Photobioreactors for microalgae cultivation – An Overview

M. K Egbo, A. O Okoani, I. E Okoh

Abstract - One of the ways to combat global warming is to substitute the conventional fossil fuels that are used to meet most of the world energy demand with cheaper, cleaner, renewable and therefore sustainable energy (heat, electricity, and transport fuel) sources. Not only can microalgae biomass serve as a sustainable source of energy, it can also serve as food supply for both humans and animals, as raw material for the chemical and pharmaceutical industry, as wastewater treating agent and, as a biological atmospheric carbon dioxide removal (CDR) agent for geoengineering purpose. Since photobioreactors (PBRs) show higher potential for use in the large-scale production of microalgae biomass when compared to the other production systems (raceways or open ponds), this paper focuses on the overview of the different types of PBRs and the design types, the operation principles, advantages, limitations and possible applications. It goes further to discuss some of the existing work on PBRs and lists the maximum performance properties/characteristics (as reported by other authors) such as biomass productivity in g L^{-1} for different PBRs that has been achieved over the years.

Keywords: Microalgae, Biomass, Photobioreactor (PBR)

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1 Introduction

Climate change, increasing demand for energy due to the rapid growth in the world population (see Figure 1 and Figure 2), and the finiteness of our conventional energy sources means that it is imperative that alternative energy sources are found. Although the claim that fossil fuel reserves are limited might not be plausible, but the increase in the Earth's average temperature, the extreme weathers occurrences, the melting polar ice caps and the consequent sea level rise, and the unusual gradual movement of different plant and animal species in search of comfortable living conditions are some of the glaring proofs of the imminent dangers of global warming. There is a clear connection between the activities surrounding the use of fossil fuels by the humans and these measurable global warming effects, and due to the exponential increase in the human population and the consequent increase in the fossil fuel utilization, these global warming effects will continue to rise [1]. This helps put into perspective the level of urgency in demand for securing a sustainable means of providing cheap, clean, and renewable energy (heat, electricity, and transportation fuel).

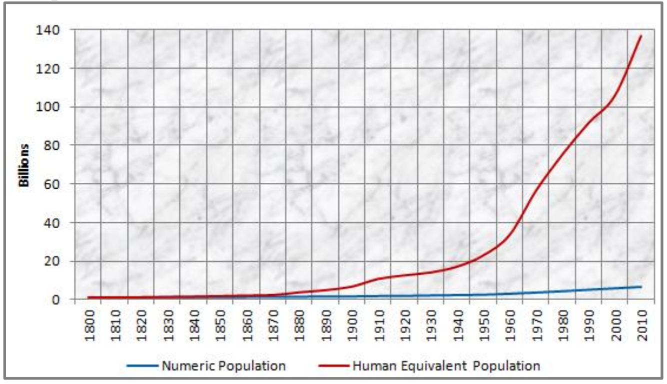

Figure 1 Human population from 1800 to 2010 [2]

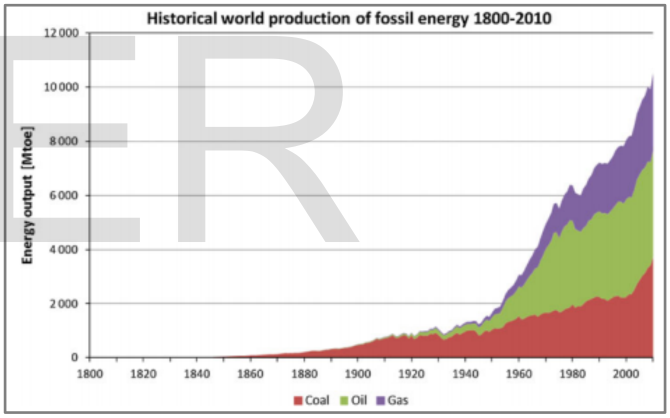

Figure 2 World production of fossil energy between 1800 – 2010 [3].

Despite some of the technical and economic challenges currently facing the commercialization of microalgae production, microalgae have been identified as one of the potential fossil fuel replacements. These tiny living organisms, known as a third-generation biomass, when extracted from their growth medium can be converted into solid (biomass), liquid (such as bioethanol and biodiesel) or gaseous (such as methane) fuels. The liquid fuels are known as drop-in replacements for the unsustainable fossil-based transportation fuels such as diesel and petrol as they exhibit similar performance characteristics, such as high energy density, flammability and volatility [4]. They are also very compatible with the existing infrastructures such as the distribution channels and energy conversion technologies (such as the internal combustion engines). There are no waste products associated with microalgae. For instance, a microalgae biomass whose oil contents have been extracted can be used as fodder for animals or as fuel in an energy from waste (EfW) plant for energy (heat and power) generation. In addition to the use of algal biomass as an energy source, some species are highly nutritious, making them suitable for human consumption. Other species are also used in the production of

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stabilising agents, manufacture of high-value products in chemical and pharmaceutical industries, and in the wastewater treatment plants. The use of microalgae as a biological carbon dioxide removal (CDR) system in geo-engineering is also a huge area of study.

Some of the advantages microalgae have over other biomass (first and second generation) includes: higher productivity; more efficient land use and; higher energy density. They can also be grown in unfavourable conditions (such as wastewater and saline land), which are unsuitable for almost all the first generation and most of the second-generation biomass [5]. The ability of microalgae to double in size over the course of a few days means that continuous high-volume biofuel production is feasible. However, as previously mentioned, large-volume production of highly concentrated algal biomass for manufacturing biofuels has been delayed by the some of the technical and economic challenges associated with the process. The technical issues are functions of the cultivation system design, and the inefficiencies relating to lipid extraction from the harvested microalgae biomass, while the ratio of the net benefit to cost ratio must be greater than unity for the investment in a cultivation system design to be economically justifiable.

1.1 Microalgae cultivation systems

There are two major types of cultivation systems that are currently being used for microalgae production – open pond (raceway) systems and closed systems. Closed cultivation systems are primarily known as photobioreactors (PBRs).

1.1.1 Open ponds

Open ponds (Figure 3) are compartments in the form of annular channels of small thickness that are open to the atmosphere. They are called raceways because most open pond systems have similar shape as a race track [6]. Other types of open pond microalgae cultivation systems which have been reported are: (a) circular ponds (b) unmixed open ponds, and (c) thin layer inclined ponds [7]. Circular ponds, just as the name implies, are circular open ponds with a centralised mixing system, usually a three-blade hydrofoil impeller and four-pitched blade turbine (PBT) agitators [8]. This open pond system type is widely used in Asia for the production of Chlorella [7]. Unmixed open pond systems could be in the form of a raceway system or a circular type. The only disparity is the absence of agitation, and as a result, this cultivation system type exhibits very low productivities (less than 1 g m^{-2} d^{-1}) prompting its use in the large-scale growth of few algal species such as *D. salina* [7]. On the other hand, in thin layer, inclined ponds, algal culture flow continuously in marginally inclined shallow (6-8 mm) trays [9]. Thin layer, inclined ponds may achieve productivities up to 31 gm^{-2} d^{-1} with only 15-20% the costs of biomass production in raceway systems. In general, open pond systems are cheaper to construct and maintain compared to the closed-type systems as they require only a trench or pond of shallow depth [10]. Due to this low-cost involvement, these systems are the most commonly used for growing microalgae [11]. Mixing in an open pond system is usually achieved with a paddle wheel [11]. Only a handful of microalgae species can be grown using this type of system due to its susceptibility to contamination as they are open to the atmosphere. They are difficult to monitor, and are known to have high water requirements due to evaporation [12]. An open pond system is suitable only for outdoor cultivation where sunlight is utilised as the primary source of energy for photosynthesis.

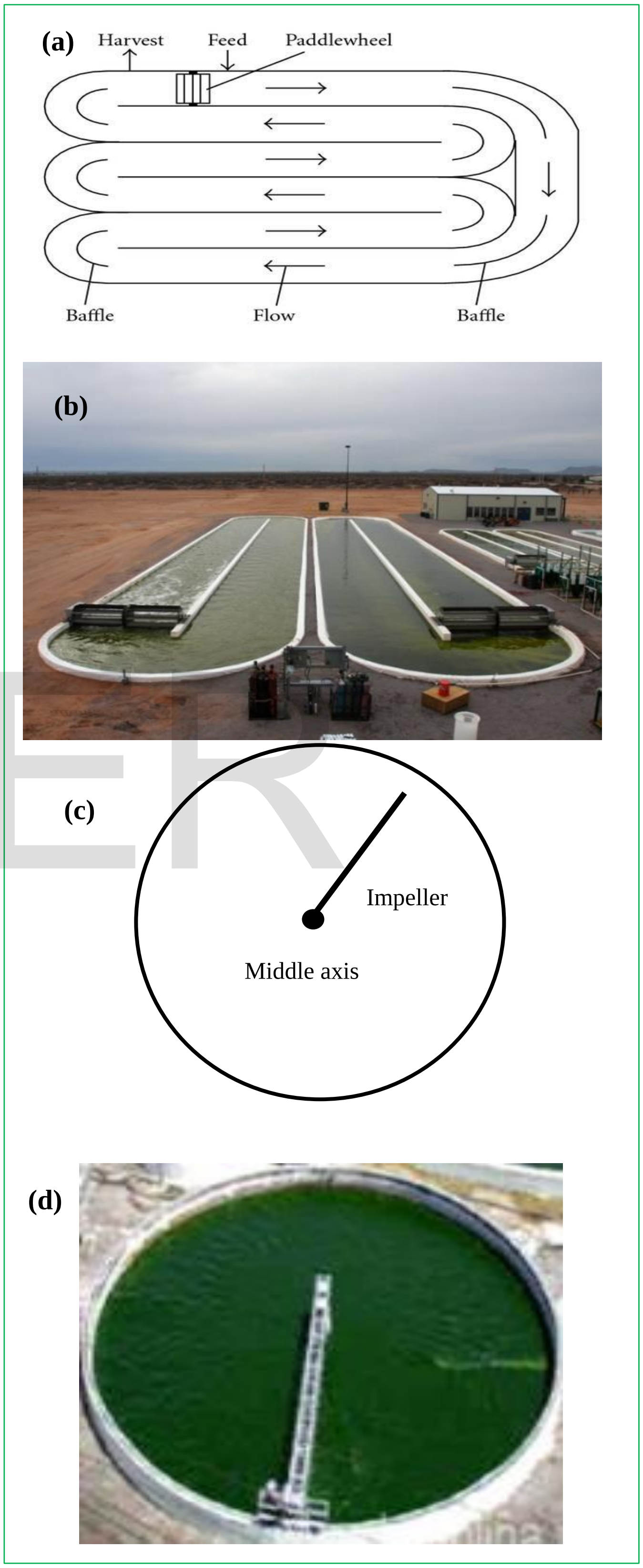


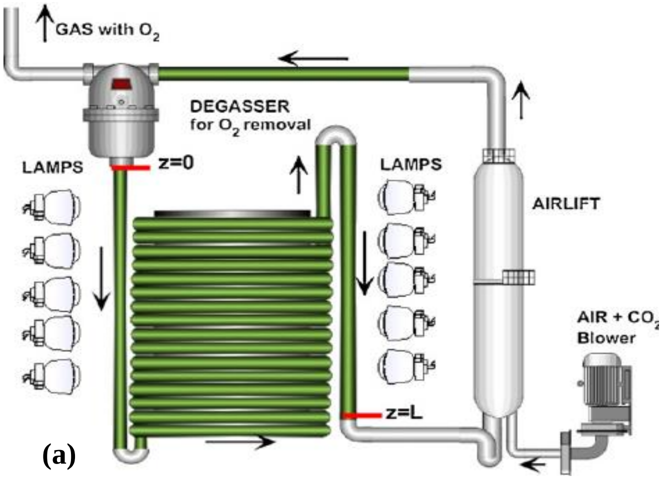
Figure 3 (a) Schematic diagram of a raceway system (b) A picture of two raceway systems [6] *(c) Schematic diagram of a circular pond system (d) Picture of a circular pond system.*

In reality, only about 1.5% conversion of the solar energy to chemical energy has been achieved using this system, and this is partly due to the limitation of light penetration during microalgae growth in this system [12]. There are other drawbacks with the application of this system such as the large land area uptake, the variation of the solar radiation availability, and the diffusion of CO_2 to the atmosphere [10]. Despite these flaws, open ponds currently contribute heavily to the worldwide total annual microalgae production, and the harvested products are mostly used in the manufacture of high-value goods such as drugs in the pharmaceutical industry and in wastewater treatment plants.

1.1.2 Closed systems

The closed systems or photobioreactors (PBRs) are transparent containers designed for microalgae cultivation. Different PBR cultivation systems have been designed and patented, and some have been developed to have different geometries and sizes [7]. Some of these PBR types whose patent has been awarded include the vertical bubble columns and airlift reactors, the tubular photobioreactors, the helical photobioreactors, the combined bubble column and inclined tubular reactors, and the flat plate photobioreactors [7]. Figure 4 shows the schematics of a tubular PBR fitted with an airlift system, a flat-plate PBR with a peristaltic pump for nutrient supply, and a picture of a tank PBR containing a high-density culture.

Closed systems are not open to the atmosphere and therefore are less prone to contamination [16], [17]. This characteristic isolation of a culture within a photobioreactor from the environment also contributes to the low loss of water and carbon dioxide gas molecules during operation. These cultivations systems are usually oriented vertically, horizontally, or at an angle depending on the design, and can make use of both the natural light (sunlight) and artificial light as the energy source. With closed systems sensitive algal strains can be grown as these systems can be used to provide the optimum conditions and growth requirements. However, as previously mentioned, these systems are more expensive in terms of construction and maintenance than the raceways, and therefore are rarely used for large-scale production purposes.



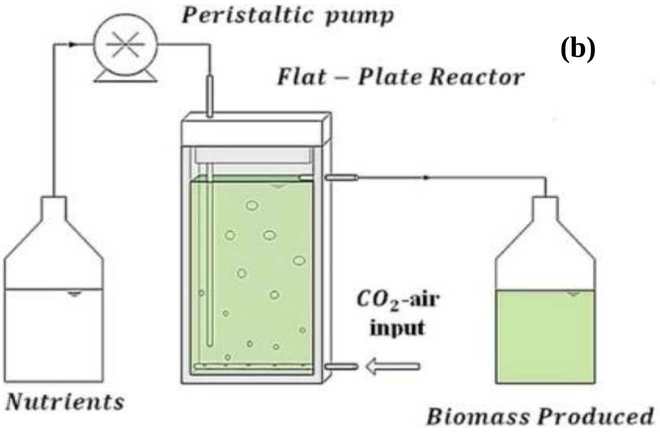


Figure 4 (a) Tubular PBR *[13]* (b) Flat-plate PBR *[14]* (c) Tank PBR *[15]*

2 Photobioreactors (PBRs)

As previously stated, PBRs are transparent containers or enclosures - including greenhouses, used for the cultivation of microalgae. These enclosures are usually made of glass, poly vinyl chloride (PVC), low-density polyethylene (LDPE), or high-density polyethylene. Other materials are also available. The material of construction of a PBR determines the longevity of the system and contributes to the overall initial investment. Photobioreactors have numerous advantages over the open system types. These benefits include: lower vulnerability to species contamination; higher productivity; lower harvesting cost; reduced water and carbon dioxide losses and; easier control of the cultivation conditions such as temperature and pH [16]. Despite these many benefits, the prohibitive costs of building and maintaining these microalgae production systems have limited their use in commercial application. Table 1 summarises some of the differences between PBRs and open pond systems.

Table 1 A direct comparison between photobioreactors and open pond systems.

Cultivation system type	Photobioreactors (PBRs)	Open ponds (OP)
CAPEX cost	High	Low
OPEX cost	High	Low
Probability of contamination	Low	High
Water requirement	Low	High
CO_2/nutrient losses	Low	High
Hydrodynamic stress	Low (albeit depends on the energy input)	
Lighting efficiency	High	Low
Physical footprint	Low	High
SA/V ratio	High	Low
Productivity	High (>2 times that of OP)	Low
Temperature control	Easy	Difficult
DO accumulation	High	Low
Scalability	Difficult	
Portability	Possible	Mostly impossible
Energy requirement	High	Low
Commercial application	Low	High
Species grown	Many	Few
pH/light control	Easy	Difficult

2.1 PBR types

As previously mentioned, different PBR types have been designed and patented, and some have been developed, and are currently in use in small-scale microalgae production - mostly for research purposes.

2.1.1 Tubular photobioreactor

These are PBRs of cylindrical geometries. The Optical properties of the material enclosure of this PBR type is essential only when the light source is external to the culture system – an example is when sunlight is used. With their high surface area to volume ratios, tubular PBRs are known to have high lighting efficiencies. Depending on their orientations, this PBR type is further classified into two – Vertical and Horizontal tubular PBR.

2.1.1.1 Vertical tubular photobioreactor

This type of tubular PBR is made of clear vertical tube and is often provided with an external illumination. As mentioned earlier, the transparent nature of the tubing is to ensure that light gets to the culture during operation. By attaching a sparger at the bottom of the reactor, mixing is provided by passing a gas, usually a mixture of air and carbon dioxide, into the system, creating gas bubbles that travel all the way to the free surface of the culture [10]. Mixing by sparging provides mass transfer of both the nutrients and the cells; transporting the nutrients to the cells, preventing cell sedimentation, and maintaining the light/dark cycle movements within the photobioreactor [17]. It also affects the gas exchange (dissolved oxygen and carbon dioxide) between the reactor and the atmospheric air and eliminates culture stratification. A lot of publications have been produced on this PBR type [18], [19], [20], [21]. Two major types of the vertical tubular PBR exists – Bubble column and Airlift type, depending on the flow pattern within the PBR.

Bubble column photobioreactors (Figure 5 (B)) are the most common of the vertical tubular PBRs. The height of this reactor is more than double its diameter, and as such possess a high surface area to volume ratio [10]. The required culture mixing, and carbon dioxide supply are made available using spargers. This reactor has a low CAPEX cost compared to most PBR types, and have shown adequate heat and mass transfer efficiencies [10]. Unlike the bubble column PBRs, an airlift PBR (Figure 5 (A)), is partitioned into two; the “riser” which houses the sparged region, and the “downcomer” which houses the rest of the culture. These two regions are parallel to each other and are connected at the top and at the bottom. The bubbles created in the riser force the liquid/gas in the riser and downcomer to move in the upward and downward directions, respectively, creating a constant fluid recirculation within the PBR. This fluid flow is as a result of the difference in the average density between the riser and the downcomer which induces the pressure gradient required for fluid circulation [22].

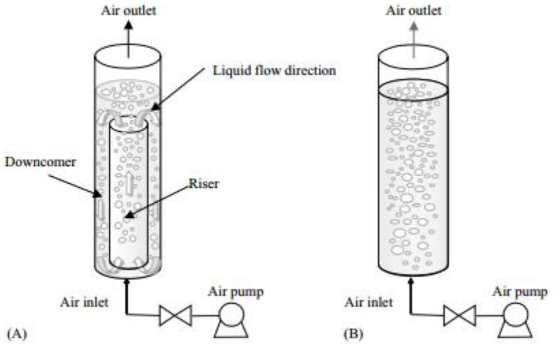


Figure 5 Schematic diagram of (A) Airlift PBR (B) Bubble column PBR [23].

Airlift type vertical tubular PBR are further divided into the internal loop and the external loop type. In a split type internal-loop system (Figure 6 A), the riser and the downcomer are separated with a split vessel or baffle which is designed to create the duct required for the fluid circulation. For a concentric type internal-loop system (Figure 6 B), two concentric tubes are used to form these two partitions, with the internal tube serving as the riser. This is the most common airlift vertical tubular PBR system. The external-loop airlift PBR (Figure 6 C) is unique in that the fluid circulation takes place between separate and distinct channels [22].

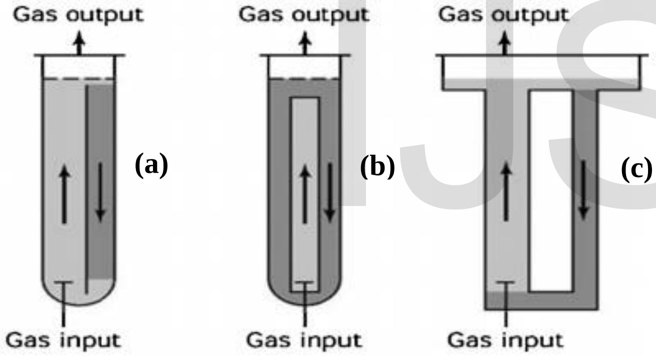


Figure 6 Different designs of airlift PBRs (A) Internal-loop split (B) Internal-loop concentric tube (C) External-loop [22].

Different conclusions have been reported on the use of the vertical tubular PBRs in the growth of different microalgae strains. For instance, Henrard et al. [19] reported a maximum specific growth rate of 0.127 d^{-1} in a 2-L vertical tubular photobioreactor when the microalgae *Cyanobium sp.* was grown in a semi-continuous mode at 30 °C, 3200 Lux, and 12 h light/dark photoperiod. The observed maximum productivity was (0.071 $g\,L^{-1}\,d^{-1}$) when the blend concentration, the renewal rate, and the bicarbonate concentration were 1.0 $g\,L^{-1}$, 30%, 1.0 $g\,L^{-1}$, respectively. They concluded that the right combination of these three parameters in vertical tubular photobioreactors would yield the optimum growth rates and productivities. Chen et al. [21] in their publication claimed maximum biomass and protein productivities of 268.1 and 155.4 $mgL^{-1}d^{-1}$, respectively, when they cultivated *C. vulgaris* FSP-E using a 50 L outdoor vertical tubular PBR. These optimum cultivation conditions were established as 18.4 mM urea concentration, 0.2 g/L inoculum size, and aeration of 2.0% CO2 at 0.05 vvm. Their conclusion was that *C. vulgaris* FSP-E production could be achieved in 50 L outdoor vertical tubular-type PBRs with performance levels close to those obtained using other types of outdoor PBR. In the same study, Chen et al. [21] also compared the growth performance between indoor and outdoor cultivation using the same medium and aeration condition on the same PBR. The final biomass production (2.35–2.38 g/L), protein content (54.2–52.4% per dry cell weight), protein productivity (110.1–114.5 mg/L/d) and urea utilization percentage (90.1%–90.3%) were similar for both indoor and outdoor growth. They suggested that this performance similarity could be due to the photon flux density level (about 2000 $\mu mol\ m^{-2}\ s^{-1}$) in the outdoor culture, which allows the algal cells to grow quickly within the 8 hours sunlight availability, as opposed to the constant 150 $\mu mol\ m^{-2}\ s^{-1}$ in the indoor culture.

One of the drawbacks to the use of vertical tubular PBRs is the issue of DO accumulation. At quantities above air saturation (0.225 $molO_2\ m^{-3}$ at 20 ºC) oxygen can hinder photosynthesis in most microalgae species, irrespective of the concentration of carbon dioxide in the culture [16]. These DO concentrations when combined with high levels of culture illumination can also lead to the formation of lipid peroxides which are known to be harmful to microalgal cell membrane, and in extreme cases can lead to cell death – this phenomenon is known as photo-oxidation [24], [25]. Another major drawback is the issue to self-shielding. This occurs when multiple or multi-column outdoor vertical PBRs are closely packed together [26]. Tubes directly facing the sun cast shadows on the adjacent tubes, leading to lower overall lighting efficiency. As this problem is dependent on the orientation of the sun, one way to counter it is to increase the proximity of the tubes. This method, however, demands large land area requirements. The best method to solve this problem is to internally or externally illuminate the system(s) using artificial lighting. Figure 7 shows the image of an operational indoor bubble column vertical tubular PBRs.

Figure 7 Cultivation of different algal species in bubble columns vertical tubular PBR at Plymouth Marine Laboratory [27].

2.1.1.2 Horizontal tubular photobioreactor

Unlike the vertical-type, horizontal tubular PBRs which are a parallel set of connected loops of tubes (Figure 8), are placed horizontally or inclined at an angle to the horizontal [10]. This offers an advantage when used in outdoor cultures, as they are inherently oriented towards the sun, and hence have higher light conversion efficiency [10]. However, like the vertical-type tubular PBR, the horizontal-type PBR has some factors limiting its performance. The predominant factors are the high energy requirement and DO accumulation [10], [18]. Their average energy requirement is about 4000% that of the bubble column and the flat plate PBRs [10]. The energy required to constantly circulate the culture within the tubes is a major contributor to their overall energy consumption. The second largest contributor is the heat exchanger which is used in the temperature control of the culture.

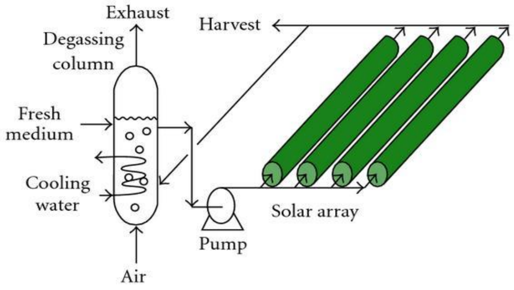


Figure 8 Schematic diagram of a typical horizontal tubular PBR [28].

The rate of oxygen production within a PBR is dependent on the rate of photosynthesis which is also dependent the rate of carbon dioxide consumption. Unlike in the open cultivation systems where the photosynthetic generated oxygen can easily escape into the atmosphere, in a closed system, the oxygen gases accumulate within the PBR, mixing with the microalgae cells and the growth medium. And as previously discussed, this oxygen accumulation becomes detrimental to the growth and productivity of most microalgae culture strains when its concentration exceeds the air saturation level. In a horizontal tubular PBR, this accumulating oxygen can be removed with the help of a degassing system. The effectiveness of this gas exchange system is dependent on the length of the tubes of the PBR. The longer the tubes, the longer it will take to passes the entire volume of the culture through the degassing system. This problem can be solved by increasing the rate of circulation of the culture through the tubes. As stated earlier, increasing the flow rate increases the energy consumption of the circulating pump, and hence the overall energy requirement. It can also damage the cell walls of the algal species that show high sensitivity to hydrodynamic stresses.

Figure 9 Picture of a horizontal tubular photobioreactor [29].

Figure 9 shows a photograph of an outdoor horizontal tubular PBR. A lot of research have been carried out on this PBR type. Some of the publications that are based on this PBR are listed in Table 2.

Table 2 Literature on the horizontal tubular photobioreactors.

Focus of the study	Reference	Results/Conclusions/Observations
Scenario analysis of large scale algae production in tubular photobioreactors	Slegers et al. [29]	Horizontal tubular PBRs have higher productivities than raceways but lower than those of vertical tubes and flat panels.
Appraisal of a horizontal two-phase flow photobioreactor for industrial production of delicate microalgae species	Muller-Feuga et al. [30]	The Daily observed production of the dry biomass of the chlorophyte *Neochloris oleoabundans* and the rhodophyte *Porphyridium cruentum* varied between 0.2 and 1.7 Kg and depend on the sunlight availability and the period on the year.
CO_2 mass transfer and conversion to biomass in a horizontal gas–liquid photobioreactor	Valiorgue et al. [31]	Stripping increases with the length of the photobioreactor and affects the CO_2 conversion to biomass efficiency.
Cultivation of *Chlorella vulgaris* in tubular photobioreactors: A lipid source for biodiesel production	Frumento et al. [32]	The configuration of a photobioreactor is an important factor for the growth and the composition of microalgae.
Outdoor continuous culture of *Porphyridium cruentum* in a tubular photobioreactor: quantitative analysis of the daily cyclic variation of culture parameters	Rebolloso Fuentes et al. [24]	The culture conditions during the growth of *Porphyridium cruentum* in an outdoor horizontal tubular-type PBR changes with time because of the variation of solar irradiance.
Improving mass transfer in an inclined tubular photobioreactor	Babcock et al. [33]	The enhanced version of the Tredici-design near-horizontal tubular photobioreactor (NHTR) is better than the original design in terms of the oxygen stripping, carbon dioxide dissolution, and the overall mixing efficiency.

2.1.2 Flat Panel Photobioreactor

Flat panel PBRs (Figure 10 and Figure 11) are made of transparent materials for holding the culture just like the tubular-type PBRs, and can be illuminated externally (naturally using solar radiation or artificially using artificial light sources such as LEDs) or internally (artificial illumination). This cultivation system has a large illumination surface area to volume ratio and can be positioned to have maximum exposure to an external light source (e.g., solar radiation) [34]. The use of internal, hence artificial illumination minimises the effect of self-shading during microalgae cell multiplication. The use of flat panels for microalgae cultivation dates back to the early 1950s and have since undergone numerous modifications to enhance their productivity [35]. Mixing in modern flat panel PBRs are created by aeration (passing a gas mixture through a perforated air tubing into the culture) due to its low energy and material requirements compared to the use of pumps. The governing equation for the mixing power per unit volume P for a typical flat panel photobioreactor is given by the well-known fluid mechanics relationship:

$$P = \rho_l \cdot g \cdot U_g \qquad (1)$$

Where ρ_l is the density of the liquid, g is the gravitational acceleration, and U_g is the aeration rate; also known as the superficial gas velocity. Much of the energy consumed by this PBR type comes from aeration [35].

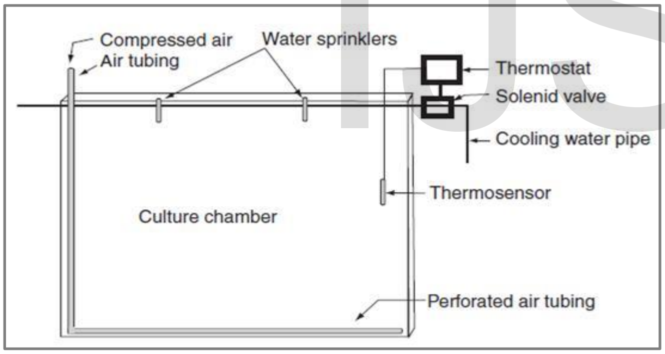


Figure 10 Schematic diagram of a flat panel photobioreactor fitted with an aeration system [36].

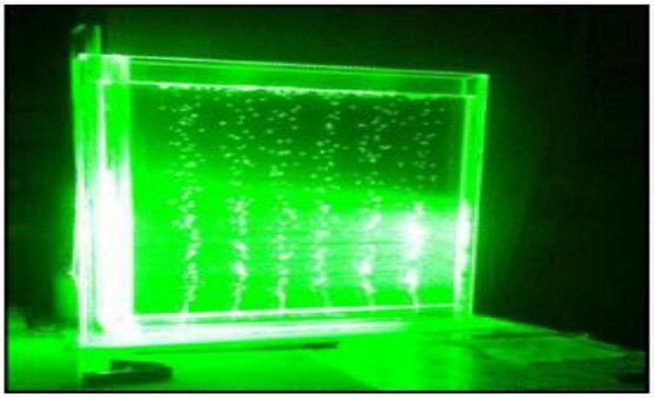


Figure 11 Picture of an indoor aerated flat panel PBR [37].

Flat panels can be constructed to have a desired light-path. However, flat panels with smaller width (lower light-path) modules require more materials for construction. This increases the overall cost of the system. Some cheap synthetic materials, however, have been developed to reduce material cost. For instance, Solix biofuels have developed PBRs made of synthetic bags. The mixing is carried out by attaching spargers at the bottom of each bags, while cooling is achieved by submerging the bags in ponds. Other problems associated with the use of flat panel PBRs are the issues of fouling and gas hold-ups. Fouling is more detrimental to a PBR system that is illuminated externally and occurs when microalgae cells adhere to the internal surfaces of the PBR wall, blocking the light rays from reaching the inner regions of the culture medium. The gas hold-up is a measure of the residence of gases in a culture medium which depends on the superficial inlet gas velocity, the fluid properties of the culture medium, and the geometry of the PBR. Reyna-Velarde et al. [38] in their study of a 50-L airlift flat-panel PBR reported that gas hold-up is higher in flat-panel PBRs than those reported in other types of PBR. High gas hold-up is desirable for carbon dioxide but not for the photosynthetic generated oxygen in the culture medium.

In terms of productivity, Zou and Richmond [39] in their experiment with *Nannochloropsis sp.* reported that the optimal cell density of microalgae increases with decreasing light-path in a light-limited outdoor flat panel PBR. They reported an optimal light-path of 0.1 m, with biomass productivity of 0.5 g L^{-1} day^{-1} in the summer time. Degen et al. [40] in their study of a newly constructed flat panel airlift PBR with baffles noted that the biomass productivity of *Chlorella vulgaris* was higher when organised mixing (‘laminar-like’) was carried out rather than randomly. This flat panel reactor achieved a biomass productivity of 1.7 times greater than in a chaotically mixed bubble column PBR of the same dimension. A 2.5-fold increase in productivity was also reported with a reduction of the light-path from 30 to 15 mm. Degen et al. [40] also recorded a maximum dry biomass productivity of 0.11 g L^{-1} h^{-1} at an artificial illumination of 980 μE m^{-2} s^{-1}.

Flat panel PBRs are still under development and therefore are yet to be deployed for the commercial production of microalgae. A company known as Proviron, which specialises in the manufacture of steroids has claimed that it is developing thin flat panels capable of achieving biomass concentrations of up to 10 g L^{-1} while consuming power as low as 2 W m^{-2} [35].

2.1.3 Tank photobioreactor

This PBR type can be of any shape (e.g., tubular, cuboidal) and is known to have high volume to surface area ratio. This ratio contributes to the increased light attenuation experienced when using this PBR type for outdoor microalgae production, or when using other external light source. As such, very few of this PBR have been developed over the years. However, with the possibility of internal illumination, this PBR type is beginning gain some interest, especially from the industry, as it holds the potential of higher biomass output per land area.

For instance, Yim et al. [41] when studying the biochemical properties of *Spirulina platensis* under different light-emitted diode (LED) wavelengths with different light intensities, used a unique design of an internally illuminated PBR (IIPBR). Their design (see Figure 12) produced highest specific growth rate, maximum biomass, and phycocyanin productivity under the red LEDs

(0.39/day, 0.10 g/L/day, and 0.14 g/g-cell/day, respectively) at 1,000 µmol/m2 /sec; while the lowest growth rate was obtained under blue LEDs. They concluded that their work could be used to design pilot scale IIPPBRs and develop cheaper lighting systems.

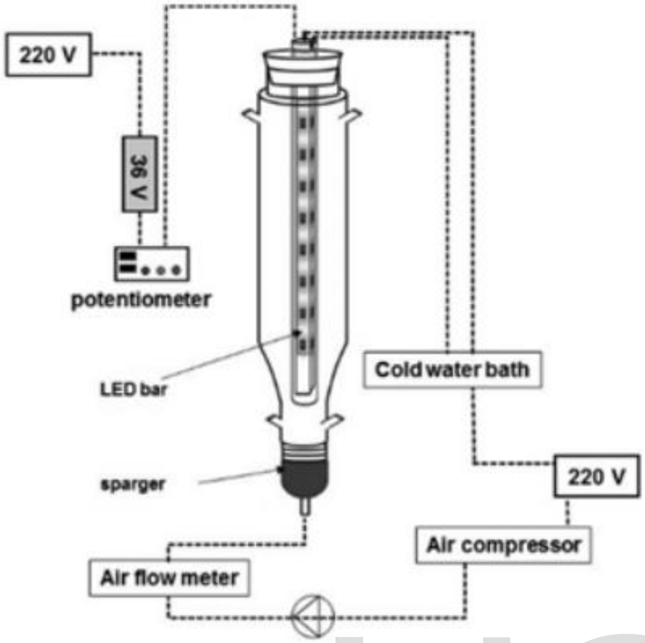


Figure 12 Schematic diagram of an internally illuminated PBR [41].

Mixing in tank PBRs can be achieved with impellers or by aeration. The use of impellers requires high energy consumption and can cause hydrodynamic stress when used to grow sensitive microalgae strains. Ogbonna et al. [42] in their study developed a novel internally illuminated stirred tank PBR and used it to cultivate *Chlorella pyrenoidosa*, and reported that their this PBR achieved a higher cell yield than the commercially available photobioreactors. Their system was made up of a detachable 4-W fluorescent bulb with controllable light intensity and an impeller. The lighting system was designed to be separable from the rest of the system to enable the sterilisation of the PBR by autoclaving.

2.1.4 Hybrid type PBR

Just as the name implies, hybrid type PBR is a single PBR that is constructed from a combination of two or more PBR types. As different PBRs have one or more drawbacks, a hybrid-type exploits the individual advantages of the component PBRs. Fernandez et al. [43] developed a 0.2 m^{-3} hybrid-type PBR by integrating an airlift system and an external tubular loop. A degasser in the airlift section was used to minimise dead and dark zones while removing the oxygen produced during photosynthesis. A biomass productivity of 1.20 g l^{-1} d^{-1} was obtained at a dilution rate of 0.050 h^{-1} when *Phaeodactylum tricornutum sp.* was grown using their design. The same productivities were observed when the solar receiver linear liquid velocities were 0.50 and 0.35 m s^{-1}, with a dramatic fall at lower velocities. Fernandez et al. [43] reported that the accumulation of the photosynthetic generated oxygen in this hybrid reactor could be reduced by increasing the velocity with which the liquid circulates around the airlift-tubular loop system.

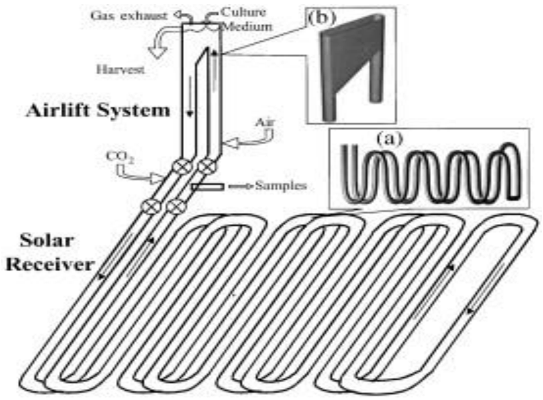


Figure 13 A hybrid-type outdoor culture system with details of the solar loop (a) and the degasser zone (b) [43].

Huntley et al. [44] in their experimental study of large-scale hybrid and open pond cultivation systems reported that the biomass and lipid yields are higher in the former than what have so far been reported for the latter. In this study, a 25-m^3 hybrid PBR and a 400-m^2 open pond system were used, with marine microalgae, *Staurosira sp.* and *Desmodesmus sp*. Huntley et al. [44] also concluded that a large-scale hybrid PBRs are more economically viable for use in the inoculation of short-period batch cultures in large-scale open pond systems Other hybrid-type PBRs have been designed and developed. Other designs have been suggested to develop an optimised PBR system with combined characteristics of both tubular and flat panel PBRs.

For the purpose of comparison, Suh and Lee [45] in their work listed a couple of different designs and sizes of PBRs which have been developed between 1953 and 2001. These PBRs were listed against their respective productivities in Table 3.

Table 3 Performance of different PBRs [45].

Culture chamber design	Total vol. L	S/V Ratio/m	Productivity per area g m^2 day^{-1}	per vol. g L^{-1} day^{-1}	Max. biomass g/L
Tubular	1	170[a]	11.7	1.3	18.5
Tubular	40	40[a]	17		17.5[a]
Column	30	28.6[a]			1.85[a]
Tubular	4.6	127	52.8		20
Tank	2.4	580		1.65 [a]	5
Falling-film	190	7.5[a]			1.2
Tubular	8,000	10	25		1.2
Column	1	1[a]		10.41[f]	4.19
Column	4.6	80	23	0.57	
Tank	2.5				8.2
Column	200	0.66[a]		0.246	
Helix	0.315	127			4.6
Cylinder	1	320		1.51	7.5[a]
FPARL[c]	10	50			2.27
VAP[b]		80	23.9		7
LDOF[d]	2.5	692[e]		1.94	11.2
Tank	5.6	19.3		0.51	2.67
LDOF	2.5				1.9
Tubular	145	54	27.8		6.3
Slab	0.1	100	44	3.15	25
Inclined slab	6	85	51.1	4.3	15.8
Flat-plate	0.34	132		28.8	26.6
Flat-panel	1.5	56		2.64	4.8

Suh and Lee [45] came to the conclusion that for algal commercialisation to be achieved within the next few decades, efforts should be focused on improving the designs of the existing PBRs, and that such efforts should be directed towards improving the lighting efficiencies, gas exchange and mixing mechanisms, temperature and pH controls, and creating more resilient strains of microalgae through genetic biotechnology.

3 Conclusions

To combat climate change and satisfy the ever-increasing world energy demand, it is imperative that sustainable energy sources are developed and deployed. Bioenergy, unlike other renewable energy sources such as wind energy and hydro, theoretically, has the desired potential to provide cleaner, cheaper, and reliable energy (heat, electricity, and energy for transport). Microalgae, a third-generation biomass, can provide solid (microalgae biomass), liquid (e.g., bioethanol and biodiesel) and gaseous (e.g., biogas) fuels which can be used as drop-in replacements for the conventional fossil-fuels. In addition to providing bioenergy, these tiny living unicellular organisms can also find application in other areas such as in the production of high-value products in the pharmaceutical industry and in the waste-water treatment plants. Therefore, there is a huge demand for the commercialisation of microalgae production. As the size of PBR systems for microalgae cultivation increase, factors such as self-shading, photoinhibition, and high energy requirement for both lighting and mixing become more apparent. Other challenges that face large-scale PBRs include: (a) the sustainability of the source(s) of nutrients for microalgae farming; (b) availability of concentrated and uncontaminated carbon dioxide and; (c) ideal means of decontamination. To facilitate the commercialisation of microalgae production, these challenges, especially the technical drawbacks, that currently face the existing PBRs need to be dealt with. Microalgae specialists have also suggested the effort to come up with genetically modified microalgae species as these genetic engineered microalgae species could significantly reduce the technical and financial demands of optimising PBRs. This paper has provided a relatively comprehensive review of the existing PBRs that will encourage and direct efforts towards developing and deploying systems that will facilitate the commercialisation of microalgae production.

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