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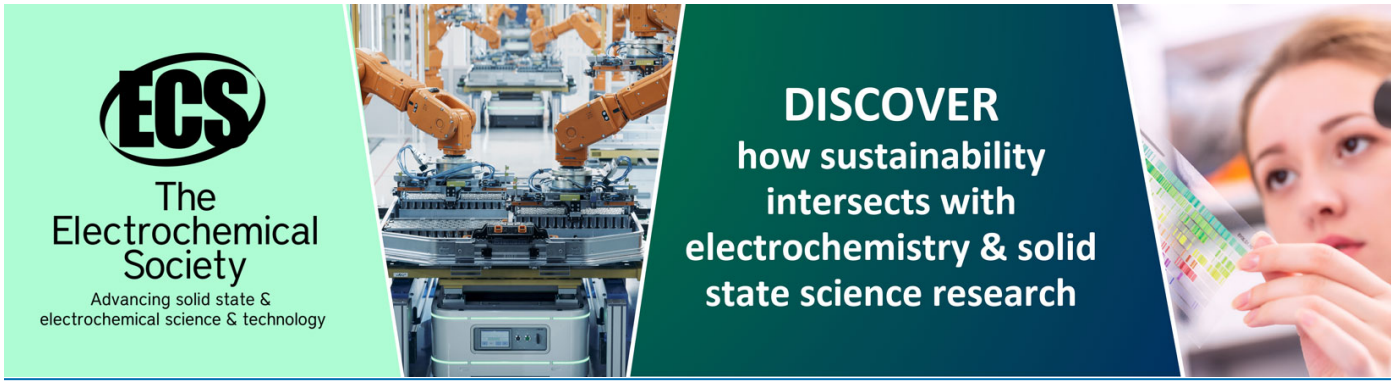

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Design, construction and evaluation of solarized airlift tubular photobioreactor

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Abstract. An innovative photobioreactor is developed for growing algae in simulated conditions. The proposed design comprises of a continuous tubular irradiance loop and air induced liquid circulation with gas separation through air lift device. The unique features of air lift system are to ensure the shear free circulation of sensitive algal culture and induce light/dark cycles to the photosynthetic micro-organisms. The design strategy employs to model and construct a 20-liter laboratory scale unit using Boro-silicate glass tubing. The material is selected to ensure maximum photon transmission. All components of the device are designed to have flexibility to be replaced with an alternative design, providing fair chance of modification for future investigators. The principles of fluid mechanics are applied to describe geometrical attributes of the air lift system. Combination of LEDs and Florescent tube lights (Warm white) were used to illuminate the photosynthesis reaction area providing a possibility to control both illumination duration and light intensity. 200 Watt Solar PV system is designed to power up the device which included air pump (100 Watt) and illumination system (100 Watt). Algal strain *Chlorella* sp was inoculated in photobioreactor which was sparged with air and carbon dioxide. The growth was sustained in the batch mode with daily monitoring of temperature, pH and biomass concentration. The novel photobioreactor recorded a maximum experimental average yield of0.65 g/l.day (11.3 g/m^2.day) as compared to theoretical modeled yield of 0.82 g/l.day (14.26 g/m^2.day), suggesting the device can be efficiently and cost-effectively employed in the production of algal biomass for biofuels, concomitantly mitigating CO_2.

Keywords: Photobioreactors; Microalgae; *Chlorella vulgaris*; Airlift; Biomass

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Nomenclature

μ	Specific growth rate	day^{-1}
μ_{max}	Maximum specific growth rate	day^{-1}
X	Biomass concentration	g/L
C_{algo}	Initial algal concentration	g/L
$C_{alg(t)}$	Algae concentration at time "t"	g/L
U_{Lr}	Liquid circulation velocity	m/s
U_G	Superficial gas velocity	m/s
ϵ_r	Riser gas holdup	-
ϵ_d	Down-comer gas holdup	-
A_d&A_r	Area of riser and down-comer	m^2
h_d	Gas liquid dispersion height	m
h_L	Un-gassed liquid column height	m
K_B	Frictional loss coefficient	-
C_f	Fanning friction factor	-
Re	Reynold's Number	-
V	Culture volume	Liter
L	length of continuous irradiance loop	ft
I_{in}&I_{out}	Incident & transmitted light intensities	$W.m^2$ or Lux
I_k	Light intensity saturation constant	$W.m^2$ or Lux
b	Light path (diameter of tube)	m
a_c	spectral average absorption coefficient	m^2/kg
R_{O_2}	Vol- rate of oxygen generation by photosynthesis	$molO_2\ m^{-3}\ s^{-1}$
U_b	Bubble rise velocity	m/s
X & W	Height & width of degasser	m
U_{LH}	Velocity of liquid in degasser	m/s

1. Introduction

Micro algae biomass offers more sustainable and carbon efficient alternative for biofuels production. Aquatic microorganisms have the ability to double their mass in less than 24 hours by efficient utilization of CO_2 in presence of light for biofuels production.

The limited growth rate and photosynthetic efficiency of open raceways due to the extended radiance pathway, which results in self-shadowing and additional ecological parameters like temperature, poisonous contamination with other microbes has facilitated the design and construction of closed photobioreactors [1]. Of the many designs of closed photobioreactors tubular photobioreactors are the most promising for growing algae [2, 3]. Table-1 represents published tubular photobioreactors with their engineering analysis.

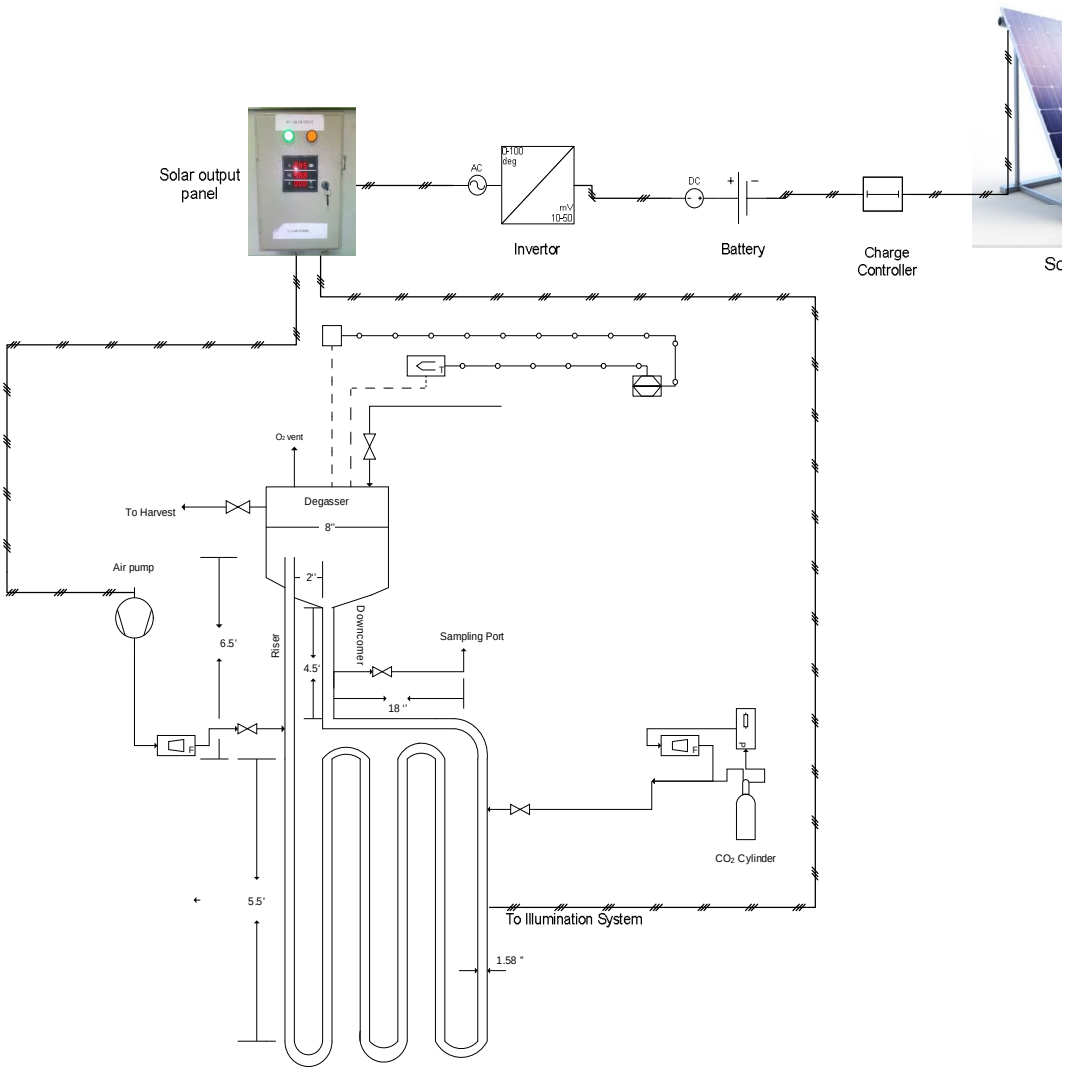

Figure 1. Schematic of the solarized airlift tubular photobioreactor

Table 1. Published tubular photobioreactors specifications

Year	Specifications	Specie Tested	Results	Investigators
1983	52 pyrex glass tubes, length: 1m, Dia: 1cm, Horizontally stacked, circulation via pump	Chlorella type green alga	Productivity: 24 $gm^{-2}d^{-1}$, light intensity: 38 W/m^2, high S/V ratio (127), oxygen accumulation not considered	[4]
1988	Area: 100 m^2, 20 polyethylene tubes, length 20 m, dia: 6cm	Porphyridiumcruentum	20-25 gm^{-2} d^{-1} Low scaling due to self cleaning via two plastic balls	[5]
1993	8 Poly carbonatemanifold tubes, Length: 20m. Dia: 3cm, Outdoor, Temp control by water spraying	Cyanobacteria	Vol- Productivity : 0.55 g $l^{-1}d^{-1}$, Reduction of head losses and lower oxygen concentrations	[6]
1995	300 L, Elevated manifold, Covered land area 12 m^2, 10 PVC tubes, Length: 25m, Dia 3 cm	Dunaliellasalina	72 gm^{-2} d-^{1}	[7]
1998	Manifold Rigid or flexible tubes, ID: 5cm, Length: 30m	A. platensis, A. siamensis, Nannochloropsis	Vol prod: 1.3 gl^{-1}d-^{1}, Areal Prod: 28gm^{-2}d-^{1}, low shear stress	[8]
2000	Airlift Serpentine 200 L, Plexiglass tubes, dia 2.5-5 cm, loop length : 98.8 m, riser length: 3-3.5 m,Dilution rate : 0.04 h^{-1}	Phaeodactylumtricornutum	Vol-productivity:1.2-1.9 $gl^{-1}d^{-1}$, Areal Productivity: 32 g $m^{-2}d^{-1}$, Degasser for effective gas exchange	[2]

Tubular photobioreactors that comprise of an airlift device is especially attractive to circulate the fluid without any moving parts [9]. Airlift device combines the function of a pump and a gas exchanger that removes the oxygen produced by photosynthesis [10]. Continuous removal of oxygen is necessary to avoid excessive buildup that inhibits photosynthesis. In addition, the photobioreactors geometry must ensure the capturing of maximum photons while minimizing the land surface occupied [11].

Effect of illumination duration on algae was studied by many researchers in literature. One study revealed that the most advantageous illumination duration for algal growth is 16 hours; however illumination for 24 hours gives a slight increase in productivity [12]. In another study growth of algal sp. *Botryococcusbraunii* was investigated at different illumination cycles, The best growth was achieved under 24 hour continuous illumination with The highest specific growth rate of 3.6 per day as compared to 0.05 under diurnal light cycles (12hr light/12 hour dark) [13]. In present study the purpose of reactor solarization is to prove the concept of exploiting solar energy to provide 24 hour continuous illumination cycle for future outdoor algae cultivation.

Here, we present a method for designing solarized airlift tubular photobioreactor. Effects of light intensity, hydrodynamics and temperature on various evaluation parameters are discussed. A photobioreactor designed using the approach outlined is proved for culture of the microalga *Chlorella Vulgaris.*

2. Photobioreactor design

A solarized airlift tubular photobioreactor is shown in figure 2. Air lift system induces circulation of fluid through the continuous tubular loop where main photosynthesis reaction occurs. The oxygen produced from the photosynthesis is separated in the air lift section when fluid returns to that section. A liquid or slurry pool at the top of the riser and down comer tubes prevents the gas bubbles from recirculating. The transparent Borosilicate glass continuous loop is designed to ensure maximum photon capturing. The diameter of tubing is selected on the basis of light beam attenuation so that dark zone is kept minimal. In addition, the light-dark fluctuations must be sufficiently robust to prevent long dark zone exposure of fluid.

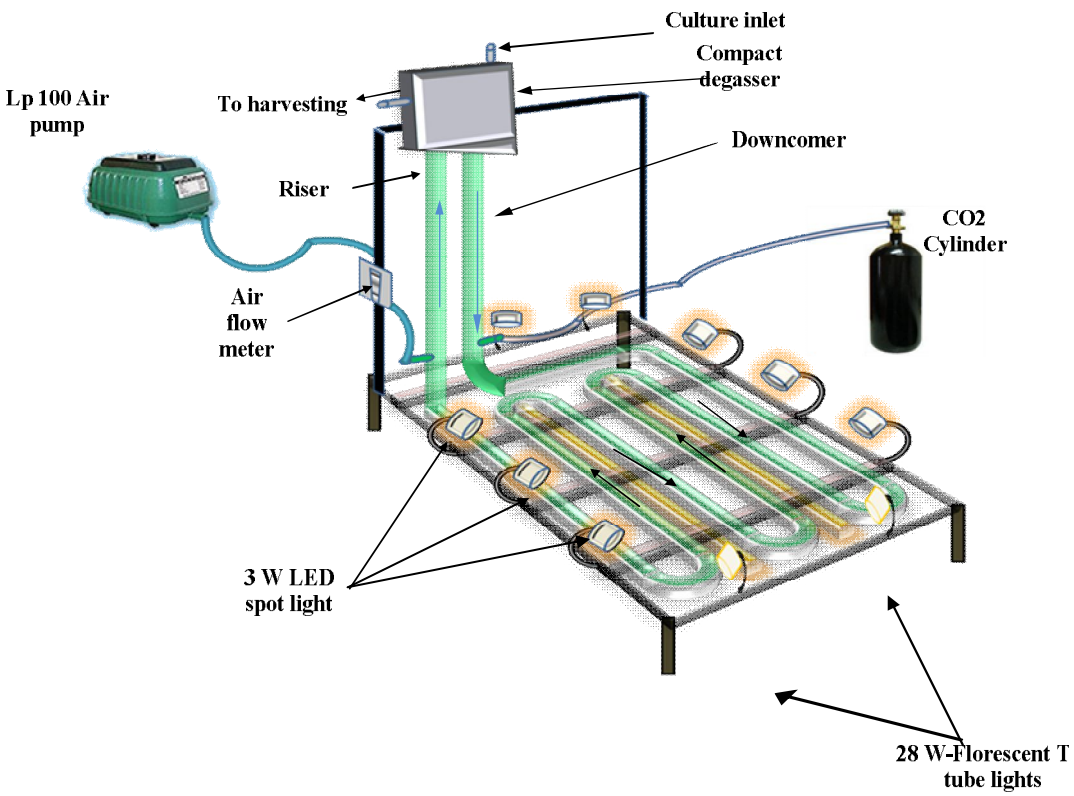

Figure 2. The photobioreactor

2.1. Continuous irradiance loop

Continuous irradiance loop is actually the photosynthetic area where illumination is provided for growth of algae. To avoid mutual shading it was proposed to construct a single continuous loop (figure 2.) so that maximum photons could be utilized in given surface area. In phototrophic cultures biomass productivity is usually control through available light intensity. In batch cultures specific growth rate

of algae depends on level of irradiance, light path and algae concentration. The volumetric productivity can be easily determined as:

$$\frac{dC_{alg(t)}}{dt} = \mu C_{alg(t)} \tag{2.1}$$

Where $\frac{dC_{alg(t)}}{dt}$ is the volumetric growth rate at any given batch time t, $C_{alg\,(t)}$ is algae concentration in photobioreactor and μ is the specific growth rate of algae.

Specific growth rate is a kinetic expression for this biochemical reaction. Monod kinetic model is (Equation 2.2) used as light-limited growth kinetic model to determine specific growth rate [2].

$$\mu = \frac{\mu_{max} I_{avg}}{I_{avg} + I_K} \tag{2.2}$$

Where μ_{max} is the maximum specific growth rate, I_K is the light intensity saturation constant for specific algal specie and I_{avg} is the average light intensity on irradiance loop.

Areal productivity can be easily calculated after knowledge of volumetric productivity by employing this relation:

$$P_{alg_A} = P_{alg_V} \frac{V}{S} \tag{2.3}$$

Where V is the volume of the reactor and S is the land surface occupied by it.

Estimation of μ is important in determination of volumetric productivity. Specific growth rate requires the identification of average irradiance on tubular loop surface. Lambert-Beer's law is used to determine the average light intensity and the light gradient inside tubular photobioreactor as light attenuation along tube diameter contributes to the algae growth limitation due to light transmission and self shading phenomena [14].

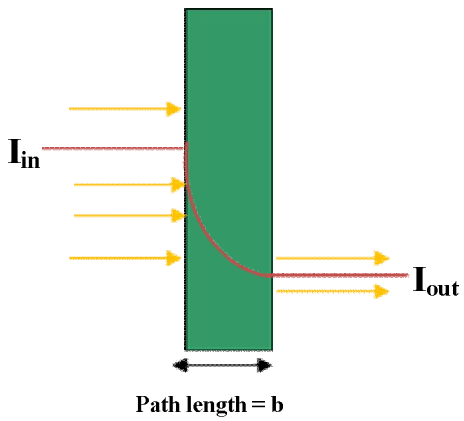

Figure 3. Light attenuation in PBR

Lambert beer's relationship along with principles of astronomy after simplification yields Equation-2.4:

$$I_{avg} = I_{in} \cdot \frac{1}{b}\left(1 - e^{-a_c \cdot C_{alg_o} \cdot b}\right) \cdot \frac{1}{C_{alg_o} \cdot a_c} \tag{2.4}$$

In above equation I_{in} & I_{out} are light intensities falling on PBR surface and coming out from PBR, a_c is the spectral average absorption coefficient and b is the path length which is the diameter of the tube in this case.

Thus from a knowledge of the characteristics parameters of the algal strain (i.e.μ_{max},a_c ,I_K) and using Equations 2.1-2.4, the biomass productivity may be determined for any combination of external irradiance and the diameter of tubes.

It is recommended that loop configuration must ensure a turbulent flow to avoid stagnation of cells in dark regions of irradiance loop [2]. Simultaneously, shear stress on algal cells will decide the upper limit on turbulence. To avoid the damage associated with shear stress, the dimensions of micro eddies generated through turbulence should be greater than the size of specific algal specie cell [15].

Certain factors restrict the maximum length of continuous irradiance loop which include liquid circulation velocity in loop, rate of photosynthesis and acceptable upper limit on DO (dissolved oxygen) concentration [10]. The maximum restricted length L of a continuous loop is determined by under mentioned relation:

$$L = \frac{U_L([O_2]_{out} - [O_2]_{In})}{R_{O_2}} \tag{2.5}$$

Where $U_L$is the maximum allowable fluid velocity in consideration with shear stress,$[O_2]_{In}$ is the oxygen concentration at the entrance of loop which is almost equal to saturation value when the fluid is in equilibrium with the atmosphere, $[O_2]_{out}$ is the oxygen concentration at the outlet which should be the maximum acceptable value that does not inhibit photosynthesis and R_{O_2} is volumetric rate ofoxygen generation by photosynthesis.

2.2. Airlift device with gas separator

Gas induced liquid circulation is the interesting feature of airlift system. Gas-liquid contact operations in process industries are now a days shifting to airlift system due to its simplicity and low energy consumption. The liquid slurry pool at head region of riser and down-comer (figure 4.) can be designed as effective separator for continuous removal of O_2 from culture.

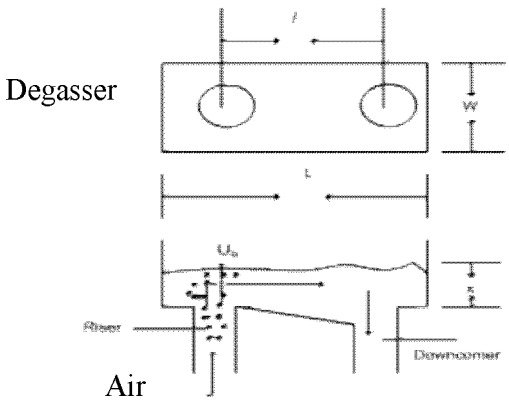

Figure 4. Airlift device

For effective separation of gas bubbles, the time taken by the bubbles to raise height '**X**' should be equal to or less than that of time taken by the fluid to traverse length '***l***'. Apply equation of continuity as same quantity of fluid passes through the regions of riser, down-comer and degasser

$$U_L A_r = U_{Ld} A_d = U_{LH} XW \tag{2.6}$$

Where A_r is the cross-sectional area of the riser tube, A_d is the mean vertical cross-sectional area of the degassing zone, U_{Ld} is the mean superficial liquid velocity in the degasser, U_{LH} is the liquid velocity in degasser tube, X is the height of liquid in degasser and W is the width of degasser. To satisfy the disengagement criterion [16], the length ***'l'*** of the degasser is governed by the relationship:

$$l \geq U_L A_r / U_b W \tag{2.7}$$

Where U_b is the bubble rise velocity, 0.2 m/s was used to determine length ***'l'***
Superficial gas &liquid velocities and gas hold up are considered as significant hydrodynamic attributes for the design and performance of air lift and bubble column reactors. Energy balance on air lift reactor results in the equation to determine the superficial liquid velocity in the reactor [16]. "U_{Lr}" The superficial liquid velocity is found by Equation 2.8

$$\boldsymbol{U_L} = \left[\frac{2gh_D(\epsilon_r - \epsilon_d)}{K_B\left\{1/(1-\epsilon_r)^2 + \left(A_r/A_d\right)^2 1/(1-\epsilon_d)^2\right\}}\right]^{0.5} \tag{2.8}$$

ϵ_r=Riser gas hold up with respect to liquid

ϵ_d=Downcomer gas hold up

A_d and A_r= Areas of the down-comer and the riser (m^2)

h_d= Gas liquid dispersion height (m)

The factor h_d is associated to the overall gas hold up inside the reactor (ϵ) and un-aerated liquid height (h_L), as explained in under mention equation [16]:

$$h_d = h_L/(1-\epsilon) \tag{2.9}$$

The following equation can be used to determine K_B which frictional loss coefficient is

$$K_B = 4C_f \frac{L_{eq}}{d} \tag{2.10}$$

$$C_f = 0.0791 Re^{-0.25} \tag{2.11}$$

The riser gas hold up can be determine using the following governing equation [18]

$$\epsilon_r = \frac{U_G}{[0.24+1.35(U_G+U_L)^{0.93}} \tag{2.12}$$

Where

$$\epsilon = \frac{\epsilon_r A_r + \epsilon_d A_d}{A_r + A_d} \tag{2.13}$$

The equations 2.8 to 2.13 are solved through numerical iteration procedures assuming an initial value or superficial liquid velocity. The iteration process is used to model liquid circulation velocity with respect to superficial gas velocity.

3. Material and methods

3.1. Specie and nutrient Media

Samples of locally grown fresh water algal specie *Chlorella vulgaris* were taken from Pakistan Agriculture Research Council (PARC). Initially sample was inoculated in a glass column by providing specified media, light and air for its initial growth. Bold Basal Medium and Modified Bold Basal Medium were the stock solutions as mentioned in Appendix A.

3.2. Dry biomass concentration

The dry mass of algal specie *Chlorella Vulgaris* was determined manually by taking samples from PBR after specified period. A filter paper was utilized to determine the dry biomass concentration, which was previously dried in an oven at 150 ^{o}C for one hour and weighed for its initial weight. The filter papers were dried in the lab oven after filtration at 150 ^{o}C for about 2 hours. Final weight was determined by cooling the filter paper at room temperature. After filtration and before filtration difference in weights divided by the filtered sample volume provided the dry mass concentration.

3.3. Temperature and pH

TECPEL 4-Channel input DTM 319 digital temperature data logger (FIG-4.14) was used to record temperature at four different locations around PBR. Martini thermometer coupled with a type K thermocouple was also employed to determine the temperature of fluid inside the photobioreactor. The temperature was recorded by adjusting the tip of thermocouple at least two inches below the water level in the degasser. Martini pH meter Mi-160 pH meter was used to record online pH for all the photobioreactor experiments.

3.4. Light Intensity

DLM105HA digital light meter was used to measure light intensity. The units of measurement were Lux. As the reactor had light sources on its both sides, the sensor was placed on both upper and downward sides of the reactor; the readings were noted and averaged to get the light intensity.

3.5. Liquid circulation velocity

Actual gas induced liquid circulation was determined using tracer analysis. Series of experiments were undertaken at different airflow rates to determine actual velocity of the culture. A coloured piece of cotton fibre cloth whose density was almost equal to algal dry cell density inserted in photobioreactor, for a predefined distance time taken by that coloured piece was noted to get the actual velocity of the culture.

Table 2. Overview of experimental observations.

Test No	Duration	Light Intensity (Lux)	Liquid circulation velocity (m/s)	Avg. Volumetric Productivity (g/L.d)	Avg. Areal Productivity (g/m^2.day)	Nutrient Media
1	25 Nov-01 Dec	1300	0.60	0.55	9.56	Bold Basal
2	02 Dec-15 Dec	1300	0.65	0.33 [a]	5.74	Bold Basal
3	14 Jan-23 Jan	700	0.43	0.46	8	Bold Basal
4	24 Jan-30 Jan	700	0.5	0.37 [b]	6.43	Bold Basal
5	03 Feb-14 Feb	650	0.5	0.25 [c,d]	4.35	Bold Basal
6	17 Feb-27 Feb	1350	0.55	0.65	11.30	4xN Mod Bold Basal
7	01 Mar-10 Mar	1350	0.55	0.50	8.70	4xN Mod Bold Basal

a= No external carbon dioxide, b= Low mass transfer/position changed
c= very low temperature <10°C, d= Algae attached to the inner side of tube walls

4. Results and discussions

4.1. Design of Photobioreactor

Biomass productivity in a batch mode was predicted using equations 2.1-2.4 for *Chlorella vulgaris* at known maximum specific growth rate and light intensity. Batch mathematical model gave volumetric productivity of 0.82 g/l.day (Areal productivity: 14.26 g/m^2.day), this modeled yield can be compared well with the experimentally achieved maximum average yield of 0.65 g/l.day. With the increment in tube diameter, he volumetric growth rate decreases, on the other hand, the areal growth rate increases as higher culture volumes can be contained in a particular area [17]. To make a compromise between the contradictory demands of volumetric and areal productivities, available culture velocity, the energy dissipation per unit mass and local availability, a tube diameter of 0.038 m was preferred for fabrication of continuous irradiance loop.

4.2. Hydrodynamics

The mathematical model equations discussed were solved by iteration. The results revealed are for the flow rate used in all tests performed to validate PBR. The results show the expecting superficial liquid velocities in PBR with respect to superficial gas/air velocity. The model expectation for circulation time of culture through continuous tubular irradiance loop is about 16 seconds at the maximum velocity of 0.65 m/s. This period referred to as 'light side' period of complete cycle. Based on the length of the riser (2 m) and down-comer the culture from the bottom of the riser to the bottom of the down-comer takes 8 seconds, this period is 'dark side' period. The experimental observations were found in the range of ±5-10% of the modeled values. figure 5 is the graphical representation of hydrodynamics comparison.

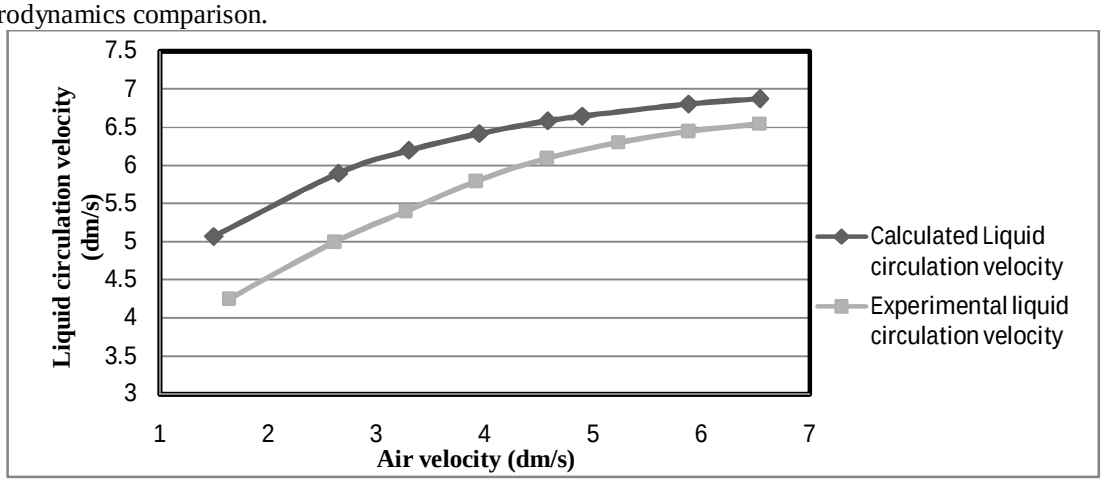

Figure 5. Calculated and experimental hydrodynamics comparison

4.3. Indoor batch culture

Performance of indoor batch culture was assessed using different irradiance, liquid circulation velocities, temperatures and Nutrient media. As analyzed from Table-2 maximum average yield was recorded at light intensity of 1350 Lux while growth rate decreased more than half of maximum average yield at 650 Lux. The experimentally obtained maximum growth rate was almost 20 % less than that of estimated using mathematical model. The major reason of this deviation is low temperature than optimal in actual conditions. Effect of liquid circulation velocity was also investigated at five different liquid circulation velocities (m/s): 0.43, 0.5, 0.55, 0.60 and 0.65. A graphical plot between liquid circulation velocities against growth rate (figure 6) reveals that

maximum growth rate was achieved at velocity of 0.55 m/s. The optimal range of liquid circulation velocity obtained from experimental evaluation is 0.47 to 0.57 m/s.

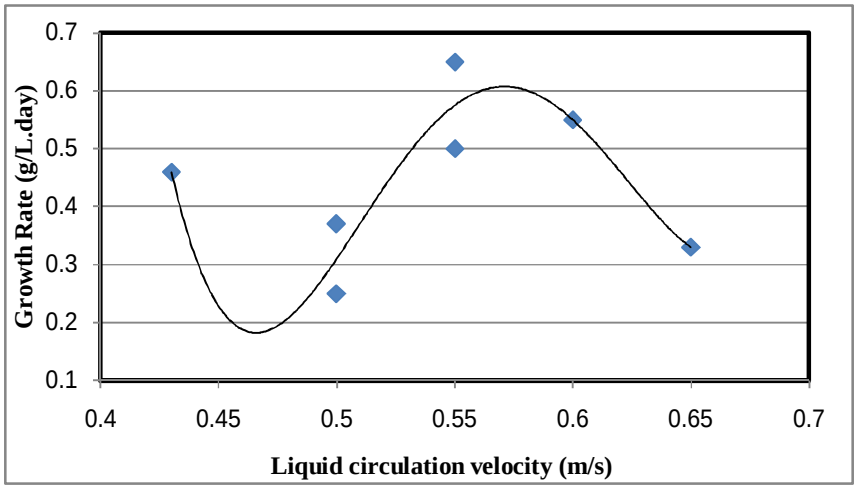

Figure 6. Effects of liquid circulation velocity on productivity of algae data were obtained in winter at different temperatures

The optimum temperature range for many algal species is 25-35 °C. In this research effects of low temperature range 10-20 °C were observed. Different studies reveal that low temperature causes the algal activity of multiplication slows down. In this study temperature below 12°C caused a considerable slow growth as depicted from the graph. A general trend in figure 7. shows that growth rate increases with increasing temperature. Maximum productivities are observed in the range of 13-20 °C.

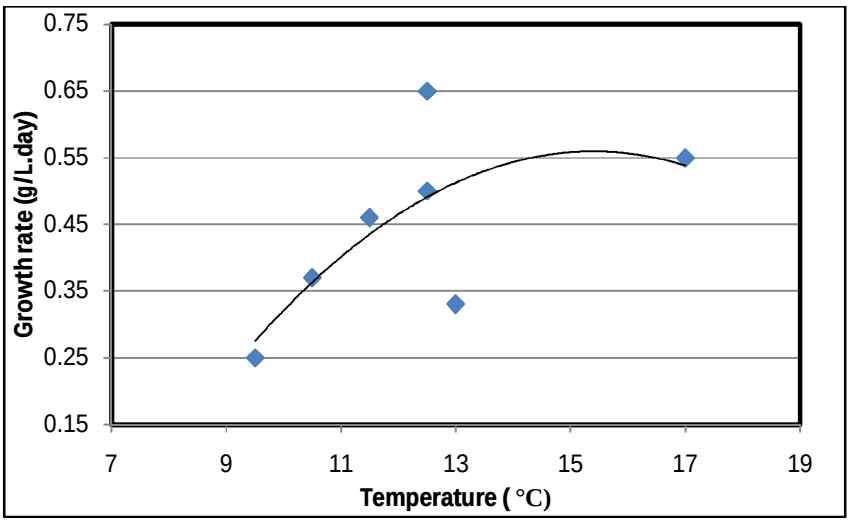

Figure 7. Effects of temperature on growth rate

Artificial illumination system was employed to study the effects of light intensity on biomass productivity. The main purpose of using artificial lights comprising warm white T-5 florescent tubes and warm white LEDs was to control both light intensity and illumination duration. It was observed by different experiments that algal growth primarily depends on the light intensity. In indoor conditions, it

is believed that there was no photo-inhibition effects as controlled or limited light intensity conditions were provided. A general trend is obtained by plotting light intensity versus growth rate as described in figure 8. The investigation reveals that by increasing light intensity productivity increases.

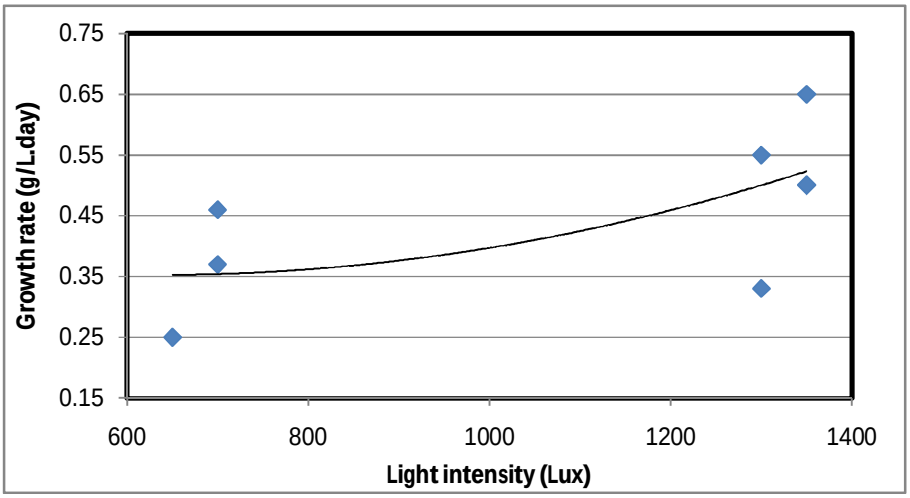

Figure 8. Light intensity versus average growth rate

Two tests 6-7 were performed using the 4xN Modified Bold Basal recipe as growth media. It can also be concluded that the use of 4xN Modified Bold Basal media instead of simple Bold Basal media resulted in the most vigorous *Chlorellasp* growth in photobioreactor. Figure 9. shows that nutrient media is vital for the growth of algae. Nitrogen, Phosphorous and Potassium are essential for the growth. Dedicated experiments are performed to validate this factor. Nitrogen-deprived culture causes the growth rate to decrease as compared to nitrogen-excess media. Nitrogen excess definitely associated with the higher protein formation and a bit lower lipid production.

A bar graph is plotted to compare the performance of PBR with different nutrient media. Test 6 & 7 were performed using 4xN Modified Bold Basal media, and all other tests 1-5 were conducted with simple Bold Basal media. It is clearly depicted from graph (figure 9.) that modified media results in the higher growth rates.

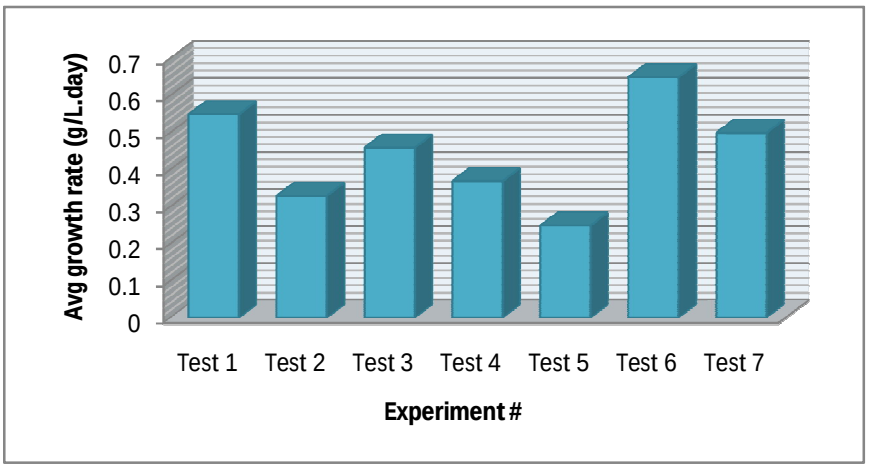

Figure 9. Effects of nutrient media on growth rate

5. Concluding comment

An engineering approach is discussed to design solarized airlift tubular photobioreactor. The novel system convenes all the design measures and restraints in terms of maintenance, mobility and flexibility for potential future amendments. The design approach effectively simulates light intensity-dependent biomass productivity, hydrodynamics that determines liquid circulation velocity in continuous loop and gas separation in airlift system. 20 L photobioreactor designed using proposed strategy was assessed in batch indoor culture of *Chlorella vulgaris*. Biomass productivity and hydrodynamics predicted from a mathematical model were in close agreement with measured experimental results. A horizontally stacked single layer continuous loop with optimal diameter of 0.038 m, length 42 ft, connected to 2 m tall airlift system. This configuration covered a land area of about 1.15 m^2. Optimal liquid circulation velocities were in the range of 0.47-0.57 m/s. The reactor practiced algae bio-fouling to the tube walls which caused the cell productivity to decline. 200 Watt Solar PV was employed to power up the reactor including 100 Watt air pump and 100 Watt illumination system.

Modeling/simulation parameters used in photobioreactor performance prediction is summarized in Table 3.

Table 3. Modeling & Simulation parameters

Factor	Unit	Value range
μ_{max}	h^{-1}	0.09
I_k	W/m^2	8
C_{algo}	g/L	0.25
I_{in}	W/m^2	15
a_c	m^2/kg	200
b	m	0.038
Illumination duration	hr	24 hr

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