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Review

Photobioreactors for mass cultivation of algae

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Abstract

Algae have attracted much interest for production of foods, bioactive compounds and also for their usefulness in cleaning the environment. In order to grow and tap the potentials of algae, efficient photobioreactors are required. Although a good number of photobioreactors have been proposed, only a few of them can be practically used for mass production of algae. One of the major factors that limits their practical application in algal mass cultures is mass transfer. Thus, a thorough understanding of mass transfer rates in photobioreactors is necessary for efficient operation of mass algal cultures. In this review article, various photobioreactors that are very promising for mass production of algae are discussed.

Keywords: Algae; Biomass; Mass transfer; Mixing; Photobioreactors

1. Introduction

Algae are grown either in open culture systems or closed systems (photobioreactors). Early attempts to grow algae in open ponds were conceived by Germans (Europe) during the world war II. At that time, algae were grown mainly as food supplements. As industrialization began, some groups of workers in Carnegie Institute at Washington implemented mass cultivation of algae for CO_2 abatement (Burlew, 1953). Between early 1970s and late 1970s, commercial production of algae was initiated in East Europe, Israel and Japan. During these periods, algae were grown commercially in open ponds as healthy food. In Africa, Lake Chad and Lake Texcoco were the major sources of *Spirulina* biomass for the people living in those areas. As a matter of fact, the purpose of growing algae depended on the specific needs of the people. In the United States, algal pond systems were developed for water treatment. The biomass recovered was converted to methane, which was a major source of energy (Burlew, 1953; Oswald and Golueke, 1960). As time went on, algal biomass became very important in the field of aquaculture (Muller-Feuga, 2000). Recently, algae have attracted much attention due to their potentials in the production of fine chemicals (Borowitzka, 1999; Lorenz and Cysewski, 2000) and as useful supplements in humans and animals (Dallaire et al., 2007). Algae have also found application in other areas such as in immobilization systems for production of some extracellular compounds (Chetsumon et al., 1994), and also for biosorption of heavy metals (Wilde and Benemann, 1993; Lodeiro et al., 2005; Karthikeyan et al., 2007). Some studies have also indicated the importance of algae in carbon dioxide fixation (Benemann, 1997; Sung et al., 1999; Chae et al., 2006). Given the advantages of closed systems over open ponds, a good number of them (ranging from laboratory to industrial scale) photobioreactors have been proposed. Closed photobioreactors have attracted much interest because they allow a better control of the cultivation conditions than open systems. With closed photobioreactors, higher biomass productivities are obtained and contamination can be easily prevented. It is anticipated that algal biotechnology would pave way to the development of Closed Ecological Life Support System (CELSS) (Lee and Palsson, 1995; Cogne et al., 2005). Despite that a good number of

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photobioreactors have been investigated, only very few of them can effectively utilize solar energy for mass production of algae. One of the major setbacks in mass production of algae is lack of efficient photobioreactors. To improve algal productivity, a thorough understanding of some aspects of hydrodynamic and mass transfer of photobioreactors is required.

Most outdoor photobioreactors are characterized by largely exposed illumination surfaces. From this point of view, flat-plate, horizontal and inclined tubular photobioreactors are promising except for the difficulty in scaling them up. Photobioreactors such as bubble-column, airlift, and stirred-tank have good scalability though their use in outdoor cultures is limited since they have low illumination surface areas. In this review article, some photobioreactor designs that are promising for mass cultivation of algae are critically examined. Furthermore, some aspects of hydrodynamics and mass transfer characteristics of these photobioreactors are briefly discussed.

2. Photobioreactors

Algal culture systems can be illuminated by artificial light, solar light or by both. Naturally illuminated algal culture systems with large illumination surface areas include open ponds (Hase et al., 2000), flat-plate (Hu et al., 1996), horizontal/serpentine tubular airlift (Camacho Rubio et al., 1999), and inclined tubular photobioreactors (Ugwu et al., 2002). Generally, laboratory-scale photobioreactors are artificially illuminated (either internally or externally) using fluorescent lamps or other light distributors. Some of these photobioreactors include bubble column (Degen et al., 2001; Ogbonna et al., 2002; Chini Zittelli et al., 2003), airlift column (Harker et al., 1996; Kaewpintong et al., 2007), stirred-tank (Ogbonna et al., 1999), helical tubular (Hall et al., 2003), conical (Watanabe and Saiki, 1997), torus (Pruvost et al., 2006), and seaweed-type (Chetsumon et al., 1998) photobioreactors.

Furthermore, some photobioreactors can be easily tempered. Tempering could simply be achieved by placing a photobioreactor in a constant temperature room. This approach is limited to compact photobioreactors. Large-scale outdoor systems such as tubular photobioreactors cannot be easily tempered without high technical efforts. However, several commercially available photobioreactors, for example, BIOSTAT photobioreactors (developed by Sartorius BBI Systems Inc.) can be readily tempered. Also, some efforts were undertaken to design temperature-controlled photobioreactors, such as double-walled internally-illuminated photobioreactor with a heating and cooling water circuit (Pohl et al., 1988).

2.1. Open ponds

Cultivation of algae in open ponds has been extensively studied in the past few years (Boussiba et al., 1988; Tredici and Materassi, 1992; Hase et al., 2000). Open ponds can be categorized into natural waters (lakes, lagoons, ponds) and artificial ponds or containers. The most commonly used systems include shallow big ponds, tanks, circular ponds and raceway ponds. One of the major advantages of open ponds is that they are easier to construct and operate than most closed systems. However, major limitations in open ponds include poor light utilization by the cells, evaporative losses, diffusion of CO_2 to the atmosphere, and requirement of large areas of land. Furthermore, contamination by predators and other fast growing heterotrophs have restricted the commercial production of algae in open culture systems to only those organisms that can grow under extreme conditions. Also, due to inefficient stirring mechanisms in open cultivation systems, their mass transfer rates are very poor resulting to low biomass productivity. Table 1 summarizes the advantages and limitations of open ponds.

Table 1
Prospects and limitations of various culture systems for algae

Culture systems	Prospects	Limitations
Open ponds	Relatively economical, easy to clean up after cultivation, good for mass cultivation of algae	Little control of culture conditions, difficulty in growing algal cultures for long periods, poor productivity, occupy large land mass, limited to few strains of algae, cultures are easily contaminated
Vertical-column photobioreactors	High mass transfer, good mixing with low shear stress, low energy consumption, high potentials for scalability, easy to sterilize, readily tempered, good for immobilization of algae, reduced photoinhibition and photo-oxidation	Small illumination surface area, their construction require sophisticated materials, shear stress to algal cultures, decrease of illumination surface area upon scale-up
Flat-plate photobioreactors	Large illumination surface area, suitable for outdoor cultures, good for immobilization of algae, good light path, good biomass productivities, relatively cheap, easy to clean up, readily tempered, low oxygen build-up	Scale-up require many compartments and support materials, difficulty in controlling culture temperature, some degree of wall growth, possibility of hydrodynamic stress to some algal strains
Tubular photobioreactors	Large illumination surface area, suitable for outdoor cultures, fairly good biomass productivities, relatively cheap	Gradients of pH, dissolved oxygen and CO_2 along the tubes, fouling, some degree of wall growth, requires large land space

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In order to overcome the problems with open ponds, much attention is now focused on development of suitable closed systems such as flat-plate, tubular, vertical-column and internally-illuminated photobioreactors.

2.2. Flat-plate photobioreactors

Flat-plate photobioreactors have received much attention for cultivation of photosynthetic microorganisms due to their large illumination surface area. The work presented by Milner (1953) paved way to the use of flat culture vessels for cultivation of algae. Following this work, Samson and Leduy (1985) developed a flat reactor equipped with fluorescence lamps. A year later, Ramos de Ortega and Roux (1986) developed an outdoor flat panel reactor by using thick transparent PVC materials. As time went on, extensive works on various designs of vertical alveolar panels and flat plate reactors for mass cultivation of different algae were reported (Tredici and Materassi, 1992; Hu et al., 1996; Zhang et al., 2002; Hoekema et al., 2002). Generally, flat-plate photobioreactors are made of transparent materials for maximum utilization of solar light energy. Accumulation of dissolved oxygen concentrations in flat-plate photobioreactors is relatively low compared to horizontal tubular photobioreactors. It has been reported that with flat-plate photobioreactors, high photosynthetic efficiencies can be achieved (Hu et al., 1996; Richmond, 2000). Flat-plate photobioreactors are very suitable for mass cultures of algae. However, they also have some limitations as indicated in Table 1.

2.3. Tubular photobioreactors

Among the proposed photobioreactors, tubular photobioreactor is one of the most suitable types for outdoor mass cultures. Most outdoor tubular photobioreactors are usually constructed with either glass or plastic tube and their cultures are re-circulated either with pump or preferably with airlift system. They can be in form of horizontal/serpentine (Chaumont et al., 1988; Molina et al., 2001), vertical (Pirt et al., 1983), near horizontal (Tredici and Chini Zittelli, 1998), conical (Watanabe and Saiki, 1997), inclined (Lee and Low, 1991; Ugwu et al., 2002) photobioreactor.

Aeration and mixing of the cultures in tubular photobioreactors are usually done by air-pump or airlift systems. Advantages and limitations of tubular photobioreactors are shown in Table 1. Tubular photobioreactor are very suitable for outdoor mass cultures of algae since they have large illumination surface area. On the other hand, one of the major limitations of tubular photobioreactor is poor mass transfer. It should be noted that mass transfer (oxygen build-up) becomes a problem when tubular photobioreactors are scaled up. For instance, some studies have shown that very high dissolved oxygen (DO) levels are easily reached in tubular photobioreactors (Torzillo et al., 1986; Richmond et al., 1993; Molina et al., 2001).

Also, photoinhibition is very common in outdoor tubular photobioreactors (Vonshak and Torzillo, 2004). When a tubular photobioreactor is scaled up by increasing the diameter of tubes, the illumination surface to volume ratio would decrease. On the other hand, the length of the tube can be kept as short as possible while a tubular photobioreactor is scaled up by increasing the diameter of the tubes. In this case, the cells at the lower part of the tube will not receive enough light for cell growth (due to light shading effect) unless there is a good mixing system. In any case, efficient light distribution to the cells can be achieved by improving the mixing system in the tubes (Ugwu et al., 2003, 2005a).

Also, it is difficult to control culture temperatures in most tubular photobioreactors. Although they can be equipped with thermostat to maintain the desired culture temperature, this could be very expensive and difficult to implement. It should also be noted that adherence of the cells of the walls of the tubes is common in tubular photobioreactors.

Furthermore, long tubular photobioreactors are characterized by gradients of oxygen and CO_2 transfer along the tubes (Camacho Rubio et al., 1999; Ugwu et al., 2003). The increase in pH of the cultures would also lead to frequent re-carbonation of the cultures, which would consequently increase the cost of algal production.

2.4. Vertical-column photobioreactors

Various designs and scales of vertical-column photobioreactors have been tested for cultivation of algae (Choi et al., 2003; Vega-Estrada et al., 2005; García-Malea López et al., 2006; Kaewpintong et al., 2007). Vertical-column photobioreactors are compact, low-cost, and easy to operate monoseptically (Sánchez Mirón et al., 2002). Furthermore, they are very promising for large-scale cultivation of algae. It was reported that bubble-column and airlift photobioreactors (up to 0.19 m in diameter) can attain a final biomass concentration and specific growth rate that are comparable to values typically reported for narrow tubular photobioreactors (Sánchez Mirón et al., 2002). Some bubble column photobioreactors are equipped with either draft tubes or constructed as split cylinders. In the case of draft tube photobioreactors, intermixing occurs between the riser and the downcomer zones of the photobioreactor through the walls of the draft tube. A summary of the prospects and limitations of vertical-column photobioreactors is shown in Table 1.

2.5. Internally-illuminated photobioreactors

As mentioned earlier, some photobioreactors can be internally illuminated with fluorescent lamps. Fig. 1 shows a typical internally-illuminated photobioreactor. The photobioreactor is equipped with impellers for agitation of the algal cultures. Air and CO_2 are supplied to the cultures through the spargers. This type of photobioreactor can also

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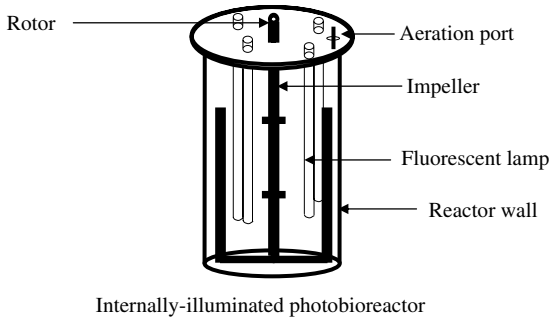

Fig. 1. Schematic diagram of an internally illuminated photobioreactor.

be modified in such a way that it can utilize both solar and artificial light system (Ogbonna et al., 1999). In that case, the artificial light source is switched on whenever the solar light intensity decreases below a set value (during cloudy weather or at night). There are also some reports on the use of optic fibers to collect and distribute solar light in cylindrical photobioreactors (Mori, 1985; Matsunaga et al., 1991). One of the major advantages of internally-illuminated photobioreactor is that it can be heat-sterilized under pressure and thus, contamination can be minimized. Furthermore, supply of light to the photobioreactor can be maintained continuously (both day and night) by integrating artificial and solar light devices. However, outdoor mass cultivation of algae in this type of photobioreactor would require some technical efforts.

3. Hydrodynamics and mass transfer characteristics of photobioreactors

Although relationship between hydrodynamics and mass transfer has been extensively investigated and correlated in bioreactors for heterotrophic cultures, only a few studies on these aspects are available in phototrophic cultures. Hydrodynamics and mass transfer characteristics that are applicable in photobioreactors include; the overall mass transfer coefficient (k_La), mixing, liquid velocity, gas bubble velocity and gas holdup.

The overall mass transfer coefficient (k_La) is the most commonly used parameters for assessing the performance of photobioreactors. The term k_La is generally used to describe the overall volumetric mass transfer coefficient in photobioreactors. The volumetric mass transfer coefficient (k_La) of photobioreactors is dependent on various factors such as agitation rate, the type of sparger, surfactants/antifoam agents and temperature.

Mixing time can be defined as the time taken to achieve a homogenous mixture after injection of tracer solution. Lee and Bazin (1990) defines mixing time as the time taken for a small volume of dye solution added to the liquid to transverse the reactor. Generally, mixing time is determined in photobioreactors using tracer substances such as dyes. However, mixing time can also be measured by signal-response method using tracer and pH electrode (Camacho Rubio et al., 1999; Ugwu et al., 2003; Pruvost et al., 2006). Furthermore, computational fluid dynamics (CFD) was used to evaluate global mixing in torus photobioreactor (Pruvost et al., 2006; Sato et al., 2006).

Mixing time is a very important parameter in designing photobioreactors for various biological processes. Good mixing would ensure high cell concentration, keep algal cells in suspension, eliminate thermal stratification, help nutrient distribution, improve gas exchange as well as reduce the degree of mutual shading and lower the probability of photoinhibition (Janvanmardian and Palsson, 1991). It was also reported that when the nutritional requirements are sufficient and the environmental conditions are optimized, mixing aimed at inducing turbulent flow would result in high yield of algal biomass (Hu et al., 1996). Bosca et al. (1991) demonstrated that the productivity of alga is higher in mixed culture than in an unmixed one under the same condition. Various mixing systems are currently used in algal cultures depending on the type of photobioreactors. In open pond systems, paddle wheels were used to induce turbulent flow (Boussiba et al., 1988; Hase et al., 2000). In stirred-tank photobioreactors, impellers were used in mixing algal cultures (Ogbonna et al., 1999; Mazzuca Sobczuk et al., 2006). In tubular photobioreactors, mixing can be done by bubbling air directly or indirectly via airlift systems (Ogbonna and Tanaka, 2001; Tredici and Chini Zittelli, 1998) or by installing static mixers inside the tubes (Ugwu et al., 2002). Mixing systems that utilized baffles in bubble-column photobioreactors were also demonstrated in algal cultures (Merchuk et al., 2000; Degen et al., 2001).

In bubble-column and large diameter tubular photobioreactors, demarcation exists between the light-illuminated and dark surfaces. Thus mixing strategies should be introduced in cultures to circulate algal cells between the light-illuminated and dark regions of the photobioreactors (Molina Grima et al., 1999; Ugwu et al., 2005b; Mazzuca Sobczuk et al., 2006).

Increase in aeration rate would improve mixing, liquid circulation, and mass transfer between gas and liquid phases in algal cultures. However, high aeration could cause shear stress to algal cells (Mazzuca Sobczuk et al., 2006; Kaewpintong et al., 2007). Gas bubble velocity is a measure of culture flow rates in tubular photobioreactors (plug flow regime) since algal cultures are circulated along with gas bubbles. When fine spargers are used to increase gas dispersion inside horizontal tubular photobioreactors, relatively large bubbles are produced. However, the bubbles coalesce during flow to form interface between the liquid broth, gas and the walls of the tube. The contact area between the liquid and the gas is reduced, thereby, resulting to poor mass transfer rates.

Gas bubble velocity and size of the bubbles are dependent on the liquid flow rate. By increasing the gas flow rate, the bubble diameter increases, which consequently, would increase the gas bubble velocity. The rate of gas circulation may be interrupted when baffles or static mixers are installed inside the reactors to increase gas dispersion.

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However, the mixer elements would help to break down the large bubbles into fine ones thereby, improving the mass transfer rates. Some studies have indicated that relationship exists between superficial gas velocity, bubble velocity and the overall mass transfer coefficient in bioreactors (Lu et al., 1995; Wongsuchoto et al., 2003; Couvert et al., 2004). In some photobioreactors, the relationship between superficial gas velocity and the overall mass transfer coefficient (k_La) studied in various algal cultures can be evaluated (Table 2). In concentric tube airlift photobioreactor (which was used for *Phaeodactylum tricornutum* cultures), it was reported that at superficial gas velocity of 0.055 m s^{-1}, the k_La of about 0.02 s^{-1} was obtained (Contreras et al., 1998). This k_La value was about the same as the one reported by Ogbonna et al. (1998) (with 3-L internally-illuminated photobioreactor) for *Chlorella pyrenoidosa* cultures at superficial gas velocity of 0.009 m s^{-1}. In 6-L inclined tubular which was used for cultivation of *Chlorella sorokiniana*, the k_La of about 0.003 s^{-1} (at superficial gas velocity of 0.02 m s^{-1}) was obtained (Ugwu et al., 2002). Merchuk et al. (2000) reported that by varying the superficial gas velocity ($5.4–82 \times 10^{-4}$) in 13-L bubble-column photobioreactor (which was tested for cultivation of *Porphyridium* sp.), the k_La obtained was in range of 1.7 and 4.7×10^{-3} s^{-1}. With 3-L flat plate photobioreactor (which was used for cultivation of *Synechocystis aquatilis* cultures), the k_La obtained was 0.002 s^{-1} at superficial gas velocity of 0.009 m s^{-1} (Zhang et al., 2002). At superficial gas velocity of 0.024 m s^{-1}, the k_La reported in 2-L split-cylinder internal-loop airlift photobioreactors (which was used for cultivation of *Haematococcus pluvialis* cultures) was 0.009 s^{-1}(Vega-Estrada et al., 2005). By using 200-L airlift tubular horizontal photobioreactors (at superficial gas velocity of 0.16 m s^{-1}), the k_La reported was about 0.014 s^{-1} (Camacho Rubio et al., 1999). In the case of 200-L external-loop airlift tubular, which was tested for outdoor cultures of *Phaeodactylum tricornutum*, k_La of 0.006 s^{-1} was obtained at superficial gas velocity of 0.25 m s^{-1} (Acién Fernández et al., 2001). It should be noted that comparison of the k_La based on only superficial gas velocity could be misleading considering the differences in photobioreactor scales (volume), geometry, algal strains and cultures as well as the methods used for such studies.

Furthermore, liquid velocity is a measure of liquid flow and degree of turbulence in photobioreactors. Some degree of turbulence is required in photobioreactors to ensure that all the cells are frequently exposed to light (Carlozzi, 2003; Pruvost et al., 2006).

Also, solid velocity would give an indication of how algal cells can be uniformly transported along the tube length as the cultures are aerated. Solid velocity is also a very important parameter for the determination of hydrodynamics and mass transfer characteristics of bioreactors. Couvert et al. (2004) reported that the nature (i.e., shape, size, and porosity) and quantity of solids have an influence on the mass transfer of bioreactors. In intense algal cultures, cells can aggregate to form some clumps inside photobioreactors. In narrow bore tubes, these clumps may settle such that they cannot be re-circulated uniformly along the tubes.

Another important aspect of hydrodynamics which has been used in characterizing photobioreactor design is gas holdup. Gas holdup is described as the fraction of the reactor volume taken by the gas. This can be estimated as the volume of the liquid displaced by the gas (expansion of liquid volume) due to aeration. Gas holdup is very important in photobioreactor design as it determines the circulation rate, the gas residence time, as well as the overall mass transfer rate (k_La). Some studies have demonstrated that relationship exist between gas holdup, bubble size, gas–liquid interfacial surface area and the overall mass transfer coefficient, k_La (Chisti, 1998; Vandu et al., 2005).

4. Mass cultivation of algae

A good number of photobioreactors can be used in production of various algal products. Apparently, while many photobioreactors are easily operated at laboratory scale, only few of them can be successfully scaled up to pilot scale. Scale-up of photobioreactors can be done by increasing the length, diameter, height or the number of compartments of the culture systems (depending on the type of photobioreactor). These scale-up strategies are very challenging, mainly

Table 2
Relationship between the superficial velocities and overall mass transfer coefficient (k_La) in various cultures systems

Photobioreactor	Volume (L)	Superficial velocity (m s^{-1})	k_La (s^{-1})	Strain	References
Concentric tube airlift	12	0.055	0.020	*Phaeodactylum tricornutum*	Contreras et al. (1998)
Internally-illuminated	3	0.009	0.020	*Chlorella pyrenoidosa*	Ogbonna et al. (1998)
Airlift tubular horizontal	200	0.160	0.014	*Porphyridium cruentum*	Camacho Rubio et al. (1999)
Bubble-column	13	$5.4–82 \times 10^{-4}$	$1.7–4.7 \times 10^{-3}$	*Porphyridium* sp.	Merchuk et al. (2000)
External-loop airlift tubular	200	0.250	0.006	*Phaeodactylum tricornutum*	Acién Fernández et al. (2001)
Inclined tubular	6	0.020	0.003	*Chlorella sorokiniana*	Ugwu et al. (2002)
Flat-plate	3	0.009	0.002	*Synechocystis aquatilis*	Zhang et al. (2002)
Split-cylinder internal-loop airlift	2	0.024	0.009	*Haematococcus pluvialis*	Vega-Estrada et al. (2005)

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Table 3
Productivity of algal strains reported in some outdoor photobioreactors

Photobioreactors	Volume (L)	Photosynthetic strain	Productivity ($g\ L^{-1}\ d^{-1}$)	Reference
Airlift tubular	200	*Porphyridium cruentum*	1.50	Camacho Rubio et al. (1999)
Airlift tubular	200	*Phaeodactylum tricornutum*	1.20	Acién Fernández et al. (2001)
Airlift tubular	200	*Phaeodactylum tricornutum*	1.90	Molina et al. (2001)
Inclined tubular	6.0	*Chlorella sorokiniana*	1.47	Ugwu et al. (2002)
Undular row tubular	11	*Arthrospira platensis*	2.70	Carlozzi (2003)
Outdoor helical tubular	75	*Phaeodactylum tricornutum*	1.40	Hall et al. (2003)
Parallel tubular (AGM)	25,000	*Haematococcus pluvialis*	0.05	Olaizola (2000)
Bubble-column	55	*Haematococcus pluvialis*	0.06	García-Malea López et al. (2006)
Flat plate	440	*Nannochloropsis* sp.	0.27	Cheng-Wu et al. (2001)

due to difficulty in maintaining optimum light, temperature, mixing, and mass transfer in photobioreactors.

Nevertheless, few large-scale photobioreactors with relatively good biomass productivities have been developed. Table 3 shows the algal biomass productivities reported with different types and scales of outdoor photobioreactors. In 200-L airlift tubular photobioreactor (which was used for outdoor cultivation of *Phaeodactylum tricornutum*), biomass productivity of 1.20–1.50 $g\ L^{-1}\ d^{-1}$ was obtained (Camacho Rubio et al., 1999; Acién Fernández et al., 2001). Furthermore, with 200-L airlift-driven-tubular photobioreactor tested for outdoor cultivation of *Phaeodactylum tricornutum*, biomass productivity of 1.90 $g\ L^{-1}\ d^{-1}$ was attained (Molina et al., 2001). In 11-L undular row tubular photobioreactor (for *Arthrospira platensis*), the productivity reported was about 2.7 $g\ L^{-1}\ d^{-1}$ (Carlozzi, 2003). Furthermore, about 0.27 $g\ L^{-1}\ d^{-1}$ was obtained in 440-L outdoor flat-plate photobioreactor, which was used for cultivation of *Nannochlorospis* (Cheng-Wu et al., 2001). In 55-L bubble column photobioreactor (for outdoor cultivation of *Haematococcus pluvialis*), the biomass productivity obtained was 0.06 $g\ L^{-1}\ d^{-1}$ (García-Malea López et al., 2006). Also, in 25,000-L outdoor photobioreactor (developed for commercial production of astaxanthin from *Haematococcus pluvialis*), about 0.05 $g\ L^{-1}\ d^{-1}$ was obtained (Olaizola, 2000). It should be noted that aside from volumetric productivity (productivity per unit of reactor volume per unit of time) algal biomass productivity can be evaluated in photobioreactors based on areal productivity (productivity per unit of occupied-land area per unit of time), photosynthetic efficiency or biomass yield (g-biomass per unit of solar radiation).

5. Conclusion and perspectives

Despite that a great deal of work has been done to develop photobioreactors for algal cultures, more efforts are still required to improve photobioreactor technologies and know-how of algal cultures. Photobioreactor development is perhaps, one of the major steps that should be undertaken for efficient mass cultivation of algae. The major issue in the design of efficient photobioreactors should be their capacity to maximize the outdoor solar radiation. Large-scale outdoor photobioreactors should have large volume and occupy less land space. In addition, they should have transparent surfaces, high illumination surfaces, high mass transfer rates and should as well, be able to give high biomass yields. Furthermore, design and construction of any photobioreactor should depend on the type of strain, the target product, geographical location, as well as the overall cost of production.

It should be noted that for mass cultivation of algae, vast areas of land are required. This is actually a very serious setback of algal cultivation in many developed countries. Thus, the increasing population and consequently, the exorbitant cost of land have attracted the attention of many scientists to look for alternative cultivation sites. In order to reduce the cost of producing algal biomass and products, intensive efforts should be made to increase the algal biomass productivity. Also, high-value metabolites should be produced to compromise the technical costs involved in algal production.

Given that outdoor photobioreactors are usually naturally illuminated using solar light, biomass productivities (in such systems) would depend on the prevailing weather conditions in a particular locality. Although commercial cultivation of algae is done in developed countries, there are seasonal variations in temperatures and solar light energy throughout the year in most of these regions. Due to these problems, it is difficult to carry out outdoor mass cultivation of algae all year round in such regions. However, in most tropical developing countries, outdoor cultures of algae can be maintained for relatively long period of time in a year because there is neither winter nor cold seasons in those regions. Thus, tropical developing countries might be potential cultivation sites for commercial production of algal products.

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