Biotechnology of algal biomass production: a review of systems for outdoor mass culture

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Abstract

Microalgae are very efficient solar energy converters and they can produce a great variety of metabolites. Man has always tried to take advantage of these properties through algal mass culture. Despite the fact that many applications for microalgae have been described in the literature, these microorganisms are still of minor economic importance. Industrial reactors for algal culture are at present, all designed as open race-ways (shallow open ponds where culture is circulated by a paddle-wheel). Technical and biological limitations of these open systems have given rise to the development of enclosed photoreactors (made of transparent tubes, sleeves or containers and where light source may be natural or artificial). The present review surveys advances in these two technologies for cultivation of microalgae. Starting from published results, the advantages and disadvantages of open systems and closed photobioreactors are discussed. A few open systems are presented for which particularly reliable results are available. Emphasis is then put on closed systems, which have been considered as capital intensive and are justified only when a fine chemical is to be produced.

Introduction

Photosynthesis is one of the basic biochemical processes of photosynthetic micro-organisms which convert solar energy into chemical energy. Man has used this natural process of harvesting the sun in the development of algal cultivation systems for secondary waste water treatment (Oswald, 1988a; De la Notie et al., 1992), for the production of human food (Becker, 1986), animal feeds (De Pauw & Persoone, 1988; Benemann, 1992), fertilizers (Metting, 1988), chemicals (Chapman & Gollenbeck, 1989; Calvin & Taylor, 1989) and secondary metabolites of pharmaceutical potential (Glombitza & Koch, 1989).

In 1952 the Carnegie Institution of Washington published ‘Algal culture from laboratory to pilot plant’ (Burlew, 1953), which summarized what had been done on large-scale algal culture before, during and shortly after World War II. In that document, many workers foresaw the great potential of algae as a product different from the fermentation industry and as a potential source
for agricultural and chemical commodities. The first concept adopted immediately after World War II envisioned algal biomass as the principal supplement or even replacement for animal proteins for direct consumption by humans. This work was continued by many research groups during the sixties and the seventies, most notably in the USA, Germany, Israel, Czechoslovakia, Japan, Thailand and France. With the onset of the energy crisis, microalgae were then suggested as a source of biomass for methane. It is only recently that significant attention has been paid to microalgae as a source of feedstock for the production of chemicals.

Several reviews list the main biological possibilities offered by microalgae including those by Cannell (1990), Richmond (1990) and Borowitzka (1992). The present review avoids methods and applications of cell immobilization techniques, which have been reviewed recently by Robinson et al. (1986) and Brouers et al. (1989). The design of culture vessels for laboratory applications is also not included (see Lee, 1986 and Edmund et al., 1990).

Algal culture systems are generally classified according to their engineering (full or non-confining) and hydraulic characteristics in open systems (including ponds, deep channel, shallow circulating units etc.) and closed or fully hydraulic systems commonly called photobioreactors. Microalgal mass culture technology, and most particularly open systems, have been reviewed by Terry and Raymond (1985), Soeder (1986), Richmond and Becker (1986), Borowitzka and Borowitzka (1989) and Richmond (1990). Because of their technical complexity, photobioreactors have been considered for a long time as the antithesis of open ponds technology. It is only recently, because of the difficulties of overcoming the limitations of open ponds, that closed bioreactors have been considered as a complementary way of algal mass culture. The increasing interest in this technology is apparently leading algal culture to an exponential phase of technical evolution, and a large number of relevant patents continue to be granted (see Patents section in this journal).

The challenge of large-scale algal culture: conclusions of the 1990 Congress on Applied Algology in Tiberias, Israel

Richmond and Vonshak (1991) reported the main points of scientific interests in microalgal culture presented during this Congress:

1. The control of microalgal species is the major unsolved problem in large-scale open systems. Only a few strains are cultured at industrial scale. Much work continues to be done on Spirulina (Richmond, 1988), Dunaliella salina (Ben Amotz & Avron, 1989) and Porphyridium cruentum (Vonshak, 1988). In addition, special emphasis was given to Haematococcus pluvialis which is able to produce astaxanthin, a red carotenoid of a particular interest in aquaculture (Bubrick, 1991).

2. All industrial plants are based on open pond technology. These systems seem to have reached their technical limits. The gap between the theoretical biological potential of microalgae and their biomass productivities actually obtained could be narrowed by developing closed photobioreactors.

What culture technology to choose?

Productivity comparison between microalgal mass culture systems are difficult because of different geographic locations, culture strategies (batch or continuous culture), algae species etc. Furthermore, salt concentration in the culture medium are sometimes 10 times higher than dry biomass concentration: a correct estimation of biomass productivities requires reliable methodologies for representative measurements of cell and metabolite concentration (Gudin & Chauumont, 1991). Published data on algal productivity range from 10 to 50 g m\(^{-2}\) d\(^{-1}\) (Weissman et al., 1988) with an average rate around 20 g m\(^{-2}\) d\(^{-1}\). The maximum practical photosynthetic efficiency is still a problem to be resolved (Pirt, 1983). However, a theoretical photosynthetic yield of 6 to 7% of total solar energy