Evolution of Photobioreactors: A Review based on Microalgal Perspective

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Abstract. Energy is indispensable for bringing competence, resilience, and comfort for the ever-advancing human lifestyle. Therefore, to satisfy the growing energy requirement researchers are trying to delve in exploring sustainable and renewable energy sources that will contribute to the reduction of carbon footprint and ultimately help to check the issue of global warming caused by the increased emission of CO2, due to the excessive usage of non-renewable and exhaustive fossil fuels. Microalgae are having the potential which can be exploited to produce biofuels (substitute for fossil fuels) and other value-added compounds. Microalgae is a form of unicellular photoautotrophic microorganism which can attain higher rate of proliferation. Microalgae is having merits over other terrestrial crops and fossil fuels as they have higher productivity of oil per hectare of land. Various other advantages of microalgae include their tolerance in different types of environment because of their ubiquitous nature (in terms of pH, salinity, and temperature). Furthermore, they can be cultivated in nonarable land and wastewater which will resolve the food-fuel duel and problem of freshwater usage, therefore leading towards environmental sustainability. The main factors governing the growth and cultivation of microalgae are light, CO2/air, nutrients, process parameters (pH, temperature, growth medium etc) and most importantly the type of system used for cultivation. The systems usually employed for the cultivation of microalgae are open system (open ponds, raceway ponds, scrubbers), closed system also commonly known as photobioreactors (flat plate and tubular photobioreactors) and hybrid system in which separation of biomass growth and lipid accumulation is achieved in two stages. All the systems have some merits and demerits but photobioreactors are widely accepted and used because they are having an upper hand over open system because of the optimised control of the growth conditions, contamination evasion and efficient productivity of microalgal biomass. This review will provide an insight to different parameters which govern the growth of microalgae and various types of photobioreactors with their advantages and disadvantages. This study will help in the optimized selection of the photobioreactors for a particular species of microalgae because despite the continuous and intensive research going on the cultivation systems it is a challenge for the researchers to achieve a suitable and economically viable system.

Keywords: Microalgae; Photobioreactors; biomass; open ponds; energy and environment
1. Introduction

Algae are considered as one of the common and impactful living organisms which are having various applications. They can be used as feedstock to produce biofuels, a rich source of pigments and a tool for environmental bioremediation. Various useful products obtained from algal biomass are shown in Figure 1. That is why scientists are emphasizing on algal research to find efficient and viable technologies to be used in the bulk production of algal biomass to match the ever-increasing demand. Figure 2 shows the increasing interest of researchers for the microalgal aspect of photobioreactors in last three decades. Since the natural environmental bodies are lagging in the production of but of algal biomass thus it led to the development of manmade cultivation systems to increase the yield of algal biomass. The initialization off mono algal cultivation was made in 1890 using microalgae chlorella vulgaris, the study focused on the physiology of the algae. It is reported that approximately 5000 tons of dry algae are produced every year on the global scale [1]. It is considered as green gold of future.

There are different technologies which are employed for the mass production of algal biomass i.e., the open systems and the closed systems. Open systems are simple and economic while the closed systems have higher biomass yield as well as they have better control of the operational parameters. Open ponds were used for the cultivation of chlorella pyrenoidosa and scenedesmus and the diatom nitschea palea during World War II in Germany for the purpose of studying their lipid content [2]. Initially the photobioreactors (PBRs) were developed in 1950s. The application of PBRs for the removal of pollutants was first studied at Carnegie Institute, USA in 1953 and the main objective was CO2 sequestration [3]. PBRs are robust cultivation systems which employ the effective cultivation techniques this providing all the essential elements i.e., light, nutrients, temperature and mixing for the healthy growth of microalgae. the operating conditions are monitored, regulated, and controlled for the high yield of algal biomass [4]. PBR can be defined as a closed vessel for the photoautotrophic cultivation of microalgae where energy is supplied by artificial light or sunlight. PBRs can be installed outdoor or indoor depending upon the light collection and distribution together with their commercial feasibility. There are different types of PBRs based on their configuration and operation modes but the most common are flat plate, tubular, and column PBRs. Every microalga based PBRs are having their advantages and drawbacks in terms of operation mode, biomass yield, remediation potential and upscaling level [5]. The research is going on and the PBRs are continuously being modified and improved for the optimization of biomass yield, economic aspects, efficiency in bioremediation, space factors and resilience under varying environmental conditions [6]. This review will focus on the different growth factors and growth modes of microalgae and detailed classification of open and closed system of microalgal cultivation with greater emphasis on the closed PBRs.

Figure 1. Microalgae the green gold of future [7]
2. Factors affecting the growth of microalgae

To attain the maximum production of microalgae via PBRs studies are going on to optimize the shapes of PBRs, regulating and controlling the environmental conditions, gas diffusion in PBRs and operational parameters like temperature, pH etc., (Table 1). The key elements which are responsible for algal growth are light source for the photosynthesis, medium containing proper nutrients and CO₂/air flow [1].

Table 1. Factors affecting growth of microalgae

| PBR Design and Installation | Environmental Parameters | Operational Parameters |
|-----------------------------|--------------------------|------------------------|
| Material                    | Light                    | pH                     |
| Geometric configuration     | Temperature              | Nutrients              |
| Location and Orientation    | CO₂/Air                  | Water and Salinity     |
| Scaling                     | Predation or contamination| O₂ Removal             |
| Surface area to volume ratio|                          | Cleaning               |

2.1. pH

pH defines the alkalinity or acidity of the water medium. The optimum range of pH for the growth of microalgae and photosynthetic ability is 6-8. The variation in pH can affect the growth of microalgae in many ways. During the daytime pH increases due to the photosynthetic assimilation of CO₂ by microalgae and during the night time pH decreases due to the respiratory process of the species [9]. Increase in CO₂ may lead to high biomass accumulation but causes decrease in pH which has an adverse effect on the physiology of microalgae [10].

2.2. Nutrients

For the optimum growth of microalgae phosphorus and nitrogen are required as macro nutrients and Fe, Mg, B, Mo, K, Co, Zn, Mb are required as trace metals. The nutrients especially nitrogen and phosphorus together are of much importance in the production of lipids. Studies have reported that the growth medium which is deficient in nitrogen accelerates the algae to produce more lipids. Both the excess of nutrients as well as their deficiency can cause morphological and physiological changes in microalgae because they impede with the metabolic pathways [11]. Nowadays researchers are going for two phase algal growth, in the first phase micro algae are grown in the medium having excess nutrients and then transferred to the nutrient deficient medium.

2.3. Temperature

Generally, algae can tolerate the temperature range of 15-40°C. Some studies revealed that microalgae can be best grown in the range of 25-30°C. The optimal temperature growth varies with the species of microalgae. It is difficult and expensive to control the temperature in the open cultivation systems because they are more susceptible to overheating, evaporation of the medium, cooling and composition.
of lipids. This is one of the reasons of opting the close systems i.e., the photobioreactors (PBRs), as it is comparatively easier to control the temperature in these systems [10].

2.4. Mixing
Mixing is vital to prevent the problem of sedimentation and to promote the movement of algae between the dark and light regions of the cultivation systems. Otherwise, the algae at the surface will absorb all the light and can become photo inhibited while the algae which is in the inner or deeper part is deprived of the light. Furthermore, it aids in maintaining the homogeneous cell concentration in the medium. Mixing can be done by using mechanical stirrers like paddlewheels in the ponds or by giving bubbling in the PBRs [9].

2.5. Light intensity
The intensity of light and the efficiency of photosynthesis plays a critical role in the productivity of algae as it affects the rate of growth, biomass production and lipid accumulation. The components which affect the light intensity are the density of algal biomass, depth of culture medium and the type of PBR. Increased light intensity is required if the cell concentration and depth of the culture is on the higher side but it should be kept in mind that sometimes direct sunlight and high-density artificial light may also lead to the photoinhibition. Overheating of the system should be avoided. Light intensity of 1000 Lux is appropriate for the culture in Erlenmeyer flasks while about 5000-10000 Lux is required for larger volumes. An important aspect is to provide the light-dark cycles to enhance the efficiency of photosynthesis. Light cycle is required for photochemical phase to produce ATP and NADPH and the dark cycle is provided for the biochemical phase to synthesize the essential biomolecules for the microbial growth [12].

2.6. Predators or invasive species
They can be any type of living organisms, that are totally unwanted and unexpected in the microalgal culture system because they hinder the microalgae growth, cause nutrient deficiency, and pollute the medium. They can be fungi, insects, bacteria, or predator algae species. This is the reason behind the cultivation of extremophilic microalgae at industrial level because they can survive in extreme environment in which the predator species cannot. Open systems are more vulnerable to invasion by predator species while on the other hand close systems i.e., the PBRs helps in preventing the contamination by keeping the algae protected from the external environment [13].

3. Autotrophic vs Heterotrophic vs Mixotrophic Cultivation
Microalgae can go through different types of metabolisms like autotrophic, heterotrophic and mixotrophic [14]. Autotrophic culture is the most common mode of microalgae cultivation. In this cultivation process microalgae directly converts the inorganic carbon present into the organic matter through the photosynthetic process. As most of the microalgal cells are efficient in harnessing solar energy and utilizing CO$_2$ as the carbon source therefore contributing to the abatement of CO$_2$. Hence autotrophic mode is considered as environmentally sustainable and economic mode of microalgae cultivation [15].

In heterotrophic mode of cultivation microalgae use organic carbon for its growth and does not require light. Therefore acetate, glycerol, and volatile fatty acids (VFAs) may be utilized as sources of organic carbon for the synthesis of biomass. In heterotrophic cultivation the biomass yield is better than autotrophic cultivation, but the organic carbon is expensive as compared to CO$_2$. Therefore, to overcome this limitation organic carbon must be utilized from wastewater [16]. Mixotrophic cultivation is to counter the limitations of autotrophic and heterotrophic cultivation modes. So, in this mode of cultivation microalgae is utilizing inorganic carbon through photosynthesis as well as organic carbon.

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1 Adenosine triphosphate
2 Nicotinamide adenine dinucleotide phosphate hydrogen
The mixotrophic cultivation mode is divided into two stages in the first stage the growth is heterotrophic, and the microalgae cells consume organic carbon present in the medium and when it is consumed up to a certain limit the autotrophic growth is induced and the assimilation of organic carbon start taking place [17].

4. Classification of photobioreactors (PBRs): The agencies for microalgae cultivation

The selection and design of PBRs for microalgae cultivation depends upon various factors such as mixing strategy, orientation, surface area to volume ratio (S/V), illumination, air/CO₂ supply, accumulation of oxygen and temperature. PBRs can be closed or open systems having various advantages and disadvantages but closed PBRs have an upper hand due to better control of the operational parameters. The prospects and limitations of both type of systems are summarized in the Table 2.

Table 2. Advantages and disadvantages of open and close PBRs. Adapted and modified [18, 19]

| No. | Advantages | Disadvantages |
|-----|------------|---------------|
| 1   | The construction, operation and maintenance are easy (easy to clean-up). | High risk of contamination by predators and heterotrophs. |
| 2   | Requirement of energy is low. | Poor biomass productivity (0.1-0.2 gm/l). |
| 3   | Economical compared to closed systems. | Harvesting is a tedious job as well as uneconomical. |
| 4   | Better for mass cultivation of microalgae. | CO₂ diffusion to atmosphere, evaporation losses and poor light utilization. |
| 5   | Does not compete with agricultural land. | Requirement of large area/space. |
| 6   | Solar trackers can be used for the cultivation in open systems. | Limited to few strains of microalgae and difficult to grow for long periods. |
| 7   | The construction, operation and maintenance are easy (easy to clean-up). | The CAPEX and OPEX is high. |
| 8   | Better control of culturing conditions and growth parameters. | Chances of overheating and biofouling. |
| 9   | Reduction in water and CO₂ losses. | Accumulation of oxygen can decrease the biomass yield. |
| 10  | Higher microalgal density, concentration and biomass productivity is achieved (2-8 mg/l). | The formation of algal biofilms causes fouling of PBR surfaces hindering the light penetration. |
| 11  | No or little risk of contamination or invasion by the predators | There is difficulty in scaling up of microalgae. |
| 12  | Higher biomass ratio is attained. | Shear stresses may damage the cells. |

4.1. Open systems

Microalgae cultivation in open ponds using the energy obtained from sunlight has been regarded best for the past six decades and can be carried in covered or open places, artificial basins and natural water bodies like lakes and lagoons [20]. Some of the open systems are regarded as favorites due to their simple and economical construction and high production capacities like circular ponds and raceway ponds. Compressed earth and concrete are the building materials for the construction of open ponds. While the closed ponds are generally constructed using acrylic or plexiglass which cost higher than the open ponds but comparatively less than the closed PBRs for the same cultivation conditions [21]. To fulfill the requirement of nutrients for the cultivation of microalgae nowadays the researchers are going for the integration of microalgae cultivation with wastewater treatment plants as a measure of phycoremediation and to minimize the upstream processing cost. Open systems are significant in terms of the
ease of scalability, economical perspectives, and massive microalgal biomass productivity. Albeit they have many advantages, but unmonitored light intensity and temperature can affect the tolerance of the microalgae thus reducing the biomass productivity. Poor light distribution is also an issue as the light can reach up to a certain depth thus the light distribution is uneven and open ponds can also not hold the optically dark zones [22]. Different configurations of open bioreactor systems are discussed in the following sections.

4.1.1. Raceway ponds. In this type of open systems microalgae culture is recirculated along the racetrack loop. They are made shallow with a depth of 15-50 cm to enhance the exposure to sunlight and subsequently good growth rate of microalgal cells [22]. The configuration is equipped with paddle wheels to provide recirculation and mixing as well as the baffles to direct the flow at the bends. The system is operated on a continuous basis with the help of paddle wheels to avoid any chances of sedimentation {Figure 4 and 5}. So that the algae cells are suspended within the culture medium during the cultivation cycle with simultaneous influent feed of microalgae broth and nutrients at the feeding port which is there at the front of paddle wheel. After the complete circulation in the loop microalgae containing water is removed at the harvesting port which is in the rearmost of the paddlewheel [23]. The turbulent mixing abets uniform density of microalgae and the formation of eddies will reduce the residence time of algae in the dark regimes. Microalgae cultivation gravitates towards open raceway ponds due to the advantages possessed by them. The world’s largest raceway pond is being operated at Calipatria (USA) meant and specialized for the mass production of spirulina based products occupying a tremendous area of 4,44,000 m² [24]. The algae species reported in previous studies which are cultivated in this type of reactor system are spirulina, chlorella, dunaliella, haemotococus.

4.1.2. Circular pond system. The ponds have depth of 20-30 cm and diameter 40-50cm. It is the circular pond in which movement and mixing of the culture is assisted by a central pivot rotating agitator {Figure 4 and 6}, but it can only facilitate up to a size of 10,000 m² [25]. The CAPEX and OPEX is too high which is a barrier for circular ponds to be implemented for commercial scale. The other bottlenecks are the problems of temperature control and the vulnerability to contamination. In Asian countries it is cultivated commercially for chlorella sp. To overcome the limitations of open ponds and provide better control of microalgae culture conditions, researchers are going for closed ponds by just covering them with green house and reducing the problem of contamination associated with open ponds [20].

4.1.3. Inclined surface system. In this type of system, microalgae suspension flows over the planes having slope and given a cascade arrangement. The thickness of layer is < 1 cm and the arrangement facilitate the turbulence preventing the self-shading. Surface area to volume ratio of 130/m can be operated in these systems leading to high volumetric productivity (Figure 3). Due to short optical path high densities of 15-35 g/l can be operated. Productivity of 40g dry matter m²·d⁻¹ can be achieved even in temperate zones [26].
4.2. Closed system
Closed systems are studied and recommended to overcome the limitations of open systems. The growers are concerned to cultivate monoculture of microalgae in axenic enclosed PBRs which offer lower or no contamination chances in the production of biochemical and high value metabolites. It is a man-made closed vessel that helps microalgal cells to carry out photosynthesis in artificial illumination or sunlight as the source of energy [28]. Closed PBRs are generally characterized by the geometric configurations and the commonly manufactured closed PBRs are vertical and horizontal tubular PBRs, vertical column PBRs (bubble column and airlift systems), and flat panel PBRs. In the family of photobioreactors closed PBRs are 5 to 10 times more efficient than the open systems because they are having high surface to volume ratio but at the same time, they are uneconomic [29].

4.2.1. Flat panel PBRs. It is having a cuboidal shape of flat panels (plexiglass, polycarbonate, or plastic bags) from which dense microalgal culture is passed [30]. Since it has high surface area to volume ratio and cell densities, making it suitable for algae wastewater co-cultivation, as well as pure algae culture. The agitation is given by air bubbling or by the mechanical rotation of a motor through the perforated tube. Bubbling provides the mixing, prevents the oxygen accumulation, nutrients transfer and light distribution in an adequate manner [23].
Flat panel PBRs have many advantages for mass culture as the risk of accumulation of dissolved oxygen is less with high photosynthetic efficiency as compared to other closed PBRs. Self-shading of microalgae cells between the flat plates may disrupt the photosynthetic efficiency and microalgae growth. To overcome this problem LED lights can be used for the additional illumination [31]. Continuous research is going on to assess the microalgal biomass scale-up and lipid productivity in flat panel PBRs. Different views and photos are shown in Figure 7 and 8.

![Diagram](image-url)

**Figure 7.** Side view and front view of flat panel PBR [32]

![Pictures](image-url)

**Figure 8.** Pictures showing flat panel PBR [33]

4.2.2. Tubular PBRs. They are manufactured using plastic tubes, straight glass that are arrayed in vertical, inclined, or helical configuration, and fence like and horizontal [20]. The basic design principle of tubular PBRs can be divided into two parts. The first part is the tubular part or the reactor in which the microalgae are grown and the second one is the degasser unit which is used to remove the gas and the pump system which provides circulation and mixing of the microalgae culture (Figure 9). Optimum light penetration is the prime aspect leading to high biomass productivity by photosynthesis. Solar array is designed with small diameters up to 0.1 m to increase the light penetration through the dense microalgal culture.
Microalgae culture is circulated from the degasser unit to the solar array and return to the degasser unit in continuous operation mode. The configuration can be understood from the Figure 10. Usefulness of tubular PBR is proven for many existing operation modes such as semi-batch, batch, turbido-static and continuous thereby making it the most reliable type of PBR for scaling up due to better control [30].

4.2.3. **Vertical column PBRs.** These PBRs are economical, have easy operation and better control. Microalgae is cultivated in large volume of cylindrical shaped vessels. Vertical column PBRs can further be classified into bubble column or airlift reactors based on their flow pattern. A gas sparger system is the significant feature which is installed at the bottom of the reactor and converts the influent gas or air into tiny bubbles which are the driving force for the mixing, mass transfer of CO₂ and removing the O₂ produced during photosynthesis [13]. **Bubble column** PBRs are designed with height greater than twice their diameter. They have the features like low CAPEX, high surface area to volume ratio, satisfactory heat and mass transfer, relatively homogeneous culture density and no moving parts. Gas bubbling is provided by the spargers therefore the design of the sparger is critical relative to the area and volume of the cylinder. The illumination for autotrophic cultivation comes from outside the reactor but now days internal illumination is also getting acceptable because of higher light penetration capability and better light distribution. Photosynthetic efficiency and biomass yield greatly depends upon the gas flow rate and light/dark cycles are created when the liquid is circulated on regular basis from central dark zone to peripheral zone at a higher gas flow rate [34].

**Air lift** PBRs are designed on the principle that the cylindrical vessel is divided in interconnecting zones. The inner tube is called as gas riser or the up corer where the gas mixture flows upwards to the surface from the sparger. While in the outer portion called as the downcomer the medium flows downwards and circulates again into the riser. Further they can be subdivided into (a) draft tube airlift PBR and (b) Split cylinder PBR (Figure 11). In the former system a tube is inserted into the centre of the main cylindrical vessel two draft and the flow is forced in opposite direction. In the later one the culture flow in the cylinder is carried out with a rising region and the refluent region the design and flow directions can be understood from the Figure 11. Air lift PBRs are the systems in which mixing, gas transfer and air supply are carried simultaneously [19]. Table 4 shows pros and cons of various types of PBRs discussed in this paper.

The productivity of microalgae using different PBRs varies depending upon the type of microalgae species, type of PBR, light conditions and medium of nutrients used for the cultivation of microalgae. Performances of some of the PBRs with specific operating conditions with the species of cultured algae are shown in Table 4. It was found that flat plate PBRs have the highest biomass concentration and productivity followed by column and tubular type of PBRs.
Figure 9. Pictures showing tubular PBRs [35]

Figure 10. Mechanism in a tubular PBR [36]

Figure 11. Configurations of Bubble column and airlift PBR [37]

Figure 12. Pictures showing vertical column PBRs [33]
Table 3. Salient features and limitations of various closed PBRs [12, 19, 38]

| Type of closed PBRs       | Salient features                                                                 | Limitations                                      |
|---------------------------|----------------------------------------------------------------------------------|--------------------------------------------------|
| Flat panel PBRs           | • Large illumination surface area                                                | • Difficulty in controlling culture              |
|                           | • Low oxygen build-up                                                            | • Possibility of algal wall adhesion             |
|                           | • High biomass productivity                                                      | • Scaling-up requires support materials          |
|                           | • Economical installation and operation                                          | • Small degree of hydrodynamic stress            |
|                           | • Good immobilization of microalgae                                              |                                                   |
|                           | • Have good light path and easy to sterilize                                     |                                                   |
|                           | • Suitable for outdoor cultures                                                 |                                                   |
|                           | • Temperature control can be monitored effectively                              |                                                   |
|                           | • Mass transfer can be improved by installing internal mixers                   |                                                   |
|                           | • Good biomass productivities                                                    |                                                   |
| Tubular PBRs              | • Economical and suitable for outdoor cultivation                                | • Difficulty in scaling-up                       |
|                           | • Temperature control can be monitored effectively                              | • Accumulation of O2                             |
|                           | • Mass transfer can be improved by installing internal mixers                   | • Acidification may occur due to inadequate fixation of CO<sub>2</sub> |
|                           | • Good biomass productivities                                                    | • Requires large land space                      |
|                           | • Economical and suitable for outdoor cultivation                                | • High microalgae density can shade light penetration in the tubes |
|                           | • Suitable for outdoor cultures                                                 | • Some degree of wall growth and fouling         |
|                           | • Temperature control can be monitored effectively                              | • Sedimentation of microalgal cells              |
|                           | • Mass transfer can be improved by installing internal mixers                   | • Random flow pattern with the microalgae cultivation |
|                           | • Good biomass productivities                                                    |                                                   |
| Bubble column PBRs        | • High potential of scalability                                                  | • Scale up process is difficult                  |
|                           | • Reduced photoinhibition and photooxidation                                     | • Insufficient turbulence creation by the airlift mechanism |
|                           | • High mass transfer due to sparging                                             | • Restricted working volume due to the insertion of additional shaft |
|                           | • Bubbles promote light scattering and penetration                               |                                                   |
|                           | • Reduced physical stress to microalgal cells                                    |                                                   |
| Airlift PBRs              | • High productivity and biomass concentration                                   |                                                   |
|                           | • Efficient light utilization                                                    |                                                   |
|                           | • Comparatively economical                                                      |                                                   |
|                           | • High CO<sub>2</sub> utilization efficiency                                     |                                                   |
|                           | • Good for immobilization of microalgae                                          |                                                   |
Table 4. Performance of different types of PBRs with operating conditions

| Type of PBR  | Algae Species                          | Light Intensity (μmol/m²·s) | Source of Light/Light-Dark cycle (h:h) | Biomass Concentration (g/l) | Biomass Production (g/m²·d) | Ref. |
|-------------|----------------------------------------|----------------------------|--------------------------------------|-----------------------------|-----------------------------|------|
| Flat plate  | *Botryococcus braunii*                  | 100                        | Fluorescent/24:0                     | 96.4                        | 0.71                        | [39] |
| Flat plate  | *Chlamydomonas reinhardtii*             | 1500                       | LED/24:0                            | 4.5                         | 29–54                       | [40] |
| Column      | Green algae (genus *Chlorella* and *Stigeoclonium*) | 204                        | Metal Halide/12:12                   | 0.49–0.84                   | 0.039–0.084                 | [41] |
| Column      | *Dunaliella tertiolecta*                | 1000                       | LED/Continuous                       | 19.78                       | 10.18                       | [42] |
| Tubular     | *Phaeodactylum tricornutum*             | 50–700 W/m²                | Sunlight/Natural cycle               | 0.2–12                      | 1.4–3.29                    | [43] |
| Tubular     | *Nannochloropsis salina*                | 500                        | LED/24:0                            | 7.2                         | 0.888                       | [44] |

4.3. Membrane Photobioreactors (MPBR)
In a nutshell the open systems have the limitation of susceptibility to contamination and inadequate control of the operational parameters. While in closed PBRs the problem of washout persists, which causes reduction in concentration of obtained biomass. Since microalgae are having a smaller size and negligible relative density as compared to water, they are difficult to settle, rather they form homogeneous suspension. Therefore, it is almost impossible to decouple the retention time of microalgae (MRT) from the dilution rate (D) in an ordinary PBR merely using settling but this can be achieved by using membrane photobioreactor (MPBR)[45]. Using MPBR serves two purposes i.e., they help to hold the biomass inside the reactor (preventing washout) and assisting CO₂ transfer. MPBR provides complete retention of microalgae cells while the medium passes through (as permeate) thereby enhancing the concentration of biomass in the bioreactor. The biomass concentration can be better controlled by partly returning the retentate. As the biomass is concentrated in the retentate stream, the permeate can be reused as feed medium. PBRs coupled with membrane for harvesting algal biomass and wastewater treatment are shown in Figures 13 and 14.

As discussed in earlier sections of review that microalgae can be used to treat wastewater and simultaneously produce biofuels, compensating the cost in an ecologically sustainable manner. To make this technology feasible it is again necessary to separate and harvest the suspended algal biomass from water both to produce biofuels and to get better effluent after wastewater treatment. Although this has proven too difficult and uneconomical hence, to overcome these problems researchers are studying and employing the membranes in PBRs. The membrane will act to separate solid and liquid, thereby helping to isolate the microalgal cells from the effluent[46]. Furthermore, the hydraulic retention time (HRT) and solids retention time (SRT) of the bioreactor can be controlled independently during the culture and the microalgal biomass concentration is not affected by the hydraulic loading and the growth of algal cells. Consequently, improved performance in terms of nutrients/pollutants removal and algal biomass productivity can be achieved in MPBR [47].
Conclusion
The review concludes that PBRs have better control of cultivation conditions as well as higher productivity as compared to open systems and natural water bodies. PBRs are expensive as compared to open systems but this bottleneck can be resolved by enhancing the yield of microalgal biomass and deriving various other useful metabolites. The review provide an insight to the factors responsible for the optimum growth of microalgae with different modes of growth. The details of different types of open systems and PBRs are elaborated with the figures to understand the mechanism of their operation and their prospects. Since all the PBRs are having advantages and disadvantages therefore having a clear understanding of the features will help the phycologists to choose the suitable PBR for their research.

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