Volume : 4 | Issue : 1 | January 2015 • ISSN No 2277 - 8179

Research Paper

Development of Photobioreactors for Improvement of Algal Biomass Production

Engineering

KEYWORDS : Algal biomass, design considerations, developed photobioreactors.

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ABSTRACT

Today's era is in need of more potential energy source due to continuous depletion of conventional energy. Over increasing population and so of demand for fuel has become major concern. In such scenario biofuel from algal biomass looks better way out to overcome the energy crisis. Thus, algal bio prospect and mass cultivation has captured most of the focuses for researchers. The only mean for maximum production of algae is photobioreactor. Here, challenge is scalable design and development of optimal photobioreactor. This paper gives overview of various design considerations such as geometric, operating and hydrodynamic parameters. Also, material for construction is overviewed and a selection criterion is concluded. An attempt is made to understand the effect of performance parameters on biomass productivity in developed photobioreactors. Thus, few modified designs are considered such as periodically shaded Tubular Photobioreactor, Modular Flat Panel Photobioreactor, Annular Photobioreactor, Bubble Column Photobioreactor and Vertical Tubular Photobioreactor. Selected microalgae species, construction, design and parameters studied are discussed.

1. Introduction

Power generation is necessary element of today's society. However, society is no longer as accepting of the methods used to generate the energy we crave. The older methods are becoming too expensive and due to energy crises it has become one of the global problems confronting the world. Presently, fossil fuel is considered to be a major source of energy. Fossil fuel accomplishes 80% of world's energy needs; whatever in the industrial production sector, domestic uses or in the transportation sector [1].This rapidly increasing consumption raises two concerns. First, all fossil fuels are, nonrenewable and this means that there is a limited supply and that this supply will become harder to reach and therefore increase in price as the end draws nearer. The other concern is that when fossil fuels are burned, CO2 is released which a greenhouse gas is. It retains heat that has been stored for millions of years and will add to total carbon in the atmosphere in its current state [2]. Because of ever increasing demand of fossil fuels at one end as well as its limited availability and non-renewable reservoir at the other it is obvious that we need an alternative source of energy [3].

1.1 Biomass

The biomass is measured as an alternative source of energy. The Biomass Energy Center in the United Kingdom describes biomass as the "biological material derived from living, or recently living organisms, generally used when talking about plant material [4]. Biomass is carbon based, but does contain organic compounds and elements like oxygen and nitrogen as well as some other heavy metals. Biomass is considered a carbon neutral fuel because when plant material is burned it releases CO2 back into the atmosphere. This CO2 is then used by plants for growth. This is called carbon cycle. When biomass is burned and new plant material is planted and allowed to grow the total carbon in the atmosphere is relatively unchanged.

Agricultural products	Forestry products	Wastes	Energy crops
Harvesting residues	**Harvesting residues**	**Domestic/Industrial**	**Wood**
Cereal straw Oil seed, rape and linseed Oil shives Pea straw Corn stover	Forestry residues	Municipal solid waste(MSW) Construction and demolition Wood wastes Scrap tyres Waste pallets	Willow Poplar Jatropha
Processing residues	**Primary processing residues**	**Urban green wastes**	**Grasses and other crops**
Rice husks Sugarcane baggase Olive residues Palm oil residues Citrus fruit residues	Sawdust Bark Offcuts	Leaves grasses and hedge cuttings	Switch grass Reed canary grass
Animal wastes	**Secondary processing wastes**		
Animal fat Poultry litter Tallow Meat bone meal	Saw dust Offcuts		

Table 1: Typical sources of biomass for energy production [5]

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Biomass comes in many forms, from waste material to crops grown specifically for energy. Many of the biomass fuels used today come in the form of wood products, dried vegetation, crop residues, and aquatic plants. Biomass has become one of the most commonly used renewable sources of energy in the last two decades, second only to hydropower in the generation of electricity. It is such a widely utilized source of energy, probably due to its low cost and indigenous nature, that it accounts for almost 15% of the world's total energy supply and as much as 35% in developing countries, mostly for cooking and heating.

However, biomass from crops creates a problem of supply. This **issue** affects the evaluation of biomass as a viable solution to our energy problem. Quick access to large quantities of plant biomass can be difficult as only a specific amount is grown or collected. Once this has been used more must be grown, and for traditional forms of biomass this could take a full season. It is therefore vital that a new source be found that can be grown quickly and in large amounts. That source is believed to be algae; however the process of growing algae still has not been perfected on industrial scale[5].

1.2 Biofuels

Biofuel is one of the alternatives derived from organic matter. Biofuels are classified depending on the source of biomass. Biofuels has broadly four classifications namely natural biofuel, first generation biofuel, second generation and third generation [6].

Generation	Sources	Limitations
Natural Biofuel	Derived from organic sources such as firewood, vegetables, animal waste, landfills	Limited availability Low yield
First Generation	Derived from edible feedstock such as corn, wheat, palm, oil crops, soybean, sugarcane, sugar beets, maize	High arable land requirement for food production High water and fertilizer requirement
Second Generation	Derived from plant waste, lignocellulosic biomass and woody part of plants	Requires costly conversion technologies involving pretreatment with special enzymes for commercial application.
Third Generation	Derived from micro and macroalgae	Scale up of processes for growth of algae

Table2: Biofuel classification [6], [7].

Previously, algae were lumped in withsecond generation biofuel. Many researchers suggested algae to be moved to their own categories due to high potential to produce biofuel compare to other feedstockin terms of quantity or diversity. Fuels that

Volume : 4 | Issue : 1 | January 2015 • ISSN No 2277 - 8179

can be derived from algae include Biodiesel, Butanol, Gasoline, Methane, Ethanol, Vegetable oil, Jet fuel. Diversity is not the only thing that algae has going for it in terms of fuel potential. It is also capable of producing outstanding yields. Microalgae compare to all other biomass contains up to 70% oil by wt in biomass, can yield 136,900 L oil/ha year and 121,104 kg biodiesel/ha year can be produced[11].

1.3 Algae potential for biofuel production

Algae are a broad term that represents a vast grouping of organisms that can range in size from microscopic to enormous-seaweeds. Nearly all algae contain chlorophyll α and β –carotene for photosynthesis. Photosynthesis is an important biochemical process in which algae like plant converts the light energy into chemical energy. Algae capture light energy through photosynthesis and convert inorganic substances into simple sugars using the captured energy. Thus, these types of algae have been taken in consideration as a residual biomass ready to be used for energy purposes [9]. Algae based biofuel research was first exaggerated in 1970's with the energy crises, along with other plans for renewable energy [10].

Microalgae are currently considered the most potential types of algae for biofuel production, based on their high lipid contents. The term lipid is defined as a biological component of and derived from organisms. Lipid contains hydrocarbon group in its structure. Also store high reducing power and energy [13]. Algal lipid mainly consists of fatty acid, Polyketide, Glyceride, Terpenoid, Steroids, Carotenoid composed of carbon, hydrogen and oxygen [13]. Triglycerides is one of the neutral lipid bearing a common structure of triple esters where usually three long chain fatty acids are coupled to a glycerol molecule generally serve as energy storage in microalgae that, once extracted, can be easily converted into biodiesel through transesterification reactions [12,15].

The benefits of algal biofuel production being less land-intensive with high biomass production rate per unit area (aquatic microorganisms have the ability to double there mass in less than 24 hours by efficient utilization of co2 in presence of light for biofuel production [14], having high CO2 fixation ability compared to terrestrial plants [13], no diversion of food from the human food chain, easier depolymerisation as they counting less complex cell wall metrics, ability to be grown in salt water or using municipal and industrial waste or even in the open ocean, having much faster growth rates than other crops, and finally having higher percentage of the biomass produced as oil [7]. Large scale cultivation of microalgae may be 10-20 times more productive on a per hectare basis than other biofuel crops, are able to use a wide variety of water resources, and have a strong potential to produce biofuels without the competition for food production[7,11,].Moreover other valuable compounds may also be extracted from diversified microalgae species such as polyunsaturated fatty acids, natural dyes, polysaccharides, pigments, antioxidants, high value bioactive compounds, and proteins [16,17, and 18].

Microalgae cultivation very much depends on the growth techniques or metabolism and is capable of metabolic shift as response to changes in environmental conditions.Heterotrophic growth technique is not as effective as photosynthetic growth mechanisms because the carbon source used to feed the algae was ultimately derived from another plant by photosynthesis, [19] in addition, the carbon source may compete with sources for human consumption. Henceforth, the generic term "algae" is used to be described as photosynthetic microalgae and the term 'photobioreactor' is defined as a system that uses light to grow algae via only the photosynthetic mode of cultivation.

Growth techniques	Energy source
Photoautotrophic	Uses light as a sole energy source that is converted to chemical energy through photosynthetic reactions.
Hetrotrophic	Utilizes only organic compounds as carbon and energy source
Mixotrophic	Uses combination of light and organic compounds as energy source
Amphitrophic	Energy source depends on the concentration of organic compounds and light intensity available.

Table3: Different growth techniques for microalgae cultivation [11], [16].

At present, extensive utilization of this resource faces a grand challenge, namely how to acquire a large quantity of microalgae biomass to meet the energy demand on commercial scale [12].

2. Photobioreactor

To acquire the huge algal biomass, cultivation of algae is the major concern. Cultivation of algae can be done in open systems (ponds, lakes, lagoons) and closed system [15]. Open systems are easier in construction and operation over the closed systems, resulting in low production cost and low operating costs [20]. However, major limitations in open pond include growth dependency on location and season, poor light utilization by cells, evaporative losses, CO2 diffusion to atmosphere, requirement of large areas of land, poor mass transfer rate due to inefficient stirring mechanism, contamination by predators and other fast growing heterotrophs, uncontrolled growth environment such temperature, pH level, controlled nutrient supply, CO2 supply to overcome the losses due to diffusion [21].Open system drawbacks results in low biomass productivity. To overcome the problems associated with an open system, researchers have tried for closed systems [15].

Closed system commonly called as photobioreactor, is closed equipment which provides a controlled environment and enables high productivity of algae. As it is a closed system, all growth requirements of algae are introduced into the system and controlled according to the growth requirements. Photobioreactors facilitate better control of culture environment such as CO2 supply, watersupply, optimal temperature, efficient exposure to light, culture density, pH levels, gas supply rate, mixing regime, culture density, etc.

2.1 Types of Photobioreactor

Due to the different physiological demands of the cells for growth and product yield, the value of the product and its field of application, various types of PBR's have been designed and developed for algae production. However a few standard designs which lay the foundation for further improvisations can be categorized as flat plate reactors, annular reactors and tubular reactors as shown in the fig. 1[22].

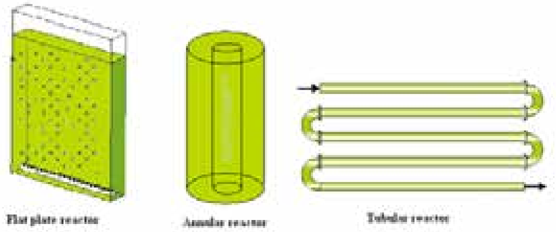

Fig1: Common Closed Photobioreactor Designs

2.2. Photobioreactor Operating Principles

Photosynthetic organisms, including microalgae, use light through photosynthesis as their energy source. Therefore, closed PBRs are typically constructed of materials that light can penetrate sufficiently for photosynthesis. Initially there is water inside a photobioreactor. Air with CO2 enters into the system as bubbles through spargers and circulates with water. With the presence of sufficient light; photosynthesis occurs which results in algal growth inside the photobioreactor. Air is bubbled through the bottom of the PBR to provide good overall mixing in order to produce the uniform dispersion of microalgae within the culture medium, for better light penetration, sufficient supply of CO2, and efficient removal of O2. The photosynthesis lowers the CO2 content of the air being injected into the PBR and increases the concentration of oxygen (O2) which comes out of the system through an outlet. Different sensors are provided such as oxygen sensors, pH sensors, temperature and optical sensors. In order to sustain the growth of algae, some nutrients are injected into the reactor [23].When algae reach its maximum growth, it is considered to be ready for harvesting. Grown algae are passes through the connected filtering system. This filter collects the algae that are ready for processing, while the remaining algae passes back to the feeding vessel. After harvesting water with nutrients can be added to mixing unit. Agitation system is also incorporated which prevents microalgae from sticking to the walls of the vessels and diminishing the amount of available light. Fig.2 shows the schematic representation of a photobioreactor.

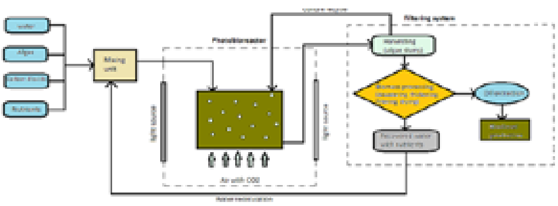

Fig2: Schematic of Photobioreactor

3. Materials used in Photobioreactor design

The selection of material used in photobioreactor design is an important aspect to ensure cost effectiveness and high efficiency. The materials used for PBR's construction include glass, Plexiglas, acrylic, polyvinyl chloride, polypropelene, polystyrene, polyethylene terephthalate, polyurethane etc. Selected material should possess the characteristics such as high transparency, high flexibility & durability, Non -toxicity, high resistance to chemicals and metabolites produced by the microorganisms, low cost, high stability and long lasting property.

Material	Features & benefits	Disadvantages
Glass	Glass is most commonly used material because of high transparency up to 95%. Borosilicate glass or Pyrex is most prevalent among the types of glass because of its high density 2.35-2.52g/cm3. The glass tubes have a life span of about 20 years. The glass has significantly low energy content ranging from 13.0 MJ/kg to 26.2 MJ/k makes it a suitable material in principle	Glass tubes require a supporting structure Glass tubes requires more fittings as lengths of more than a few meters are not produced Installation costs are high Difficult to transport and assemble
Low density polyethylene Film (LDPE)	High energy content compare to glass ranging from 78.1MJ/kg and 74.0MJ/kg. The variants of basic LDPE plastic film used are single layer LDPE, fiber-reinforced LDPE, linear low density polyethylene (LLDPE) with density varying from 0.85 – 0.94 g/cm3. Possess high resistance to acids, alkalis and solvents. Other benefits include high visible light, low UV transmission and low cost.	Short lifespan as even with addition of UV stabilizers, lasts only for 3 years. Environmental factors such as UV radiation, temperature, thermal cycling affects the film lifetime. Contact with rigid surfaces, chemicals and atmospheric pollutants causes loss in transparency.
High density polyethylene film (HDPE)	HDPE is cheap and commercially viable and would cost approximately only one –third that of the current plastic material used. HDPE gives higher specific strength with density varying from 0.94-0.97 g/cm3. The HDPE employed reactors are found to produce algae with oil content 1% higher than that of the LDPE. The opaqueness of HDPE helps to prevent photo - oxidative damage or photo-inhibition.	HDPE cannot be sustained at normal conditions, requires autoclaving, unlike LDPE. Difficult to weld as it owns less tensile strength.
Rigid Acrylic or Polymethyl Methyl Acrylate(PMMA)	Acrylic sheets possess high transmissivity. It transmits up to 95% of the incident light from 390 to 800 nm. The acrylic tubes are also known by the trade names such as Acrylite, Lucite, Plexiglas and Perspex. The energy content and density of PMMA is high and is estimated about 131.4 MJ/kg and 1.18g/cm3 respectively. PMMA is an economical alternative to polycarbonate (PC) when extreme strength is not necessary. The lifespan of acrylic in outdoor conditions is at least 10 years. Other benefits are increased productivity, less water loss from evaporation, screening out contaminant algae, greater control over the culture, and ability to grow a pure culture of algae.	Installation costs are high and make PBR too costly. More prone to scratching compare to conventional inorganic glass. PMMA is not auto clavable and offer poor resistance to many solvents. The algae may stick to the inside of the tubes and block sunlight, and tubes may get too hot.
Polyvinyl Chloride (PVC)	Transparency of PVC is up to 80% and density varies from 1.2-1.34g/cm3. Benefits of PVC include corrosion resistance, excellent resistance to acids and alkalis, low permeability to gases, high tensile strength, UV resistant,no conductivity, light weight.	PVC when attacked by UV rays will discolor the surface of the pipe preventing or limiting the light from getting to the medium. Also, when exposed to UV light PVC tends to break down and get brittle. PVC holds poor resistance to aldehydes, esters, and aromatic and halogenated hydrocarbons.

Table 4: Material of construction & Characteristics (modified from 2)

Choice of favorable material for PBR design is a critical task as it is difficult to select the best material that satisfies all the criteria of an efficient PBR design. From the table no, it is concluded that LDPE is the preferred material of choice due to its efficient features. However, it has low lifespan compared to glass and acrylic. It is also found that PMMA has more advantages and retain transparency over months when exposed to natural climatic conditions but for bioreactor construction still PVC remains as an alternate when chemical resistance is of more concern than transparency [24, 25].

3. Performance Parameters of closed PBR

Many PBR's are designed and developed, but comparative evaluation is hardly possible. The problem in comparing different designs of PBR's is the use of different measures depending on the purpose of the reactor and depending on the research discipline. Evaluation parameters are divided into three which are geometric parameters, hydrodynamic parameters and operating parameters [22]. Table (5) gives the geometric parameters, definition and importance in the design of PBR and table (6) gives information about the important geometric design factors and their acceptable limits.

3.1 Geometric Parameters

Geometric parameters	Definition	Importance
V_R (Working volume)	It is the total working volume of the reactor including the liquid and the gas phase.	It is necessary for mass balancing.
A_R (Total surface area)	It is the total surface area of the transparent part of the reactor.	It determines the amount of light which could eventually enter the reactor and makes serious contributions to the reactor cost
A_G (Aperture area)	This is the aperture (ground) area of the reactor which measures the area from which light energy is collected.	Importantly considered for multiple installations to account for the area between two reactors.
P_R (Volumetric productivity)	It is the volumetric productivity which measures the product formation per reactor volume and time span.	Important for high value applications like pharmaceuticals and for assessment of process intensification.
P_G (Areal productivity)	It is the product per ground surface area and the time. It is the most important parameter to assess the larger PBR plants.	Important in determining the performance criteria, especially for conversion of solar energy to chemical energy.
I_0 (Irradiance)	It is given as the photon flux density PFD. Photosynthetic photon flux density PPFD accounts for the fact that photons can only be used from the photosynthetic active radiation range(400nm-700nm)	This is given as power density in [W/m²] for feasibility studies of bio-energy production.
I_S (Saturation light intensity)	It determines the light utilization efficiency and overall photosynthetic efficiency. it roughly varies from 30-45watt/m²(140-210μE/m2/s1)	It determines the biomass productivity.

Table 5: Geometric Parameters Important for Performance Evaluation [22],[29],[30]

Geometric factors	Definition	Preferable Range
AR/VR	**The relationship of external surface area that is available to the volume that is supposed to be provided with light.**	**50/m-100/m. Modern concepts go in the direction of larger values.**
VR/AG	**Ratio of volume of medium in the reactor to the amount of medium piled on the ground area.**	**Upto 100L/m2. Higher values indicate a greater weight and lower intensity of the process.**
I0/IS	**The ratio of incident light intensity and saturation light intensity.**	**10-20 depending upon the strain of algae, the time of the day, season and location.**

Volume : 4 | Issue : 1 | January 2015 • ISSN No 2277 - 8179

PCE (conversion efficiency)	**Fraction of solar energy that is converted to chemical energy in a photo bioprocess.**	**9-10% depending on the energy content of biomass.**

Table 6: Geometric Design Factors[22], [29], [30]

3.2 Operating Parameters

3.2.1 Light

Light requirement is the most important parameter in order to enhance microalgal growth in PBR's. Light condition affects directly the growth and photosynthesis of microalgae.Light should indeed be provided at the appropriate intensity, duration and wavelength. Excessive intensity may lead to photo-oxidation and inhibition whereas low levels will become growth limiting [31]. The wavelength of the light used to cultivate algae is also a design factor because the different cultures grow differently when exposed to different colours of light. The algal culture systems can be illuminated by artificial light or solar light or both. In outdoor cultivation, ultimate source of light is sun, which cannot be controlled. Indoor cultivation can be achieved successfully using artificial illumination. To successfully use artificial light for photosynthesis, photons with wavelengths between 600-700nm must be generated.

Duration that is light and dark cycles strongly influence the growth of algae. Microalgae needs light for photochemical phase to produce (ATP) adenosine tri phosphate and also needs dark for the biochemical phase. During this phase, essential molecules are synthesized which are necessary for growth [32]. The selection criteria of artificial light sources for cultivation of photosynthetic microalgae include high electrical efficiency, low heat dissipation, good reliability, high durability, long life time, reasonable compactness, low cost and spectral output falling within the absorption spectrum of the microorganism of interest.

Table no (7) discusses the main characteristics of different types of light and their relative luminous efficiencies [33].

Type of light	Feature	Intensity (W/m^2)	Energy emission in the region 400-600 nm	Energy emission in the region 600-700 nm	Conversion of energy into heat	Shape of lamps	Lifetime (typical value)	Cost
Incandescent bulbs	Energy is emitted in infra red region which is very different from the ranges required for photosynthesis	3.1	0.5%	3.8%	Very high	Spherical	750-2,000h degradation of light output along time	Low price
Halogen lamps	The light output level does not diminish over time.	1.6	0.5%	3.3%	High	Spherical	3,000-4,000h light output level does not diminish over time	Low price
Fluorescent lamps	Most light is emitted in visible region and is thus closer to the spectrum of day light	5.9	25.0%	20.7%	Low	Tubular	10,000h duration degradation of light output along time	10* more expensive than incandescent bulbs
Light emitting diodes (LED's)	Produce more red light and thus improves photosynthetic efficiency	14.7-55.5	0.04-0.28%	87.6-98.3%	Very low (below 10%)	Elliptical	High quality diode lasers with 100,00h	2*more expensive than LED's

Table 7: Characteristics of artificial light [31].

3.2.2 Temperature

Maximum algal growth depends on optimal temperature. The optimal temperature for microalgae culture is 20-24oC, although it may vary with the composition of the culture medium, the species and strained cultured [45]. Several species have been identified which can tolerate high temperature up to 60oC. Temperature lower than 16oC will slow down growth whereas those higher than 35oC are lethal for no. of species [34].Table (8) discusses the temperature tolerance limit of some algal species.

Microalgal species	Maximum temperature
Cyanidium caldarium	60
Scenedesmus sp.	30
Synechococcus elongates	60
Chlorella sp.	45
Eudorina sp.	30
Chamydomonas sp.	35
Nannochloris sp.	25
Monoraphidiumminutum	25
Chaetocerossp.	25
Rhodomonassp.	30
Cryptomonassp.	30
Isochrysissp.	30
Phaeodactylumtricornutum	30
Chlorella ellipsoidea	30
Pavlovalutheri	30
Spirulinaplatensis	25
Chlorella vulgaris	30
Botryococcusbraunii	30

Table 8: Temperature tolerance of various algal species [46] [47].

Due to the possible lethality of microalgae and probable overheating in closed photobioreactor, temperature control is of major concern. Within photobiorector temperature can be controlled by evaporative cooling by spraying water on the surface of tubes, by regulating the temperature of feed or recirculation stream, by placing the light harvesting unit inside a pool of water, by selecting the proper material of construction which can withstand high temperature [3].

3.2.3 pH

pH of the medium is an important operating parameter as it is directly related with concentration of CO2. In closed photobioreactor, as CO2 consumption increases, pH increases. The pH affects the liquid chemistry of polar compounds and availability of nutrients such as iron, organic acids and even CO2 [35,36]. pH can be controlled by aerating the culture. Optimum pH of the medium is usually around 7, except for Chlorella and Spirulina which require higher pH around 10 for biomass production [3].

3.2.4 CO2 Supply

For photosynthesis to occur, CO2 is one of the necessary requirements. Carbon dioxide concentration is considered as an optimal parameter because an excess of CO2 can be unfavorable to photosynthesis and cell growth. CO2 concentration from 5%to 10% by volume is considered optimum for the maximum growth. Further the amount of CO2 needed for growth varies according to microalgal species and PBR type. CO2 concentration can also affect the lipid composition [37].

3.3 Hydrodynamic Parameters

3.3.1 Mixing

Mixing in PBR's is known to enhance biomass productivity by avoiding light and temperature gradient across the bioreactor and ensuring the homogenous distribution of nutrients [3]. Inadequate mixing will result in settling of biomass, stagnant or dead zones, cell aggregation and formation of multiphase system, thus affecting the mass transfer rate. Mixing can be enhanced by using horizontal and vertical baffles in the PBR itself or by using auxiliary devices for recirculation using devices such as pumps. Mixing and lighting are closely related. It minimizes the I0 (Incident Light Intensity) and takes advantage of flashing light effects.

3.3.2 Bubble size

Bubble size is an important parameter which decides the photobioreactor performance [38]. For this reason it is important to optimize the design of a gas distributor from which dispersed gas is sparged. Type of sparger also influences the overall mass transfer coefficient in a reactor. The use of fine spargers could result in the formation of large bubbles which leads to poor mass transfer because of reduced contact area between liquid and gas [16]. Bubbling is a critical parameter, as it may be responsible for cell damage. The cell damage associated with bubbling are-

- Cell interaction with bubble generation at the sparger.
- Cell interaction with bubbles coalescence and breaking up in the region of bubble rise and
- Cell interactions with bubbles at the air-medium interface [39] [40].

3.3.3 Gas velocity

Superficial gas velocity is the average velocity of gas being bubbled into the column through the sparger, which is given by following relation:

$$U_g = \frac{Q}{A}$$

Where, $U_g = superficial\ gas\ velocity$

$Q = volumetric\ flow\ rate$

$A = cross\ sectional\ area$

3.3.4 Gas Hold Up

Gas holdup is one of the most important PBR design criteria and it characterizes gas liquid system. Gas holdup is defined as the volume fraction of gas that is taken up by gas bubbles. It governs gas phase residence time and gas liquid mass transfer. It depends on superficial gas velocity and type of sparger. Many researchers from their experiments reveal that as the diameter of bubble increases, which depends on type of sparger, superficial gas velocity also increases and thus gas holdup increases [41]. Gas holdup is also affected by the column height when height to diameter ratio of column is less than 5:1.When the ratio is less than this, height effect on holdup is negligible [42].

4.Developed Photo bioreactor

Numerous aspects influence the growth and the lipid content of algae. In view to increase the algal growth and lipid content, many researchers have developed a variety of photobioreactors. Design considerations such as geometric parameters, operating parameters and hydrodynamic parameters are considered as the basis to make the study of performance of different designs easier. In this paper five designs are considered which discusses about the effect of evaluation parameters on biomass productivity.

Design	Microalgal Strain used	Lipid content (Δ dry weight biomass)	Biomass productivity (g/L/day)	Culture medium	Ref.
Design 1- Tubular Photobioreactor	*chlorella pyrenoidosa*	2.0	2.9-3.64	Grown in Brostol's solution medium.	[43]
Design2- Modular flat panel photobioreactor	*Nannochloropsis sp*	12.0-53.0	0.17-1.43	Grown in artificial sea water at $33gL^{-1}$ enriched with F/2 medium nutrients	[44]
Design 3- Annular photobioreactor	*Nannochloropsis sp*	12.0-53.0	0.17-1.43	Grown in f-medium made with artificial sea water at $33gL^{-1}$ salinity.	[26]
Design 4- Bubble column photobioreactor	*Botryococcus braunii*	25.0-75.0	0.02	Grown in chu-13 (1942 medium)	[27]
Design 5- Vertical tubular photobioreactor	*Nannochloropsis oculata* and *chaetoceros calcitrans*	22.7-29.7 and 14.6-16.4/39.8 respectively.	0.37-0.48 and 0.04 respectively.	Grown in 3 different medium i.e. F2 medium, MN III	[28]

Development of PBR in order to enhance the biomass production depends on microalgal species selected, their cultivation conditions and nutrients available for the growth. Selection of algal species for biofuel production depends on factors such as growing rate, lipid content, resistance to changing environmental conditions, nutrient availability, ease of biomass separation and processing. The above table no. (9) shows the species chosen by the researchers for biomass production in the developed photobioreactor based on the availability and the literature information on the algal lipid content and biomass productivity. The following table no. (10) shows the specifications of different photobioreactors considered for discussion.

PBR types	Design and dimensions
Periodically Shaded Tubular Photobioreactor 	This tubular photobioreactor consists of a serpentine glass tube, fabricated by setting straight glass tubes connected with U shaped joints and a conical flask. A silicon tube is used to join the serpentine tube to the conical flask. To create controllable light dark cycles, outer surface of the serpentine tube was periodically shaded by light shading material at pre set interval. Total length of serpentine tube- 3m and inner diameter 5mm. Material of construction: glass for tubes, black paint with the thickness of 15±3μm as light shielding material.
Modular Flat Panel Photobioreactor 	MFPP consists of 6 removable "alveolar" panels placed vertically back to front and 24 cm apart, forming a closely packed unit. Alveolar panel width: 108cm, height 165 cm and thickness 1.2cm. Total working volume 123L. Total illuminated surface area: 20.4m². Material of construction: perforated plastic.
Annular Photobioreactor 	The annular reactor consists of 2 cylinders of different diameter so as to form an annular culture chamber which is closed at the bottom. were developed of different dimensions. Smaller reactor was constructed from two cylinders, inner cylinder 40cm and outer cylinder 50cm in diameter of 0.5cm wall thickness. Volume of reactor- 120L, width-4.5cm, height-1.90m and illuminated surface area- 5.3m². Large reactor was constructed from two cylinders, inner cylinder 84cm and outer cylinder 91cm in diameter of 0.5cm wall thickness. Volume of reactor- 140L, width-3cm, height-1.7m and illuminated surface area- 9.3m2. Material of construction: plexi glass cylinders .
Bubble Column Photobioreactor 	Bubble column PBR consists of two circular concentric glass columns of 50mm inside diameter height of 726mm and 65mm outside diameter height of 711mm. Total working volume 4L. Sparger centrally located. Material of construction- glass.
Vertical TPBR 	Tubular PBR consists of 6 hollow glass tubes(75cm×45mm) inserted between two wooden sheets(top and bottom) of 0.25 inch thickness with UPVC couplings in specific positions. Artificial light was fixed in the centre of the two wooden sheets using 1" plastic brackets. Provisions for O_2,CO_2 and nutrient supply was assembled with the top wooden sheet. Total volume- 4L. Material of construction- PVC.

Table 10- The design comparison between the different PBRs [43] [44] [26] [27] [28]

Volume : 4 | Issue : 1 | January 2015 • ISSN No 2277 - 8179

4.1 Photobioreactor Performance

Design1: Periodically Shaded Tubular Photobioreactor

It is a novel tubular photobioreactor with the outer surface periodically shaded to generate L/D cycle for enhancing the microalgae growth by overcoming the problems of photo inhibition, thermal dissipation and electron transport which are responsible for low productivity. In this study, transmission of light shielding material, the frequency of L/D cycles, the effect of light intensity and the biomass specific growth rate was studied. Fluorescent light was used for the illumination and it was found that the light intensity at 240μmolm-2s-1 showed the highest growth rate for the proposed design. Results also revealed that the dark regions could be efficiently generated using the shielding material. Higher dry weight of biomass was seen in the periodically shaded TPBR at 100Hz than compared to the biomass yield at 2Hz, thus proving that a high frequency L/D cycle should be considered for optimal design of this reactor. The study claims that the performance of this photobioreactor is more efficient as a 21.6±2.1% increase in biomass productivity was achieved compared to the conventional photobioreactor.

Design 2: Modular Flat Panel Photobioreactor

This reactor consisting of a closely packed unit of 6 alveolar panels and 12 fluorescent tubes contained in a thermo regulated cabin is operated to provide good quality *Nannochloropsis* biomass. Two different irradiance levels (115 and 230μmol photon m-2 s-1) and both single side and two-side illumination were tested at steady state conditions. Air flow rate of 0.5L L-1 min-1, gas hold-up of 3.3%, pH of 7.5±0.2, temperature of 25±1°C and a cell concentration of 2.6-3.2g(was maintained. It was seen that for one side of the panel illumination, the mean volumetric productivity increased from 0.61g to 0.85g (d. wt) L-1 24h-1 when the irradiance was increased from 115 to 230μmol photon m-2 s-1 respectively. Significantly, with illumination on both the sides, the culture productivities were higher. However, cultures illuminated with 115μmol photon m-2 s-1from both sides showed 14% higher productivity and higher light conversion efficiency. This reactor has successfully shown that due to the high surface to volume ratio of the single panels, the cell concentration at harvesting and the volumetric productivities achievable in the MFPP are 15-30 times higher than those attained in 200L fiber glass cylinders under artificial light. Also in comparison to other systems for microalgae culture, the MFPP provides a very efficient utilization of light since photons do not escape the system and are efficiently conveyed to the culture

Design 3: Annular Photobioreactor

Two types of annular reactors that were illuminated from the inside using natural, artificial (six58W fluorescent tubes or one 400W metal halide lamp) or combined illumination were developed and evaluated during several months for the mass cultivation of *Nannochloropsis* sp. While maintaining the air flow rate at 0.1Lmin-1, gas hold-up of 2%, pH at 7.5±0.3 and a temperature of 25±0.2°C in both the reactors, the productivity on per reactor basis was studied. The productive yield using metal halide lamps which was 34g reactor-1 24h-1 compared to 27g reactor-1 24h-1with fluorescent tubes showed that the former source was an efficient for illumination. Under artificial illumination, the culture in the 91-cm annular reactor was from 30 to 60% more productive than the culture in the 50-cm reactor with both the metal halide lamp and the fluorescent lamp. This proved that the cultures subject to combined illumination always attained higher yields. Also the study of the 1200L plant produced an average of 270g of dry Nannochloropsis sp. biomass per day under combined illumination. Thus the design claims to represent a successful attempt to use remotely produced Nannochloropsis biomass as live feed in commercial hatcheries.

Design 4: Bubble Column Photobioreactor

This bubble column photobioreactor was specially designed to grow the cultures of Botryococcous Braunii for the production of biodiesel. The photobioreactor was designed to supplement CO2 at a high rate of 1.5L/min to induce hydrodynamic stress on algae for exchange of gases and light regions.Also lipid estimation tests using Blight and Dyer method, alcohol determination using gas chromatography and biofuel production using soxhlet apparatus was conducted to validate the design. The shake flask studies were performed prior to the inoculation to the photobioreactor which showed that the total weight of the biomass was found to be higher in the bubble column photobioreactor with 4.1g/L while low from the shake flask studies with 1.2g/L of culture. Thus the proposed photobioreactor design showed higher growth rates with maximum lipid content of 78% as measured gravimetrically.

Design 5: Vertical Tubular Photobioreactor

This vertical tubular photobioreactor was constructed economically using low cost material. Studies were performed to determine the suitable growth medium, optimum pH and optimum inoculum level at a light intensity of 1.2±0.2Klux and temperature of 25°C±1°C at an incubation period of 3 weeks for the mass cultivation of microalgae. The F2 medium showed higher amount of biomass with the species Chaetoceros Calcitran and Nanochloropsis Occulata giving a dried biomass yield of 4.6g/L and 3.4g/L respectively in it. pH studies were conducted in the range of 6-10 in F2 medium and were found that higher amount of microalgae biomass was obtained at a pH of 8. Also growth studies were conducted at four inoculum concentrations of 0.05, 0.10, 0.15 and 0.20 at an optical density of 620nm. The results reveal that the microalgae cultivated at an inoculum concentration of 0.15 produces maximum amount of biomass at the 12th day of cultivation.

6 Concluding

In last decade numerous photobioreactor designs has made good evolution. Basic Principal is incorporated and design considerations have been utilized extensively to increase biomass productivity. So far most emphasize is given on performance parameters such as light intensity and distribution, algal cell biology and geometry but limited to small scale production. To obtain maximum production at large scale, design is the major factor. At commercial scale selection of optimal reactor is associated with cost effectiveness of the reactor, low maintenance cost, space expediency and energy requirement which need to be optimized. Hydrodynamic is one of the critical aspects in designing an efficient photobioreactor. Complete hydrodynamic study can be accomplish by using modeling and simulation technique, which can be considered as one of the approach to develop an innovative design that may overcome scaling complexity up to some extent. Overall, the ultimate goal is to produce algal biomass in large scale that should be cost effective and economic to compete with fossil fuels.

To date, it is a big challenge as to how a suitable, economical and scalable photobioreactor is to be designed which fulfills all the requirements. Hybrid photobioreactor that is combinations of open and closed reactors seems to have great potential from volumetric productivity prospective and brings lot of scope for future investigation to make it economical.

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