Algal biotechnology: real opportunities for Africa

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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 50g(dw) m–2 d–1 have been reported from several locations over the years (Grobbelaar 1981) for open ponds, which corresponds to about 180t ha–1 y–1. In closed reactors, rates as high as 72g(dw) m–2 d–1 were reported by Lee et al. (1995) for their α-reactor and 79g(dw) m–2 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
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 $k_l$ (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 photocentric 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...
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ty. Depending on the availability of water, algal biotechnol-
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
151 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 sup-
port for maintenance and repair are essential.

Harvesting and down-stream processing
Essentially very dilute culture suspensions need to be har-
vested 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 dri-
ers), extraction (e.g. β-carotene) or incorporation with other
foods and feeds.

Quality control
The microalgal biomass produced is subject to contaamina-
tion from the entire range of contaminants and pathogens
and it is essential that quality control be part of entire pro-
duction 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 fol-
lowing 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 pharma-
cuticals 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

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 indi-
cated 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 essen-
tial. Depending on the availability of water, algal biotechnol-
ogy does not require good agricultural land and this technol-
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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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