Large-Scale Algal Culture Systems: The Next Generation

Michael A. Borowitzka, Algal Biotechnology Lab, School of Biological & Environmental Sciences, Murdoch University, Perth, W.A. 6150

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The large scale commercial culture of microalgae for the production of health foods, for aquaculture feeds and for high value fine chemicals such as β-carotene is a well established biotechnology. Other microalgal products close to commercialisation are astaxanthin (Borowitzka, M.A., 1992b) and essential long chain polyunsaturated fatty acids such as docosahexaenoic acid (Martek, USA - pers. com). The discovery of a range of unique biologically active substances with anti-neoplastic, anti-viral and anti-fungal activity produced by several microalgae, especially cyanobacteria, provides a further range of potentially valuable algal products (Knobel et al., 1990; Patterson et al., 1991, 1993) and studies to optimise production of these are already under way (e.g. Patterson & Bolis, 1993). Furthermore, progress is being made in genetic engineering of microalgae (Blankenship & Kindle, 1992; Davies et al., 1992; Gunson et al., 1993) and in the next few years it is likely that transgenic algae will also be used to produce selected chemicals.

In order to be able to commercialise these products new and more effective large-scale algal culture systems are needed. The design of algal culture systems requires consideration of (a) light availability to the cells, (b) optimum turbulence (mixing), (c) CO₂-supply, (d) temperature control, and of course (e) capital and operating costs.

There are three types of large scale algal culture systems in use for commercial microalgal culture at present. These are: (a) the very large (several hectares), shallow, unstirred ponds used in Australia by Western Biotechnology Ltd and Betatene Ltd for the culture of Dunaliella salina and in Mexico for the culture of Spirulina (Borowitzka, L.J. & Borowitzka, 1989b); (b) the circular stirred ponds (up to approx 500 m²) used in Taiwan for the culture of Chlorella; and (c) paddle-wheel driven raceway ponds (up to approx 1000 m²) used for the culture of Spirulina, Chlorella and D. salina in Thailand, Taiwan, China, the USA and Israel. Each of these systems has specific advantages, some of which only become apparent when the whole process is considered (Borowitzka, M.A., 1992a) and some of which are site-specific. However, since these are open-air systems their applicability is generally limited to algae which live under very selective conditions such as high salinity, high pH or high nutrient conditions. There is also little scope for controlling the culture conditions so as to optimise cell and product yields. All of these systems also achieve only low cell densities of generally <1 g dry weight, which means that harvesting costs are high.

Further significant development of new algal species and products, and also new geographical locations for algal culture requires new, cost effective closed culture systems. In the last few years a major effort has been undertaken to develop such systems and these include illuminated fermenters with either internal or external light sources (Burgess et al., 1993), alveolar panels (Tredici & Materassi, 1992) and a variety of tubular photobioreactors (Borowitzka, L.J. & Borowitzka, 1989a). Although illuminated fermenters are very effective and high growth rates and culture densities can be achieved, the high capital and operation costs limit their applicability for commercial culture to all but a very small number of high value products such as pharmaceuticals. The production of lower value products such as algae for health food or animal feed, the production of carotenoids (i.e. astaxanthin), fatty acids (e.g. eicosapentaenoic acid & docosahexaenoic acid), polysaccharides etc. requires that the culture system be much cheaper.

Of the above systems, the tubular photobioreactors show the most potential. These reactors basically consist of long transparent tubes made of glass, polyacrilamide or PVC, some sort of pumping device (e.g. centrifugal pump, diaphragm pump, lobe pump, air-lift), a means to remove O₂ and add CO₂ and a heat exchanger for temperature control. The tube diameter in these systems has varied from about 15 cm to about 25 mm, and a number of large systems with volumes of up to 14,000 L have been operated very successfully in France, UK, Israel and Australia with a range of algae including Spirulina, Haematococcus, Porphyridium, Chlorella, Phaeodactylum, Tetraselmis, Anabaena and Isochrysis (Chaumont et al., 1988; Borowitzka, L.J. & Borowitzka, 1989a; Tredici & Materassi, 1992; Richmond et al., 1993; Chrismadha & Borowitzka, 1994). Other species have been grown at laboratory scale and the Australian navy is experimenting with such a system as a CO₂-scrubber for submarines. The tubes have been arranged horizontally on the ground, vertically in parallel arrays and wound helically around a frame. We have been working with the latter system (the Biocoil system). The helical arrangement has several advantages; a very long total tube length can be arranged in a stable structure which occupies relatively little land while maximising the amount of light incident upon the tube and the helical arrangement generates a non-laminar flow pattern within the tube, giving better

¹The design of the Biocoil system is patented by Biotechna Ltd, London (%) 758(Robinson et al., 1988) %
mixing than long straight tubes. Furthermore, the helical reactor has no sudden changes in flow direction which can give problems with algal accumulation in other arrangements. Through the use of small diameter tubing (about 25-60 mm i.d.) and appropriate flow rates the adhesion of the algae to the tube wall can be minimised or eliminated, thus ensuring that all cells receive the maximum amount of light available to the algae.

Table 1 compares some of the characteristics of tubular photobioreactors with other algal culture systems, and this table clearly shows the advantages of the Biocoil system over other kinds of algal culture systems.

The main limitations of tubular photobioreactors, such as the Biocoil system, relate to the pumps used to circulate the culture and to the efficiency of gas exchange. A wide range of pump types have been used in tubular reactors and no one type of pump has yet been shown to be consistently better than another. The pump is the main source of shear in the system leading to cell damage and, ultimately, death (Gudin & Chaumont, 1991). Cell growth in tubular reactors is also carbon limited and O₂ build-up in the long tubes may also lead to photorespiration and a reduction in growth. An efficient gas exchange system is therefore essential and some further design modifications may be necessary to minimise O₂ build-up. Alternatively, algal strains resistant to photorespiration could be used (Vonshak & Guy, 1992).

Figure 1 illustrates the effects of cell density and irradiance on the maximum biomass achieved in a semi-continuous culture of the marine diatom, Phaeodactylum tricornutum, grown in a 30 l tubular photobioreactor in the laboratory. Increasing irradiance increases the maximum cell number achieved, and the addition of 5% CO₂ in air greatly increases the biomass (ash free dry weight) due to an increase in cell size as well as the maximum cell number. However at high cell densities of about 15 x 10⁶ cells.ml⁻¹ the cultures are no longer light limited and increasing the irradiance from 286 to 1712 µEinsteins.m⁻².sec⁻¹ no longer results in an increase in biomass. Figure 2 shows the effects of these culture conditions on the productivity of eicosapentaenoic acid (EPA) in mg.1⁻¹.day⁻¹ in the same culture. Maximum productivity of EPA occurs at a cell density of 8 x 10⁶ cells.ml⁻¹ and an irradiance of 286 µEinsteins.m⁻².sec⁻¹ with 5% CO₂ added. These results show how the yield and productivity of a desirable algal product can be optimised in a closed bioreactor by changing culture conditions. Such optimisation is not easily done in open large scale culture systems.

The microalgae are an extremely diverse group of organisms and this diversity is also expressed in the range of biomolecules produced by these algae. The potential of these organisms is still largely untapped and only a very small number of the available species has been screened so far for valuable compounds. The development of new culture systems means that the opportunity now exists to exploit the potential of these organisms.

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Table 1. Comparison of the characteristics of different types of large-scale microalgal culture systems.

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Mixing</th>
<th>Light utilisation</th>
<th>Temperature</th>
<th>Gas Transfer</th>
<th>Hydrodynamic Stress</th>
<th>Species Control</th>
<th>Scale-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstirred Shallow Ponds</td>
<td>Very poor</td>
<td>Poor</td>
<td>None</td>
<td>Poor</td>
<td>Very Low</td>
<td>Difficult</td>
<td>Very difficult</td>
</tr>
<tr>
<td>Shallow Cascade System</td>
<td>Excellent</td>
<td>Excellent</td>
<td>None</td>
<td>High</td>
<td>Low - High</td>
<td>Difficult</td>
<td>Very difficult</td>
</tr>
<tr>
<td>Paddle-Wheel Raceway Ponds</td>
<td>Fair - Good</td>
<td>Fair - Good</td>
<td>None</td>
<td>Poor</td>
<td>Low</td>
<td>Difficult</td>
<td>Very difficult</td>
</tr>
<tr>
<td>Stirred Tank Reactor</td>
<td>Largely Uniform</td>
<td>Fair - Good</td>
<td>Excellent</td>
<td>Low - High</td>
<td>High</td>
<td>Easy</td>
<td>Difficult</td>
</tr>
<tr>
<td>Air-Lift Reactor</td>
<td>Generally Uniform</td>
<td>Good</td>
<td>Excellent</td>
<td>High</td>
<td>Low</td>
<td>Easy</td>
<td>Difficult</td>
</tr>
<tr>
<td>Tubular Reactor (Biocoil-type)</td>
<td>Uniform</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Low - High'</td>
<td>Low - High'</td>
<td>Easy</td>
<td>Easy</td>
</tr>
</tbody>
</table>

*Gas transfer efficiency depends on the design of the gas exchange system, and hydrodynamic stress is a function of the pumping system used to circulate the culture.*
Figure 1. Changes in biomass (Ash Free Dry Weight in g.L⁻¹) of Phaeodactylum tricornutum (strain MUR-136) grown in semi-continuous culture in a 30 l helical tubular photobioreactor at a range of cell densities (x10⁶ cells.ml⁻¹) and irradiances (Einstein.m⁻².sec⁻¹). Culture conditions were: f/2 medium (Guillard & Ryther, 1962) with 1.764 mM nitrate and 0.072 mM phosphate, pH 9-10, 14-18°C, with illumination provided by cool-white fluorescent lamps or a 1000-watt halogen lamp. The irradiance was measured at the surface of the reactor tubes. At the highest irradiances 5% CO₂ in air was added to the culture. The analytical methods are described in (Chrismadha & Borowitzka, 1994).

References
Chrismadha, T., & Borowitzka, M.A. (1994) Effect of cell density and irradiance on growth, proximate composition and eicosapentaenoic acid production of Phaeodactylum
tricornutum grown in a tubular photobioreactor. J. Appl. Phycol., 6, 67-74


