of microalgae are relatively low in comparison to higher plants. For example, saturating light intensity of *Chlorella* sp. and *Scenedesmus* sp. is approximately 200 $\mu mol/sec/m^2$ (Hanagata et al., 1992). Microalgae often exhibits photoinhibition under excess light conditions. Photoinhibition is often suspected as the major cause of reducing algal productivity.

The use of a photobioreactor with a solar collector device for the CO_2 mitigation has been explored. Maximum light intensity of 15.7 Wm^{-2} could be attained using the system, and the culture of

Chlorella sp. could be maintained. The efficiency of light collection and transmission to the algal cells was 8% (Hirata 1996a). Recently, improvements are being made to the solar collecting devices. For example, Oak Ridge National Laboratory has been developing hybrid lighting systems (Muhs, 2000). The system can utilize infrared heat as well as visible light. In addition, artificial lighting is combined so that lighting is possible when there is no natural sunlight. The use of such novel solar collecting and distributing devices would improve CO_2 sequestration efficiency.

SOLID SUPPORT

The application of microalgae on solid support is being considered for CO_2 sequestration projects (Bayless et al., 2001). However, the majority of previous research on microalgae has been conducted under liquid suspension conditions.

The potential advantage of solid support application is an increased surface area and probable improvement on harvesting efficiency. It has been suggested that the development of the efficient harvesting system is crucial for the development of successful CO_2 sequestration systems.

DISCUSSION

From previous studies, several high CO_2 tolerant species have been identified, for both freshwater and seawater species. Figure 1. shows habitable temperature-CO_2 concentration conditions of microalgae species previously tested. As most of these species are in the mesophilic temperature range, it is apparent that only few studies have been done on thermophilic species.

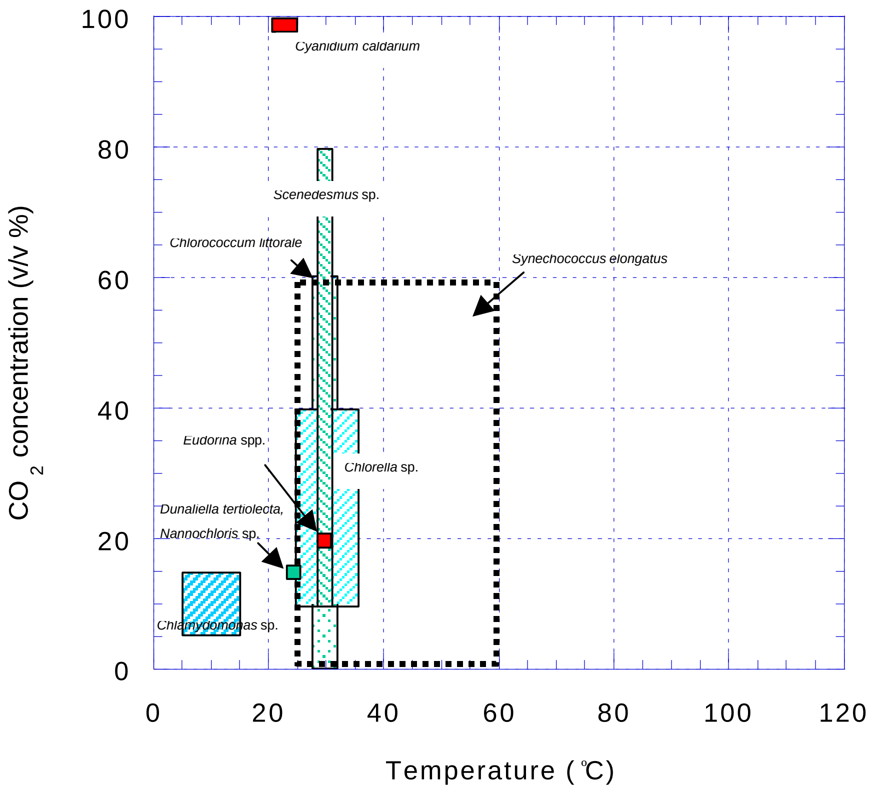

Figure 1. Habitable temperature-CO_2 concentration conditions of microalgae species tested. Publications listed on the table 1 were used to illustrate this figure.

So far, no overwhelmingly useful microalgae species have been found for CO_2 sequestration, even though a number of studies have been conducted. For example, *Chlorella* sp. has commercial value and it can grow under high CO_2 concentration, but it does not grow over 45°C (Hanagata et al., 1992; Hirata et al., 1996b). The use of marine strains is advantageous for biological CO_2 assimilation facilities which are located by the coastline. However, this is less attractive for those facilities which are located inland. Each species has disadvantages to some extent. It is also obvious that only a few studies have been done in certain areas, such as the use of thermophilic species and the behavior of microalgae on the solid support cultivation systems.

CONCLUSION

For the purpose of CO_2 sequestration, the use of microalgae is a unique technology. For example, microalgae can assimilate CO_2 within various ranges of concentration from ambient (0.04%) to 100% v/v CO_2 by selecting adequate species. The technology also works under a wide range of thermal conditions, ranging from 25 to 100°C. Adapting microalgae for the use of CO_2 sequestration also has the potential to produce useful byproducts, and could function multi-purposely. In addition, it is an environmentally friendly technology.

As discussed, there are a variety of technological solutions possible for microalgae-based CO_2 sequestration systems, and thus optimal microalgae employed would differ from system to system. While efforts to find the "ideal" microalgae species will continue, strategic engineering decisions and engineering modifications will be taken into great consideration to realize effective microalgal CO_2 sequestration systems.

REFERENCES

Arizona Department of Environmental Quality. (1995) Arizona guidance manual for constructed wetlands for water quality improvement. Arizona Department of Environmental Quality, Arizona.

Bayless, D. J., Kremer, G. G., Prudich, M. E., Stuart, B. J., Vis-Chiasson, M. L., Cooksey, K., Muhs, J. (2001) Enhanced practical photosynthetic CO_2 mitigation. Proceedings of the first national conference on carbon sequestration, 5A4, 1-14.

Becker, E. W. (1994) Microalgae: Biotechnology and microbiology. Cambridge University press, Cambridge, Great Britain. pp293.

Benemann, J. R. (1993) Utilization of carbon dioxide from fossil fuel - burning power plants with biological system. Energy conversion and management 34(9/11), 999-1004.

Benemann, J. R. (1997) CO_2 mitigation with microalgae systems. Energy conversion and management 38(Suppl), S475-S479.

Bennett, P. (1998) Ashfield's alternative. Landscape Architecture 88(1), 44-49.

Edwards, C. (1990) Thermophiles. Microbiology of extreme environments. Ed. Edwards, C. Open university press, Milton Keynes, Great Britain. pp218.

Graham, L. E., Wilcox, L. W. (2000) Algae, Prentice-Hall, Inc., Upper Saddle River, NJ. pp 640.

Hanagata, N., Takeuchi, T., Fukuju, Y., Barnes, D. J., Karube, I. (1992) Tolerance of microalgae to high CO_2 and high temperature. Phytochemistry 31(10), 3345-3348.

Hirata, S., Hayashitani, M., Taya, M., Tone, S. (1996a) Carbon dioxide fixation in batch culture of *Chlorella* sp. using a photobioreactior with a sunlight-collection device. Journal of fermentation and bioengineering. 81(5), 470-472.

Hirata, S. Taya, M., Tone, S. (1996b) Characterization of *Chlorella* cell cultures in batch and continuos operations under a photoautotrophic condition. Journal of chemical engineering of Japan 29(6), 953-959.

Kodama, M., Ikemoto, H., Miyachi, S. (1993) A new species of highly CO_2-tolreant fast-growing marine microalga suitable for high-density culture. Journal of marine biotechnology 1, 21-25.

Laws, E. A., Berning, J. L. (1991) A study of the energetics and economics of microalgal mass culture with the marine chlorophyte Tetraselmis suecica: implications for use of power plant stack gases. Biotechnology and bioengineering 37, 936-947.

Maeda, K., Owada, M., Kimura, N., Omata, K., Karube, I. 1995. CO_2 fixation from the flue gas on coal-fired thermal power plant by microalgae. Energy convers. Mgmt 36, 717-720.

Matsumoto, H., Shioji, N., Hamasaki, A., Ikuta, Y., Fukuda, Y., Sato, M., Endo, N., Tsukamoto, T. (1995) Carbon dioxide fixation by microalgae photosynthesis using actual flue gas discharged from a boiler. Applied biochemictory and biotechnology 51/52, 681-692.

Matsumoto, H., Shioji, N., Hamasaki, A., Ikuta, Y. (1996) Basic study on optimization of raceway-type algal cultivator. Journal of chemical engineering of Japan 29(3), 541-543.

Miura, Y., Yamada, W., Hirata, K., Miyamoto, K., Kiyohara, M. (1993) Stimulation of hydrogen production in algal cells grown under high CO_2 concentration and low temperature. Applied biochemistry and biotechnology 39/40, 753-761.

Miyairi, S. (1995) CO_2 assimilation in a thermophilic cyanobacterium. Energy conversion and management 36(6-9), 763-766.

Muhs, J. (2000) Design and analysis of hybrid solar lighting and full-spectrum solar energy systems. Proceedings of the international solar energy conference, solar engineering 2000, 229-237.

Nagase, H., Eguchi, K., Yoshihara, K., Hirata, K., Miyamoto, K. (1998) Improvement of microalgal NOx removal in bubble column and airlift reactors. Journal of fermentation and bioengineering 86(4), 421-423.

Nakano, Y., Miyatake, K., Okuno, H., Hamazaki, K., Takenaka, S., Honami, N., Kiyota, M., Aiga, I., Kondo, J. (1996) Growth of photosynthetic algae *Euglena* in high CO_2 conditions and its photosynthetic characteristics. ActaHort 440, 49-54.

Ono, E., Koshimizu, H. (2002) Significance of the closed artificial ecosystem approach for urban and natural landscape studies. The 5th International Sympsium of Japan, Korea and China on Landscape Architecture. 215-221.

Pedroni, P., Davison, J., Beckert, H., Bergman, P., Benemann, J. (2001) A proposal to establish an international network on biofixation of CO_2 and greenhouse gas abatement with microalgae. Journal of energy and environmental research 1(1), 136-150.

Pesheva, I., Kodama, M., Dionisio-Sese, M. L., Miyachi, S. (1994) Changes in photosynthetic characterics induced by transferring air-grown cells of *chlorococcum littorale* to high-CO_2 conditions. Plant and cell physiology 35(3), 379-387.

Seckbach, J., Gross, H., Nathan, M. B. (1971) Growth and photosynthesis of *Cyanidium caldarium* cultured under pure CO_2. Israel journal of botany 20, 84-90.

Sivak, M. N., Vonshak, A. (1988) Photosynthetic characteristics of *Spirulina platensis* on solid support. Chlorophyll fluorescence kinetics. New Phytol 110, 241-247.

Takano, Hi., Takeyama, H., Nakamura, N., Sode, K., Burgess, J. G., Manabe, E., Hirano, M., Matunaga, T. (1992) CO_2 removal by high-density culutre of a marine cyanobacterium Synechococcus sp. using an improved photobioreactor employing light-diffusing optical fibers. Applied biochemistry and biotechnology 34/35, 449-458.

Yoshihara, K., Nagase, H., Eguchi, K., Hirata, K., Miyamoto, K. (1996) Biological elimination of nitric oxide and carbon dioxide from flue gas by marine microalga NOA-113 cultivation in a long tubular photobioreactor. Journal of fermentation and bioengineering. 82(4), 351-354.