PHOTOSYNTHETICA 46 (2): 283-285, 2008

BRIEF COMMUNICATION

Influence of shading inclined tubular photobioreactor surfaces on biomass productivity of *C. sorokiniana*

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Abstract

Shading of the tubular photobioreactor (PBR) surfaces that diminished solar irradiance to 70 % led to higher biomass productivity and greater accumulation of total chlorophyll and carotenoids compared to the values obtained when the PBR was completely exposed to full sunlight.

Additional keywords: algae; carotenoids; chlorophyll; flashing radiation; intermittent radiation.

Algae are usually cultivated in open or closed systems. One of the major advantages of the later over the former is efficient control of contamination. Tubular photobioreactor (PBR) is one of the most promising closed systems for outdoor cultivation of algae given its potential advantages, such as large irradiated surface area. However, microalgal cultures grown in narrow tubular PBR are prone to photoinhibition (with low density cells), especially during the midday. Aside from the effect of photoinhibition on the cells, excessive supply of radiant energy would lead to photon loss since cells can only absorb a small part of photons for photosynthetic growth. This implies that the yield of biomass per unit of solar energy would depend not only on the irradiation supplied but also on the utilization efficiency by the microalgal cells. Various strategies for improving efficiency of photon energy utilization in PBRs have often been tested (Richmond and Qiang 1997, Carlozzi 2002, Ugwu *et al*. 2005). To overcome problems of photoinhibition during outdoor cultivation, large-diameter tubes can be used. However, biomass productivity in large-diameter tubes would be very low unless either vertical or radial mixing is induced in the PBR to circulate algal cells between the upper and lower parts of the tubes (Molina Grima *et al*. 1999, Ugwu *et al*. 2005). Thus there is a need to design efficient outdoor tubular PBRs that utilize solar energy by principle of light/dark cycling of algal cells for improvement of biomass productivity. We attempted to shade an inclined outdoor tubular PBR with opaque paper to test the effect of intermittent radiation on biomass productivity of *C. sorokiniana.*

The PBR consisted of transparent plastic tubes that were joined together by aeration and degasser ports. The diameters of the riser and downcomer tubes were both 0.038 m while the total length of the tube was 4 m. The volume of PBR was 6 000 cm^3 (including volumes of the tubes, ports for aeration, and degasser). The PBR was inclined at 8^o to the horizontal plane. Aeration rate, the overall volumetric mass transfer coefficient k_La, mixing time, and gas hold-up were 0.25 vvm, 9.6 h^{-1}, 240 s, and 0.02, respectively.

We used *C. sorokiniana* IAM-212, obtained from the Culture Collection Centre of the Institute of Applied Microbiology, University of Tokyo, Japan. The pH of modified MM4 medium (Ugwu *et al*. 2005, 2007) was adjusted to 6.0. *C. sorokiniana* was inoculated into 1 200 cm^3 of the medium in Roux flask and grown for 48 h. Seven daylight fluorescent lamps (*8FL-40-s-PG*, *National Electric*, Tokyo, Japan) arranged in parallel on a vertical plane were used for irradiation. The irradiance at the surface of the Roux bottles was 350 µmol m^{-2} s^{-1}. Aeration and mixing were achieved by sparging air enriched with 5 % CO_2 through a glass-ball filter, which was inserted to the bottom of the flasks, at 0.3 volume of air per volume of liquid per minute (vvm). The preculture was used to inoculate the tubular PBR. The PBR was naturally irradiated by sunlight. Cooling was carried

Received 14 June 2007, *accepted* 3 October 2007.
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Abbreviations: Chl – chlorophyll; DCM – dry cell mass; PBR – photobioreactor.

out by sprinkling the surface of the PBR with tap water. The cultivation period was 06:00–18:00 (12-h period) during the summer. Stripes of opaque papers were arranged alternately at the lower and upper surfaces of the PBR (*Kimtowel, Crecia Co.,* Tokyo, Japan) in the afternoon (12:00–16:00) when solar irradiances were very high.

Biomass concentration, optical density, and irradiance were measured as previously described (Ugwu *et al.* 2002, 2007). Chlorophyll (Chl) fluorescence of the cultures (maximum photosystem 2 photochemical yield, F_v/F_m) was measured as described in Ugwu *et al.* (2007). The increase in the biomass at 06:00–18:00 was calculated as the daily productivity. Mean values of the results were used in all the experiments. The standard error of the mean (SE) and confidence limits were calculated and the mean values were plotted with 95 % confidence limits (Parker 1980). Analysis of variance (ANOVA) followed by least significant difference (L.S.D.) tests were used to compare the results.

Effect of daily weather on the biomass productivity of *C. sorokiniana* is shown in Fig. 1. The culture was maintained on semi-continuous mode by daily dilution of the cultures with fresh medium. Every morning, the optical density of the cells was measured to estimate the cell concentrations from a predetermined calibration curve. The culture was then diluted to the desired standing biomass concentration with fresh medium (0.5 kg m^{-3}). As shown in Fig. 1, the biomass productivity varied with the daily solar irradiation. On days 1–6 there was a reduction in biomass productivity from 0.60 to 0.45 kg m^{-3} d^{-1} mainly due to bad weather, especially during the cloudy days. As from day 7, the weather improved as evidenced by solar irradiation, which varied from 8.5 to 10.0 MJ m^{-2} d^{-1}. The average and highest biomass productivities during these periods were 0.73 and 0.90 kg m^{-3} d^{-1}, respectively.

Solar irradiance received by the PBR on very bright days (between 06:00 and 18:00) varied from 200 to 2 500 µmol m^{-2} s^{-1}, depending on the weather. It was necessary to cover the surfaces of PBR in the afternoon (12:00–16:00) when solar irradiance was very high [average solar irradiance = 2 000 µmol(photon) m^{-2} s^{-1}] to avoid photoinhibition and thus improve the photon energy utilization efficiency. Preliminary studies showed that covering the PBR all through the day or on cloudy days resulted in low biomass productivity. Furthermore, exposure of 90 % of the PBR surfaces did not result to any significant difference in productivity ($p<0.05$) compared to that of the completely exposed PBR (*i.e.* when 100 % or all of the PBR surfaces was exposed).

As shown in Fig. 2, exposure of 70 % of the PBR surfaces to sunlight gave the highest biomass productivity (1.1 kg m^{-3} d^{-1}). This value corresponded to about 22 % higher biomass productivity than that of the uncovered PBR, and 57 % higher biomass productivity than that of the PBR with 50 % of its surfaces exposed to solar irradiance. Furthermore, total Chl and carotenoid contents in cell biomass were the highest in PBR which had 70 % of its surface exposed to solar radiation. Comparatively, Chl and carotenoid contents are ranked as follows: 70 % exposure>complete exposure (100 % exposure)>50 % exposure of PBR surfaces.

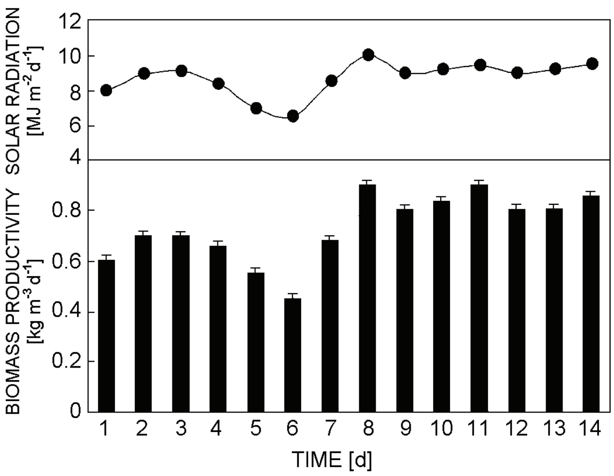

Fig. 1. Biomass productivities of *C. sorokiniana* during outdoor cultivation under various ranges of solar radiation.

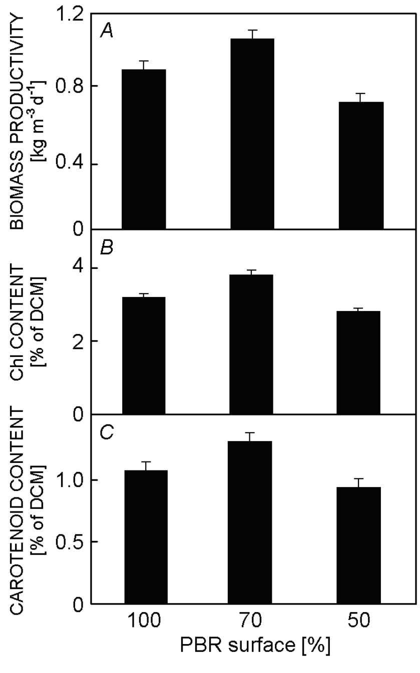

Fig. 2. Effect of shading the photobioreactor (PBR) surfaces with opaque paper on biomass productivity (*A*), and total cellular chlorophyll (Chl) (*B*) and carotenoid (C) contents.

Improved biomass productivities when PBR was covered with opaque paper (*i.e.* when 70 % of PBR was exposed to sunlight) could be attributed to intermittent radiation. Thus, covering the PBR surfaces with opaque paper resulted in light/dark cycling of algae in the tubular

PBR. The role of flashing irradiation in improving algal productivities has been extensively studied (Lee and Pirt 1981, Ogbonna *et al*. 1995, Grobbelaar *et al*. 1996, Janssen *et al*. 2001). Most of these studies have shown that when algal cells are irradiated by very short flashes, the rates of photosynthesis are comparable with that under continuous irradiation, depending on irradiance. At high irradiances, existence of dark periods between the short flashes would increase the photosynthetic growth of algae. Certain depression of photochemical activity at midday is necessary for optimum productivity (Richmond 2004). In our study, certain depression of the photochemical activity might have occurred at the midday. Analysis of the Chl fluorescence (F_v/F_m) of the cells showed a decline from 0.75 in the morning (06:00) to 0.50 (14:00), which reverted to 0.70 in the evening (18:00). Despite the reduction in F_v/F_m, the pigment contents in the 70 % shaded PBR were higher than those of the unshaded one. Both the biomass productivity and pigment contents obtained when surfaces of the PBR were covered depended on the prevailing solar irradiance and the diameter of the tubular PBR.

Hence covering a fraction of outdoor tubular PBR surface during the midday (when the solar irradiance is very high) helps in improving the algal productivity and pigment formation, especially in narrow tubular PBRs.

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