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Evaluation of the Mass Transfer Capacity of a Long Tubular Photobioreactor with Static Mixer and its Outdoor Performance with Microalgal Cultures

C.U. Ugwu and H. Aoyagi
Graduate School of Life and Environmental Sciences, University of Tsukuba, Japan

Corresponding Author: C.U. Ugwu, Graduate School of Life and Environmental Sciences, University of Tsukuba, Okinawa Industrial Technology Center, Suzaki 12-2, Uruma, Okinawa 904-2234, Japan Tel: +81-98-929-0111 Fax: +81-98-929-0115

ABSTRACT

This study was aimed at improving the performance of a long outdoor tubular photobioreactor for high yield of algal biomass. A long tubular photobioreactor (with total tube length of approximately 20 m) was developed. In order to understand the performance of the tubular photobioreactor, hydrodynamics and gas-liquid transfer characteristics, as well as outdoor cultivation of microalgae were evaluated. Parameters that were used to evaluate the gas-liquid transfer characteristics of the photobioreactor included the overall mass transfer coefficient (k_La) and mixing time at various aeration rates (i.e., 0.05 to 0.35 vvm). At 0.35 vvm, presence of 8 static mixers on the riser section at a spacing of 1 m increased the k_La by 25 fold and prolonged the mixing time by 2.7 fold compared to that of the photobioreactor without static mixers. By using the tubular photobioreactor without static mixers, the average biomass productivities attained with *Synechocystis aquatilis* (*S. aquatilis*) and *Chlorella sorokiniana* (*C. sorokiniana*) were 0.55 and 0.35 g/L/day, respectively. However, upon installation of static mixers, biomass productivities of *S. aquatilis* and *C. sorokiniana* increased by 27 and 49% (i.e., 0.70 and 0.52 g/L/day), respectively. This study has indicated that efficiency of a 20 m long tubular photobioreactors and outdoor biomass productivities with the photobioreactor can be significantly improved when static mixers were 1 m apart from each other.

Key words: Aeration rate, mass transfer, microalgae, photobioreactor, scale up

INTRODUCTION

Photobioreactors have attracted much interest in recent years given their potential uses in growing microalgae (Hoekema *et al*., 2002; Oncel and Akpolat, 2006; Ugwu *et al*., 2008; Hsieh and Wu, 2009). Photobioreactors are used for growing microalgae for two major reasons (1) production of high-value compounds such as vitamins, amino acids and colorants (Akpolat and Eristurk, 2008; Harith *et al*., 2010) and (2) for environmental sustainability (e.g., biofuel, carbon dioxide mitigation, bioremediation (Yoshihara *et al*., 1996; Azmat *et al*., 2007; Chisti, 2007; Fereshteh *et al*., 2007). Of all the photobioreactors proposed to date, tubular photobioreactor is one of the most commonly studied closed systems for outdoor cultivation of microalgae (Torzillo *et al*., 1991; Lee and Low, 1991; Briassoulis *et al*., 2010). Although there are lots of potential advantages of using tubular photobioreactors, the limitation in scaling it up has restricted its application in commercial scale. Scaling up of tubular photobioreactor can be done

either by increasing the length or diameter of the tubes (Grima *et al*., 1999; Ugwu *et al*., 2003). Nevertheless, just like any other type of reactors, any aspect of scaling up a tubular photobioreactor to a larger scale would result in decrease in the mass transfer capacity and consequently, would affect the biomass productivity. If the scale up method is done by increasing the diameter of the tubes, the availability of light to the cells has to be taken into consideration to avoid light stratification in the tubes. It was previously reported that static mixers would ensure efficient mixing, increased mass transfer capacity and better light utilization in tubular photobioreactors that were scaled up by increasing the diameter of the tubes (Ugwu *et al*., 2005). However, there is yet no report on the use of static mixers in tubular photobioreactors with their lengths exceeding 4 m. This study was therefore, aimed at improving the mass transfer capacity of a 20 m long tubular photobioreactor by using suitable numbers of static mixers, at an appropriate spacing distance with the ultimate goal of improving the outdoor microalgal productivities.

MATERIALS AND METHODS

Microorganisms and precultivation: *Chlorella sorokiniana* (*C. sorokinaiana*) IAM-212 and *Synechocystis aquatilis* (*S. aquatilis*) SI-2 were used in this study. *C. sorokiniana* was grown in culture medium as previously described (Ugwu *et al*., 2002) while *S. aquatilis* was grown in a modified SOT medium which was composed of (in 1 L): $NaHCO_3$, 5 g; $NaNO_3$, 4 g; K_2HPO_4, 0.2 g; $MgSO_4$. $7H_2O$, 0.1 g; Clewat 32 microelemental mixture, 0.05 g; aged sea water, 0.1 L and tap water 900 mL.

For the pre-cultivation, slant cultures were inoculated into 1.5 L Roux flask that contained 1 L of culture medium. Seven daylight fluorescent lamps (8FL-40-s-PG, National Electric, Tokyo) arranged in parallel on a vertical plane were used to provide light intensity of 350 μmol/m^2/sec. The culture was operated for 60 h in Roux flask before they were inoculated to the 25 L outdoor tubular photobioreactor.

The outdoor tubular photobioreactor: The tubular photobioreactor is shown in Fig. 1. It consisted of two parallel transparent tubes that were connected by manifolds (i.e., the aeration and upper degasser ports). The total length of the tubes was 20 m (10 m each for the riser and downcomer sections). The photobioreactor had a total volume of 25 L. Eight static mixers were inserted on the riser section at a spacing distance of 1 m. The tubular photobioreactor was inclined

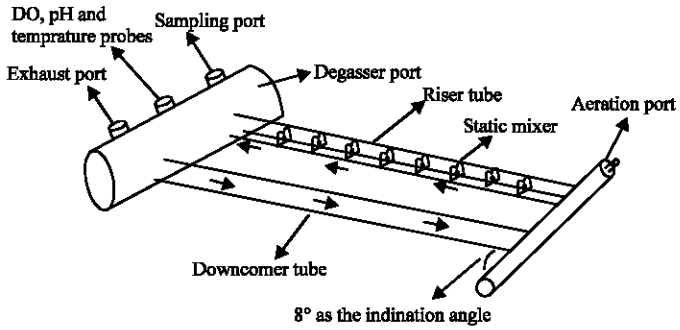

Fig. 1: A schematic diagram of an inclined tubular photobioreactor. Aeration and mixing were applied from the riser tube while the liquid flowed from the riser to the downcomer sections of the photobioreactor

Table 1: Mass transfer characteristics of a 20 m-long tubular photobioreactors used for the outdoor cultures

Parameters or dimension	Values
Tube diameter (m)	0.038
Volume (l)	25
Total tube length (m)	20
Number of static mixers	8
k_La (sec^{-1})	0.001
Mixing time (sec)	540
Gas holdup	0.02
Liquid velocity (m sec^{-1})	0.06
Solid velocity (m sec^{-1})	0. 03

at 8 degrees to the horizontal plane. Detailed information about the characteristics of the tubular photobioreactors used for outdoor cultures is summarized in Table 1. Aeration and mixing of the cultures in the tubular photobioreactor were done by sparging air (with air pump) and then enriching it with 5% CO_2 at 0.15 volume of air per volume of liquid per min (vvm).

The overall volumetric mass coefficient (k_La), mixing time and gas holdup were measured as previously described (Ugwu *et al*., 2002). Liquid velocity was estimated as the distance travelled by the tracer (to make a significant change in pH) from the injection point to the degasser port through the riser section. Solid velocity was calculated using a 5 mg dried algal cells. Thus, the velocity attained by the cells for a complete cycle within the photobioreactor was estimated. Cell concentration was determined as follows; 10 mL culture was centrifuged at 5,000 rpm for 5 min and cells were collected, washed with 0.5 M HCl to remove the precipitated salts and other non-organic substances. The cells were later on rinsed with distilled water, dried at 105°C for 24 h, cooled over silica gel in a desiccator and then weighed. The optical density was measured at 680 nm wavelength using spectrophotometer (Spectronic 20A, Shimadzu, Tokyo, Japan). The solar light intensity on the surface of the photobioreactor was measured using photorecorder (PHR-51, T and D Co., Japan). Dissolved oxygen concentrations in the photobioreactors were measured using DO controller (Mk-250 DO, B.E. Marubishi Co., Japan). Culture temperature in the photobioreactor was maintained at 30-35°C for *C. sorokiniana* by sprinkling the surfaces of the photobioreactor with tap water. In the case of *S. aquatilis*, there was no need to sprinkle the reactor with water since optimum growth of this strain occurs at relatively high temperatures (i.e., between 38 and 40°C). The experiment was carried out during the summer of 2003 (at the Agricultural Research Center, University of Tsukuba, Japan. Biomass productivities were evaluated at solar radiation between 8 and 10 $MJ/m^2/day$. The culture was operated at a standing biomass concentration of 0.50 g L^{-1} and then maintained on a 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 increase in the biomass concentration at 06:00-18:00 was calculated as the daily productivity (g/L/day).

RESULTS AND DISCUSSION

A general approach to scale up a tubular photobioreactor is to increase the length or diameter of the tubes (Fig. 2). For instance, when scaling up a small scale tubular photobioreactor, the tube diameter can be kept constant while the diameter is being increased. The other option is to keep the tube diameter constant and then increase the length of the tube. Each of these options has its prospects and demerits as previously reviewed (Ugwu *et al*., 2008). It should be noted that small

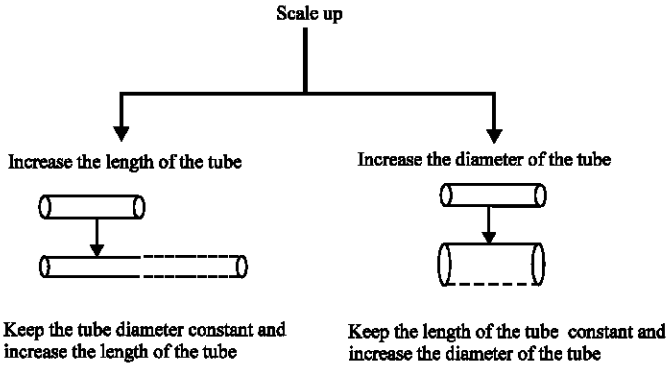

Fig. 2: Scheme for scaling up tubular photobioreactors by increasing the length or diameter of the tubes

diameter tubular photobioreactors are usually advantageous since they have lower degree of light/dark effect and thus would provide better biomass productivity compared to large diameter types. However, inhibition and accumulation of gradients along the tubes has been noted as the major constraints in this type of photobioreactor. To overcome this kind of problem, efficient mixing systems are necessary mixers to improve the gas-liquid transfer in long tubular photobioreactors. Oxygen transfer in bioprocesses is one of the major parameters for evaluation of productivity (Garcia-Ochoa and Gomez, 2009; Sauid and Murthy, 2010). Although increasing the aeration rate would improve oxygen uptake in bioreactors for non photosynthetic microorganisms (Jafari *et al*., 2007; Emily *et al*., 2009), very high oxygen accumulation tends to inhibit the growth of photosynthetic microorganisms (Grima *et al*., 1999; Ugwu *et al*., 2008). This implies that moderate turbulence that will not affect the growth of microalgae has to be maintained in photobioreactors. Long tubular photobioreactors, in particular, are prone to accumulation of much higher dissolved oxygen than other types of photobioreactors (Grima *et al*., 1999). To maintain considerable turbulence by aeration in tubular photobioreactors, vertical mixing system such as static mixers are desirable. We have previously reported that when vertical mixing was induced by static mixers, movement of gas and liquid in the tubular photobioreactors efficiently progressed between the upper and lower sections of the tubes and thus, improved both mass transfer capacity of the photobioreactors and algal biomass productivities (Ugwu *et al*., 2002, 2003). Figure 3 shows the k_La of tubular photobioreactor without static mixers and the one with 8 static mixers. The k_La increased in both photobioreactors when the aeration rate was varied from 0.05 to 0.35 vvm, however, there was no significant difference in their k_La values at the aeration rate ≤0.05. At 0.35 vvm, installation of 8 static mixers in the tubular photobioreactor resulted in about 25 fold increase in k_La compared to that at 0.05 vvm.

Although static mixers improved the k_La, their presence resulted in longer mixing time in the tubular photobioreactors. As shown in Fig. 4, the photobioreactor without static mixers had shorter mixing time compared to the one without static mixers at all the aeration rates tested. By increasing the aeration rate from 0.05 to 0.35 vvm, the mixing time became shorter in the photobioreactors. At 0.35 vvm, installing of static mixers in the tubular photobioreactor prolonged the mixing time by about 2.7 fold compared to that without any static mixers. There was no significant change in the mixing times of the photobioreactor with and without static mixers at aeration rate ≤0.05 vvm. Eight static mixers were the most suitable among other numbers tested and further attempt to

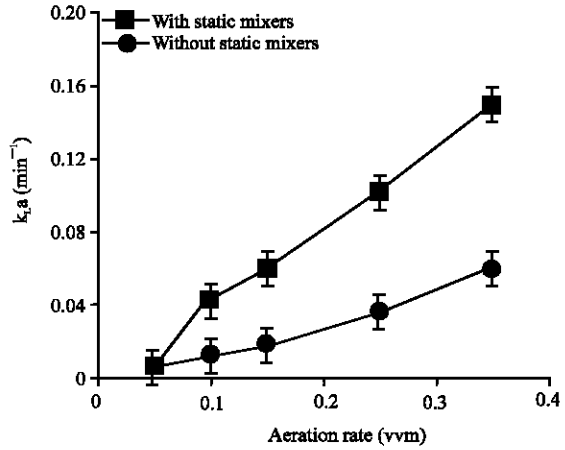

Fig. 3: Effect of aeration rate on the k_La of a 20 m long tubular photobioreactor with static mixers and without static mixers

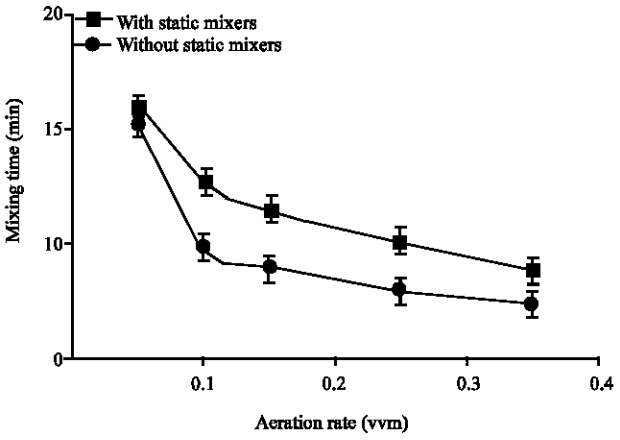

Fig. 4: Effect of aeration rate on the mixing time of a 20 m long tubular photobioreactor with static mixers and without static mixers

increase the number above 8 resulted in decrease in k_La and greatly elongated the mixing time. Furthermore, when too many static mixers were installed, algal cells became flocculated to them, making the cleaning process very difficult after the cultivation. To improve the installation of the mixers, their removal after cultivation, as well as for better high liquid-gas exchange, the tubular photobioreactors were inclined at 8 degrees to the horizontal plane. Although the static mixers were more efficient at higher aeration rate, 0.15 vvm was considered for outdoor cultures since it was necessary to make a compromise between the mass transfer (i.e., k_La) and power consumption. In our previous studies, 4 static mixers that were placed at spacing distances of 0.25 m apart from each other proved to be the best in terms of k_La and gas holdup (Ugwu *et al*., 2002). However, with the long tubular photobioreactor, such as the type used in this study indicated that higher aeration rate (greater than 0.15 vvm) would induce too much turbulence which consequently resulted in culture crash at the beginning of the experiment. In light of this, the characteristics features of the tubular photobioreactor with static mixers, indicated a relatively high mass transfer properties (i.e., k_La, gas

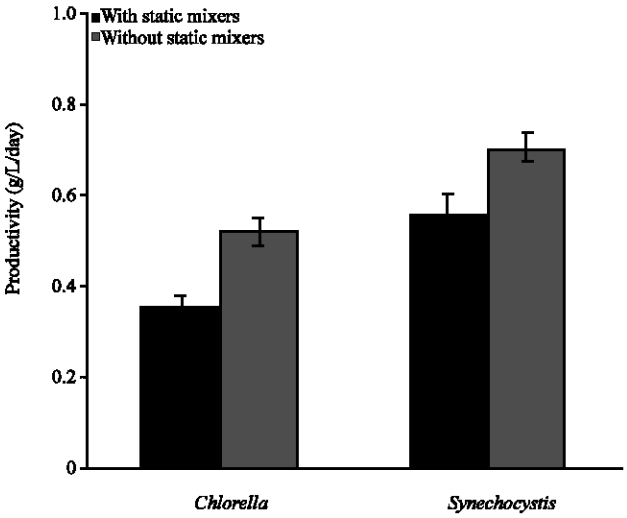

Fig. 5: Outdoor biomass productivities of *C. sorokiniana* and *S. aquatilis* in 20 m long tubular photobioreactor with static mixers and without static mixers. Three replicate experiments for each of the data was obtained at 8-10 MJ/m^2/day solar radiation

holdup, mixing time, liquid velocity and solid velocity) that were enough to generate good liquid-gas transfer and thus improved the biomass productivities. In this study, the maximum k_La of 0.0025 sec^{-1} was obtained at an aeration rate of 0.35 vvm (superficial gas velocity = 0.14 m sec^{-1}). However, Babcock *et al.* (2002) reported the maximum k_La of 0.0022 sec^{-1} at a superficial gas velocity of 0.025 m sec^{-1} for a near-horizontal tubular photobioreactor. In an external-loop airlift tubular which was tested for outdoor cultures of *Phaeodactylum tricornutum*, k_La of 0.006 sec^{-1} was obtained at a superficial gas velocity of 0.25 m sec^{-1} (Fernandez *et al.*, 2001).

Figure 5 shows the outdoor biomass productivities of *C. sorokiniana* and *S. aquatilis* that were carried out at solar radiation between 8 and 10 MJ/m^2/day. In the tubular photobioreactor without static mixers, the biomass productivities for *S. aquatilis* and *C. sorokiniana* were 0.55 and 0.35 g/L/day, respectively. On the other hand, biomass productivities obtained with *S. aquatilis* and *C. sorokiniana* using the tubular photobioreactor with static mixers were 0.70 and 0.52 g/L/day, respectively. Higher productivity in *S. aquatilis* culture can be attributed to the fact that the strain grows very fast and has optimum growth at high temperatures above 40°C (Zhang *et al.*, 2002). This implies that high temperature which is common in summer will rather favor the growth of this strain. On the other hand, *C. sorokiniana* cannot withstand temperatures above 38°C and thus there is a need to sprinkle the tubes with cool tap water during the outdoor cultures. High dissolved oxygen concentration in narrow diameter tubular photobioreactors has been reported (Weissman *et al.*, 1988). In this study, 8 static mixers were efficient in reducing the dissolved oxygen concentration in the long tubular photobioreactor by 30%. By using tubular photobioreactor with static mixers, the increase in biomass productivities compared to the one without static mixers in *S. aquatilis* and *C. sorokiniana* cultures were 27 and 49%, respectively.

CONCLUSION

This study has apparently shown that gas-liquid transfer rate of a 20 m long tubular photobioreactor was improved upon installation of 8 static mixers on its riser section at a spacing

distance of 1 m apart from each other. Furthermore, when outdoor biomass cultures of *S. aquatilis* and *C. sorokiniana* were performed with the tubular photobioreactor at an aeration rate of 0.15 vvm, significant improvement in the biomass productivities was observed. In addition, the static mixers reduced the accumulated dissolved concentration in the culture by 30%.

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