9.4.1 Introduction

Global climate change requires substantial reductions in anthropogenic GreenHouse Gas (GHG) emissions, particularly of fossil carbon dioxide (CO₂), and also changes in the way we produce and use energy resources. Due to the global quantities, diversity, and geographical distribution of fossil CO₂ sources, no single GHG abatement technology will be applicable to all locations, and so a portfolio of technologies will be required that can be used singly or in combination. Among the mitigation options, CO₂ capture and sequestration technologies prevent CO₂ from fossil fuel combustion from building up in the atmosphere, thus allowing the continued use of fossil fuels on which the world is presently heavily dependent. Most of these capture and sequestration technologies are based on the capture of fossil CO₂ from stationary sources, such as power plants and other industrial facilities, followed by its long-term storage in geological formations, soils or oceans, or beneficial re-use.

Biofixation of CO₂ with microalgae is one such GHG abatement technology. It is based on the use of solar energy through photosynthesis to capture and utilize concentrated CO₂ streams produced by power plants and other sources. Microalgae are microscopic aquatic plants (Fig. 1) and, as is the case for other biomass options, mitigation of GHG emissions by biofixation processes results from the conversion and utilization of the harvested algal biomass either as renewable biofuels that substitute fossil fuels, or as products that reduce energy consumption compared to current technologies. Renewable biofuels that can be produced from algal biomass include methane, ethanol, biodiesel and hydrogen, while energy-sparing products include fertilizers, biopolymers, chemicals and even animal feeds. Microalgae CO₂ capture and utilization can also be combined with environmental services such as wastewater treatment and nutrient recycling, providing additional GHG abatement benefits by

Fig. 1. Microalgae currently grown commercially or of potential interest for GHG abatement. A, *Micractinium* sp. (green alga), dominating high-rate wastewater treatment ponds (courtesy of EPA); B, *Spirulina (Arthrospira) platensis*, a filamentous microalga produced as a nutritional supplement (courtesy of UTEX); C, *Navicula* sp. (diatom), potentially oil-producing species (courtesy of the Authors).
reducing energy consumption compared to conventional processes. Compared to higher plant biomass production, the most important attribute of microalgae-based processes is their potential for achieving high solar conversion efficiencies, thereby reducing land and water requirements, the major limiting factors in any technology based on photosynthesis.

The concept of CO₂ capture and renewable biofuels production by large-scale microalgae cultures was already proposed half a century ago (Oswald and Golueke, 1960), and has been the subject of extensive R&D, principally in the US (Sheehan et al., 1998) and Japan (Hamasaki et al., 1994; Usui and Ikenouchi, 1997; Murakami and Ikenouchi, 1997). Microalgae are currently grown commercially for nutritional products in both open ponds and closed photobioreactors, using both concentrated CO₂ sources and flue gases, and are also used in practical wastewater treatment processes (Fig. 2). This practical knowledge base provides a foundation for applications of microalgae mass cultures in GHG abatement. A general representation of such a process is presented in Fig. 3, showing the various inputs, processes and outputs that are discussed here.

To advance the development and the applications of microalgae biofixation processes for renewable energy production and GHG abatement, EniTecnologie and the National Energy Technology Laboratory of the US Department of Energy initiated the organization of the International Network on Biofixation of CO₂ and Greenhouse Gas Abatement with Microalgae, herein called the ‘Biofixation Network’ (Benemann et al., 2001; Pedroni et al., 2001, 2002). This initiative operates under the auspices of the IEA (International Energy Agency) GHG

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**Fig. 2. Microalgae production systems.**
A, Circular open pond (approximately 1,000 m²), mass culture system for *Chlorella* production; B, *Spirulina* and *Haematococcus pluvialis* production plant with paddle wheel-mixed, high-rate ponds; C, closed tubular photobioreactor system for *Haematococcus pluvialis* production; D, wastewater treatment ponds incorporating high-rate ponds (courtesy of the Authors).
R&D Programme and includes as members energy companies, government agencies, and other organizations supporting R&D activities in this field. The purpose of the Biofixation Network is to provide a forum enabling participants to share information and expertise, to coordinate and collaborate in R&D efforts, to prepare techno-economic analyses and resource assessments, and to develop and demonstrate, within a decade, practical microalgae-based processes for GHG abatement. This review presents the status of microalgae technology in GHG abatement and some current R&D efforts being carried out within the Microalgae Network.

9.4.2. Photosynthesis, microalgae productivity and GHG abatement

Biological photosynthetic processes for CO₂ fixation into plant biomass, and its subsequent conversion to and use as renewable fuels, is one of the most promising technologies available for GHG abatement. Globally, photosynthesis captures well over one order of magnitude more CO₂ than is emitted from fossil fuel combustion, although essentially all this carbon is quickly recycled back to the atmosphere, within a few days to a few years. Human appropriation and disturbance of ecosystems and primary productivity, that is, of CO₂ fixed into biomass, already exceeds our use of fossil fuels by a large factor. Therefore, better management of our biosphere could mitigate a significant fraction of fossil CO₂ and other GHG emissions.

For example, some of the carbon fixed by photosynthesis can accumulate and remain in soils or even above ground in forest biomass for the long term, and enhancing such carbon sequestration processes is an important route for GHG abatement. Another major route for GHG abatement through photosynthesis is the use of biomass as an energy source, either directly (through combustion) or after conversion to gaseous or liquid fuels. The biofuels could be derived from wastes and residues from agriculture, forestry and other sources, could be co-produced with food, feed or forest products, or could be produced in single-purpose enterprises, like some current sugar cane and palm oil plantations and trees or other plants in so-called energy farms. Biofuels remain an important energy source in many countries, and indeed are a major source of fuels for the poorer majority of the human populations. Increasing biofuels production and utilization globally, without impacting food production and other human needs, or destroying remaining natural environments, is a major technological and social challenge for this century. This will require a worldwide transformation of current agricultural and forestry practices. One
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priority must be prevention of further soil carbon and vegetation losses, a major source of anthropogenic CO₂ in the atmosphere, second only to fossil fuel combustion.

Biomass production is fundamentally limited by the solar conversion efficiency of photosynthesis. In theory and in the laboratory, photosynthesis can be a highly efficient solar energy converter, with an efficiency of about 10% (solar to biomass higher heating value) being generally agreed upon as a maximum upper limit. Indeed this can be achieved with microalgae cultures in the laboratory under low light conditions (Radmer and Kok, 1977). In practice, however, agriculture operates at an efficiency of well below 1% of annual solar incident radiation converted to harvested biomass. Also, in conventional agriculture the fossil energy inputs (fertilizers, pesticides, chemicals, fuel, etc.) can greatly reduce the net fossil CO₂ reduction from use of the biomass as an energy source (Pimentel and Patzek, 2005). The R&D challenge is how to increase the practical efficiency of photosynthesis in open pond systems and thus minimize land area requirements (the so-called ‘footprint’ of the process) while reducing energy inputs, thereby increasing the potential of biomass systems for biofuels, as well as for food, feed, and fibre production and for overall GHG abatement.

Microalgae are microscopic plants that usually grow in aquatic environments, marine, brackish or fresh waters, and are generally able to reproduce very rapidly, often doubling in mass daily, or even in a few hours. There are many types (colloquially named after their normally dominant pigments as green, red, brown, blue-green, etc.) with thousands of species recorded (see again Fig. 1 for a few examples). Aside from their water environment and very fast growth rates, their cultivation also differs from higher plants in requiring a concentrated source of CO₂, such as is present in the flue gases from power plants (5-15%), since absorption by algal cultures of CO₂ from air (0.04%) would be expensive and greatly reduce their productivity. Since water and nutrients, including CO₂, are not limiting factors, and fast growth allows for continuous production, much higher solar conversion efficiencies (e.g. biomass productivities) can potentially be achieved with microalgae cultures than with higher plants. This, coupled with the direct utilization of CO₂ from power plant flue gases, is the fundamental advantage and attraction of microalgae mass cultures in GHG abatement. The challenge is to develop microalgae biomass production processes that are cost competitive with conventional agriculture or forestry, which currently can produce biomass at remarkably low costs (at well below $ 100/t of biomass, or less than $ 5/GJ). As discussed in this chapter, to achieve the goal of low-cost production current microalgae cultivation processes must be simplified and productivities must be maximized to, as close as practically possible, the theoretical 10% solar conversion efficiency. This is the central goal of the Biofixation Network.

As stated above, one way that microalgae mass cultures overcome the limitations of higher plants is through fast growth rates. This avoids the considerable time required by higher plants to grow from seeds to a closed canopy, during which time they do not intercept all sunlight. Also, as stated, microalgae are not limited by water, nutrients, or CO₂, the latter provided by the power plant or similar stationary sources. Thus microalgae can operate nearer to the maximum potential of photosynthesis and, indeed, microalgae mass cultures are typically more productive than higher plants. Although reliable data on large-scale algal mass cultures are scarce, and in many cases productivity is limited by factors in addition to those mentioned above (sub-optimal temperatures, culture instabilities, poor mixing, excessive O₂ build-up, etc.), current maximum achievable productivities with mass cultures using sunlight can be estimated at between 50 to 70 metric tons of organic dry biomass per hectare per year (t/ha yr). Although this is about ten times higher than the corn yields in the US, it is actually not much higher than that already achieved by the most productive of crops, sugar cane, based on whole plant biomass output (cane and leaves) in tropical climates. However, this yield represents at most between a 1% to 2% total solar energy conversion efficiency, depending on location. This is a modest productivity when compared to the 10% maximum that can be projected based on what has been achieved in the laboratory.

When the rate of photosynthesis (measured as CO₂ uptake or O₂ production) by microalgae cultures is measured in the laboratory as a function of light intensity in short-term experiments with dilute cultures, there is a linear increase in rate at low light intensities, but then a rapid slow-down as light intensities increase beyond about 10 to 20% of full sunlight. As stated above, at low light intensities and when all other factors are controlled, photosynthesis is indeed quite efficient, approaching the theoretical 10%
conversion of sunlight into biomass energy (calculated by assuming that 45% of sunlight radiation is in the photosynthetically active, or visible, part of the spectrum). But at higher light intensities photosynthesis becomes less efficient, and at intensities corresponding to full sunlight, efficiencies in such short-term measurements, or in longer-term continuous laboratory culture studies, decline to 2 to 3% light-to-biomass conversion efficiency. This is in line with what is observed in outdoor algal mass cultures, after factoring in respiration (particularly night-time losses) and other more or less unavoidable limitations of outdoor cultivation (temperature, O2 concentrations, surface reflection, etc.). This drop-off in efficiency at higher light intensities, the so-called ‘light saturation effect’, is also observed with higher plants, but is more pronounced with microalgae cultures, and accounts for much of the lower-than-anticipated productivities observed with these aquatic plants.

The explanation for the light saturation effect is found in the structure of the photosynthetic apparatus: light energy (photons) is captured by arrays of so-called light harvesting or antenna pigments, principally chlorophyll in higher plants and green algae, and other pigments in blue-green algae (cyanobacteria), brown algae (diatoms) and red algae (see again Fig. 1). The photon energy captured by these antenna pigments is then transferred to the so-called reaction centre chlorophylls where the captured photon energy is converted, in a two-photosystem process, to chemical energy. First, Photosystem II splits water (yielding O2) and the electrons are transferred to Photosystem I where additional photon energy generates a strong reductant (reduced ferredoxin) and metabolic energy (ATP) is generated. These are then used in a series of dark enzymatic reactions to fix CO2 into carbohydrates. Carbohydrates are then used to build proteins, lipids, nucleic acids, as well as all the components of microalgal cells, resulting in cell growth and multiplication.

In this process, the greater the number of antenna pigments, the more photons the algal cells can capture at low light intensities. However, at high light intensity, a large number of such antenna pigments results in more photons being absorbed than can be processed by the reaction centres; this excess energy is quickly lost, wasted as heat or re-emitted as fluorescence. As microalgae cells, in nature and particularly in mass culture systems, move frequently from high to low light and vice versa, it is not possible for cells to continuously adjust their light harvesting pigment content to an optimal level of antenna pigments, allowing for more efficient solar energy conversion. The best evolutionary strategy for microalgae is to adapt to low light intensities, in other words to always have a large number of antenna pigments, even if this wastes photons at high light levels.

Simply put, microalgae cells are designed by evolution to grow most efficiently at low light levels, as it makes no great difference to the individual cells, the unit of evolutionary selection, if they are inefficient at full sunlight, because any light wasted could not be used anyway. Put another way, the individual cells at the surface of the pond, exposed to full sunlight, are not penalized for wasting photons, even if they shade their cohorts underneath them. But the cells do need to capture every available photon when they are deeper down in the culture, where they will be shaded by the cells above them. Indeed, it might even be argued that those on the surface benefit from shading out those below them, thus reducing the growth of competing cells. More critically, when the cell moves in the water column from higher to lower light intensities, any time lag in adjusting to the changing light intensity is wasted to growth.

In brief, evolutionary pressures and selection have strongly favoured a relatively large antenna pigment complex in the photosynthetic apparatus of microalgae, and this is the major factor accounting for relatively low productivity of algal mass cultures, compared to their potential. This argument explains the low productivity of dense algal mass cultures, and algal cultures must be dense to capture all the sunlight, in which algal cells with their large antenna sizes capture most of the sunlight at or near the surface of the culture, but use only a small fraction of the captured photons, wasting the rest, while shading the cells below them.

Furthermore, high light intensities (at or near full sunlight) are actually inhibiting and even damaging to cells with large antenna sizes, resulting in the phenomena of photoinhibition, which is manifested as a decrease in the rate of photosynthesis on exposure of the cells to high light intensities. This effect actually reduces the overall productivity (e.g. efficiency) of algal mass cultures even more than would be expected from the light saturation effect alone. Indeed, algal cells exposed to high light intensities for long periods will reduce their antenna size to avoid these inhibitory effects; however, by the time make such
an adjustment, their photosynthetic apparatus is already damaged. In short, antenna size reduction resulting from photoinhibition is subordinate in individual cells to antenna size maximization, resulting from light limitation.

In summary, due to the large antenna size of the photosynthetic apparatus of microalgae, the productivity of algal mass cultures under sunlight is at best only about one third to one fourth what might be anticipated from laboratory experiments at low light intensity. Over the years, several solutions have been proposed to overcome this fundamental limitation to productivity:

- Mixing algal cultures rapidly so that all cells get their moment in the sun (‘flashing light effect’).
- Dispersing sunlight through the culture by means of prisms or, more recently, optical fibres.
- Using vertical columns or panels that do not receive full sunlight, as does a horizontal pond.
- Searching for algae with low antenna pigment content, which do not exhibit slight saturation.

Each of these approaches has been investigated over the years, as described below.

Rapid agitation of algae cultures. Rapid mixing can be used to bring cells in and out of high light zones, such that photons are absorbed at the rate at which they can be used in the dark reactions (most critically electron transfer between the two photosystems). This can overcome the effects of light saturation and even photoinhibition. Unfortunately, because of the time constants involved, only a few milliseconds at high light followed by period in the dark several times longer (the ‘flashing light effect’ first described in detail by Kok, 1953), such fast mixing is required that in any practical process the power inputs would be prohibitive. Although an enormous amount of research on the effects of light fluctuations, periodicities, modulation, mixing (both organized and random), etc., has been carried over the last fifty years, the limitations of practical algal mass culture do not allow the use of intensive mixing to overcome light saturation. The often reported beneficial effects of intensive mixing on productivity in mass cultures can be attributed to secondary effects, such as reducing O₂ tensions in the cultures, or even photoinhibition, rather than to success in overcoming the light saturation effect by application of the flashing light effect (Weissman et al., 1988).

Dispersion of sunlight through prisms or optical fibres. Optical fibres or other devices (prisms, etc.) that disperse light throughout the algal cultures, require concentrating mirrors to capture sunlight, and these need to be as large as the photobioreactors themselves, and would be prohibitively expensive. Added to this are the cost and trouble (e.g. fouling) of operating such complex systems, which make such approaches entirely impractical, as discussed further below (see Section 9.4.3).

Use of vertical columns or panels. Vertical photobioreactors, although much cheaper than optical fibre photobioreactors, would still be far more costly than simpler mass culture systems, e.g. ponds, and in any event too expensive for GHG abatement applications. For example, to maximize solar conversion efficiency with vertical systems, would require at least 3 m² of photobioreactor surface area per m² of land (to allow more efficient interception of all the sunlight).

Algal strains with low content of antenna pigments. Algae with small antennae have, as mentioned above, a competitive disadvantage and thus evolution has selected against such types. Therefore, they are not expected to be found in nature, and indeed were not (Kok, 1973). However, as also noted, microalgae can adjust their antenna sizes in response to environmental conditions, and it is now possible to create what nature has avoided: biotechnology techniques can be used to develop algal strains with a permanently reduced light harvesting pigment content. These, even if not competitive in nature, would exhibit higher productivity in controlled algal mass cultures. This was proposed as the most promising approach for achieving high productivity at low cost (Benemann, 1989; Benemann and Oswald, 1996), leading to the initiation of R&D efforts in Japan and the US to develop low antenna pigment strains (Nakajima and Ueda, 1997 and 2000; Neidhardt et al., 1998; Polle et al., 2000). It should be noted that reduced antenna mutants should be able to simultaneously overcome both the light saturation and the photoinhibition effects, as both are due to the large antenna pigment content of wild algal strains.

Research to develop and demonstrate reduced antenna pigment strains that can be mass cultured is now being pursued through a Microalgae Network affiliated project (Polle et al., 2005). The immediate goal of this research is to demonstrate a doubling of current productivities to a sustained solar conversion efficiency of about 3-5%, or 100 to 150 t/ha-yr (depending on the location and the composition of the algal biomass). Such a
productivity goal is required to allow for applications of microalgae biomass production in GHG abatement. In the longer term, even higher productivities should be possible with outdoor algal mass culture ponds. Such high productivities reduce the footprint and improve process economics, major factors in GHG abatement applications.

Though they are of fundamental importance, light saturation and photoinhibition are not the only phenomena reducing productivities of algal mass culture to well below their theoretical maximum. Respiration is another important factor, discussed briefly below, that also needs to be addressed in any future applications of biotechnology to develop improved strains. In conclusion, achieving high productivity outdoors in a microalgae mass culture still requires considerable R&D. However, the tools are now available to accomplish this objective, and the achievement of greatly increased productivities can be forecast with confidence.

9.4.3 Microalgae cultivation systems and CO₂ capture

Even before achieving the goal of high productivities, how to actually mass culture microalgae and capture CO₂ from power plant flue gases at low cost needs to be addressed. Two fundamentally different approaches have been considered: open (to the atmosphere) pond cultures and enclosed photobioreactors. Ponds can, of course, also be considered photobioreactors, but here we use the term specifically for enclosed systems, where, unlike open ponds, there is no direct gas exchange with the atmosphere.

Open ponds

Open pond cultures can be of several designs. The simplest is a large pond where microalgae grow essentially as they do in nature, suspended in the water column and mixed only by wind. Although widely used in wastewater treatment (Fig. 2D) and even in some commercial microalgae production systems, such unmixed pond designs need not be further considered here as they are inherently of very low productivity. This is due, at least in part, to CO₂ limitations, as these system designs do not allow for CO₂ fertilization. CO₂ distribution requires mixing the pond for even distribution of this nutrient, as well as others.

One of the first open, mixed, algal mass culture systems was a circular pond design, first developed in Japan 50 years ago for *Chlorella* mass culture (Tamiya, 1957) and used since the 1960s for commercial *Chlorella* production (Fig. 2A). The main disadvantage of these ponds is their limited size: due to uneven mixing by the central pivot sweeping mechanisms, these cannot be scaled up above about 1,000 m². Also, this mixing system is expensive to construct and operate. In short, the mixing and hydraulics of these systems are major limiting factors in scale up.

In the early 1950s, the raceway-type open pond (also called the high rate pond) was first studied for wastewater treatment in California, with a sump and recirculation pump provided mixing (Oswald and Golucke, 1960). Such systems were installed in several wastewater treatment ponds in California starting in the 1960s (see again Fig. 2D), although other mixing systems were also used (e.g. Archimedes pumps). During the 1960s paddle wheels were introduced in Germany to mix small raceway ponds for algal mass cultures and subsequently for pilot-scale wastewater treatment systems (Benemann *et al.*, 1980) and the raceway, paddle wheel-mixed pond design has since become the dominant design in the microalgae industry. They are used extensively in commercial production of *Spirulina* and *Dunaliella*, the major algal species currently produced commercially, and have also been applied in wastewater treatment (Figs. 2B, 2D). Paddle wheel-mixed raceway ponds are shallow (typically 20 to 30 cm liquid depth), and a single pond can be readily scaled-up to several thousand square meters, and plausibly several hectares.

For large ponds, large paddle wheels will be required and it may appear that these would require large amounts of power. However, this is not the case as long as mixing velocities are kept in the 20-30 cm/s range, mixing power inputs are modest. Slower mixing could result in algal settling, as well as insufficient CO₂ replenishment. Because energy inputs increase as a cube function of flow velocity, faster mixing would consume too much energy.

CO₂ is supplied to the ponds in commercial systems from concentrated sources although in at least one case the microalgae production plant is coupled to a small power plant. The two key issues are how to transfer the CO₂ into the pond culture and how to prevent loss of CO₂ from the ponds due to outgassing to the atmosphere. Transfer of CO₂ is best achieved by bubbling the gas through the liquid in a sump, typically a short distance
downstream of the paddlewheel. For a power plant flue gas, typically 8-13% CO₂, a large amount of gas needs to be transferred, and to maximize CO₂ absorption and reduce pressure drop at the orifice, the sump would be best operated in a counter-current contacting mode. Because bubbles rise at velocities of 30 cm/s, similar to the liquid flow velocity in the pond, the transfer sump need not be very deep for efficient mass transfer. Transfer efficiency of 80 to 90% should be possible with flue gas, and over 90% if pure CO₂ were to be used.

Once transferred into the pond culture, the CO₂, in the form of aqueous CO₂ and carbonic acid (which equilibrates with the carbonate alkalinity), will then tend to outgas to the atmosphere due to its higher concentration in the ponds relative to the atmosphere. Outgassing coefficients for ponds can be calculated and have also been measured, but depend on many factors, including bottom roughness coefficient, mixing velocities, depth, pH, alkalinity, and, possibly even the algal culture. Losses of no more than about 10% should be achievable, but this requires operations within specific ranges of pH, alkalinity, mixing velocities, etc.

The power required to pump flue gas to the algal ponds limits the distance between the power plant and the algal ponds, preferably next to each other. It should be further noted that for power plant flue gases, CO₂ is only used by the microalgae cultures during the day-time, and that much more CO₂ is used in summer than in winter. This reduces the maximal annual CO₂ utilization from a stationary base-load power plant to approximately one third, and in practice considerably less, of the total output.

A key issue is the ability of microalgae to grow on actual power plant flue gases. The concentration of CO₂ (CO₂aquaeous + carbonic acid) to which the algae cells are actually exposed in the ponds is relatively low, at most to those of flue gas levels (equivalent to less than 10% CO₂ in the gas phase), and then only for part of the time, because the CO₂ is used up as the algae grow in the ponds. Also, the effect of CO₂ on microalgae is modulated by pH, which depends on both alkalinity and CO₂ concentrations. In short, there is no requirement for high CO₂-tolerant algae, which can grow under pure (100%) CO₂ or under acidic (low pH) conditions. Extensive research over many years (starting in the 1950s), mostly in the laboratory (Olaizola, 2003, and references therein) and to a lesser extent with outdoor cultures (Matsumoto et al., 1995; Pedroni et al., 2004), has demonstrated that it is possible to effectively culture microalgae on combustion flue gases.

The potential for removing additional contaminants from power plant flue gases along with CO₂, specifically NOₓ and SOₓ, presents an opportunity for integrating power plant flue gas clean-up with microalgae production. To the extent that they are actually absorbed (depending on the mass transfer coefficients of the flue gas transfer system), these contaminants will react in water to produce dilute acids, which are neutralized by the alkalinity in the growth medium. In the case of NOₓ, both NO and NO₂ would be used by the microalgae (Negoro et al., 1993; Nagase et al., 2001), resulting in no net change in alkalinity. However, NO, would provide only a few percent of the nitrogen requirement of the algae. SO₂ neutralization could be an issue where SO₃ concentrations are high, water reuse is extensive and alkalinity is a limiting factor, requiring the addition of some base (e.g. NaOH, or equivalent) to the ponds, as would also be used in a conventional flue-gas clean-up process. The small amounts of such contaminants in relation to CO₂ makes these a relatively minor issue, but the potential for microalgae cultures to contribute to flue gas clean-up is worthwhile considering.

One additional issue in this context of gas transfer, is the O₂ produced by the microalgae cultures, which accumulates in the pond cultures to several times the air saturation levels, and which should be outgassed to reduce its build-up and thus avoid inhibitory levels of O₂. This could be accomplished by a degassing station upstream of the carbonation station. At night, the algal cultures respire and will use up any dissolved O₂ and whatever additional O₂ is transferred from the atmosphere. Both factors, high O₂ during the day and respiration at night, result in significant losses in daily productivity, but have been somewhat neglected in algal mass culture studies, and requires further study.

Flue gas CO₂ supply, transfer and utilization are a significant factor in the overall costs of any GHG abatement process based on microalgae. An alternative would be to capture and concentrate the flue gas CO₂ to 100% pure CO₂, to supply the algal pond. This would be of significantly lower cost than the use of flue-gas CO₂, due to the lower costs of piping and transfer structures. Also, it would allow storage of CO₂ at night for daytime use, increasing the overall utilization factor. However, after factoring in the cost of CO₂ concentration from power plants, direct flue gas
utilization is still favoured for most situations. Although the issues of CO₂ supply, transfer and utilization are complex, and further work is required, the conclusion drawn from experimental data, theoretical analysis and engineering calculations is that the supply of flue gas CO₂ to, and its utilization by, open ponds is not a limiting factor in microalgae mass cultures, although these factors do constrain specific design options (Benemann et al., 1982; Weissman and Goebel, 1987).

Another major issue in the engineering design and economics of open pond cultures is the pond lining, which serves to prevent water loss to percolation, groundwater contamination and silt suspension, and allows for pond cleaning. Most commercial microalgae production ponds are lined with either plastics or concrete. However, most wastewater treatment ponds are lined with only low cost clay, as are a few large-scale *Spirulina* production ponds. Experimental work comparing ponds lined with clay and ponds lined with plastic (Weissman and Tillett, 1989) suggests that there is not much difference in performance, principally productivity, between these options, and that unlined ponds could be operated at the mixing velocities suggested above (e.g. about 20 to 30 cm/s). For GHG abatement and energy production, low-cost clay-lined ponds would be required because plastic lining would in most cases be too expensive, unless combined with wastewater treatment or with the production of co-products of higher value than fuels. To advance the development of GHG abatement technologies with microalgae mass cultures, future R&D must include a demonstration of large-scale (more than 1 ha) clay-lined ponds.

The capital cost of high-rate ponds with clay lining mixed by paddle wheels can be estimated, very approximately, at $100,000/ha for large-scale (more than 100 ha) systems, including general infrastructure (water, power and CO₂ supplies to the facility), biomass harvesting and processing. This estimate is based on many favourable site-specific assumptions and an annual average productivity of 30 g/m²·d (110 t/ha·yr). This is over an order of magnitude higher initial capital cost than the costs of establishing even irrigated conventional agriculture or forestry. Even much higher productivities cannot make up for these very high capital investments. Operating costs for power, nutrients, maintenance, and management, including algal harvesting and processing (see below), will also be higher for microalgae cultures than for typical crop plants or tree plantations. Thus, overall, microalgae production economics with such open ponds are not very favourable compared to other biomass-biofuels processes (see Section 9.4.6).

However, microalgae can be grown using lands, waters, and other resources, including power plant flue gas CO₂, which are not suitable for conventional agriculture or forestry. Counter-intuitively, water utilization by microalgae ponds is actually lower than for higher plant agriculture, where water consumption, due to evapotranspiration, is a direct function of productivity. Microalgae biomass can also be more readily converted to liquid and gaseous fuels compared to most higher plant biomass. At this time, the most plausible near-term application of microalgae in GHG abatement is in combination with wastewater treatment and similar environmental applications, as discussed in Section 9.4.5.

One of the major drawbacks of open ponds is that the algal culture can easily become contaminated with invading algal species, algal grazers, and biological infections of various sorts (bacteria, protozoa, etc.), resulting in the loss of the culture. Indeed, such events have until recently restricted the mass culture of microalgae in open ponds to only a few species, in particular *Spirulina* and *Dunaliella*. These algae can be maintained readily in open ponds as continuous cultures because their cultivation medium contains very large amounts of bicarbonate or salt which discourages the growth of most other algae and microorganisms. However, such a selective medium also reduces the productivity of such systems, compared to fresh or seawater cultivation. Other microalgae grown commercially in open ponds, specifically *Chlorella* and *Haematococcus* require relatively large amounts of inoculum produced under controlled conditions in closed photobioreactors. The amount of inoculum production required is a key issue, but appears not to present a major limitation (Benemann, 2004).

**Closed photobioreactors**

Closed photobioreactors are of many designs, in particular tubular and flat plate designs. Closed photobioreactors are characterized by the fact that they prevent direct gas exchange with the atmosphere, and this definition includes greenhouse-covered pond, even if ventilated. Indeed, such covered algal ponds have been used commercially to grow *Chlorella* and *Spirulina*, both in full-scale plants and for starter cultures, in
locations where temperatures are too low to allow rapid production start-up in spring. As discussed here, there is little justification for covered raceway ponds or other closed photobioreactors for algal mass cultures for GHG abatement, except for the purposes of inoculum production.

Closed photobioreactors, in particular tubular systems, but also flat plate and other designs, have recently become more common in the commercial production of high value products from microalgae, specifically the carotenoid astaxanthin (a colouring agent fed to salmon grown in aquaculture), which is produced by the microalga *Haematococcus pluvialis* (Fig. 2C). Indeed, closed photobioreactors have been the main focus of most microalgae R&D in the past two decades. They were investigated for GHG abatement during the 1990s in Japan (Maeda et al., 1995; Usui and Ikenouchi, 1997) and more recently in the US (Bayless et al., 2001; Olaizola, 2003).

The major attraction of closed photobioreactors has been their reputation for very high productivities, reportedly much higher than for open ponds. However, actual studies directly comparing closed photobioreactors with open ponds have been lacking. Recently such a study was carried out at the Monterotondo research facility of EniTecnologie near Rome, with tubular photobioreactors operated outdoor side-by-side with open ponds using a simulated power plant flue gas (Pedroni et al., 2004). Overall, both systems exhibited similar productivity in grams of dry biomass produced per m² of surface area per day. Indeed, there are no compelling theoretical or practical reasons why open ponds and closed photobioreactors should not have the same productivities, if operated under similar conditions. One difference is temperature, which is higher in closed systems than in open ponds. However, this can be both a problem as well as an advantage, as photobioreactors need to be cooled in the daytime, whereas evaporative cooling in open ponds limits temperatures (except in exceptionally humid zones). Another potential difference is that there is less outgassing and loss of CO₂ from closed photobioreactors. However, there is also a much greater accumulation of O₂ in closed systems, which inhibits algal growth. Gas exchange is the limiting factor in the design and operation of such closed systems (Weissman et al., 1988) and insufficient gas exchange capacity has been the likely cause for the failure of several commercial ventures using photobioreactors for production of *Spirulina* and *Dunaliella*.

The greatest limitation of closed photobioreactors is their very high capital and operating costs. The glazing (e.g. transparent covering) materials are often only a small part of overall capital costs, with the greater costs resulting from the relatively small maximum unit size of such systems, at most only a few a hundred square metres, or over two orders of magnitude smaller than the maximum scale for open ponds. This requires that mixing devices, gas exchangers, nutrient supply, harvesting, control systems, etc., all be replicated and operated hundreds of times, at great cost, compared to a single open pond system. Cooling and cleaning of closed photobioreactors are additional major cost factors. The lowest published costs for photobioreactors were about $50/m² (Tredici, 1999), about ten times higher than for open ponds (excluding harvesting processing). However, these projections excluded many important components, with estimates for commercial systems much higher, generally well over $100/m². In brief, based on their lack of clear advantage, their many limitations and, most importantly, their very high costs, over ten times higher than for open ponds, closed photobioreactors are not applicable for microalgal biofuels production and GHG abatement, or even to wastewater treatment. The somewhat higher concentration of algal biomass in closed photobioreactors, compared to open ponds, does reduce the biomass harvesting costs (see Section 9.4.4), but this defrays only a small part of the much higher capital and total costs of closed photobioreactors compared to open ponds.

One advantage to closed photobioreactors does have merit: they can allow the cultivation of algal strains that otherwise could not be cultivated in open ponds due to invasion and take-over by other microalgal species or algal grazers. However, here too the advantage of closed photobioreactors over open ponds is smaller than generally assumed: although contamination can be delayed, sooner or later such systems do become contaminated with invading algae, rotifers or other unwanted organisms, and dislodging such invaders requires cleaning and re-starting the system, which is not always effective and is generally more difficult than for open ponds.

Closed photobioreactors can and will have an important role in GHG abatement technologies: the production of the required microalgal inoculum for large-scale open ponds. In such inoculum production sites, closed photobioreactors would not be operated for
maximum productivity, but rather for maximum growth rates, to allow for rapid build-up of the culture under conditions that minimize contamination. Provision of ample inoculum produced under controlled conditions would be most critical if genetically improved algal strains, such as those with reduced antenna pigment content (see above), were to be cultivated. Such strains would be particularly susceptible to contamination and take-over by wild strains of microalgae and other biological factors. Build-up of an inoculum of such strains, for a large-scale open pond system, would be carried out with a succession of closed photobioreactors of increasing scale and decreasing per-unit area cost and sophistication. Starting with laboratory cultures, and proceeding in about ten-fold increments of size, from small (1 to 10 m²), closed, sterilized photobioreactors, through a succession of ever larger (100 to 1,000 m² and even 10,000 m²) but progressively less costly (per m²) closed photobioreactors. The largest would be lined and covered raceway ponds that produce the final inoculum used to start-up the large, open, unlined ponds described above. Six to nine such scale-up stages from a laboratory culture requires about 20 to 30 generations, or two to three weeks of growth. Production of such an inoculum would represent 5% or less of overall production costs. Inoculum production based on a series of closed photobioreactors will be a key component in the development of algal mass culture systems for GHG abatement that use open ponds and genetically improved algal strains for high productivity and other desirable attributes.

It must be noted that closed photobioreactors are often promoted as a GHG abatement technology in their own right. In Japan, a very large microalgae GHG abatement R&D program was carried out during the 1990s, involving over two dozen industrial laboratories and costing many hundreds of millions of dollars. The main objective of this program was to develop closed photobioreactors for CO₂ capture from power plants (Usui and Ikenouchi, 1997). In particular, this program aimed at photobioreactors using optical fibres, which had been proposed as a solution to the light saturation problem (Karube et al., 1992). However, as pointed out above, this requires large and enormously expensive concentrating mirrors to capture the light energy and transfer it to the optical fibres, among other problems. A similar project has been carried out recently in the US (Bayless et al., 2001), and has even received favourable notice in the popular science press (Di Justo, 2005) and is being pursued commercially for CO₂ capture and production of algal oils. However, such technologies have no merit in GHG abatement. Even simpler tubular photobioreactors, although of much lower cost than optical fibre models, still exceed the cost of open ponds by over an order of magnitude and cannot, as mentioned above, be considered for GHG abatement applications outside inoculum production. Nevertheless, several private companies in the US are engaged in related R&D efforts (Olaizola, 2003). A recently established venture affiliated with the Massachusetts Institute of Technology (MIT) is demonstrating, at a small power plant on the MIT campus, the use of triangular-shaped glass bubble column photobioreactors (Vunjak-Novakovic et al., 2005). They are designed to capture NOₓ and SOₓ along with CO₂ from the flue gases of a power plant with the goal of producing algal oils that can be converted to biodiesel. However, mass transfer coefficients are too low and/or power inputs too high in these bubble columns reactors (Miyamoto et al., 1988; Nagase et al., 2001) for such applications, even ignoring the highly unfavourable economics and the enormous numbers of such closed photobioreactors that would be required in practice.

In conclusion, closed photobioreactors have an important, indeed critical, role in the applications of microalgal technologies for GHG abatement - the production of inoculum, in particular of algal strains selected for high productivity and other favourable attributes. However, photobioreactors are too expensive by large factors, in both capital and operating costs, even when allowed the most favourable of assumptions, for actual algal biomass production. Also, they do not provide any major advantages over open ponds. As photobioreactors cannot be viewed as the main approach to GHG abatement using microalgae, the remainder of this review will consider only open pond cultures.

### 9.4.4 Microalgae harvesting and conversion to fuels

#### Microalgae biomass harvesting

Cultivation of microalgae at high productivities in open ponds using flue gas CO₂ from power plants or similar sources is only a first step in a GHG abatement process. The algal biomass has to then be harvested and converted to a renewable fuel that can substitute for fossil fuels (see again Fig. 3).
Harvesting microalgae, that is, concentrating microscopic algal cells from the dilute solutions of the algal mass culture ponds, has been a major problem and limitation of microalgae production processes. Typically, microalgae biomass concentrations in open ponds are only a few hundred milligrams per litre of dry biomass, and even very high productivity cultures would be well below 1 g/l. This has to be concentrated over 100 times to achieve a sufficient concentration (at least 50 g/l of biomass, and preferably 100 g/l or above) to allow for the further processing of the biomass and its conversion to biofuels. Three main harvesting technologies have been developed over the years and are briefly discussed below: centrifugation, filtration, and flocculation, the latter followed by sedimentation or dissolved air flotation. Many other approaches have also been investigated, such as high gradient magnetic separations and the use of the swimming behaviour of some algae, but these have not been realized in practice and are not further discussed.

Centrifugation can be used for most algal types, though not for very fragile cells, such as Dunaliella. The major problem is the very high capital and operating costs of centrifuges, well above $1,000/t (dry mass basis), much too expensive for any GHG abatement process, and even for wastewater treatment. Centrifugation can be considered for a secondary or final harvesting step to increase biomass concentrations, for example, from 10-20 g/l to 100-200 g/l of biomass (dry mass basis), as this requires handling a much smaller amount of liquid and reduces costs almost proportionately. Such secondary concentration has been proposed in several engineering-economic studies, possibly in combination with oil extraction from high oil-containing algal biomass (Benemann and Oswald, 1996).

Filtration is used commercially for harvesting Spiroducta, a filamentous species, and this process is relatively low cost, using so-called ‘microstrainers’: rotating screens with a backwash, inclined screens, or vibrating screens. However, filtration is limited to filamentous or large colonial microalgae types, which hold up on more than 20 μm opening screens, whereas the unicellular or small colonial microalgae (typically less than 20 μm in size) cannot be effectively harvested by such processes. Finer mesh screens prevent water flow and clog rapidly. Filtration by screens also often requires a secondary concentration step, such as a filter press or centrifugation, for further processing of the biomass. Filtration with membranes (e.g. cross-flow filtration) is another possibility and may be advantageous in some applications, but would likely be too expensive for GHG abatement applications.

Chemical flocculation, using lime, alum, ferric chloride, and/or polyelectrolytes is the most general and common method of harvesting microalgae, and such method is applicable to most algal cells. They depend on the negative charge of algal cell walls, which is neutralized by the flocculant, allowing the formation of large flocs which then can be recovered by settling or by dissolved air flotation. The latter process is generally preferred because, although somewhat more expensive, it results in a more concentrated biomass. Harvesting with chemical flocculants is used at a number of wastewater treatment plants and for commercial Dunaliella production. However, these processes are still rather expensive, both for the flocculants and operations, and would not be applicable for low-cost GHG abatement processes. Furthermore, the chemical flocculant can interfere with processing the biomass, such as in anaerobic digestion or in the recycling of nutrients.

Many, perhaps even most, microalgae exhibit the phenomenon of bioflocculation, which is the spontaneous aggregation of algal cells into large flocs. These flocs will then settle rather rapidly (from Stokes’ law, settling velocity is a cube function of floe diameter). Unfortunately, the process of bioflocculation is not well understood: it depends on the elaboration of polymers by the algal cells that makes the cells stick together. What triggers the bioflocculation phenomenon is unclear, but it is often observed in the laboratory, in nature, and also in wastewater treatment ponds. It depends on the algal species, even the strain, and the environmental conditions, with nitrogen and other nutrient limitations appearing to favour bioflocculation. Specific information and studies are lacking. In one long-term, pilot-scale wastewater treatment pond study with two 1,000 m² high-rate ponds, the algal culture, dominated by Micractinium sp. (Fig. 1A), was removed from the ponds and allowed to sit for 24 hours, at which point over 90% of the cells from at least one of the two ponds had spontaneously flocculated (Benemann et al., 1980). However, that study was never followed up and this field requires much more research to develop this phenomenon into a reliable and effective process. Bioflocculation followed by gravity sedimentation (as is practiced in the activated sludge process in conventional wastewater treatment systems) is certainly the
lowest cost, primary harvesting process applicable to GHG abatement processes with microalgae. It thus has been the basis for most techno-economic analyses in this field (Benemann and Oswald, 1996), even though it has not yet been applied in practice.

In conclusion, low-cost microalgae biomass harvesting remains a major R&D challenge, without which the goal of practical applications for microalgae in GHG abatement, or even wastewater treatment, cannot be reached. However, sufficient experience exists to suggest that bioflocculation, possibly in combination with centrifugation, could achieve the cost goals for GHG abatement. Further study and development of this process remains a central problem, next to productivity and controlled cultivation of specific algal species, in the development of practical, low-cost, microalgae production technology for GHG abatement.

Microalgae biomass conversion to fuels

The final step in a microalgae-based GHG abatement process is to convert the harvested biomass to a fuel (see again Fig. 3). This is perhaps the least difficult step, at least compared to the much greater challenges of producing a concentrated biomass (e.g. minimum 5 to 10% solids) at high productivity and low cost. The high water content of the harvested biomass makes drying or any thermochemical conversion process (e.g. combustion, gasification, pyrolysis) impractical. Solar drying is possible in principle, but would require significant additional land area (about 5-10% of the pond area), plastic lining of the drying beds and specialized equipment.

Although plausible, an even more critical problem is the high nitrogen content of algal biomass. This argues against any thermochemical processing, as that would result in unacceptable NOx generation and, most important, loss of this valuable nutrient and resource. Thus, although some schemes show the use of microalgae biomass as a solid fuel, even as direct replacement for coal (Matsumoto et al., 1995), this is not practical or feasible. Nor are schemes to pyrolyze microalgae to produce oils. Thus, microalgae biomass fuel conversion processes are dependent on biological processes, specifically fermentations to produce methane or ethanol, or the metabolism of the algae themselves, to produce oils and hydrocarbons, useable for conversion to biodiesel, or to evolve hydrogen. These options are discussed here.

Considerable research has been carried out with respect to the production of methane (actually biogas, roughly 50:50 CH4:CO2) from algal biomass. This derived mainly from the work on wastewater treatment with microalgae, as methane fermentation (anaerobic digestion) is a widely practiced technology in that field and is also a potentially low cost and high yield means of recovering energy from the biomass. Anaerobic digestion of wastewater sludges, both primary (settled sewage) and secondary (settled activated sludge), at wastewater treatment plants is carried out in large steel or concrete vessels, typically mixed by liquid or gas recirculation and heated, either to mesophilic (30-40°C) or thermophilic (50-65°C) temperatures, with solids loadings typically between 5 to 10% and hydraulic dilution rates of 15 to 25 days. This is a widely established technology and depends on the natural anaerobic decomposition of biomass. However, the anaerobic digestion of microalgae biomass presents two major issues:

- Many microalgae, specifically green algae such as *Scenedesmus* or *Micractinium*, which generally dominate in high-rate wastewater treatment ponds, are rather resistant to anaerobic fermentations, resulting in poor yields or requiring longer fermentation times.
- The high nitrogen content of microalgae biomass, typically 8-10% on an organic dry weight basis, results in very high ammonia levels in the digester, resulting in inhibition of the process, and thus, also, poor yields in terms of methane recovered, even with longer fermentation times.

These two problems can be addressed by a combination of pre-treatments of the biomass (e.g. heat treatment), longer fermentation times, adaptation of the bacterial community to high ammonia levels, and co-digestion with lower N-containing biomass. Longer fermentation requires lower cost digesters, and for this purpose plastic-lined and covered earthen reactors, already applied in animal manure digestion, appear both cost-effective and practical as low-cost volume can allow much longer-term retention of biomass. A complementary approach is to cultivate lower N-content algal biomass, as this would have higher digestibility and less ammonia inhibition. On the other hand, cyanobacteria, such as *Spirulina* or the nitrogen-fixing species, are readily fermented to methane gas, although, again, their high nitrogen content causes ammonia inhibition. As stated, this can be overcome by addition of low-N wastes (food wastes or agricultural residues), by adaptation of the bacterial cultures, or, again, by...
cultivation of low N-content biomass. In brief, methane production from microalgae biomass is technically and economically feasible, but still requires some R&D to improve yields and overall efficiency.

Compared to anaerobic digestion, very little work has been done on ethanol fermentations of algal biomass. The reason is that ethanol fermentations, typically carried out by yeast, are restricted to sugars, starches and similar easily degraded carbohydrates. Microalgae typically contain only about 20% or less of such carbohydrates, present as starch in green algae and glycogen in cyanobacteria. For practical ethanol production, an algal biomass with a very high fermentable carbohydrate content, preferably over 60% on a dry weight basis, is required. Such high starch or glycogen accumulation is only observed under conditions of nitrogen limitation, where cell growth is reduced and much or most of the photosynthetically-fixed CO₂ is diverted to storage reserves. The issue is thus whether it is possible to optimize for both high carbohydrate storage reserves and productivity. These observations still need to be demonstrated and applied in outdoor pond cultures. In conclusion, nitrogen limitation is a key tool in the production of algal biomass with a high carbohydrate (or oil, see below) content, and further, in potentially improving its harvestability and digestibility, as discussed above.

The other major potential fuels from microalgae are those that the algae themselves can produce: oils, both vegetable oils and hydrocarbons, as well as hydrogen. Hydrogen production is discussed in greater detail in a companion review (see Chapter 4.3) and is not discussed further here. The production of oils and hydrocarbon fuels by microalgae has been a major subject of R&D, in particular by the Aquatic Species Program supported by the US Department of Energy from 1980 to 1995 (Sheehan et al., 1998). Interest in this area dates to the 1940s, when it was observed that, particularly under conditions of nitrogen limitation, some green algae exhibit a very high content of vegetable oils (triglycerides), exceeding 50% and on occasion even 80% of total biomass dry weight. Although some of the highest values can be discounted, certainly some algal strains, particularly among the green algae and diatoms, will accumulate large amounts of storage triglycerides, just as other species, sometimes even strains of the same species, accumulate starch.

As in the case of carbohydrate production, the key issue is the relationship between oil accumulation and productivity. Here again, relatively high productivity can be achieved in the laboratory, but only under batch, not continuous, cultivation conditions (Tillett and Benemann, 1987), and the achievement of such results in mass cultures remains to be demonstrated. More fundamentally, carbohydrate storage is metabolically more efficient than triglyceride storage and thus preferable. However, the choice between algae high in fermentable carbohydrates (for ethanol fermentations) or vegetable oils (for conversion to biodiesel) is secondary to the issues of productivity, culture control, and harvestability. In any event, either option still requires considerable R&D.

Recently, microalgae have been touted as high yield sources of oil, able to produce hundreds of barrels of biodiesel per hectare per year (Huntley and Redalje, 2006). Such claims must be heavily discounted, as they are based on mistaking projected hypothetical, and even theoretical, productivities (e.g. Benemann and Oswald, 1996), with current practical reality. Compounding such mistakes by citing discredited studies and presenting false analogies with failed commercial enterprises, and further proposing closed photobioreactors (Vunjak-Novakovic et al., 2005) as a major or even main component in such processes, does little to bolster the claims that algal biodiesel production is a near-term enterprise. Thus, despite many commercial activities in this field, all cloaked in great secrecy but projecting astonishingly low costs and high yields, algae biodiesel production, outside of wastewater treatment applications, still requires a long-term R&D effort, whose outcome is far from certain.

One attractive possibility for oil production by microalgae is the green alga Botryococcus braunii, a species that even under normal growth conditions (e.g. no nitrogen limitation) contains up to 50% pure hydrocarbons (about 26 to 40 C, some unsaturation), by weight, a potential source of fuels and specialty lubricants (Metzger and
Largeau, 2005). Indeed, natural blooms of these algae, which washed up on shorelines, were used a century ago in Australia as fuel. Some oil deposits contain hydrocarbons derived from the botryococcenes produced by these algae. Strains collected from different locations belong to several races, each characterized by its own suite of botryococcene molecules, which have been extensively studied over the past two decades. Why this species produces, as part of its normal metabolism, such large quantities of hydrocarbons which are not used as energy or for carbon storage is a mystery.

The mass culture of these algae was proposed for large-scale renewable fuel production (Benemann and Oswald, 1996), such as those envisioned by the US Aquatic Species Program. However, there has been little if any advance in the mass culture of these algae, mainly due to the very slow growth of these species, typical doubling rates 3 to 7 days (compared to as many hours by most other algae). The reason for the slow growth rates is plausibly the great deal of metabolic energy devoted to produce the large amounts of hydrocarbons. This makes such species non-competitive in open mass cultures, since other algae, not so burdened, can grow much faster and soon dominate an outdoor pond. However, this does not necessarily prevent the application of B. braunii to mass cultures or GHG abatement. As pointed out above, closed photobioreactors can be used to produce the inoculum required for the production of open pond algal mass cultures, even for strains that are not very competitive with wild type strains. And a low maximum growth rate is not necessarily correlated with low productivity in dense algal ponds where growth rate is determined by the imposed hydraulic dilution rate, not the inherently maximum rate of cell division. The mass culture of B. braunii is a long-term goal of microalgae technology for renewable fuels production and GHG abatement.

However, the production of renewable fuels alone from microalgae biomass cannot be justified economically in the foreseeable future, even with the inherent GHG abatement benefits of such processes and the recently rising costs of fossil fuels. Higher plant biomass is much cheaper than microalgae biomass, with lignocellulosic biomass available for well under $ 100/t and starch or sugars costing just over $ 100/t. The most plausible case scenario for microalgae biomass in the near- to mid-term (e.g. less than 20 years), is that algae biomass would cost several times this figure, before conversion to fuels. Thus, microalgae renewable fuels production must be combined with other environmental services, such as waste treatment co-processes, or with the co-production of other products, as discussed next.

9.4.5 Microalgae multipurpose processes for GHG abatement

Municipal wastewater treatment and CO$_2$ utilization

Municipal wastewaters are often treated in the US and many other countries with so-called oxidation ponds. These are relatively deep (less than 60 cm) and are not mechanically mixed. Indeed, in the US there are more wastewater treatment facilities using such microalgae ponds than any other wastewater treatment technology. However, most, though not all, of these systems are very small, typically serving only a few thousand or even hundreds of persons, and in aggregate they treat only a small fraction of total municipal wastewaters. In such ponds, both a primary (settling of solids) and secondary (reduction in Biological O$_2$ Demand, BOD) wastewater treatment process is achieved. The main function of the microalgae is to produce the dissolved O$_2$ required by bacteria that break down the organic wastes. In conventional wastewater treatment, such as in activated sludge systems, air is injected into the waste for this purpose, at a significant energy input and cost (about 1 kWh of power per kg of O$_2$ transferred). Roughly speaking, one kg of O$_2$ is equivalent to 1 kg of algal biomass, which could generate, through anaerobic digestion, as much renewable fuel as would be consumed by the conventional activated sludge process. Simply put, microalgae wastewater treatment could generate as much renewable fuel as fossil fuel is consumed in conventional wastewater treatment, thus reducing GHG emissions two-fold: by avoiding use of fossil fuels and producing a renewable fuel that can replace fossil fuels.

Advanced microalgae wastewater treatment processes use raceway, mixed high-rate ponds, which produce much more algal biomass per unit area, and thus also more O$_2$, than conventional facultative ponds. This allows for higher loadings (volume of wastewater applied per hectare per day). However, in either case (oxidation or high-rate ponds), a fundamental problem is the
high cost of algae harvesting, currently, where harvesting is practiced, carried by chemical flocculation, as previously discussed. Harvesting by bioflocculation would be favoured because of its low costs. However, practical bioflocculation harvesting, even from high rate sewage oxidation ponds, most likely, require development of techniques for the mass culture of specific algal strains that bioflocculate well in wastewater treatment ponds. That has not yet even been attempted, and remains a subject for future R&D. Also, productivity in such wastewater treatment ponds is currently limited by lack of CO₂, which is presently not used in such processes. This presents another opportunity for technology development.

After the removal of suspended solids and BOD, the removal of nutrients (mainly N and P) from wastewaters to achieve tertiary treatment level is of both great need and also great potential for applications of microalgae in wastewater treatment. This is because nutrient removal with conventional technologies is very expensive, and energy intensive, while microalgae can remove nutrients at relatively modest additional costs above secondary treatment. However, removal of nutrients requires a supply of CO₂ and, indeed, lack of CO₂ already limits even secondary treatment. Thus, CO₂ addition would dramatically improve the algal cultivation process in wastewater treatment by increasing productivities and improving process reliability, allowing cultivation of specific and selected algal strains, and plausibly allowing for reliable harvesting through bioflocculation. As the algae would be grown to the N-limit of the wastewater, a relatively low-N algal biomass could be produced, which would also allow removal of all the phosphorous in the wastewater. As discussed above, this biomass would also be high in carbohydrates or possibly oils. If this biomass were subjected to anaerobic digestion (methane fermentation) and if the produced biogas were used to generate electricity, the flue gas would supply all the CO₂ required, as the wastewater contains sufficient carbon to make up for any losses. Indeed, sufficient carbon is available in typical wastewaters for such a process to also allow for export of considerable biofuels, such as liquid biofuels, e.g. biodiesel or ethanol.

Two major issues in such processes are seasonal variability, specifically productivity, which impacts the wastewater treatment performance, and nutrient variability, the amount of N and P, and their ratio, in the wastewater. The N and P levels in algal biomass can be varied significantly, over three-fold for P (from 0.4 to 1.2%), and only somewhat less for N (4 to 10%), with possible N:P ratios estimated to range from about 4 to somewhat over 20 times. This is the range of N and P biomass content and ratios that are expected to allow for high productivities, though the actual range remains to be determined experimentally. In any event, such wastewater treatment processes for nutrient removal allow for considerable adjustment to both seasonal variations in productivity and wastewater compositions, a major requirement in any such process.

In the proposed CO₂-supplemented wastewater treatment process, the outputs are reclaimed water, biogas (methylene) fuel, possibly biodiesel or ethanol, and anaerobic digester residuals. The latter can be applied on agricultural soils, although if classified as biosolids it would not qualify in the US as organic biofertilizer, which could command a premium price. Municipal wastewaters, because of their variability and potential for toxic contaminants, do not favour the production of additional co-products, such as animal feeds or biopolymers. However, the economics for municipal wastewater treatment using high-rate ponds are expected to be favourable, even in comparison to conventional secondary processes (e.g. activated sludge), and would be even more favourable for tertiary treatment (nutrient removal; Eisenberg et al., 1981; Green et al., 1994).

However, detailed engineering-cost studies must still be carried out for specific sites to quantify the extent of these advantages, and R&D is required to actually demonstrate the ability to achieve tertiary treatment with a low-cost and high productivity microalgal process.

A CO₂-fertilized wastewater treatment process using high rate ponds would achieve tertiary treatment while having a much smaller footprint (land area requirement) than present facultative pond technologies, which achieve at best only secondary treatment levels. The proposed process would generate net energy outputs and produce a nutrient-rich residue suitable as fertilizer. Development of such a process is one of the highest priorities in this field.

Agricultural/industrial wastewater treatment and nutrient recycling

These processes are similar to the municipal wastewater treatment described above: the cultivation of microalgae on agricultural and industrial wastewaters with sufficient content of nutrients (N, P, etc.) to allow for secondary (BOD
removal) treatment and, tertiary (nutrient removal) treatment. The main difference is the nature of these wastes, which are generally more defined, less variable, and less subject to toxic contaminants than municipal wastewaters. Agricultural wastewaters are also more seasonal, often smaller in scale and more dispersed than municipal wastes, and waste treatment is not always a priority. However, with the intensification of agriculture, particularly large-scale swine and dairy operations that generate large volumes of relatively dilute liquid wastes, animal feedlot wastewater treatment has become a major issue and an opportunity for applying microalgal technologies for nutrient removal.

A related application is in aquaculture wastewater treatment. For example, several tens of thousands of hectares of catfish ponds in the southern US generate large quantities of wastes, which are treated in situ by energy-intensive mechanical aeration. As these aquaculture systems already use ponds for raising fish, algal ponds for waste treatment is a relatively simple add-on. Such a process (the Partitioned Aquaculture System), incorporating raceway paddle wheel-mixed ponds, was developed at Clemson University, South Carolina, USA, for the treatment and re-circulation of water from fish ponds (Brune et al., 2003a). In this process, the dense algal culture in the raceway ponds is directed through the fish-holding pens to flush out wastes while also providing O$_2$ for the fish, which in turn aid, through their gill filtration, in the flocculation of the algae, allowing their ready harvesting by sedimentation. GHG mitigation could accrue to the algal process from the avoidance of power consumption by the surface aerators currently used in this industry, as well as from the biogas derived from the harvested algal biomass. The algal biomass can also be used to reduce feed inputs required by the fish, which further improves the economics of the process. It even improves the greenhouse gas balances, as conventional animal feed production results in substantial GHG emissions. A similar process is now under development for nutrient removal at the Salton Sea in California (see below).

Of even greater potential than aquaculture wastes are animal wastes, in particular from swine operations and flush dairies, some of which produce waste flows equivalent to those of small towns, in terms of BOD and nutrient contents. The lagooning and land application of such wastes is increasingly limited by groundwater contamination, but removal of these wastes from the site of their generation is impractical due to their dilute nature. Microalgal ponds could be used to remove the nutrients from these wastewaters and concentrate them into a biomass that can then be transported to a more remote location for land application, while also generating biofuels and abating GHG. As is the case for municipal wastewaters, animal wastewaters are also limited by the availability of CO$_2$. Supplying CO$_2$ would both increase algal productivity and treatment effectiveness, plausibly allowing for algal species control and bioflocculation harvesting. Control over the algal species could also enable the algal biomass to be used for animal feeds, which could improve the economics of agricultural wastewater treatment processes, which would otherwise be less favourable than those of municipal wastewater treatment. Dried algae have been used as high value chicken feeds, wet algae have been used for feeding swine, and pelletized algae can have value when added to in ruminant and aquaculture feeds. A practical process, however, remains to be demonstrated.

**Biofertilizer production**

A major source of global GHG emissions is from the fossil fuel-based production of nitrogen fertilizers by the Haber-Bosch process. In the US, where natural gas is used, somewhat over 3 kg of CO$_2$ are emitted for each kg of N fertilizer produced (West and Marland, 2002). In some countries, China for example, coal is used and emissions are much higher. Although P fertilizers require little fossil fuel for mining and processing, transportation can result in total emissions of about 1 kg of CO$_2$/kg of P delivered to the farm. Given that there are N and P contents of 10 and 1% respectively in algal biomass, this is equivalent to abatement of somewhat over 0.3 kg CO$_2$/kg of algal biomass, if the N and P of this biomass are reused in agriculture. By comparison, microalgae biomass (typically 45% C) could abate about 0.6 kg of CO$_2$ when converted to biogas and used as a renewable fuel to replace natural gas. Recovery and use of the fertilizer values in the microalgae biomass could thereby increase the GHG abatement by microalgae biomass by 50% or more. Furthermore, the economic value of these nutrients and the environmental benefits of their recovery would be as great, or greater, than those of the biofuels. Thus, nutrient reuse from the above outlined municipal and agricultural wastewater treatment processes is a central objective of any process for GHG abatement using microalgae.
One issue is the delivery of such nutrients to crops after methane fermentation. Assuming a 10% solids loading to the anaerobic digester, the nitrogen content in the effluent is only 1% by weight, with most of the N in the form of ammonia, and the remainder about 95% water. This limits feasible transportation distances and requires integrating wastewater treatment with agricultural operations as closely as possible. Irrigation systems afford a ready method for delivering such fertilizers. Of course, the nitrogen concentration in the digester effluents is several hundred times higher than in municipal wastewaters, and even over ten-fold higher than in some animal wastewaters, making microalgal wastewater treatment processes an effective nutrient concentration and recovery mechanism.

Using CO2 enrichment in these wastewater treatment processes makes nitrogen the next limiting nutrient and assures that the nitrogen, at least the biologically available fraction, is essentially completely removed, resulting in high-quality reclaimed water.

One specific example of a potentially very large-scale application of microalgal ponds in the reclamation of nutrients is the over 1 billion m3 of agricultural drainage waters flowing annually into the Salton Sea in southern California. These wastewaters contain about 1,000 t of P (as phosphates) and ten times this amount of N (mostly nitrate). Nutrient removal from these drainage waters by microalgal cultures would avoid eutrophication of the Salton Sea, while drainage waters by microalgae cultures would drain nutrient concentrations and recovery mechanism. Using CO2 enrichment in these wastewater treatment processes makes nitrogen the next limiting nutrient and assures that the nitrogen, at least the biologically available fraction, is essentially completely removed, resulting in high-quality reclaimed water.

In conclusion, fertilizer recovery and re-use, and even de novo production, could become a major practical application of microalgae at the global level and be of significance in GHG abatement. The most immediate applications would likely be in premium fertilizer production in organic agriculture, as practiced in developed countries, and in fertilization of rice paddies in

\[ \text{N}_2\text{-fixing cyanobacteria, such as } \text{Anabaena} \text{ and } \text{Nostoc} \text{ can in those cases be used} \]

as a final polishing stage, to remove P (Weissman et al., 1978). Such N2-fixing cyanobacteria have also been proposed for fertilizer production in their own right (Benemann et al., 1980). N2-fixing cyanobacteria exhibit about a one-third lower productivity than non-N2 fixing cultures, due to the high metabolic energy requirement for this reaction. Given levels of CO2 emissions released during synthetic nitrogen fertilizer production (as discussed above), this makes nitrogen fixation for fertilizer production and CO2 fixation for fuel production roughly equivalent from a GHG abatement perspective. The relative economics of such N2-fixation processes still need to be assessed, but recent interest in organic agriculture, creating demand for organic fertilizers that command premium prices, makes such approaches of significant interest in the near term. The rapidly increasing costs of synthetic fertilizer, reflecting the rising prices of fossil fuels, make such approaches also of interest in the longer-term. As noted above, the filamentous nature of the heterocystous cyanobacteria allows them to be harvested readily by filtration. In principle, the production of N2-fixing microalgae for fertilizers could thus be of very low cost, in particular for irrigated agriculture and for rice field biofertilizers, where land, water and nutrients would be available and only a source of CO2 would be required. It is estimated that one hectare of algal ponds could produce enough nitrogen fertilizer for over 25 hectares of rice or corn, in the bargain producing biofuels for farm or local use.

N2-fixing microalgae biomass, grown in high rate ponds could also be applied directly to irrigated fields, or, perhaps most promising, supplied as a large inoculum to rice paddies. There, the microalgae could be expected to multiply several times over in situ, producing substantial nitrogen fertilizers. This would allow for a ratio of rice paddy to algal pond of well over 100. This technology remains to be developed, but in principle is quite attractive. In the past, rice field inoculation with N2-fixing cyanobacteria has been attempted, but with scant success. However, in those cases the algae were grown remotely, dried, and inoculated into the rice fields in only miniscule quantities. This is significantly different from the proposed process, which envisions on-site production of relatively large amounts of algal biomass allowing massive inoculation of rice paddies with actively growing cultures.

In conclusion, fertilizer recovery and re-use, and even de novo production, could become a major practical application of microalgae at the global level and be of significance in GHG abatement. The most immediate applications would likely be in premium fertilizer production in organic agriculture, as practiced in developed countries, and in fertilization of rice paddies in
developing countries. In the longer-term, microalgae fertilizers could play an important role in the global nitrogen cycle, which must shift from a once-through process using synthetic, fossil-fuel based, and mined fertilizers to a process of nitrogen and phosphorous recycling and biological N₂ fixation.

**Biopolymers and other co-products**

In the above-described processes, biofuels, wastewater treatment, reclaimed water, biofertilizers, and possibly animal feeds were the products and co-products resulting in GHG abatement. Another alternative for achieving GHG mitigation, is to combine microalgae biofuels production with large volume, higher value (higher than biofuels) co-products. This approach is comparable to the biorefinery concepts for the conversion of starch and sugars from conventional crops into products that include fuels (e.g., ethanol), animal feeds, and higher value co-products, such as polyactic acid, used to produce a biodegradable polymer. Of course, it must be recognized that microalgae processes would not be able to compete with processes based on the conversion of cheap sugar or starch crops, mainly cane and corn. Thus, microalgae applications must yield high value co-products that the algae produce through their own metabolism, avoiding the rather expensive processing and fermentation stages of a biorefinery. The other requirement is that such co-products must have sufficiently large markets to allow for significant GHG abatement. The other requirement is that such co-products must have sufficiently large markets to allow for significant GHG abatement. Such products do not include high-end human nutritional microalgae products such as carotenoids, the main output of current commercial microalgae production. One possible co-product is bioplastics, specifically PHA (PolyHydroxyAlcanoate) polymers, which are already produced commercially by bacterial fermentations and found as storage compounds in many bacteria, including cyanobacteria (Asada et al., 1999). Cyanobacteria contain up to 10% of PHB (PolyHydroxyButyrate), and it should be possible to produce cyanobacteria in much higher amounts and with altered side chains, more suitable for functional bioplastics. Already mentioned above were the hydrocarbons produced by B. braunii, which might be fractionated to yield higher value lubricants in addition to a fuel product. Other microalgae products with large markets are the polysaccharides used as flocculating, dispersing and gelling agents in food and industrial applications, which are already produced on large scale from seaweeds. Examples include the carrageenans, which are also produced by red microalgae, and which were patented in the 1970s for tertiary oil recovery (Savins, 1978).

Replacement of synthetic biopolymers with microalgae-derived products could result in some GHG abatement. However, the main benefit of such co-products would be to improve the overall economics of such a process. Thus, bioplastics and functional polysaccharides would be valued at over $1,000/t, compared to only about $100/t for fuel production. If even a modest fraction, e.g. 20%, of the algal biomass represents the higher value product, this could justify the production of the algal biomass, with biofuels derived from the residual biomass. In the discussion above, it was implicitly assumed that microalgae biomass production solely for the purpose of biofuels production would not be economically competitive, thus requiring that such processes be incorporated into economically more viable operations, such as wastewater treatment, or production of animal feeds, biofertilizers, or biopolymers. Of course, such multipurpose processes would restrict the scale, scope, and ultimate GHG abatement potential for microalgae processes. Thus, this fundamental assumption in this review is addressed in the following section.

### 9.4.6 Economics and R&D issues

In Section 9.4.3, the basic engineering design issues of the paddle wheel-mixed high-rate pond system for microalgae biomass production were reviewed. It was asserted that the capital and operating cost of such systems would be prohibitive for biofuels production alone, with capital costs given at or above $100,000/ha, based on prior cost analyses. (The costs were reviewed, updated and extended most recently by Benemann and Oswald, 1996, and the costs were inflated by 1.4 to bring them up to 2005 $.) This is well over ten times higher than the typical costs incurred in agriculture. This was for a large-scale, unlined, pond system, producing biomass for oil (triglycerides), using power plant flue gas for CO₂, and biofloculation for harvesting, followed by centrifugations for oil extraction. A productivity of 110 t/ha-yr of a very high (60%) oil content biomass was assumed (equivalent to about 150 t/ha-yr for a normal composition biomass and almost 200 t/ha-yr for a high carbohydrate biomass). This is the maximum productivity that can be reasonably forecast for any microalgae
process based on foreseeable technology, and is within a factor of about two of the theoretical maximum.

Assuming a minimal capital charge of 20% per annum, including taxes and insurance, but not maintenance, this results in a capital charge of about $100/t for a high carbohydrate biomass and almost twice as much for a high oil biomass. Operating costs were estimated at about $15,000/ha (again allowing for inflation, as well as a small credit for by-product methane derived from the digestion of the residues after the extraction of the oil). These bring the costs per barrel of extracted raw algal oil (prior to upgrading to biodiesel suitable for vehicular fuel) to about $100/bbl or, if starch is desired, about $200/t of starch. Although high, these costs are not excessive in light of current energy and plausible future agricultural prices, these estimates are, however optimistic and are based on many favourable assumptions, and subject to uncertainties. In any event, the long-term development of microalgae production systems specifically, or even mainly, for biofuels, if successful, would require an extended period of R&D and also experience with full-scale systems. Such experience can be provided by the above described wastewater treatment and, possibly, co-production of higher value products.

To achieve even these near-term objectives, a great deal of research and development will be required, as already discussed above, and summarized here. It must be noted that essentially the same R&D issues are common to all the GHG abatement processes described above (see Section 9.4.5). They use the same fundamental production system: high-rate (raceway), paddle wheel-mixed, CO₂-fertilized (from flue gas) ponds, with low cost harvesting (bioflocculation or filtration) and biofuel recovery (anaerobic digestion, oil extraction, etc.). They all face similar fundamental and applied R&D issues: strain selection and maintenance, maximizing productivity, low-cost harvesting, and processing for biofuels and co-products recovery. Also, the engineering issues of building and operating large-scale (more than 1 ha), unlined ponds are common to all and require investigation and experience. These issues must be related to process economics and GHG mitigation potential. Present limitations include a paucity of engineering studies and cost analyses of such multifunctional processes, including quantification of their GHG abatement benefits and potential. That potential will be limited by the availability of land, water, infrastructure and other factors. These resource issues also require further study.

The general GHG abatement processes discussed differ mainly in their sources of water and nutrients, and their output biofuels and other co-products (fertilizers, animal feeds, reclaimed water, biopolymers, etc.). Water reclamation deserves additional emphasis as a valuable output of such systems. For biofuels, methane (biogas) is a likely first choice of fuel outputs for municipal and most agricultural wastewater treatment processes. However, other biofuels can be derived from microalgae biomass, in particular ethanol and biodiesel, and these may be preferable in some cases, in particular as they have higher value than biogas for vehicular fuels. However, biogas itself can be cleaned (by removing H₂S and CO₂) and compressed for use as a vehicular fuel.

Hydrogen is a long-term possibility (see Chapter 4.3). In any event, there are several options in the conversion of microalgae biomass to biofuels. The greater challenge than the production of the biofuels is the initial cost-effective production of the biomass.

The fundamental R&D issue in all large-scale, low-cost microalgae production processes is the ability to cultivate selected algal strains in large open ponds at high productivities, and recover the biomass with low-cost harvesting. Algal species control would plausibly allow control over algal productivity and harvesting, and this is therefore the key prerequisite to any such process, and all these issues must be addressed together. The only practical way to achieve the goal of mass culture of selected strains is through the use of strains that can be rapidly grown in closed photobioreactors of increasing scale (and decreasing complexity) for production of relatively large amounts of biomass used to inoculate the production ponds. An initial R&D issue is thus the isolation, selection, and maintenance of suitable algal strains that can be sustainably mass cultured in open ponds.

Attributes of such strains would be both fast growth rates (for the inoculum production phase) and high productivities (in the production ponds), ready harvestability, and desirable co-products. It is highly unlikely that candidate strains will be found in nature, and indeed, as pointed out previously, and paradoxically, high-productivity strains would be eliminated by natural selection. Thus, they have to be generated in the laboratory. However, prolonged laboratory cultivation can result in adaptation to laboratory conditions and loss of characteristics that make the strains suitable for outdoor culture, which can be avoided.
by limiting the number of generations the algae are kept in the laboratory (Polle et al., 2004). It should be noted that freshwater, brackish and seawater (marine) strains of microalgae can be used in such GHG abatement processes. It should be possible to accomplish the genetic improvements desired for algal strains for the most part, with classical mutagenesis and selection techniques, thus avoiding the issue of the release of genetically modified organisms. However, in the longer term, applications of modern genetic biotechnologies will become inevitable and must be included in any R&D plan. In brief, the selection, maintenance, and genetic improvement of algal species for high-productivity mass cultures is the central R&D effort that is required in this field. Such research cannot be carried out in the laboratory alone, and must involve close coordination between with outdoor mass culture work and laboratory strain improvement work. Activities being carried out under the umbrella of the Microalgae Network, previously introduced, are precisely based on this rationale: coordination and integration of laboratory and field R&D efforts, focused on key R&D issues, including and in particular, the genetic improvement for high productivity.

### 9.4.7 GHG abatement potential with microalgae processes

The fundamental issue in discussions of microalgae processes for GHG abatement is their potential to reduce fossil CO₂ emissions globally. Many technologies are now vying for dominance among proposed solutions to the problem, some promising to abate much, even most, of the enormous amounts of fossil CO₂ projected to be emitted into the atmosphere by an increasingly numerous and wealthy human population. Faced with the several trillions of tons of CO₂ projected to require abatement during the present century, in order to stabilize the concentration of this GHG in the atmosphere, the issue is whether there is any point in developing technologies that can be expected to reduce the projected fossil CO₂ emissions by only minor percentages. Ocean and geological sequestration are each projected to have sufficient storage capacity to theoretically sequester all the CO₂ produced from all fossil fuel combustion into the indefinite future. Some renewable energy technologies, wind and photovoltaics for examples, are poised to become major energy sources. Hydrogen fuel cells promise to greatly increase the efficiency of energy utilization and allow continuation of unrestrained personal vehicular transportation for the masses. And biofuels — bioethanol, biodiesel, and biomethane — could all generate large amounts of renewable energy in many countries and in aggregate globally. Thus, perhaps, the focus should be on these large-scale carbon sequestration technologies and already viable biofuel processes, rather than smaller scale options such as wastewater treatment or high risk large-scale long-term potions, such as algal biodiesel production.

However, all these technologies, promising as they are, must still be regarded as uncertain. For example, a decade ago ocean sequestration of CO₂ emitted from power plants was widely touted as a solution to the entire GHG abatement problem. However, major ocean sequestration projects did not come to pass due to opposition by environmental groups and others, and therefore even research on ocean sequestration technologies is now greatly delayed. Geological sequestration is the current main focus of GHG abatement technologies, based on the enormous amounts of geological storage space potentially available and the experience with geological formations and technologies. However, only the most optimistic scenarios project the abatement of more than a modest fraction of the total fossil CO₂ that is required globally. Renewable energy technologies, though promising, cannot in any plausible scenario pre-empt the need for all possible and potential sources of fuels and GHG abatement. Besides the enormous quantities of CO₂ involved, the fact that CO₂ sources are highly diverse and geographically distributed means that no single technology will be applicable to all locations. In brief, a portfolio of measures that include all of the above, singly and in combination, large and modest, deployed on a global scale or only regionally, will prove to be necessary.

Photosynthesis will certainly be the foundation for major approaches to CO₂ capture, storage and utilization. Microalgal biofixation of CO₂ is only one of the many photosynthesis-based systems that will be harnessed in the cause of GHG abatement. Others, such as annual crops (switchgrass, corn, sugar cane), trees (poplars, sycamores, eucalyptus), and aquatic plants (seaweeds, marsh plants), to name but a few, could also contribute to GHG abatement through biofuels production, and may well be more important that microalgae.

In this competition, microalgalae technologies offer several unique qualifications and promises.
First, as discussed above, is its potential for very high productivities. Microalgae plausibly are the most efficient of biological solar converters, and continuing R&D seems likely to achieve and demonstrate greatly increased productivity in practical applications. Another advantage of microalgae is their very short generation time, a day or less, in algal mass cultures. This has several implications, in terms of rapid re-start from failures (only about a week) and inoculum production. A crop failure in higher plants might cost a year’s production in an annual crop, or the loss of over a decade’s production in a forest. Microalgae research allows for the rapid advance of R&D programs compared to the much slower pace required for annual crops and trees. Productivity measurements that would take years and decades with higher plants can be accomplished in months with microalgae. Further, the rather uniform and predictable pond environment allows ready extension of findings from one location to another, something not as easily accomplished with higher plants.

The single attribute of microalgae that appears to make it most suitable for GHG abatement, is its capacity to directly utilize CO₂ from power plants. However, it must be recognized that for the purposes of GHG abatement, it makes no difference whether the CO₂ comes from the atmosphere or a power plant, or a waste source, as it is the production of biofuels, and thus the replacement of fossil fuels, that actually results in GHG abatement. However, direct capture of power plant flue gas allows for greater productivities, and, also critical, much higher water use efficiency than higher plants.

Perhaps the most important attributes of microalgae in GHG abatement technologies is their ability to be used for renewable biofuels production and environmental services in wastewater treatment and nutrient recycling, and the production of nitrogen fertilizer and other co-products and services. It must be recognized that most, if not all, biological processes for GHG abatement will be multipurpose, with multiple environmental and economic benefits, and that GHG abatement may well be among the minor on among the multiple economic benefits. This is likely to be as true for microalgae processes as it is, for example, for soil carbon storage in soils (Metting et al., 2001).

The many environmental benefits of improved wastewater treatment assure that any R&D effort will lead to at least some near-term (5-10 years) practical applications of value for GHG abatement. For the mid-term (10-15 years), it should be possible to produce high value biopolymers, lubricants, and animal feeds as co-products of microalgae biofuels production. In the longer term, the goal is to develop microalgae biomass production technology that is of low enough cost and high enough productivity to allow the production of renewable fuels as the major, even exclusive, economic function of such processes. Although feasible in principle, in practice many issues and problems will need to be addressed, as amply discussed above, and any predictions about achieving such goals, and how great an impact such a technology may have, should be hedged.

However, even with such hedging, there is a need to present at least an order of magnitude projection for the global GHG abatement potential of microalgae technologies. The fundamental assumption made here is that a realistic R&D goal is to achieve and demonstrate in the near- to mid-term, in year-round algal mass cultures, biomass productivities of somewhat over 100 t/ha-yr (e.g. an average of about 30 g/m²-d). Furthermore, it can be very roughly estimated that the biofuel produced from 1 ton of algal biomass would abate about 1 ton of CO₂ (based on the fuel output produced). Thus, 5 million hectares of algal ponds would be required to abate half a gigaton of CO₂, or about 1% of the total projected annual future GHG abatement needs, based on the assumption that current fossil fuel emissions will double under a ‘business as usual’ scenario.

This is not a great deal of land in such a context, at least compared to other solar and renewable energy and GHG abatement technologies, specifically other biomass production systems. Such a land area, 5 million hectares, would also be roughly in line with the requirements for municipal wastewater treatment for the entire human population (assuming nitrogen as the limiting nutrient). In fact, only a modest fraction of the human population, would plausibly be serviced by such technologies, because of climate, land availability and other limitations. On the other hand, waste treatment for animal husbandry operations has a greater potential as a practical economic application than municipal wastewater treatment, as does the co-production of other products, including fertilizers and animal feeds. A recent analysis, estimated the global potential of municipal and animal (dairy and swine) wastewaters for microalgae based GHG abatement at about 0.1 Gt of fossil CO₂ abated annually. This represents
about 1% of the emissions reductions required in the near- to mid-term to help stabilize GHG emissions. This is both a reasonable and realistically achievable projection for microalgae technologies, even without invoking the need for biofuel-only production processes, and would appear to be sufficient to allow for a significant R&D effort for microalgae biofixation technologies.

Such a projection represents a several thousand-fold expansion of this technology, from only about 1,000 hectares of high rate paddle wheel-mixed ponds operating at present around the world. However, considering that only about 25 years ago not even one hectare of such systems was being used in practical applications, a rapid adoption of such a technology is quite possible, if it provides real services to society and individuals.

Finally, the vision presented above is based on microalgae production ponds coupled to a conventional, that is large, fossil fuel power plant so as to make use of the flue gas produced by the plant. However, an equally, perhaps even more, valid vision is a power plant coupled to the algal ponds, in other words, a small power plant designed to service the algal plant. Perhaps most appropriate is the model where both operations would be part of an overall distributed system for provision of energy and other environmental services, including water, food, and materials. Clearly the requirements of large electricity generation by centralized (e.g. coal-fired) power plants and algal biomass production are not really compatible. The prospects for thousands, even tens-of-thousands of hectares of algal ponds co-located with large coal- or natural gas-fired power plants are limited. In the US, after eliminating both geographic constraints and land availability around large power plants, only a handful of large- or even medium-scale power plants can be plausibly identified or projected as suitable hosts to such large-scale (more than 1,000 ha) algal systems (Benemann and Oswald, 1996). However, a much greater potential exists for more modest power plants; and the greatest potential would be in integrated power generation systems that use a multiplicity of fuels and wastes, and that integrate the algal production process as one additional, though critical, component.

Although the vision of coupling algal ponds to power plants continues to be valid, it needs to be expanded by the additional vision of coupling power plants and algal biofixation systems across a greater range of scales and applications than is presently considered.

In conclusion, microalgae biofixation is unlikely to provide a cheap, easy, and centralized technology with multi-gigaton GHG abatement potential that would allow the fossil fuel power generation industry to continue operating in a ‘business-as-usual’ fashion. Microalgae can play a role in the great enterprise in which we must now urgently engage: the endeavour to develop and apply all viable renewable energy sources, both for their GHG abatement potential and for their capacity to replace increasingly scarce liquid and gaseous fossil fuels. Comparative analysis and common sense evaluations must be applied to reduce the contending technologies and proposed projects to the most reasonable options, without unduly constraining the search for alternatives.

The field of microalgae in GHG abatement research, though not uniquely, provides many examples, past and current, of implausible schemes and misdirected R&D efforts. Some of these cost great sums and, perhaps most damaging, have called the entire enterprise into question, and could do so again. The Microalgae Network was established to prevent, as much as possible, such lapses and to enable consensus building among researchers and experts regarding the most promising and viable microalgae biofixation processes for GHG abatement, and also for the R&D required to accomplish these objectives.

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