USE OF PHOTOBIOREACTORS FOR ALGAL MASS PRODUCTION

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Abstract

The cultivation of microalgae has attained much involvement in the case of the various food productions, biofuels production, and also in the production of many bio-active compounds by providing a possibility of environment cleanliness via the CO_2 segregation and the treatments of waste-water. The open cultivation systems like the open ponds are highly economical but these are highly prone to contamination and uncontrolled growth issues. So, in comparison, the closed cultivation systems like the photobioreactors are less prone to contamination, and they provide better and easily controlled growth conditions that include the supply of carbon dioxide and water, balanced temperature ranges, proper light exposure, the optimized levels of pH and the higher transferring rate of mass and heat. For massive biomass productivity, there is a need for effective and well-designed photobioreactors. This review paper discussed the various types of photobioreactors, with the purpose of microalgae biomass cultivation. This paper also highlights the advantages and drawbacks of already developed closed systems (photobioreactor) while covering the recent developments and modifications in this field for the economical cultivation of algal biomass.

Keywords: Biofuels, Cultivation, Microalgae biomass, Photobioreactors

Introduction

It has become prominent that the continued dependence upon these fossil fuel energy sources is temporary due to the world's energy resources have been wiping out. More than 80 percent of the world depends upon fossil fuels for their energy requirements whereas its extreme usage promotes environmental contamination and other health-related problems (Hallenbeck and Benemann, 2002). So therefore various researches have been planned with the purpose to develop substituting renewable energy resources and the potential liquid and gaseous biofuels as the substitute of the energy sources (Chisti, 2007).

The increasing usage of fossil fuels with their negative effects on the environment stimulates the scientists to work on the development of other sources of energy other than them that will have fewer or no side effects on the environment and they should also be economical. Whereas the biofuel production systems (lignocellulosic and algal biofuel system) can get over these problems and to generate the new clean energy sources. So the algal production of biofuels means the 3rd generation is observed to be a more reliable source as it has fewer drawbacks compared to the 1st and 2nd generation systems. Because the algae are the simplest organisms with easy growth demands like carbon dioxide, light and other sources of nitrogen, phosphorus and potassium and they are capable of producing carbohydrates, proteins and lipids in a very short time duration. These products can be further refined into biofuels and other important co-products (Singh and Sharma, 2012).

However, microalgae production is considered a viable approaching idea to overcome global warming because the oil produced from the algal biomass is more important and beneficial apart from the fuel. So the microalgae have been mainly acknowledged as the raw material for the 3rd generation of biofuels (Chisti, 2007), and this review article mainly discussed the study on the algae production and photobioreactor modeling.

1. General properties of algae

The green algae and the cyanobacteria (blue-green algae) constitute an immense group of photosynthetic organisms that grow quickly (Solmaz and Isik, 2019). Algae are considered to be the most important organisms on earth that can grow in a broad range of conditions. Algae normally reside in damp areas or in the water-bodies and also exist in the aquatic and in terrestrial surroundings (Pelczar *et al*., 2008). Algae are widely distributed over the biosphere and grow in a vast range of conditions including the aquatic or even the terrestrial environments. The individuality that isolates the algae from the various types of microorganisms is the existence of chlorophyll and its ability to carry out the process of photosynthesis in a single-cell, that facilitates the easy-going biomass production and the research in the field of metabolic and genetics. The main constituents of the algae include a prominent nucleus, some important pigments, a cell wall, stigma, a surface covered with the starch granules, chlorophyll in the chloroplast and flagella (Pelczar *et al*., 2008). The filamentous blue-green algae can distinguish the various types of cells (including the heterocyst, akinetes and the vegetative cell). The purpose of the previously mentioned cells includes their quality of carrying out the oxygenic process of photosynthesis and also the way they resist the climatic fluctuations and their best potentials of nitrogen-fixing.

Microalgae constitute a vast collection of the prokaryotic and the eukaryotic cyanobacteria. The essential feature is their higher growth rate that means the doubling of the biomass within the hours that makes them the important organisms. Besides, their growth is related to various advantageous environmental concerns that have been extensively studied in recent years (Kumar *et al*., 2011) carbon dioxide capturing, production of the biomass; and the consumption of the nutrients from waste-waters. Because of their important chemical composition, microalgae have various roles in the nutrition of humans and animals, in the cosmetic area, and also in the fields of pharmaceutics and biofuels (Brennan and Owende, 2010). One crucial problem is the improvement in the design of the photobioreactors. The design of photobioreactors and its operational conditions should promote the growth of microalgae, which helps to gain increased biomass production. The photobioreactor modeling leads to speedy progress in the improvement of its design and geometry, targeting to enhance biomass production (Cuaresma *et al*., 2011).

2. **Algal cultivation**

2.1. Algal Cultivation in Open System (Ponds):

Open cultivation systems for algal production just like the pond systems are inexpensive to build. Larger ponds exhibit the ability to give the largest production compared to other systems of equal cost. Likewise, an open pond cultivation system can exploit odd conditions that favor the growth of only some specific algae. For example, *Spirulina* sp. grows best in water containing a high amount of sodium bicarbonate. Open cultivation systems can work best to obtain high biomass of desired algae as a starter culture to inoculate the ponds. Just because of the simple nature and the inexpensive operating and production costs, these open pond systems are of much importance (Ugwu *et al*., 2008). These open pond systems are classified into two major types 1) natural waters including the lakes, ponds, and lagoons 2) artificially created ponds. The "raceway ponds" are the ones in which the algae have been grown normally. In these ponds, the nutrients, algae, and water loco mote in a race-track pattern (Fig. 1). The paddle wheels aid the rate of flow, and the algae present in the water, are moved back at a relative speed to the surface. As the algae require sunlight exposure, and sunlight can perforate only to the restricted depth of the pond water, so these ponds are normally kept shallower.

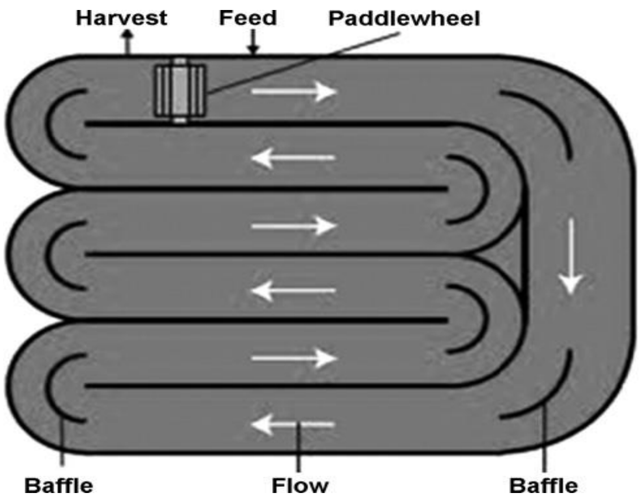


Fig 1: Schematic diagram of raceway pond adopted from (Adopted from Singh & Sharma, 2012)

The poured concrete is normally used to build these raceways or they could also be built by only digging the earth following its inner lining with the plastic liner so that the ground couldn't take up the liquid. Whereas the flow around the bends of these raceways is controlled by using the baffles just to decrease the space. The system is frequently treated continuously, in which the fresh feed that includes nutrients mainly of phosphorus, nitrogen, and inorganic salts is introduced in front of the paddle-wheel and the algal growth is collected from behind the paddle-wheel. Different algal species require different nutrients, so various types of wastewater can also be utilized for algal growth (Borowitzka, 1999). For few algae species that live in marine surroundings, seawater, or water with higher salt concentration can be utilized. The disadvantage of this system is that the surrounding environments of these open ponds cannot be controlled, so they are more prone to the problems of microbial contamination including the other species of algae or bacteria. The other drawback of these open systems is the uncontrolled temperature and light, so the closed systems are more preferable over the open system (Brennan and Owende, 2010). The growth of the algae mainly depends upon their location as the bad or contaminated air stops or inhibits the algal growth. Leading hurdles in open ponds consist of the following the uneven light strength, evaporative losings, distribution of carbon dioxide to the air, and most importantly the need for spacious land areas (Cuaresma *et al*., 2011).

Moreover, the interference by the predators and the growth of the other rapidly thriving heterotrophs have confined the algal production under the open pond systems in such a way that only extremophilic organisms can grow here. Likewise, the deficiency of the mixing procedures results in the decreased rate of mass transferring that in turn affects the rate of biomass production (Brennan and Owende, 2010). Whereas in the closed system of algal-cultivation the environment is much better controlled compared to open systems. The difference between the open and closed systems is that the covering of the latter one is done with the transparent barrier converts it to the form of a greenhouse. In the construction of these closed cultivation systems, plexiglass is being used. The advantage of using closed one is that it provides the nutrients for the growth of any species, and it also allows the grown species to stay predominant and the heating of the pound can per-long the growth of the species. The enhanced amount of carbon dioxide in the Quasi-closed systems favors more algal growth.

3. **Different cultivation conditions affecting the production of microalgae**

The cultivation conditions significantly control the growth characters and the microalgal composition. There are four important forms of cultivation conditions mainly used for algae production (Chojnacka and Marquez-Rocha, 2004) described precisely in the following portion.

3.1 Mixotrophic Cultivation: Under the mixotrophic conditions of cultivation, the microalgae perform the photosynthetic process by utilizing both the inorganic and organic compounds as their source of carbon that ultimately helps in their growth. So the microalgae acquire the organic compounds and carbon dioxide as a source of carbon, whereas the carbon dioxide discharged by microalgae through the process of respiration will be utilized in the phototrophic conditions of cultivation (Mata *et al*., 2010). For algal oil production, this type of cultivation condition is used less comparatively with the phototrophic and heterotrophic conditions.

3.2 Photoheterotrophic Cultivation: Under the photoheterotrophic cultivation conditions, the microalgae need light while utilizing the organic compounds for their source of carbon. The obvious difference between the above-mentioned cultivation and the photoheterotrophic cultivation condition is that the second one needs light for the energy source whereas the mixotrophic cultivation utilizes the organic compounds for this purpose. Therefore, the photoheterotrophic conditions require both the light and sugars simultaneously (Chojnacka and Marquez-Rocha, 2004). So this type of cultivation condition could be used to increase the production of some beneficial light-regulated metabolites (Ogbonna *et al*., 2002), but these cultivation conditions are used very less for bio-diesel production just like the mixotrophic cultivation.

3.3 Heterotrophic Cultivation: This type of cultivation is defined as when the algae utilize the organic carbon for their both carbon and energy source (Chojnacka and Marquez-Rocha, 2004). This type of cultivation helps to overcome the troubles related to the restricted light source that in turn obstruct the increased cell density in large-scale photobioreactors under the phototrophic conditions of cultivation (Huang *et al*., 2010). The heterotrophic conditions result in the increased production of biomass and also in a higher productivity rate. Few microalgae species exhibit higher lipid content as they grow under the heterotrophic conditions, i.e., 40 % increase in lipid content was observed in *Chlorella protothecoides* species by alternating their conditions of cultivation from phototrophic to the heterotrophic conditions (Xu *et al*., 2006).

Various species of the microalgae can utilize a variety of organic-carbon sources (that includes glucose, sucrose, fructose, mannose, lactose, acetate and glycerol) that promote their rapid growth (Liang *et al*., 2009). Many experiments have been done just to explore the cheapest sources of organic carbon for example the use of corn powder hydrolysate (CPH) as an alternative to sugars, that ultimately results in higher biomass production (2 gram/L/d) and higher lipid content (932 milligram/L/d) (Xu *et al*., 2006). Thus the heterotrophic growth conditions result in higher lipid productivity, as the highest lipid productivity obtained from heterotrophic conditions is almost 20 times more than that obtained by using the phototrophic conditions. The heterotrophic cultivation system, which depends upon the sugars mostly experience the issues of contamination.

3.4 Phototrophic Cultivation: Under phototrophic cultivation, the microalgae can utilize light (sunlight), as their source of energy (Zhu *et al*., 2019) and they use the inorganic carbon (carbon dioxide) as their source of carbon to produce chemical energy via the process of photosynthesis (Huang *et al*., 2010). This type is usually used for the cultivation condition of microalgae growth (Gouveia *et al*., 2009; Gouveia and Oliveira, 2009; Illman *et al*., 2000; Mandal and Mallick, 2009; Yoo *et al*., 2010). Different algal species undergo variations in their lipid content (from 5 to 68 %) during the phototrophic cultivation. The lipid content in microalgae could be enhanced by limiting its nitrogen source or any other important nutrient source resulting in decreased biomass production. As both the lipid content and biomass production should be focused at the same time. So the joint effects of the oil content and the biomass production result in the production of lipids and this effect is used as a measure to check the ability of microalgae to produce oil. The *Chlorella sp*. were able to produce the highest lipid content as mentioned in the literature (179 mg/L/d) upon exposure to phototrophic cultivation by using 2 % of carbon dioxide (Chiu *et al*., 2008). The main point of providing autotrophic cultivation to produce microalgal oil is the uptake of carbon dioxide as a carbon source for their algal growth and production of oil. Furthermore, in comparison with other conditions of cultivation, there are few chances of contamination under the autotrophic growth conditions. Thus, the phototrophic conditions are preferred in the outdoor cultivation environments for microalgae like the open ponds & the raceway ponds (Mata *et al*., 2010).

4. Photo-bioreactors

A photo-bioreactor is an enclosed, well-lighted culture vessel specially planned for the controlled production of the algal biomass. It is also termed a closed cultivation system and it involves the usage of an electric pump to circulate the media and algae within the system (El Shenawy *et al*., 2020). As there is no exchange of the gases and the other contaminants between the environment and the photobioreactor vessel, so it is considered as a closed system.

4.1 Modeling and designing of the Photo-bioreactors: The reactor should be designed in such a way that it allows the growth of the various algal species. The non-illuminating part should be designed less in the photo-bioreactors. The design of the photo-bioreactor should enhance the mass transferring rates.

4.2 Types of the Photo-bioreactors used mainly for the Algal Production

4.2.1 Vertical Tubular Photo-bioreactor: It consists of vertical tubing that permits the absorbance of the light because of its transparent nature. These reactors consist of the sparger at its end that changes the gasses in the form of small bubbles. So, this process aids the net mixing in the reactors, it also helps in transferring the carbon dioxide and in the removal of oxygen in the photosynthesis process (Kumar *et al*., 2011). These photo-bioreactors can be classified into two other important types of photo-bioreactors namely the airlift and the bubble column reactor based on their flow pattern.

4.2.2. Airlift bioreactors: This reactor consists of the two inter-connecting zones within the vessel. One part is named as riser because here the mixture of gas is sparged and the other one is named as the down-comer because it involves no interference of the gas (Fig. 2). Mostly airlift reactors are present in two types one is the internal loop and the second one is the external loop. In the former type, a draft-tube is used for the isolation of the parts whereas, in the latter reactor, different tubes are used for the parts (riser and the down-comer) isolation. Mixing is done by bubbling the gas through a sparger in the riser tube without any physical agitation. The riser of the airlift reactor is almost the same as the bubble-column the sparged gas moves in an irregular pattern in an upward direction and this movement is being done by the riser's gas hold up. Gas gets separated from in the special zone named as a dis-engagement zone.

The fluid dynamics involved in the airlift reactor is greatly affected by the gas present in the down-comer. The liquid is degassed locomotes in the downward direction in a laminar manner with proper orientation. The main focus while designing and modeling an airlift reactor is on the increased deviation of gas holdup between the down-comer and riser. The main feature of this bio-reactor is its specific mixing pattern that allows the movement of the liquid via the light and dark portions providing the flashing light to the growing algal cells (Barbosa *et al*., 2003). The stay time of the gas in different portions controls the efficiency of the various parameters including the transfer of heat, stirring, and turbulency. Several modifications can be made to this reactor. The main type of airlift photo-bioreactor is the rectangular airlift that exhibits the best stirring capabilities and photosynthetic abilities but the major drawback is its level of complexity. The model of the external looped airlift photo-bioreactor that has the swirling movement was given by Loubierre *et al*. (2009).

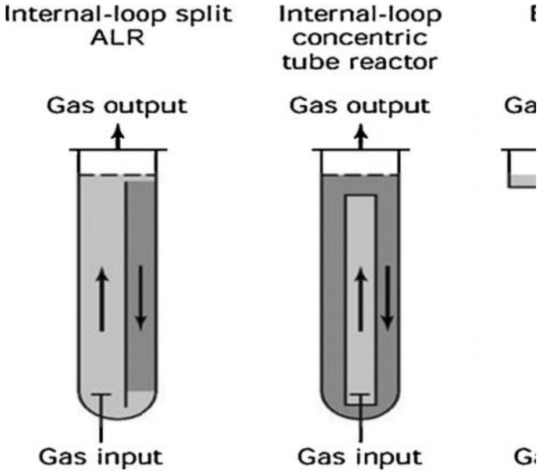


Fig 2: Various types of Airlift Bio-reactors adopted from (Adopted from Singh & Sharma, 2012)

4.2.3. Bubble-column Photobioreactor: Bubble-column reactors exhibit the cylindrical shape of the vessel with a height to diameter ratio of 2:1. The main benefits of this reactor include the absence of the moving parts, controlled transfer of biomass and heat and relatively consistent culture conditions, and also the proper release of oxygen.

Sparger is used for mixing as well as the transfer of CO_2 (Fig.3). Scale-up plates, that have perforations in them, break down the bubbles that are produced and distribute those (Doran, 1995). Light is given from the outside. The efficiency of photosynthesis is dependent upon the rate of flow of liquid in the light as well as in the dark cycle, as the liquid moves around continuously from the central darker zone towards the external zone of photic at the higher flow-rate of gas. When the rate of flow of gas is lower than 60.01 ms−, the pattern of circulation is absent due to the lack of back mixing (Janssen *et al*., 2003). The efficiency of photosynthesis can become higher when the rate of flow of gas leads to light and dark cycles of a shorter length.

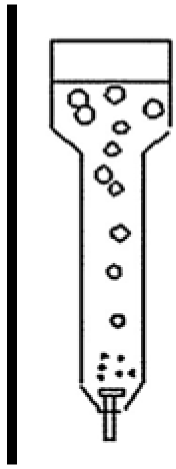


Fig 3: Schematic diagram of Bubble-Column Bio-reactor adopted from (Adopted from Singh & Sharma, 2012)

4.2.4. Flat Panel Photobioreactor: This reactor is cuboidal in shape with a minimal light path as shown in Fig.4. Transparent materials including glass, plexiglass, and poly-carbonates are used to make these types of reactors. It has the advantage of its higher surface area to volume ratio and most importantly the systems of open gas disengagement operations. In this reactor, the bubbling air is used for agitation by the mechanical rotation via the motor. A flat panel was assembled up by Barbosa *et al.* (2005) by holding together the lexans in stainless steel having a higher surface area to the volumetric ratio. Ten fluorescent tubes were used for the reactor's illumination (Barbosa *et al*., 2005). The involvement of baffles to increase the agitation was done by Iqbal *et al.* (1993); Zang *et al*. (2001) altered flat panel reactor system with regard to some engineering properties like by modifying its V shape to attain the increased mixing rate, by eradicating escape corners which decreases the shear stress Tredici and Zittel, (1998) organized kind of horizontal flat panel system which was branched longitudinally into further five more channels with two plexiglass one at the bottom while the other one is at the top. The airlift manner of circulation in a flat-panel system was introduced by Degen *et al*. (2001). Moreover, the attachment of the baffles to the front and back of the panel's larger sides is considered another important attribute of the flat panel system of cultivation.

These types of reactors are commonly used in small production scale level of microalgae but are not preferable at commercial level production because of the demand for many partitions. These reactors also exhibit the problems of temperature controlling and the hydro-dynamic stress generated from the aeration while these problems are absent in other tubular reactors (Ugwu *et al.,* 2008).

Furthermore, there are many issues like surface bio-fouling, the aeration created stress, sterilization problems, and contradictions with the equipment of the fermentation industries (Sierra *et al.,* 2008).

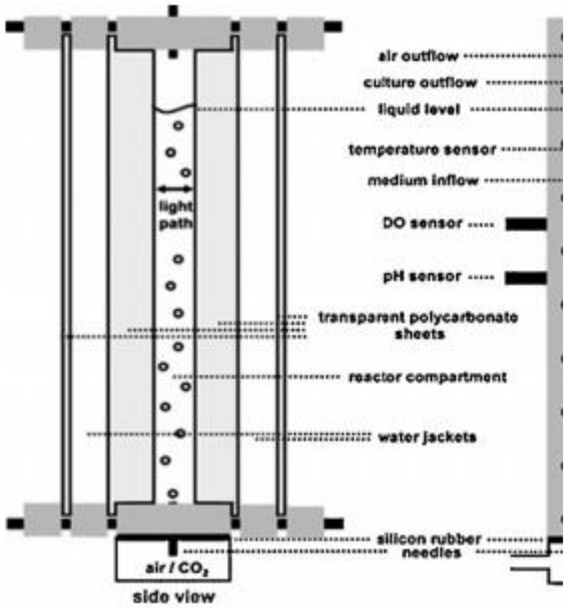


Fig 4: A side view and Front view of the Flat panel photo-bioreactor adopted from (Adopted from Singh & Sharma, 2012)

4.2.5. Horizontal Tubular Photobioreactor (PBRs): This type of photobioreactor is the most important one and most commonly used. The major difference between these and vertical column reactors lies in their surface to volumetric ratio, the quantity of the dispersed gas, the liquid mass transferring attributes, the pattern of the fluid movement (Sanchez Miron *et al.*,1999). Horizontal tubular PBRs (Fig. 5) are essential consists of many tubes organized in various achievable directions, like in horizontal direction, inclined direction, spiral direction, and helicoidally direction all working in the same manner. Besides the management of the tubes, tubular PBRs vary in the length of their tube, flow velocity, the system of circulation, and geometrical configuration of the light-receiving system.

Generally, the range of the diameter of the tube is from 10-60mm and they have lengths of many hundred meters and these tubes mainly aid the attainment of a higher surface to volumetric ratio thus making this prominent feature of this reactor (Posten, 2009). Whereas the increased diameter leads to the decreasing surface volume ratio that strongly affects the growth of the culture. The purpose of using a lens or the focusing effect is to distribute the light equally (Posten, 2009). The oxygen accumulation at the level of inhibition leading the drawback of horizontal tubular photo-bioreactors. The horizontal tubular PBRs are specifically considered to be the most feasible system of microalgae culturing but it is reported by Sanchez Miron *et al.* (1999) that these horizontal tubular PBRs are not cost-effective for large-scale productions because of its need for the cooling system. Furthermore, the light inhibition issues lead to the decreased rates of productivity compared to the airlift reactor and the bubble-column reactor.

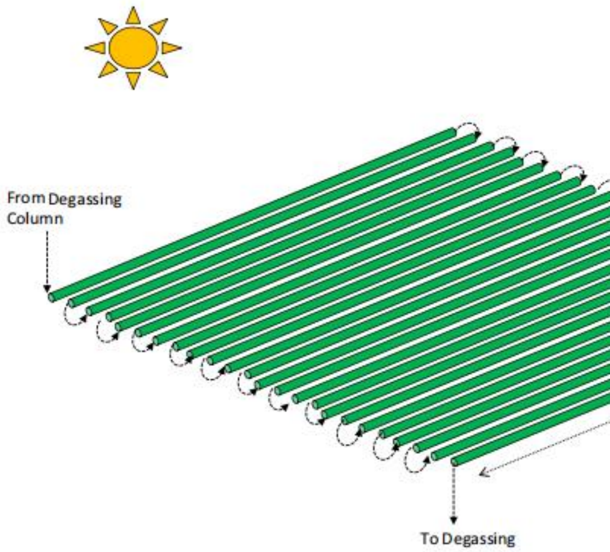


Fig 5: Schematic presentation of Horizontal Tubular PBR adopted from (Adopted from Gupta *et al*., 2015)

4.2.6. Stirred Tank PBR: The conventional aerated type of bioreactor is the stirred type. The mechanical agitation is used for the sake of mixing (Fig 6), an electric motor is used for this purpose (Sero *et al*., 2020). The major constituent of the stirred tank bioreactor is the agitator also known as the impeller, which is responsible for performing many important roles like transferring heat and mass, to supply air and homogeneous mixing (Doran, 2013). Baffles are also being used to minimize vortex mixing. So there is a need for more input energy. Normally 70-80 percent of these reactors are being filled with the liquid portion. This will ultimately lead to providing the proper space for the liquids disengagement resulting from the exhaust gas and it also adjusts any foam formation. Foam beakers which are the secondary impellers are used to prevent foaming. The air rich in carbon dioxide is introduced from the bottom side to promote algal growth. As the reactor systems exhibit a very efficient mechanism of mixing so they also have the increased rates of heat and mass transferring in turn resulting in more biomass production. The only drawback is its decreased surface to the volumetric ratio that has a great impact on its light-gathering abilities

(Franco-Lara *et al.*, 2006). As mechanical mixing is involved in these reactors so they produce more heat which is difficult to be controlled. Further modifications could be done by introducing new aerobic devices, by using various cautionary agents, and by using new kinds of mechanical mixers or impellers.

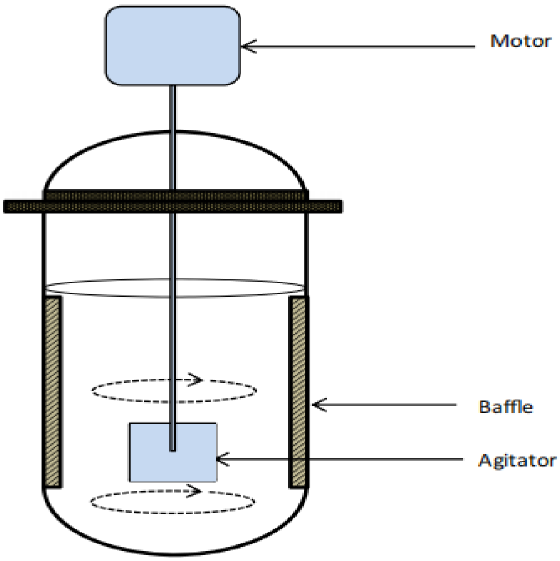
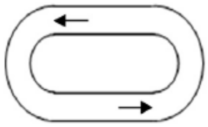
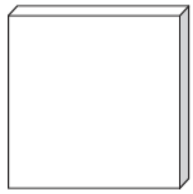


Fig 6: Schematic presentation of Stirred Tank PBR adopted from (Adopted from Gupta *et al*., 2015)

Table 1 sums up the general design features of various photobioreactors for the production of microalgae.

Table 1: Various designs of the photo-bioreactors for the production of Microalgae (adopted from *Lam et al*., 2019)

	Raceway Pond	Flat-Plate	Tub
Conceptual design			
Design characteristics	Consist of closed-loop recirculation channel (oval shape)	Bioreactor with rectangular shape	Con of st or lo tube
	Usually built using concrete or compacted earth-lined pond with white plastic	The flat-plate are usually made of transparent plastic or glass	The mad plas
	Mixing and circulation are provided by paddle wheels	Usually coupled with gas sparger	Usu pum tech
	The depth of the pond is usually 0.2−0.5 m to ensure microalgae receive adequate exposure to sunlight	The light path (depth) is dependent on microalgae strain; range between 1.3 and 10 cm	Tub limi incr volu
Advantages	Easy to construct and operate	Large illumination surface area gives maximum utilization of solar energy	Larg surf
	Low energy input and low-cost	Low concentration of dissolved oxygen	Rela bion
		Can be position vertically or inclined at an optimum angle facing the sun	Pote dam if ai is us
		Lower power consumption	
Disadvantages	Water loss due to high evaporation rate	Scale-up require many compartments and support materials	Requ beca are

5. Recent developments

Briassoulis *et al.* (2010) designed a new research-based model of the helical-tubular reactor system for the algal growth mainly the Nanochloropisis species. Its main benefits are an aggregation of higher culture volumetric ratio to the surface area beside the balanced light, effortless temperature and contamination maintenance, efficient dispersion of air and carbon dioxide. Henrard *et al.* (2011) estimated the potency of semi-continuous culturing of *Cyannobium* species in a closed-tubular bioreactor, with a combination of factors like the blend distribution, restoration rate, and amount of sodium-bicarbonate.

6. **Technologies for harvesting microalgae**

6.1. Centrifugation: Centrifugation can be used to recover many types of microalgae from the broth medium. Some laboratory tests of centrifugation were carried out on effluent taken from the pond (500-1000g). The results said that in 2 to 5 minutes only, about 80 90 percent of the recovery of microalgae is possible. Therefore, according to Grima *et al*. (2003) to harvest the biomass of microorganisms, centrifugation is a more preferable method more importantly, when concentrates for aquaculture that have higher or extended shelf lives, are to be produced. According to Knuckey *et al*. (2006) if microalgal cells are exposed to the very high forces of gravitation and shear, they can cause the cell to be damaged in terms of structure. Moreover, if a very high quantity of culture is centrifuged a lot of time and money is wasted (Grima *et al*., 2003).

6.2. Flocculation: Large particles that easily settle down can be made using the process of flocculation in which all the particles that are dispersed form aggregates.

6.3. Autoflocculation: When salts of carbonate form precipitate with cells of algae, auto-flocculation is said to occur. This occurs due to the increase in pH which itself is because of the consumption of CO_2 (with algae) in photosynthesis (Sukenik and Shelef, 1984). Therefore, the cultivation in sunlight with very little CO_2 helps to harvest the cells of algae by using the process of auto-flocculation. It was also seen that specific pH values in auto flocculation can be gained by using NaOH.

6.4. Coagulation using chemicals: Chemicals are also added to the culture of microalgae, to cause flocculation to occur, in different processes that are used to separate solids and liquids. This is mostly used as a stage before the treatment, a pre-treatment stage, which applies to the treatment of many types of microalgae (Lee *et al*., 1998). Two main types of flocculants, based on chemical composition, are inorganic and organic flocculants/poly-electrolyte flocculants). Oh *et al*. (2001) studied how the bacterial species *Paenibacillys* sp. AM49, could be used to harvest microalgae.

6.5. Inorganic coagulants: Because of the ions from organic matter that are adsorbed on the microalgae, and the ionization of functional groups on the surface, the microalgae have negative charges on them (Uduman *et al*., 2010). If the system is disturbed such that it is no longer stable, the microalgae harvesting can be done. If a coagulant that is maybe based on iron or aluminum, is added, it will cause this negative charge to become canceled, for example, this method was used to harvest *Scenedesmus* and *Chlorella* using Alum (Grima *et al*., 2003). Flocculation of microalgae can also be done by using inorganic flocculants at relatively low pH values (Uduman *et al*., 2010). However, there are some disadvantages of using inorganic flocculants that includes the requirement of a high concentration of flocculent for the separation of microalgae which causes a large amount of sludge to be produced, need for very specific pH, some coagulants are specific for certain microalgae only and the addition of iron and aluminum salts causes the products to become impure.

6.6. Electrolytic Process: The mechanism of electro-coagulation consists of 3 stages. First, the coagulants are generated through electrolytic oxidation involving sacrificial electrode, second, the particulate suspension is destabilized and the emulsion is being broken and third is the forming of flocks through the aggregation of destabilized process. It was investigated that continuous flow electro-coagulation can be used to remove microalgae from the wastewater of industries. Sacrificial electrodes are not required in electrolytic flocculation unlike electrolytic coagulation (Azarian *et al*., 2007). In electrolytic flocculation microalgae move towards anode to neutralize the charge on it and then it forms aggregates. It was showed in research that algae removal efficiency is 80-95 % when the method of electrolytic flocculation is used (Poelman *et al*., 1997).

6.7. Gravity sedimentation: The gravity sedimentation process is usually used to separate microalgae in water and treatment of wastewater. The factors that greatly influence the characteristic settling of suspended solids are the velocity of induced sedimentation, radius, and density of algal cells (Brennan & Owende, 2010). Sedimentation tanks and lamella separators are used for enhanced harvesting of microalgae by sedimentation (Uduman *et al*., 2010). To increase the efficiency of gravity sedimentation flocculation process is usually used. The density of microalgae particles has a great impact on the success of the removal of solids through gravity settling. It was found that microalgae particles that have low density show poor settling and are not separated by settling (Edzwald, 1993).

6.8. Filtration and screening: To recover biomass and economic costs related problems, Grima and his colleagues reviewed options of the harvesting process (Grima e*t al*., 2003).To introduce a suspension through a screen containing a particular size of pores is known as screening. Two screening devices that are used for the harvesting of microalgae are vibrant screen filters and micro strainer. When the concentration of microalgae is high it can result in blockage of the screen while a low concentration of microalgae results in poor capturing (Wilde *et al*., 1991). There are several advantages of micro strainer like its simple in its construction and function, easy for operation, low costs, very low chance of abrasion due to the absence of quickly moving parts, has a high ratio of filtration and is energy-intensive. It was found that those filters which are used in vacuum or under high pressure have a great ability to recover microalgae while this was not applied to organisms having dimensions like bacteria (Grima e*t al*., 2003). There is another approach called tangential flow filtration which is used for harvesting microalgae with great efficiency and almost 70-89 % of fresh algae can be harvested through this (Petrusevski *et al*., 1995). Moreover, this tangential flow filtration can maintain the structure, motility, and properties of microalgae used in the process.

7. Conclusion

The algae production at a larger scale needs more investing and operating costs. The open culture systems like the raceway ponds are although economical and cheaper to prepare and to be maintained but their requirement of more space makes them less preferable. Just because of the drawbacks of these open ponds, like their increased risks of getting contaminated, temperature issues, and light inaccessibility, leads to the developments of the outdoor closed photobioreactors. PBRs have been designed after much hard work but still, it requires a little more effort and modifications. The leading interest in designing sufficient PBRs involves the model design with minimum energy input while using maximum solar energy. Large-scale photobioreactors consist of a transparent and high illuminatory surface, higher rates of mass transferring with the increased biomass production along with the minimum space.

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