

Algal biotechnology: real opportunities for Africa

JU Grobbelaar

Plant Sciences Department, University of the Free State, Bloemfontein 9300, South Africa
e-mail: grobbeju@sci.uovs.ac.za

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The controlled and intense production of microalgae in photobioreactors has great potential for Africa. Of particular potential are; wastewater treatment, production of food and feed, production of bio-compounds, nutraceuticals and fine chemicals, and bioremediation. Microalgae have several competitive advantages over

conventional crop production using agriculture and their biotechnology offers real economic potential. For the immediate future, products for the health food market and applications in bioremediation offer real opportunities for exploitation, environmental and economic benefits.

Introduction

There has been interest in the massive outdoor cultivation of microalgae for more than a half a century (Burlew 1953) and applications such as the production of protein-rich biomass, production of high-valued biochemicals and the treatment of waste water have been investigated (Richmond 1986). A variety of cultivation systems has been proposed and tested under field conditions, including endless raceway ponds, cascading slope reactors, tubular reactors (Castillo *et al.* 1980, Soeder 1981), vertical polyethylene bag reactors (Cohen *et al.* 1991), thin-layered sloping systems (Setlik *et al.* 1970), tubular and flat plate photobioreactors (Grobbelaar and Kurano 2003). A major input in recent years has gone into photobioreactor design and optimisation and a stated aim of yield improvement and optimisation.

The interest and competitive advantages of microalgae over conventional higher plants include: (1) very high growth rates; (2) a high surface to volume ratio that promotes high uptake and release rates; (3) cosmopolitan nature and strains can tolerate extremes; (4) no requirement for good agriculture soils; (5) growth at high densities in photobioreactors under semi-controlled conditions; and (6) production of high valued products.

Maximal outdoor areal algal production rates exceeding $50\text{g(dw)}\text{ m}^{-2}\text{ d}^{-1}$ have been reported from several locations over the years (Grobbelaar 1981) for open ponds, which corresponds to about $180\text{t ha}^{-1}\text{ y}^{-1}$. In closed reactors, rates as high as $72\text{g(dw)}\text{ m}^{-2}\text{ d}^{-1}$ were reported by Lee *et al.* (1995) for their α -reactor and $79\text{g(dw)}\text{ m}^{-2}\text{ d}^{-1}$ was reported for *Spirulina* grown in a vertical coiled reactor (Tredici and Zittelli 1998). These productivities are particularly interesting for many reasons, because no land-based agri-system, even under the best conditions, can compete with such areal yields.

Commercial-scale culture of microalgae generally

requires the ability to produce large economical quantities of algal biomass. World wide, several commercial-scale operations are in production; however, to date only a few species have been grown. These include *Chlorella* spp., *Spirulina* (*Arthrospira*) *platensis*, *Dunaliella salina* and *Haematococcus pluvialis*. A species such as *Nannochloropsis* is grown extensively for aquaculture. Here, we address the questions whether algal biotechnology is suited for Africa, what potential competitive advantages does Africa offer and where are the possible major areas where this technology could be applied.

Basic Requirements and Considerations for Producing Algal Biomass

The basic requirements for producing microalgal biomass are shown in Figure 1. The growth reactor is essentially a solar energy collector and most of the design criteria of the latter apply to the photobioreactors used for mass algal culture. In essence, a distinction can be made between extensive and intensive production systems. Although extensive systems are used, most algal biotechnology involves intensive systems where biomass concentrations exceed at least 300mg l^{-1} . For intensive production essentially two options are available, namely 'open' and 'closed' systems, where 'open' means that large areas are in contact with the air, while 'closed' means little or no contact with the air (Grobbelaar 1981).

Since the available light is one of the major driving forces determining high growth rates, an important aspect in photobioreactor design and operation is the complete absorption of the penetrating fraction of irradiance through actively photosynthesising biomass. Crucial in absorbing all the available light in the optical path length, is operation of the

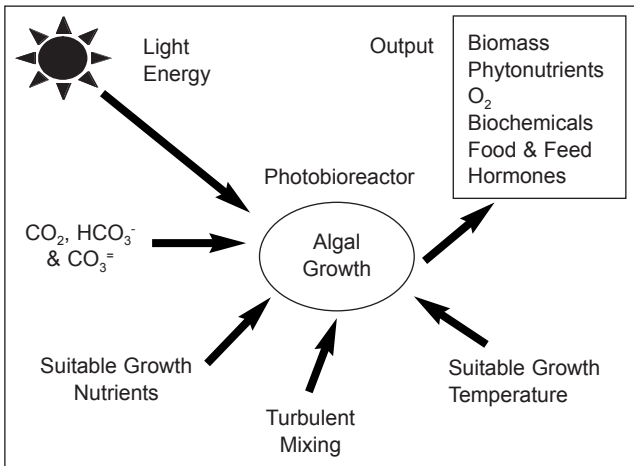


Figure 1: The growth requirements of microalgae grown in a photobioreactor and the potential products

cultures at the optimal areal density (Vonshak *et al.* 1982, Grobbelaar *et al.* 1984, Hartig *et al.* 1988). Vonshak *et al.* (1982) also showed how the optimal areal density is dependent on the season and Hu *et al.* (1996) have shown that the optimal areal density is reliant on the available light (photon flux density), being lower the lower the light intensity and *vice versa*. For closed photobioreactors the principles of light attenuation are the same as for open systems. However, the light characteristics in tubular reactors are complicated and for both tubular and vertical plate reactors the estimation of areal productivity has not been resolved for comparative purposes with open vertical systems. The alveolar panels could be inclined for maximum light exposure (Tredici and Materassi 1992) and many new materials have been developed for maximum light absorption and minimal reflection.

Paradoxically, most of the light energy available for photochemistry by algae in photobioreactors is either sub-optimal or excessive and only a small portion is optimal for maximal specific growth. The reason for this is that at any photo-acclimated state, photoautotrophic growth follows a bell-shaped response to light intensity (also referred to as the P/I curve of photosynthesis). Important to note is that for most light intensities sub-optimal productivities are measured and this differs markedly between either low-light or high-light acclimated algae (Grobbelaar *et al.* 1995).

Superimposed on the light utilisation efficiencies, is also the wavelength of available light. The spectral composition of light within the optical cross-section of a photobioreactor can vary markedly with distance from the light source. Depending on k_p (attenuation due to the algae) the longer and shorter wavelengths are absorbed first and green light is transmitted the most. For green algae the action spectra (photosynthetic rate per unit incident irradiance) of photosynthesis have maxima around 440–520nm and 650–710nm. When plant tissue decomposes, one of the products is a complex group of compounds referred to as 'humic substances'. Also microalgae excrete a bouquet of organic compounds, many absorbing specific wavelengths

of light. These yellow substances or also known as gilvin (Kirk 1994) strongly absorb wavelengths below 500nm, which is important for photosynthesis. These substances are common in batch or semi-continuous systems where the nutrient solution is re-used.

The last major variable in terms of light is fluctuation and this has a close coupling with turbulence (Grobbelaar 1994). The fluctuations considered here are not those caused by seasonal, diurnal or cloud cover, but those due to moving an alga through an optically-dense medium as a result of turbulent mixing. The light path length and the degree of turbulence determines the rate of light/dark fluctuations and as Grobbelaar *et al.* (1996) pointed out there are three major time periods: a long one of minutes to hours, a medium one of seconds to minutes, and a short one of milli-seconds to seconds. The important considerations and conditions are:

- (1) The optical cross section, where a distinction has been made between a short light path (SLP) of less than 40mm, medium light path (MLP) of 40–300mm and long light path (LLP) of more than 300mm.
- (2) The areal density where this determines the photic:aphotic ratios and the degree of attenuation.
- (3) Turbulence where this is coupled directly to the previous two determinants. For example, much higher turbulence can be achieved in a SLP, and short frequencies are common, compared to MLP reactors, implying much longer light:dark frequencies of seconds to minutes.

Grobbelaar (1994) pointed out that although the effects of light on the one hand and mixing on the other could be treated separately, they in fact are directly dependent on each other and have a synergistic effect in mass algal cultures. Mixing, therefore, determines:

- (1) The rate of movement of the cells through an optically dense medium and thus, the dynamics and frequency of light fluctuations.
- (2) The boundary layer and, therefore, the mass transfer rates between the growth solution and the organism and *vice versa*.
- (3) Definite physiological acclimation and efficiencies.

Concerning the latter Grobbelaar *et al.* (1996) showed that: (1) photosynthetic rates increased exponentially with increasing light/dark frequencies; (2) a longer dark period compared to the light period did not lead to higher photosynthetic rates; and (3) low light frequencies result in low light acclimation and *vice versa*.

Congming and Vonshak (1999) have shown that the mid-day maximum quantum yield of dark-adapted *Spirulina platensis* is depressed and that this was a result of reaction centre inactivation, which they ascribed to photoinhibition. It should be noted that the cultures were of MLP and the mixing was moderate (paddle wheel turning at 17rpm). However, it is unclear whether photoinhibition could be a factor in SLP cultures with high turbulence and where all impinging light is attenuated by the biomass. Grobbelaar *et al.* (1996) found no inhibition at light/dark frequencies of 0.05Hz to 5 000Hz where photosynthetic rates increased exponentially over this range. The crucial consideration is whether the turnover time of electron transfer to the electron transport chain is exceeded or not. If the transfer rate of electrons equals the turnover rate, then damage would be

minimal even at very high photon flux densities. Therefore, it is fair to conclude that in a high-density SLP cultures subjected to high turbulence photoinhibition would not be a factor that would influence overall yields.

It is often stated that nutrients, including CO₂, are supplied in excess or adequately. However, N, P and C are often limiting and the oversupply is also no solution to the problem as this may lead to stress and reduced growth. When growth rates are plotted as a function of the nutrient concentrations (Grobbelaar 2003), essentially four zones are recognised, i.e.:

(1) a deficient zone which is where low concentrations are found and growth increases dramatically when nutrients are supplied; (2) a transition zone where the critical concentration is found and in this zone growth is little affected by the addition of more nutrients (often referred to as the zone of the optimal concentration); (3) an adequate zone where no increase in growth is found with an increase in the supply of nutrients (luxury storage takes place at these concentrations); and (4) a toxic zone where an increase in the concentration of nutrients leads to reduced growth.

The zone of adequate supply is fairly wide for macronutrients, but much narrower for micronutrients. Not only is growth retarded in the deficient zone, but it can lead to alien species becoming dominant, as well as increased infections caused by bacteria, fungi and viruses, and finally to total collapse of the cultures. Knowledge about the quota flexibilities of the cultured organisms is important when systems are optimised for high areal growth rates. However, it is much more important to realise that complex interactions exist between the chemical constituents, their availability and uptake by algae in mass algal cultures (Grobbelaar 2003).

Culture procedures and feasibility criteria

To a large extent, the cultured algal species would determine the particular culture procedure and photobioreactor type. For example both extensive ponds and open paddle wheel race-way ponds are used for *Dunaliella salina*, race-way ponds are used for *Spirulina*, *D. salina* and *Haematococcus*, *Chlorella* and *Scenedesmus* are grown in either open or closed systems, while *Nannochloropsis* is often grown in deeper aerated systems. Among important considerations in selecting the photobioreactor are: (1) growth medium and the exclusivity thereof for alien algae; (2) influence of mixing and shear stress; (3) oxygen removal in closed systems; (4) tendency towards wall growth; (5) production and release of auto-inhibitors; and (6) scale-up potential.

Further important considerations and evaluations are indicated below.

Climatic conditions

This includes mainly the irradiance, and daily and annual temperature ranges.

Cost of land and usage

If the land costs are high then intensive systems are essential. Depending on the availability of water, algal biotechnology does not require good agricultural land and this technol-

ogy is suited for arid and semi-arid areas. Africa has large arid and semi-arid areas.

Supply and quality of water

Dunaliella is grown in highly saline water, while *Spirulina* requires about half the salinity of seawater and most other candidate species need good quality freshwater. Since evaporation losses from open systems could be as high as 15 l m⁻², significant quantities of water could be lost.

Labour, infrastructure and support

Labour costs are important and basic infrastructure such as accessibility (roads, water, and electricity) and technical support for maintenance and repair are essential.

Harvesting and down-stream processing

Essentially very dilute culture suspensions need to be harvested and it is important to consider the best method for the particular species (centrifugation, filtration or flocculation). Further processing includes either drying (spray or drum driers), extraction (e.g. β-carotene) or incorporation with other foods and feeds.

Quality control

The microalgal biomass produced is subject to contamination from the entire range of contaminants and pathogens and it is essential that quality control be part of entire production and processing procedures.

Markets and marketing

The end-users must be clearly identified and products for new markets continuously developed.

Potential Applications for Africa

Africa can benefit from algal biotechnology, mainly in the following areas:

Wastewater treatment

Water treatment and pollution are major problems and the AIWPS (Advanced Integrated Wastewater Pond System) developed by Oswald and co-workers (Oswald 2003) offers a practical solution to cost effective and reliable waste water treatment. This technology is suited to the removal of plant growth nutrients, heavy metals and organic loading. Benefits include the disinfection of effluents, coupling with methane fermentation and production, production of animal feeds, and biomass that can be used for the extraction of pharmaceuticals and nutraceuticals. Unfortunately, this technology is almost non-existent in Africa.

Health supplements, food and feed

The dietary supplement industry is extremely lucrative and amounts to USD23 billion per annum in the USA alone. The market is growing at around 15% per year and there is strong demand for high quality products. *Spirulina* has been used as a food for centuries by the inhabitants living near the alkaline lakes of Chad and Niger. The microalgal biomass is

particularly interesting because of its high crude protein contents and many other cellular components. However, production of algae biomass for direct human consumption is not feasible because it cannot compete economically with conventional food crops. However, as a by-product of one or other industrial process or when grown on waste products, the biomass could be used directly or indirectly for food and feed.

Bio-products, nutraceuticals, fine chemicals and toxins

Much has been written about the chemical composition and nutritional properties of microalgae (e.g. Payer *et al.* 1980, Becker 1995) and particularly exciting is the inhibition of HIV-1 replication by an aqueous extract of *Spirulina*. (Ayehunie *et al.* 1998). However, the range of high-value products includes pigments (β -carotene), lipids, polysaccharides, vitamins, toxins and many more. The crux is to find such products that are unique to algae and which can be produced economically.

Bio-fertilisers and growth stimulants

Algae biomass is rich in nutrients and plant growth hormones. Application as fertilisers and for soil improvement have been demonstrated in many areas of the world. Microalgae contain both auxins and cytokinins, and Ördög and co-workers (pers. comm.) using bioassays found that more than 45% of tested green algae showed auxin- and cytokin-like activity, while the same was found in about 20% of cyanobacteria. Combined with anti-bacterial, -fungal and -viral activity, it is foreseen that this area of algal biotechnology will develop strongly in the next decade.

Bioremediation

Although microalgae have been used for wastewater treatment and heavy metal uptake from contaminated soils, recent studies have shown that microalgae offer the greatest potential for the amelioration of CO₂ from point source emissions (Grobbelaar *et al.* 2000). The added advantage is that a 'neutral CO₂ cycle' is possible and that value-added biomass can be produced to offset costs.

Conclusion

Algal biotechnology has many possible applications for Africa for a variety of purposes. It is important to analyse the goals, potential benefits and support carefully, prior to embarking on new projects. There have been many failures in algal biotechnology, the important reasons for which are: (1) poor design and inferior quality products used in the construction; (2) insufficient academic support, knowledge and experience; (3) poor location, especially in terms of climate and necessary infrastructure; (4) poor quality control, product reproducibility and quality; and (5) emphasis on engineering excellence with poor photobiology outputs.

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