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ORIGINAL PAPER

A mini review: photobioreactors for large scale algal cultivation

Prabuddha L. Gupta[1] · Seung-Mok Lee[1] · Hee-Jeong Choi[1]

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Abstract Microalgae cultivation has gained much interest in terms of the production of foods, biofuels, and bioactive compounds and offers a great potential option for cleaning the environment through CO_2 sequestration and wastewater treatment. Although open pond cultivation is most affordable option, there tends to be insufficient control on growth conditions and the risk of contamination. In contrast, while providing minimal risk of contamination, closed photobioreactors offer better control on culture conditions, such as: CO_2 supply, water supply, optimal temperatures, efficient exposure to light, culture density, pH levels, and mixing rates. For a large scale production of biomass, efficient photobioreactors are required. This review paper describes general design considerations pertaining to photobioreactor systems, in order to cultivate microalgae for biomass production. It also discusses the current challenges in designing of photobioreactors for the production of low-cost biomass.

Keywords Photobioreactors · Biomass · Biofuels · Mass cultivation · Algal biotechnology

Introduction

Algae have been estimated to include from 30,000 to more than 1 million species (Guiry 2012). Although algae primarily occurs in freshwater and marine environments, but some of them occupy diverse habitats like soils, rocks, glaciers, caves and even buildings. Algae represent a significant group of organisms for biotechnological exploitation. In the last decade, commercial applications of microalgae have been used for a wide array of functions including pharmaceutical, health sector, nutraceutical, cosmetics, and agriculture (bio-fertilizers). A diverse range of metabolites with various bioactive properties are produced from algae that are yet to be fully exploited. The key substances biosynthesized by algae includes: fatty acids, polysaccharides, polypeptides, pigments, vitamins, and minerals (Cardozo et al. 2007). Blue-green algae are used as biofertilizers in rice fields, and to fix atmospheric nitrogen. Algae are used in pisciculture, as a food for fishes. Cultivation of *Spirulina*, is gaining importance as feed for fish, poultry and cattle. Microalgal biomass is also widely used for energy generation, as biodiesel, bioethanol, bio-hydrogen, and photosynthetic microbial fuel cell (ElMekawy et al. 2014). Biomass generation of microalgae also have potential benefits in cleaning the environment, owing to their CO_2 sequestration capability (Singh et al. 2012). It is estimated that 1 kg of dry algal biomass utilizes about 1.83 kg of CO_2 (Chisti 2007). Nutrients for microalgae cultivation can be obtained from wastewater (nitrogen and phosphates); therefore, apart from providing growth medium, there is a dual benefit in the treatment of organic effluent (Cantrell et al. 2008). Moreover, microalgae have potential to remove metal ions from polluted waters, and can achieve greater performance at lower cost than conventional wastewater treatment technologies (Sekabira et al. 2010; Torres et al. 2014).

The current worldwide production of microalgal biomass is about 9000 ton/year and the production cost is still high \$20–\$200/kg (Brennan and Owende 2010). The cultivation technologies currently employed for the large scale

✉ Hee-Jeong Choi
hjchoi@cku.ac.kr

[1] Department of Energy and Environment Convergence, Catholic Kwandong University, Gangneung 210701, South Korea

production of microalgae biomass use open ponds. Although open ponds are cheap and easier to build and operate than photobioreactors (PBRs), there is always the risk of contamination. Moreover, since open ponds have problems such as low gas–liquid mass transfer rate, water evaporation, low mixing rate, and poor temperature control (Chisti 2007; Ugwu et al. 2008), open pond cultivation is not suitable for the production of pharmaceutical or food ingredients (Chisti 2007).

In order to overcome the inherent disadvantages of using open cultivation, numerous closed PBRs of various volumes and shapes have been designed. The principle final goal of any PBR is a reduction in biomass production costs. This can be done by improving the design and shape of the PBR, controlling environmental parameters, and favoring minimal contamination risk. Overcoming these limitations makes monocultures and the production of pharmaceutical and food goods possible.

Although PBRs are widely used and have several advantages, still there are some major drawbacks that make them uneconomical for low-cost end-products. At higher operational volumes above 100 L, there is limited diffusion of light, which results in the inefficient growth of microalgae. A major concern is the development of microalgal biofilm on PBR surface, thus limiting light penetration. In addition, the initial investment, operational and maintenance cost of PBR is high, which eventually increases the biomass production cost (Acién et al. 2012). Hence, there is a need to overcome these challenges and develop feasible PBRs for the generation of low cost microalgal biomass. In this review, some PBR designs that are promising for mass cultivation are examined, and the current challenges in the designing of PBRs are discussed.

Microalgal cultivation systems

The idea of cultivating algae in large quantity was conceived in 1952, at the Carnegie Institute of Washington. In 1960s, the Japanese experimented with outdoor culture in an 'open circulation system', by using shallow open pond in which the algal suspension was circulated via a series of moving pipes equipped with jets for the injection of fresh culture fluid. Later on, the Japan Nutrition Association developed a 20 m diameter pilot plant to investigate the industrial cultivation of algae further. In late 1970s commercial production started in Japan, Europe, and Israel; during this period algae cultures were commercially grown as healthy foods. As time went on, algal biomass production became important in the aquaculture, as well as the production of fine chemicals and health supplements. Also, algae culturing techniques became more sophisticated and, with advent of technology, the use of PBRs becomes more common. Currently, there are two widely practice cultivation systems—open pond and closed PBRs—both of which are briefly discussed here.

Open ponds

Open pond cultivation offers a simple and cost effective approach. The idea of the open pond was derived from use of artificial lagoons and oxidation ponds in wastewater treatment (Sharma et al. 2013). Most open pond growing units are based on the race-way pond design first proposed by Oswald (1969). The most commonly used open systems include large shallow ponds, tanks, circular ponds and raceway ponds. A raceway pond is most often a rectangular canal with algal culture current flowing from a supply end to an exit end (Chisti 2007). The length to width ratio is an important parameter in designing a raceway pond. Larger width may result in weak current speed, which is not desirable for mixing and mass transfer. The length and depth is determined by the light penetration and the amount of culture volume a unit can hold. Each pond contains a paddle wheel to make the water flow continuously around the circuit.

One of the major advantages of open ponds is that they are easier to construct and operate than most closed systems. However, major constraints include poor light utilization by the cells, water loss due to evaporation, diffusion of CO_2 to the atmosphere, and large space requirements (Chisti 2007). Moreover, contamination due to microbes and other fast growing heterotrophs may result in impure culture growth, and limit the production of the algae. In addition, inefficient stirring may cause poor mass transfer and result in lower biomass productivity. The recent improvement in open culture system technology includes improvement of mixing systems to avoid sedimentation and to augment light utilization efficiency. The major advantages and limitations of open ponds and various closed PBRs are outlined in Table 1.

Closed systems

Closed systems are designed to overcome the problems associated with open pond cultivation systems (Chisti 2007). A PBR is defined as a closed (or mostly closed) vessel for phototrophic production, where energy is supplied via electric lights (Andersen 2005). A PBR design should use light efficiently; illumination should be uniform, reduce mutual shading and should provide a fast mass transfer of CO_2 and O_2. A typical PBR is comprised of a four-phase system: solid phase (microalgal cells), liquid phase (growth medium), gaseous phase (CO_2 and O_2) and superimposed light-radiation field (Posten 2009). Hence, in order to design an efficient PBR, an understanding of the

Table 1 The major advantages and limitations of microalgal cultivation system

Cultivation system	S/V ratio	Mixing	Temperature control	Gas exchange	Advantages	Limitations
Open ponds[a]	High	Paddle wheel	None	Poor, only achieved through surface aeration	Cost effective Simple and flexible design Beneficial for mass cultivation	Lower biomass productivity Less control over culturing conditions, Susceptible to contamination, Occupy large land space, lower mass transfer Water and CO_2 loss due to evaporation
Stirred tank PBR[b]	Low	Mechanical agitator	Heat exchanger	Injection through sparger	Good heat and mass transfer Good light dispersion Lower contamination issues Simple design Moderate biomass productivity	Low surface to volume ratio Heating issue due to agitation Mechanical agitation require extra energy, expensive, not scalable
Vertical column PBR[b,d]	Low	Airlift/bubble	–	Open gas exchange at head space	High mass transfer No internal structure Lack of moving parts Good mixing with low shear stress Lower photo inhibition	Low surface area for illumination Expensive construction material Limited scale up due to design constrains, shading effect issues
Horizontal tubular PBR[b,d]	High	Recirculation via pumps	Shading, overlapping, water spraying	Injection into feed, dedicated degassing unit	High surface to volume ratio Low hydrodynamic stress Suitable for outdoor cultivation, good biomass productivity, cost effective Low mutual shading effect	Dissolve Oxygen build up Susceptible to photo inhibition Fouling due to algal growth Large space requirement Poor temperature regulation
Flat panel PBR[b,c,d]	High	Airlift/bubble from bottoms or side	Heat exchange coils	Open gas exchange at head space	High surface to volume ratio Low space requirement High photosynthetic efficiency, cheap and economic, low oxygen buildup	Short light penetration depth Not scalable, requires many components, frequent fouling and clean up issues, poor temperature regulation

[a] Chisti (2007), [b] Doran (2013), [c] Ugwu et al. (2008), [d] Posten (2009)

complex interaction between biomass production and associated environmental parameters (e.g., fluid dynamics and light transfer) within the reactor is required. Based on the illuminated surface, PBRs are categorized as flat plate (Sierra et al. 2008; Slegers et al. 2011), tubular (Molina et al. 2001), and column (Eriksen 2008). Bases on their mode of liquid flow, PBRs can be grouped as stirred type, bubble column and airlift reactor. Ideal PBRs should have high transparent surface, minimal non illuminated part, high mass transfer rates and should attain high biomass growth. Moreover, PBR design should be suitable for cultivation various microalgal species universally and prevent fouling of the reactor. Various types of PBRs are discussed in following section.

Stirred tank PBRs

Stirred tanks are the conventional aerated bioreactor. The mixing is achieved by mechanical agitation (Fig. 1). The core component of the stirred tank bioreactor is the agitator or impeller, which performs a wide range of functions, including: heat and mass transfer, aeration, and mixing for homogenization (Doran 2013). This requires a relatively high input of energy per unit volume. Sometimes baffles

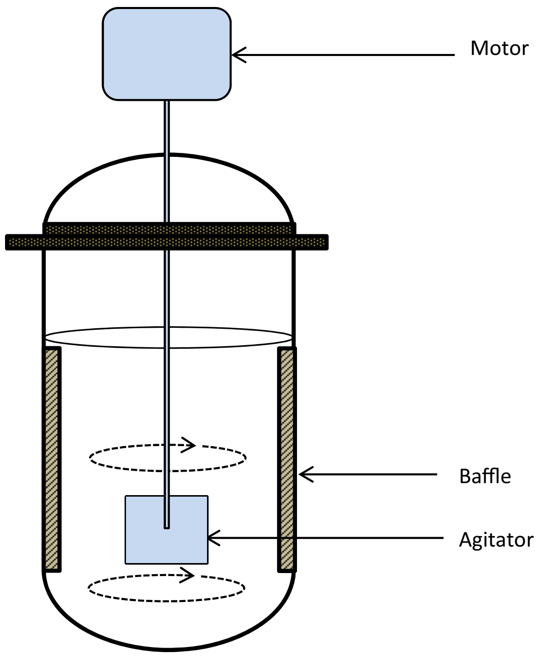


Fig. 1 Schematics of a stirred tank photobioreactor

are used in stirred reactors to reduce vortexing. Typically, only 70–80 % of the volume of stirred reactors is filled with liquid. This allows adequate headspace for disengagement of liquid droplets from the exhaust gas and to accommodate any foam that may develop. In order to prevent foaming, supplementary impellers called foam breakers are installed. CO_2 enriched air is bubbled at the bottom to provide a carbon source for the growth of algae. Stirred tanks PBRs have very effective stirring mechanism; hence, mass transfer rates and light dispersion are very high. This leads to a lower incidence of dark zones inside the reactor and higher biomass productivity. However, the main disadvantage of this system is low surface area to volume ratio, which in turn decreases light harvesting efficiency (Franco-Lara et al. 2006). Moreover, mechanical agitation generates much more heat than the sparging of compressed gas; hence, stirred PBRs are expensive to operate and maintain. Enhancements in stirred-type PBRs can be achieved by developing new oxygenation devices in order to reduce shear, exploiting different protective agents, modifying existing impellers and designing new types of agitators.

Vertical tubular PBRs

Vertical tubular PBRs are most suitable for outdoor mass cultivation, owing to their large surface area. These PBRs are made up of transparent vertical tubes that allow the penetration of light. The cultures are circulated either with air pump or by airlift system. Vertical tubular PBRs can be further grouped into bubble column and airlift reactors, based on their mode of liquid flow.

Bubble column PBRs

Bubble column PBRs are an alternative to stirred reactor, in which the agitation and mixing is achieved by gas sparging. Bubble column reactors are extensively used commercially for production of baker's yeast, beer, vinegar and the treatment of wastewater. The design is simple, with a height greater than twice the diameter (Fig. 2). Other than the sparger, there are no other internal structures, although sometimes perforated horizontal plates are used to break up and redistribute the coalesced bubbles produced from sparger. The column hydrodynamics and mass transfer characteristics depend entirely on the behavior of bubbles released from sparger. Homogeneous flow occurs only at low gas flow rates, when bubbles are evenly distributed across the column cross-section and there is little or no back mixing of the gas phase. While in a heterogeneous flow, bubbles and liquid tend to rise up the center of the column while a corresponding down flow of liquid occurs near the walls. This liquid circulation entrains bubbles, so that some back mixing of gas occurs (Doran 2013). Since light is provided externally in bubble PBRs, the photosynthetic efficiency greatly depends on gas flow rate which depends on the light and dark cycle (flashing light effect) as the liquid is circulated regularly from the central dark zone to external photic zone at a higher gas flow rate (Barbosa

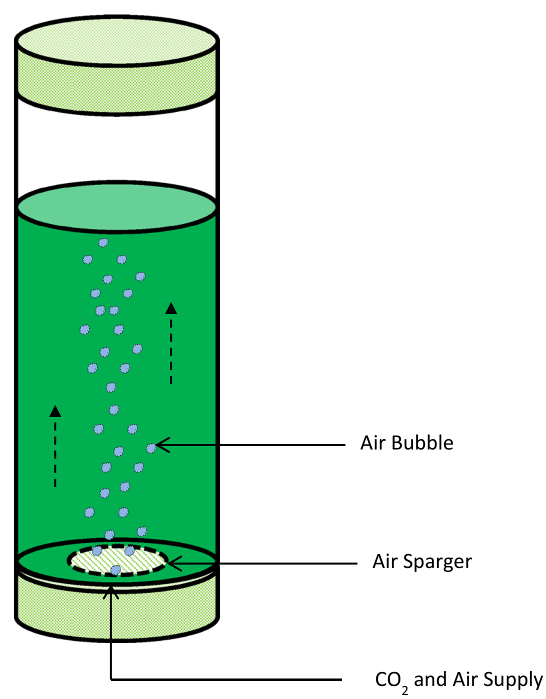


Fig. 2 Schematics of a bubble column photobioreactor

et al. 2003). Bubble column PBRs have many advantages, including low capital cost, high surface area to volume ratio, lack of moving parts, satisfactory heat and mass transfer, relatively homogenous culture environment, and the efficient release of O_2 and residual gas mixtures.

Airlift PBRs

Airlift PBRs differ from the bubble column PBRs due to the physical separation of the two interconnecting zones the riser (up flowing) and the down comer (down flowing) streams (Fig. 3). Gas is sparged through the riser, resulting in gas holdup, thereby decreasing fluid density and eventually causing liquid in the riser to move upward. As gas bubbles disengage from the liquid at the top of the vessel, heavier bubble-free liquid is left to recirculate through the down comer. Thus, liquid circulation in airlift reactors results from the density difference between the riser and down comer (Doran 2013). Airlift reactors have the characteristic advantage of creating a circular mixing pattern in which the liquid culture passes continuously through dark and light phases giving a flashing light effect to algal cells (Barbosa et al. 2003). The most common airlift configurations are: internal loop, internal loop concentric and external loop vessels. In internal loop vessels (Fig. 3a), the riser and down comer are separated by an internal baffle. In case of the internal loop concentric type (Fig. 3b), the air is sparged into the concentric tube. This causes the culture to circulate from the riser tube (dark zone) to the down comer (illuminated zone), thereby exposing culture to light and dark zones (flashing effect). While in external loop vessels (Fig. 3c), separate vertical tubes are connected by short horizontal sections at the top and bottom. Since the riser and down comer are further apart, gas disengagement is more effective. Accordingly, mixing is usually better in external loop than in internal loop reactors (Doran 2013).

Horizontal tubular PBRs

Horizontal tubular PBRs are the most popular closed systems. Horizontal tubular PBRs differ from the vertical bubble column in many ways, particularly with respect to the surface to volume ratio, the amount of gas in dispersion, the gas–liquid mass transfer characteristics, the nature of the fluid movement and the internal irradiance levels (Sánchez Mirón et al. 1999). Horizontal tubular PBRs (Fig. 4) are basically constituted of tubes arranged in multiple possible orientations, such as horizontal, inclined, spiral, helicoidal and their variations, but all orientations basically work in same way. Aside from the arrangement of tubes, tubular PBRs differ in the tube length, flow velocity, circulation system, and geometric configuration of the light receiver. Mostly, these tubes have diameters of 10 mm to maximum 60 mm, and lengths of up to several hundred meters. The use of such tubes helps in achieving high surface to volume ratio (above 100/m), which is one of the main advantages of this design (Posten 2009). Increasing the tube diameter results in a decrease in the surface/volume ratio, and this factor has a strong impact on the culture growth. Moreover, the so called "lens" or "focusing effect" helps to distribute the light homogenously. In the "focusing effect" the incident light is diluted along the circumference and is, in a radial direction, focused onto the axis of the tube, thus resulting in preventing mutual shading and increasing of radiation intensity (Posten 2009). One of the major disadvantages of horizontal PBRs includes the accumulation of O_2 to inhibitory levels (Sánchez Mirón et al. 1999), since O_2 concentrations above air

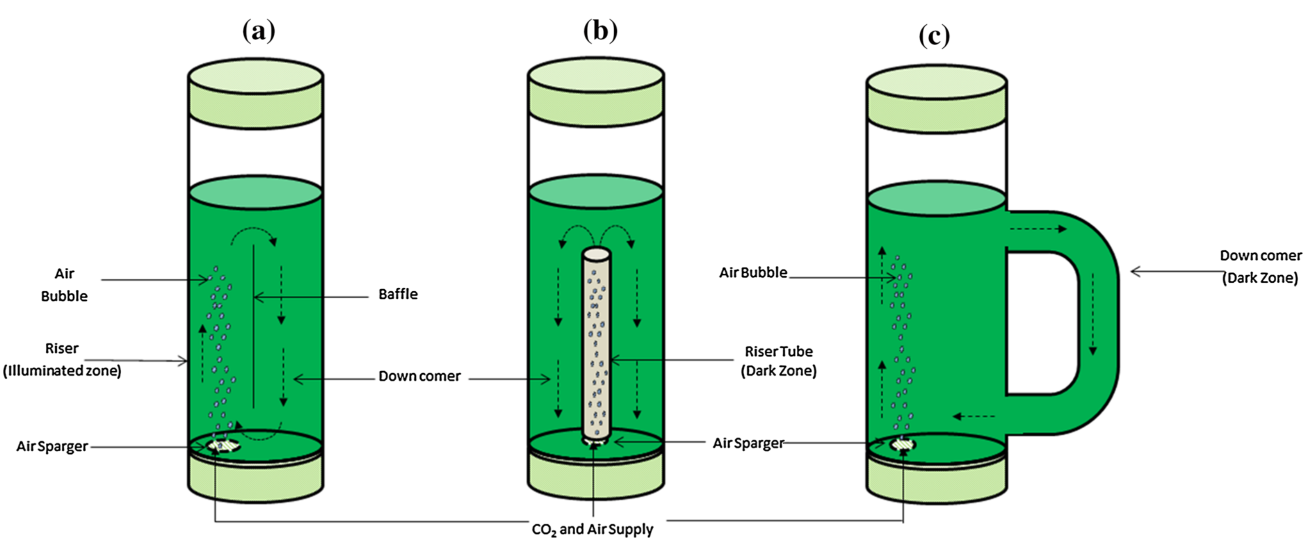
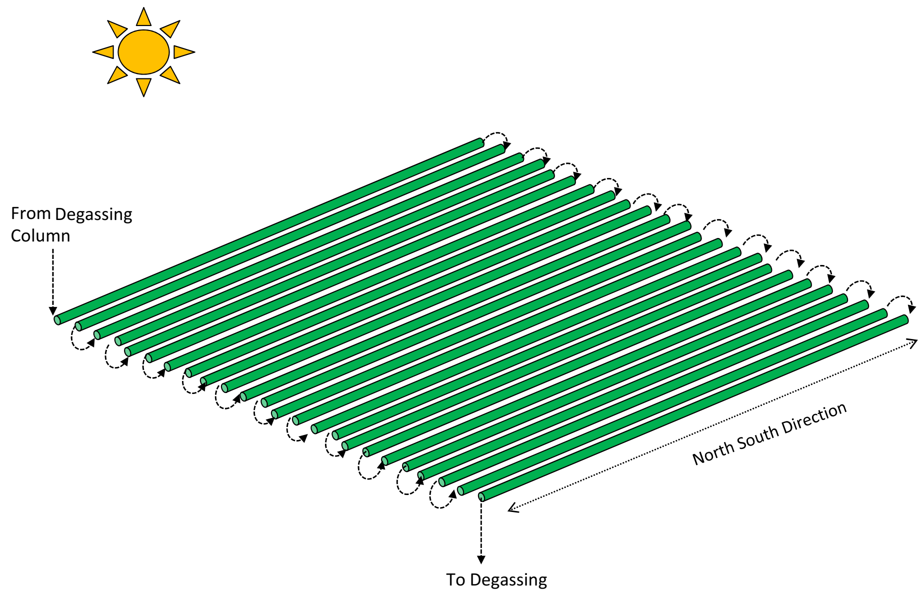


Fig. 3 Schematics of an airlift photobioreactor **a** internal loop, **b** internal loop concentric, **c** external loop

Fig. 4 Schematics of horizontal tubular photobioreactor



saturation generally inhibit photosynthesis in microalgae. Although horizontal tubular PBRs are generally believed to be the most practicable and scalable culture system but according to Sánchez Mirón et al. (1999) horizontal tubular PBRs are not economical feasible for large scale production due to requirement of cooling as they have high surface to volume ratio. Moreover, photo inhibition due the accumulation of O_2 and high light intensity results in lower productivity rates as compared to bubble column and airlift bioreactors.

Flat panel PBRs

Flat panel PBRs use simple geometry and greatly reduce the light penetration depth through the culture surface. Various researchers (Tredici and Zittelli 1998; Hu et al. 1998; Slegers et al. 2011) have used flat plate reactors for mass cultivation of various algae. Flat panel PBRs consist of a frame covered by a transparent plate on both sides (Fig. 5). A pump is used to circulate the algal cell suspension. The main characteristic of the flat panel PBRs are high surface to volume ratio, the vertical or tilted inclination from the horizontal of the channels, and absence of mechanical devices for cell suspension. Moreover the movement, gas exchange and degassing of the culture is performed by bubbling air from the base of each channel. Typical 16 mm thick plexi-glass alveolar plates are used in the construction of flat panel PBRs, owing to their high surface to volume ratio (Yang 2011). It has been reported that with flat-plate PBRs, high photosynthetic efficiencies can be achieved, due to the large illumination surface area (Hu et al. 1998). The accumulation of dissolved O_2 concentrations in flat-plate PBRs is relatively low compared to horizontal tubular PBRs. However, these systems typically give lower areal yields compared to tubular PBRs. The lower performance achieved by cultures in flat-panel PBRs has been attributed to the fact that these systems, unlike tubular PBRs, have very short light penetration depths and do not offer light dilution (unless they are placed at a high inclination with the horizontal), thus leading to photo-inhibition of microalgal growth (Tredici and Zittelli 1998). Although high biomass concentrations (up to 80 g/L) can be reached in narrow light path flat panels (Hu et al. 1998), there are some limitations. Flat panel PBRs may be used profitably for research or in small production, but are not suitable for commercial-scale settings, due to their requirement of many compartments and support materials, the difficulty in controlling culture temperature and problems associated due to hydrodynamic stress resulting from aeration, a problem that has never been reported in tubular reactors (Ugwu et al. 2008). Moreover, there are multiple issues such as biofouling on surface; high stress damage associated with aeration; sterilization issues; and incompatibility with off the shelf industrial fermentation equipment (Sierra et al. 2008).

PBR design consideration and improvements

Data collection and modeling

The measurement of real-time data is important for designing efficient PBRs; this requires either an off-gas analyzer or in-line sensors. Installing high precision sensors along the axes of the reactor, for tubular reactors (e.g., at the beginning and at the end of a tube), could further

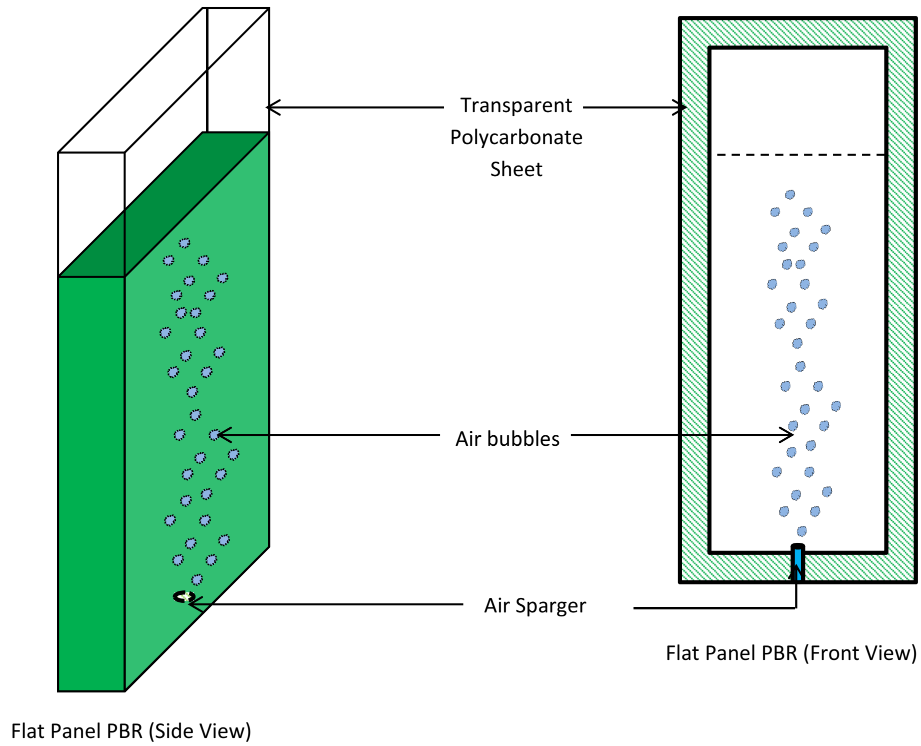


Fig. 5 Schematics of flat panel photobioreactor

enhance reactor performance by avoiding limitations or by reducing energy demand by overfeeding (Matsudo et al. 2012). Accurate monitoring and measurement of data in pilot studies is useful to designing PBRs via computer simulation studies and predicting a suitable model. Successive model development and experimental evaluation can be used to describe and predict the algal cell behavior to a wide range of different culturing conditions. PBRs design via computer simulation requires the simulation of three phase fluid dynamics, calculating light transfer and reduction by ray tracing methods (Zijffers et al. 2008) and finally combining these data to obtain a physiological kinetic and dynamic cell models (Fleck-Schneider et al. 2007). The simulated model and data can help to understand the actual and expected microalgae growth trends as a function of several parameters. Furthermore, optimization of PBR design and operating conditions can be performed in situ, which could result in high yields of biomass production.

Light utilization

Light utilization is a critical factor affecting the productivity of microalgal cultures. In general, shallower or thinner cultures can attain greater cell density and, ultimately, greater productivity since the effects of self-shading is minimized. However, in dense cultures, light utilization is reduced due to the shading effect. Flat plate PBRs are generally more efficient in sunlight utilization than tubular PBRs because they have a wider surface area (Tredici and Zittelli 1998). Hence, light utilization can be optimized effectively by using flat transparent panel tubes in various configurations and introducing light via fiber optics, and LED (Xue et al. 2013). Future photo-bioreactors have to be improved to achieve maximum photosynthetic efficiencies close to the theoretical values for achieving higher biomass concentrations with minimal energy and low investment cost (Eriksen 2008; Ugwu et al. 2008).

It is interesting to note that most early tubular PBRs used tubes 10–30 cm in diameter (Torzillo et al. 1986), but almost all tubular reactors used now have a tube diameter of <4 cm. The narrower tube diameter not only improves the light utilization efficiency, but also provides more mixing, which enhances growth. For example, Carlozzi (2003) used thin tubes (1 cm) and achieved quite high biomass concentrations of more than 6 g/L. Norsker et al. (2011) calculated algal productivity for the three systems on a monthly basis from photosynthetic efficiency (PE), algal biomass combustion enthalpy and irradiation to productivity. The open pond method utilized 1.5 % PE with algal productivity 21 ton/ha, whereas tubular PBRs utilized 3 % PE with algal productivity 41 ton/ha and flat panel bioreactor achieved the highest at 5 % PE with algal productivity of 64 ton/ha. This clearly suggests that reducing the light path length (as in case of tubular and flat panel) is beneficial for the efficient utilization of light. The orientation of PBRs with respect to the sun is also important, so that the algae receive the maximum amount of light throughout the day when operated outdoors. According to Sierra et al. (2008), for latitudes above 35°N the east-faced/west-faced orientation is favorable over north/south orientation. On the contrary, for latitudes under 35°N the north/south orientated reactors intercept more radiation and the difference is more pronounced when closer to the equator.

Mixing

The type of device used to mix and circulate the culture suspension is essential in the design of successful PBRs. Mixing keeps algal cells in suspension, eliminates thermal stratification, allows even nutrient distribution, and improves gas–liquid mass transfer to prevent O_2 accumulation, especially in tubular PBRs (Ugwu et al. 2008). Another significant role of mixing is shuttling algal cells between the light zone near illumination surfaces and the dark-interior regions, resulting in mixing-induced periodic light/dark (L/D) cycles, which are beneficial to algal growth (Molina et al. 2001; Ugwu et al. 2008). However, excess mixing can damage the microalgal cells and should be avoided (Barbosa et al. 2003). The impeller and baffles determine the effectiveness of mixing, and the O_2 transfer in stirred bioreactors. While in air driven bioreactors, the sparger plays a direct role in achieving mixing and O_2 transfer. There is a general consensus that bubble columns and airlift systems offer decent mixing, with low shear stress. However, the sparger and baffles are difficult to clean and repair because baffles are connected directly with the reactor wall and hollow fibers present in sparger pose a high risk of biofouling. Circulation is another way to ensure good mixing. Masojídek et al. (2003) applied a peristaltic pump as circulation apparatus to cultivate *Spirulina platensis* and obtained a cell productivity of 0.5 g/L/day, which was considered a relatively high value by the authors. Ferreira et al. (2012), employed three different systems for cell circulation, specifically an airlift, a motor-driven pumping, and a pressurized system, and concluded that the traditional airlift system could be substituted by the other systems to cultivate *Arthrospira platensis* in tubular PBRs.

Economics

Cost of PBRs has a major influence on production cost for large scale biomass. The reduction of the PBR cost dramatically decreases the biomass production cost. The ways to reduce cost depends on the type of algal strain, the type of PBRs, and the production technology of the biomass. The major cost factors are irradiation conditions, mixing, photosynthetic efficiency of the algae, the medium and carbon-dioxide costs. The relevance factor in reducing the cost of PBR is the consumption of raw materials. The CO_2 is the most expensive consumable in production of biomass. Using flue gases from industrial sources can reduce the cost of CO_2 to values as low as zero if flue gases are readily available (Acién et al. 2012). The utilization of wastewater containing mineral nutrients is highly recommended and could reduce the production cost. In case of biomass production, Norsker et al. (2011) calculated the cost for three different commercial-scale production systems: open ponds, horizontal tubular PBRs and flat-panel PBRs, with respective costs of €4.95, €4.15, and €5.96/kg of dry biomass. Using tubular or flat panel PBRs, the unit production cost can be reduced to €0.70 and €0.68/kg, respectively, whereas for open raceways the cost cannot be reduced below €1.28/kg. Thus, the bottleneck for the low cost production of microalgae is to develop more productive PBR systems. Moreover, large facilities capable of producing more than 150 ton/ha/year must be operated with low labor costs, using flue gases as carbon source and wastewater as growth medium to the largest possible extent (Acién et al. 2012).

Conclusion

Large scale microalgal production requires large investment and operating costs. Open ponds, such as raceway ones, are cheaper to build and operate, but require large land area. Considering the limitations of open ponds, such as high susceptibility for contamination, temperature limitations, and light availability, it is worth to intensify the efforts in developing outdoor PBRs. Although a great deal of work has been done to develop PBRs for algal cultures, more effort is still required to improve PBRs technologies and the knowledge of algal cultures production. The major concern in designing efficient PBRs is developing a scalable model, with low energy input and utilizing maximal solar radiation. A large scale PBRs should have transparent and high illumination surface, high mass transfer rates and should attain high biomass yields along with lower space requirements. While designing PBRs, factors such as type of strain, the target product, geographical location, and cost of production should also be taken into consideration.

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References

Acién FG, Fernández JM, Magán JJ, Molina E (2012) Production cost of a real microalgae production plant and strategies to reduce it. Biotechnol Adv 30:1344–1353

Andersen RA (2005) Algal culturing techniques, vol 13. Academic Press, New York, p 189

Barbosa MJ, Janssen M, Ham N et al (2003) Microalgae cultivation in air-lift reactors: modeling biomass yield and growth rate as a function of mixing frequency. Biotechnol Bioeng 82:170–179

Brennan L, Owende P (2010) Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. Renew Sustain Energy Rev 14:557–577

Cantrell KB, Ducey T, Ro KS, Hunt PG (2008) Livestock waste-to-bioenergy generation opportunities. Bioresour Technol 99:7941–7953

Cardozo KHM, Guaratini T, Barros MP, Vanessa RF, Tonon AP, Lopes NP, Campos S, Torres MA, Souza AO, Colepicolo P, Pinto E (2007) Metabolites from algae with economical impact. Comp Biochem Physiol C: Toxicol Pharmacol 146:60–78

Carlozzi P (2003) Dilution of solar radiation through "culture" lamination in photobioreactor rows facing south–north: a way to improve the efficiency of light utilization by cyanobacteria (*Arthrospira platensis*). Biotechnol Bioeng 81:305–315

Chisti Y (2007) Biodiesel from microalgae. Biotechnol Adv 25: 294–306

Doran PM (2013) Bioprocess engineering principles, vol 14. Academic Press, New York, pp 751–852

ElMekawy A, Hegab HM, Vanbroekhoven K, Pant D (2014) Techno-productive potential of photosynthetic microbial fuel cells through different configurations. Renew Sustain Energy Rev 39:617–627

Eriksen NT (2008) The technology of microalgal culturing. Biotechnol Lett 30:1525–1536

Ferreira LS, Rodrigues MS, Converti A et al (2012) Kinetic and growth parameters of Arthrospira (Spirulina) platensis cultivated in tubular photobioreactor under different cell circulation systems. Biotechnol Bioeng 109:444–450

Fleck-Schneider P, Lehr F, Posten C (2007) Modelling of growth and product formation of *Porphyridium purpureum*. J Biotechnol 132:134–141

Franco-Lara E, Havel J, Peterat F, Weuster-Botz D (2006) Model-supported optimization of phototrophic growth in a stirred-tank photobioreactor. Biotechnol Bioeng 95:1177–1187

Guiry MD (2012) How many species of algae are there? J Phycol 48:1057–1063

Hu Q, Kurano N, Kawachi M et al (1998) Ultrahigh-cell-density culture of a marine green alga *Chlorococcum littorale* in a flat-plate photobioreactor. Appl Microbiol Biotechnol 49:655–662

Masojídek J, Papáček Š, Sergejevová M et al (2003) A closed solar photobioreactor for cultivation of microalgae under supra-high irradiance: basic design and performance. J Appl Phycol 15:239–248

Matsudo MC, Bezerra RP, Sato S et al (2012) Photosynthetic efficiency and rate of CO_2 assimilation by Arthrospira (Spirulina) platensis continuously cultivated in a tubular photobioreactor. Biotechnol J 7:1412–1417

Molina E, Fernández J, Acién FG, Chisti Y (2001) Tubular photobioreactor design for algal cultures. J Biotechnol 92:113–131

Norsker N-H, Barbosa MJ, Vermuë MH, Wijffels RH (2011) Microalgal production—a close look at the economics. Biotechnol Adv 29:24–27

Oswald WJ (1969) Current status of microalgae from wastes. Chem Eng Prog Symp Ser 65:87

Posten C (2009) Design principles of photo-bioreactors for cultivation of microalgae. Eng Life Sci 9:165–177

Sánchez Mirón A, Contreras Gómez A, García Camacho F et al (1999) Comparative evaluation of compact photobioreactors for large-scale monoculture of microalgae. J Biotechnol 70:249–270

Sekabira K, Origa HO, Basamba TA et al (2010) Application of algae in biomonitoring and phytoextraction of heavy metals contamination in urban stream water. Int J Environ Sci Technol 8:115–128

Sharma NK, Rai AK, Stal LJ (2013) Cyanobacteria: an economic perspective, vol 17. Wiley, London, pp 255–271

Sierra E, Acién FG, Fernández JM, Garcia JL, Gonzalez C, Molina E (2008) Characterization of a flat plate photobioreactor for the production of microalgae. Chem Eng J 138:136–147

Singh A, Pant D, Olsen SI, Nigam PS (2012) Key issues to consider in microalgae based biodiesel production. Energy Educ Sci Technol A Energy Sci Res 29:563–576

Slegers PM, Wijffels RH, van Straten G, van Boxtel AJB (2011) Design scenarios for flat panel photobioreactors. Appl Energy 88:3342–3353

Torres E, Mera R, Herrero C, Abalde J (2014) Isotherm studies for the determination of Cd(II) ions removal capacity in living biomass of a microalga with high tolerance to cadmium toxicity. Environ Sci Pollut Res Int 21:12616–12628

Torzillo G, Pushparaj B, Bocci F et al (1986) Production of Spirulina biomass in closed photobioreactors. Biomass 11:61–74

Tredici MR, Zittelli GC (1998) Efficiency of sunlight utilization: tubular versus flat photobioreactors. Biotechnol Bioeng 57: 187–197

Ugwu CU, Aoyagi H, Uchiyama H (2008) Photobioreactors for mass cultivation of algae. Bioresour Technol 99:4021–4028

Xue S, Zhang Q, Wu X, Yan C, Cong W (2013) A novel photobioreactor structure using optical fibers as inner light source to fulfill flashing light effects of microalgae. Bioresour Technol 138:141–147

Yang ST (2011) Bioprocessing for value-added products from renewable resources: new technologies and applications, vol 19. Elsevier, Amsterdam, pp 491–507

Zijffers JWF, Salim S, Janssen M, Tramper J, Wijffels RH (2008) Capturing sunlight into a photobioreactor: ray tracing simulations of the propagation of light from capture to distribution into the reactor. Chem Eng J 145:316–327