DESIGN AND EVALUATION OF A HELICAL-TUBULAR PHOTOBIOREACTOR FOR MICROALGAE PRODUCTION

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ABSTRACT

Photosynthetic microalgae are important bioresource for producing desired and environmentally safe products including biodiesel production as third generation biofuels. Photobioreactor play important role in this process. Designing and manufacture the bioreactor for photocatalysis is still challenging at present time due to the important factors that must be closely considered with regard to light requirements. The aim of the present study was to design and evaluate a helical-tubular photobioreactor for algae production. The design considerations included light intensity controller circuit, surface-to-volume ratio, power required of both air pump and mixing pump to reach up the optimum operating parameters. Experiments were conducted to optimize light intensity and light/dark duration cycle. The photobioreactor performance was evaluated in terms of biomass productivity, lipid productivity, carbon capture efficiency and energy balance of algae production system. The experimental results reveal that the helical-tubular photobioreactor is recommended to be used under light intensity of 8 kLux and light/dark duration cycle of 18:6 h to obtain the highest biomass productivity of 1.80 kg.day^{-1} and lipid productivity 432 g.day^{-1} with carbon capture efficiency 87%. The manufactured photobioreactor is capable of produce 4.74 kWday which is equivalent to 4.39 kWday of net energy output.

1. INTRODUCTION

Algae have recently attracted significant interest worldwide in view of their extensive application potential in the renewable energy technology development, nutraceutical industries and bio-pharmaceutical. Algae are sustainable, renewable and economical resources of biofuels applications, they are ideal substitute to fossil fuels with respect to renewability, capital cost and environmental concerns.

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Algae have a considerable ability to convert atmospheric carbon dioxide to useful products including lipids, carbohydrates, proteins, vitamins, antioxidants and other bioactive metabolites. Although algae are feasible sources of renewable energy and biopharmaceuticals generally, but some constraints and challenges remain which must be beat to upgrade this technology from the laboratory scope to applied-scale domain.

The most challenges and crucial issues are promoting algae culture technique for biomass production, algae culture media and optimizing algae growth rate **(Khan et al., 2018)**. Photosynthetic microorganisms like unicellular microalgae, plant cells and cyanobacteria are high-potential sustainable bioresources that are promising in several applications including biofuel production, valuable food and animal feed production as well production of cosmetics, fine chemicals, wastewater treatment and carbon dioxide bio sequestration. Algae are photosynthetic organisms that grow in an extent of aquatic environments including rivers, lakes, oceans and wastewater. It can afford a wide domain of various light intensities, temperatures, pH values and salinities as well as, can be grow alone or in a symbiosis with other organisms (**Das et al., 2011)**.

The current studies and technology based on the third-generation biofuels derived from algae biomass have been considered as the alternative bioresource that avoids the disadvantages related to first and second-generation biofuels. Growth enhancement techniques can be used to improve algae potential as a future resource of renewable and sustainable biofuels production. **(Behera et al., 2015)**. Research studies have focused their interest, particularly on the algae biomass as an alternative feedstock for production biofuels furthermore, algae biomass has no competition with feed production and agricultural food. Algae require generally some nutrients like nitrogen, phosphorus, and potassium as well light and carbon dioxide for its growth and also to produce amount of carbohydrates and lipids, which can be processed for production biofuels and varied value-added products. Appropriate the mixing and shaking of the culture in the photobioreactor is requisite for uniform distribution of light energy to utility the same conditions for all the cells to convert maxima light energy to biomass **(Formighieri et al., 2012)**.

Most of the algae species are convenient for bio-diesel production because of high lipids content 20-50% of oil in biomass as in case of the

microalga. Algae are capable of producing algae oil 58,700 $L.ha^{-1}$ which can produce 121,104 $L.ha^{-1}$ bio-diesels. The challenges lie in the spread of algae technology due to the high operational, harvesting, conversion and maintenance costs **(Medipally et al., 2015)**. There is direct relation between algae growth and light requirements. Therefore, light intensity affects the yield of biomass and composition as well carbohydrates accumulation in the algae cells. The maximum growth rate and lipid production were achieved in range of light intensity from 5000 to 7000 Lux for most of the algae species. While biomass yield decreased when the light intensity was reduced. Duration of light/dark is vital in bioreactor to avoid the photo-oxidation **(Daliry et al., 2017)**. Light intensity and duration directly influence on photosynthesis of algae and also light requirements have effect on algae biomass yield and the biochemical composition. This should be taking in consideration for bioreactor designing system for maximum the growth and biomass collection. It is needed improvement algal culturing technology for targeted biomass production to make the biotechnology practical, economically and sustainable the biomass output should be higher than 30 $g.m^{-2}.day^{-1}$ **(Krzemińska et al., 2014)**. The total biomass of chlorella vulgaris was 3.62 $g.L^{-1}$ (dry weight). The protein, carbohydrate and lipid content were recorded 36.56, 42.13 and 28.68 % respectively **(Dineshkumar et al., 2017)**.

The challenges of this technique are that the algae products currently not available in applied style as well the other cultivation systems have been constructed by using the high expensive equipment and complex structures beside operating procedures that demand a state of the advanced techniques with fully equipped laboratories. Research efforts that gather theory and practice are still request to full advantage potential as regards the photobioreactor cultivation systems. Therefore, Objectives of the present study include design and performance evaluation of a pilot-scale system for algae production as well as optimize some operating parameters affecting performance of the manufactured system.

2. MATERIALS AND METHOD

The experiments were carried out at Electrical Engineering Laboratory, Agricultural Engineering Department, Faculty of Agriculture, Zagazig University to design and the performance evaluation of a helical-tubular

photobioreactor for production algae. Experiments were performed to improve some operating parameters for optimizing both of a biomass productivity, lipid productivity, carbon capture efficiency and energy balance of algae production system.

Algae strain and growth media

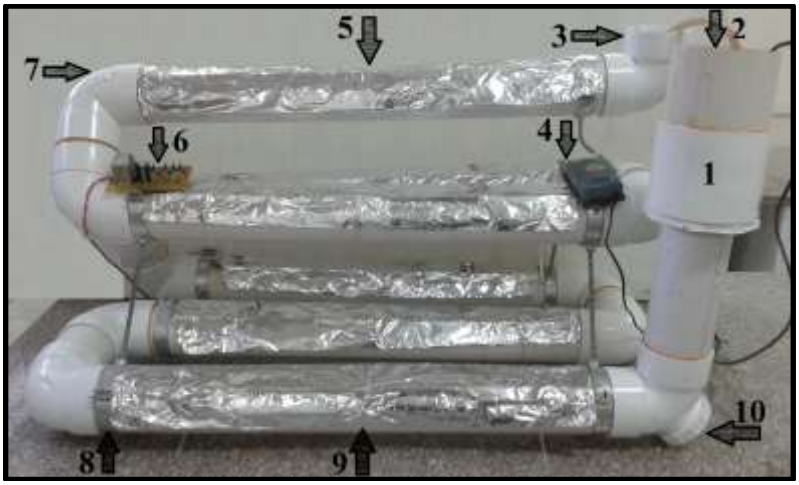
Chlorella Vulgaris is eukaryotic green microalgae from the genus Chlorella, which was obtained from the Department of Microbiology, Faculty of Agriculture, Zagazig University. It was supplied in 2 flasks with a capacity of 500 ml of algae solution and synthetic growth media. The obtained algae cultivation was started in two larger 5L vessel. The growth media was prepared at Department of Microbiology to ensure the nutrient solution composition is accurate. After seven days, whole the amount of algae solution was inoculated to the 102 L main bioreactor with (7.5 ± 0.2) pH that was kept experiment throughout. An aeration was provided using air pump to ensure homogeneous mixing for algae. The algae strain was kept under conditions 16 hour-light/8 hour-dark with a 7000 Lux illumination and power of 10 W to support growth rate.

Helical-tubular photobioreactor

photobioreactor consists of transparent tubing arranged in parallel lines connected by manifolds as shown in Fig. 1. The used tubes are followed a meandering course so called the helical solar collector. The reactor tubes were made of acrylic and have diameter of 10 cm with length of up to one meter. In this design was used a high cell density culture of 1 $g.L^{-1}$. Tubular reactor provides a high surface to volume ratio of 100 m^{-1}, which is one of an important advantage of this design. The photobioreactor is designed to enhance algae growth rate and biomass production by controlling environmental parameters including the light intensity and the light/dark duration cycle.

The helical-tubular photobioreactor consisted of five tubes attached to the top and bottom by using the 90-degree elbow in a U-bend shape to each tube forming two vertical levels which make a working volume of 102 liter. Length, breath and height of bioreactor are (123, 68 and 80 cm), respectively with total weight of 33 kg without loading biomass. An illuminated surface area is 664 cm^2 as well 6.51 $cm^2.liter^{-1}$ of surface-to-volume ratio.

Mixing of algae was done using a centrifugal pump that provided flow rate at 11.67 $m^3.h^{-1}$ through PVC tubes. In addition to the uniform distribution of light as also is focused on axis of the tube. The arrangement of the tubes has taken into consideration to achieve the most homogeneous conditions of the light. The pumping speed of liquid is done from 40 $cm.s^{-1}$ by centrifugal pump. Micro bubbles are provided for aeration process as a gases exchange unit. An electrical energy required for aeration process is 49 $W.m^{-3}$.



No.	Part Name	No.	Part Name
1	Mixing pump	**6**	Light controller circuit
2	Inlet opening	**7**	90-degree elbow
3	Gas exchange	**8**	Main frame
4	Air pump	**9**	Bioreactor tube
5	10W-LED panel	**10**	Harvesting drain

Fig. 1: Front view of a helical-tubular photobioreactor.

The light intensity distribution is non-uniform inside a bioreactor due to absorption and spread in the culture. Decrease of the radiation is dependent on design of the reactor, the light wavelength, penetration distance of light and cell concentration. The light intensity decreases highly with the distance away from the irradiated side of the bioreactor. Light intensity controller circuit was designed and integrated in the cultivation system. 10W-LED panel was installed on upper of the bioreactor tube.

METHOD:

The present study is interested in design and performance evaluation of an a helical-tubular photobioreactor for production algae. The constructed

bioreactor is a closed system which supplies a controlled environment and high productivity rate of *Chlorella Vulgaris* microalgae. Light requirements (light intensity and duration) are from the major factors which influence the level of the algae cultivation and biomass yield. Light circuit is designed and run by a fully automatic control system in order to increase volumetric productivity, lipid content, carbon capture efficiency and energy production under various operating conditions. Design criteria included both of light intensity controller circuit, choice of construction material, surface to volume ratio, power required for air pump and mixing pump.

Design of light intensity controller

This circuit was designed to control light intensity for the LED panel under various loading conditions. A light intensity controller circuit consists of X-rated capacitor, bridge rectifier, capacitance filter, voltage regulator and frequency oscillator, as illustrated in Fig. 2.

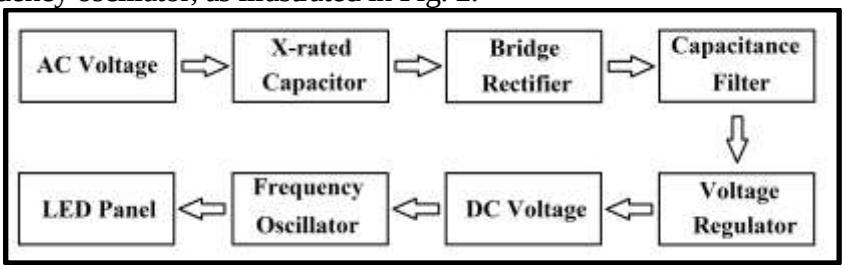
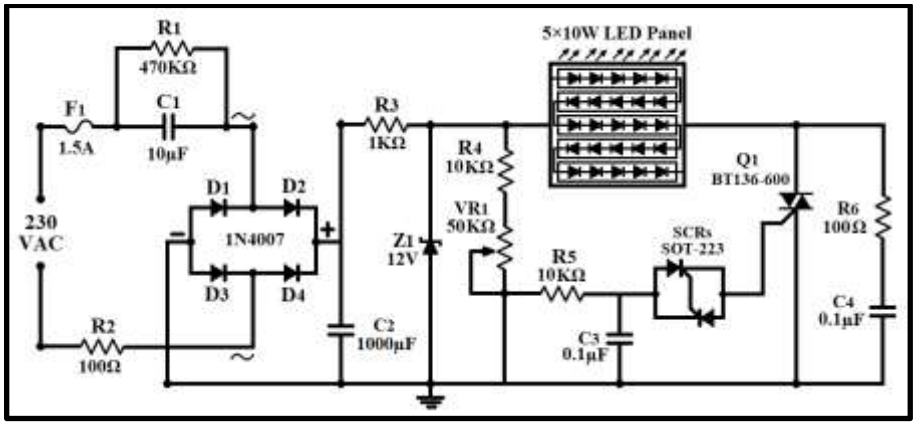


Fig. 2: Block diagram of light intensity controller circuit.

High-voltage AC into low-voltage DC is converted using capacitor power supply. Generating low-voltage 12VDC from high-voltage 230VAC mains is essential in an electronics field including LED panel. The main component of power supply is X-rated capacitors (voltage dropping capacitors), which is specially designed for AC mains.

Metallized film capacitor of 10µF (C1) is connected in series of phase line of 230VAC to lower down the voltage. A 470kΩ fixed resistance is connected in parallel with capacitor to discharge the storage current in the capacitor when the circuit auto powered off. This resistance is called bleeder resistance for preventing from electric shock. Light intensity control circuit is powered from a 12VDC power supply where, the rectified and regulated-voltage with rated current is given to the integrated circuit. The designed circuit is based the principle of power regulation using silicon-controlled rectifiers (SCRs) as shown in Fig. 3.



Symbol	Name	Specifications
F1	AC fuse	1A/230V-50/60HZ
C1	X-rated capacitors	10µF/400V
R1	Fixed resistance	470kΩ
R2	Fixed resistance	100Ω
D1, D2, D3 and D4	Bridge rectifier	1N4007/1A
R3	Fixed resistance	1kΩ
C2	Capacitor	1000µF/400V
Z1	Zener diode	1N4747A/12V
R4 and R5	Fixed resistance	10kΩ
VR1	Variable resistance	50kΩ
C3 and C4	Capacitor	0.1µF/40V
SCRs	Silicon-controlled rectifier	SOT-223
R6	Fixed resistance	100Ω
Q1	Transistor	TIP50-1A/40V

Fig. 3: Schematic diagram of light intensity controller circuit.

The controller circuit works through change the firing angle of the triac. Fixed resistance (R_5), variable resistance (VR_1) and capacitor C_3 are grouping of them in a series connection. The firing angle is varied by changing the value of variable resistance, i.e., time period in which the triac operates, this directly changes the load power driven by triac. The pulses of firing are given into the gate of triac using SCRs. Silicon-controlled rectifiers (SCRs) is unidirectional device which connect current only in one direction instead of the other methods which is bidirectional. SCRs allows the control circuit to produce an enormous range of light levels as the voltage break-over triggering device using two inverse parallel sensitive gates. As well as realizing a high-sensitivity control because two SCR form a full break back

trigger. Furthermore, a snubber circuit consisting the fixed resistance R_6 and capacitor C_4 is included with the previous electronic elements to improve the performance of the triac as well as to suppress a phenomenon of voltage transients in electrical circuit. To control the light intensity according to the required operating levels by adjusting the variable resistance (VR_1). 10W-LED panel was installed for each tube in bioreactor as well it is operated and control in light intensity using the previous controller circuit. The following table shows specifications of the closed photobioreactor system.

Table 1. Main specifications of the closed photobioreactor system.

Parameter	Value	Unit
Diameter of tube	100	Mm
Length of tube	1000	Mm
Thickness of tube	5	Mm
Cross-sectional area	78.5×10^{-4}	m^2
Working volume	102	L
Culture velocity	0.40	$m.s^{-1}$
Volumetric flow rate	11.67	$m^3.h^{-1}$
The total length of the tubes	13.00	M
Roughness factor of PVC tube	0.0015	Mm
Kinematic viscosity	1.31×10^{-6}	$m^2.s^{-1}$
Static head	80.00	Cm
Loss coefficient for pipe Entrance	0.05	–
Loss coefficient for 90^o bend	0.75	–
Friction coefficient	0.023	–
Loss coefficient	12.08	–
Dynamic head	9.90	Cm
Total system head	89.90	Cm
Power of air pump	5	W
Power of mixing pump	50	W
Illuminated surface area	664	cm^2
Surface-to-volume ratio	6.51	$cm^2.L^{-1}$

The choice of construction material

The essential criterion to design the bioreactor is the material used for main tube. This material must have high mechanical strength, high durability, high transparency, ease of cleaning and low cost as well as must be a non-toxic to algae culture. It should be noted that acrylic material is therefore selected as effective final choice. Therefore, a cast acrylic was used for designing the reactor tube with relative density,

tensile strength, refractive index and light transmission of (1.19 $g.cm^{-3}$, 75 MPa, 115 MPa, 1.49 and 92%) respectively as well as service temperature is from -40^0 C to 80^0 C.

Surface-to-volume ratio

The ratio between illuminated surface area and working volume of the bioreactor plays an important role in design concept, i.e. that higher ratios will give a high cells concentration and high biomass productivity inside bioreactor. However very high ratios will cause an excessive change in carbon dioxide absorption, nutrient depletion and oxygen evolution, which in turn has negative long-term impacts on the algae culture. So, the surface to volume ratio was 6.51 $cm^2.L^{-1}$ to achieve maximum biomass productivity.

Power required for air pump

Power input is used to compare bioreactors; which can be expressed by the power input per unit volume regarding gas exchange and culture circulation in the reactor. To calculate power required for air pump and mixing pump, it was assumed that algae culture has same the dynamic viscosity and density for water at a specified temperature. To achieve a high photosynthesis rate, the carbon dioxide and oxygen balance must adjust in a way that provided optimum conditions for algae growth. Hence, carbon dioxide must be available with remove evolved oxygen prior reaching inhibitory concentrations. The tubular helical system mixed by air-bubbling advance an important advantage in this case because they provide a lower path to transfer oxygen outside of algae culture. The power required for air pump was calculated using the following equation (**Dormido et al., 2014).**

$$P_a = \rho_L \times V_w \times g \times v_a = 5w$$

Where: P_a is power required for air pump, ρ_L is density of the culture = 925 $kg.m^{-3}$, V_w is working volume of bioreactor =102L, g is the gravitational acceleration and v_a is the superficial gas velocity = 0.54 $cm.s^{-1}$.

Power of mixing pump

The power input will be calculated that must be provided to the centrifugal pump in order to obtain the required flow rate within the system. To achieve a required flow rate through pumping system, must be estimated what the total operating head of the system that will be to select the suitable pump for it.

For the current system, the total system head is calculated as follows:

$$H_t = H_d + H_s$$

where: H_t is the total head, H_d is dynamic head and H_s is static head.

The appropriate method to mix the algae culture is essential in bioreactor design to prevent cells sedimentation, avoid thermal stratification, ensure suitable irradiance of to all the cells, supply adequate amount of carbon dioxide and distribute nutrients in the medium. Cultures of microorganisms cannot be mixed by using mechanical stirrer due to high hydrodynamic shear stress is applied on cells. So, the circulation pump is designed to operate at a culture velocity of 0.40 $m.s^{-1}$ and to pass a flow rate of 11.67 $m^3.h^{-1}$ within the bioreactor. The velocity higher than 1 $m \cdot s^{-1}$ will be produce micro eddies, which leads to damage the cells, and liquid velocities from 20 to 50 $cm \cdot s^{-1}$ were recommended **(Huang et al., 2017)**.

Dynamic head was calculated using the basic Darcy Weisbach equation:

$$H_d = \frac{kv_c^2}{2g}$$

Where: H_d is dynamic head, k is loss coefficient, v_c is culture velocity in the tube and g is acceleration due to gravity. The loss coefficient, K consists of two elements:

$$k = k_f + k_p$$

Where: K is loss coefficient k_f is associated with the fixtures used in the tube works of the system and k_p is related to the total lengths of tube used within the system which is calculated as follows:

$$k_p = \frac{fL}{D}$$

Where: f is friction coefficient, L is total length of tube and D is tube diameter.

Friction coefficient can be found through a modified Colebrook White formula as follows:

$$f = \frac{0.25}{\left[log\left(\frac{\varepsilon}{3.7 \times D} + \frac{5.74}{Re^{0.9}}\right)\right]^2}$$

Where: Re is Reynolds number and ε is roughness factor. Reynolds number is associated with fluid flow and the energy absorbed as it moves. Reynolds number was calculated using the following equation:

$$Re = \frac{v_c \times D}{\gamma}$$

Where: Re is Reynolds number, v_c is culture velocity in the tube, D is diameter of tube and γ is kinematic viscosity of water. The power required is

determined from the ultimate shaft power with margin and tolerance values of 20%. The power required for mixing process was calculated using the following equation:

$$P_m = \frac{1.5 \times Q \times H_t \times \rho_L \times g}{\eta_p}$$

Where: P_m is power required for mixing process, Q is volumetric flow rate, H_t is total system head, ρ_L is density of the culture, g is the gravitational acceleration and η_p is pump efficiency = 85%. Power of the centrifugal pump was determined 50-W with 1.5 a service factor.

The performance of the a helical-tubular photobioreactor was experimentally measured under the following parameters: four different light intensity (6000, 7000, 8000, and 9000 lx) and light/dark duration cycles of (12:12, 14:10, 16:8 and 18:6 h) throughout the cultivation period.

Measurements and determinations

There are important considerations for evaluating the performance of the algae bioreactor, can be clarified as follows:

1. Biomass productivity

Biomass productivity, BP ($kg.day^{-1}$) is estimated by the biomass accumulation using dry-weight measurement of algae culture as shown in the following equation **(Santhoshkumar et al., 2015).**

$$BP = \frac{W_f - W_i}{t_t}$$

Where: W_f and Wi are the final and initial dry biomass concentrations ($g.L^{-1}$) and t_t is time period of batch test (day).

2. Lipid productivity

Lipid productivity, LP ($g.day^{-1}$) was calculated by using the following equation (**Praharyawan et al., 2016).**

$$LP = BP \times LC$$

Where: BP is Biomass productivity and LC is Lipid content = 24%.

3. Carbon capture efficiency

Carbon capture efficiency, η_c can be calculated as follows, assuming weight of carbon capture = 50% dw of algae biomass **(Ghayal and Pandya, 2013).**

$$\eta_c = \frac{W_{cc}}{W_i} \times 100$$

Where: η_c is carbon capture efficiency, W_{cc} is weight of carbon captured and W_i is weight of CO_2 injected into the bioreactor.

Weight of CO_2 injected into the bioreactor per day was calculated as follows:

$$W_i = W_c \times Q_a$$

Where: Wc is Atmospheric CO_2 level = 0.410 $g.L^{-1}$ and Q_a is Air flow rate of air pump = 1.75 $L.min^{-1}$ = 2.52 $m^3.day^{-1}$.

4. Energy consumption

The specific energy consumption, EC (kWday) in algal growth is given by using the following equation **(Karemore et al., 2015).**

$$EC = P_m + P_a + P_L$$

Where: P_m is power required for operating mixing pump.
P_a is power required for air pump.
P_L is power required for operating light panel.

5. Energy production

Energy production, EP (kWday) can be calculated by using the following equation **(Karemore et al., 2015).**

$$EP = LHV \times LP \times \frac{1}{CF}$$

Where: LHV is Lower heating value = 39.50 $MJ.kg^{-1}$.
LP is Lipid productivity, $g.day^{-1}$.
CF is conversion factor = 3.6.

6. Net energy output

Net energy output, EN (kWday) was calculated by using the following equation **(Karemore et al., 2015).**

$$EN = EP - EC$$

Where: EP is energy production and EC is energy consumption.

3. RESULTS AND DISCUSSION

The obtained experimental results are discussed under the following items:

Biomass productivity

Representative values of biomass productivity versus light intensity at different light/dark duration cycle is given in Fig. 4. It is noticed that biomass productivity was increased by increasing light intensity up to 8 kLux, any further increase in light intensity up to 9 kLux productivity will decrease.

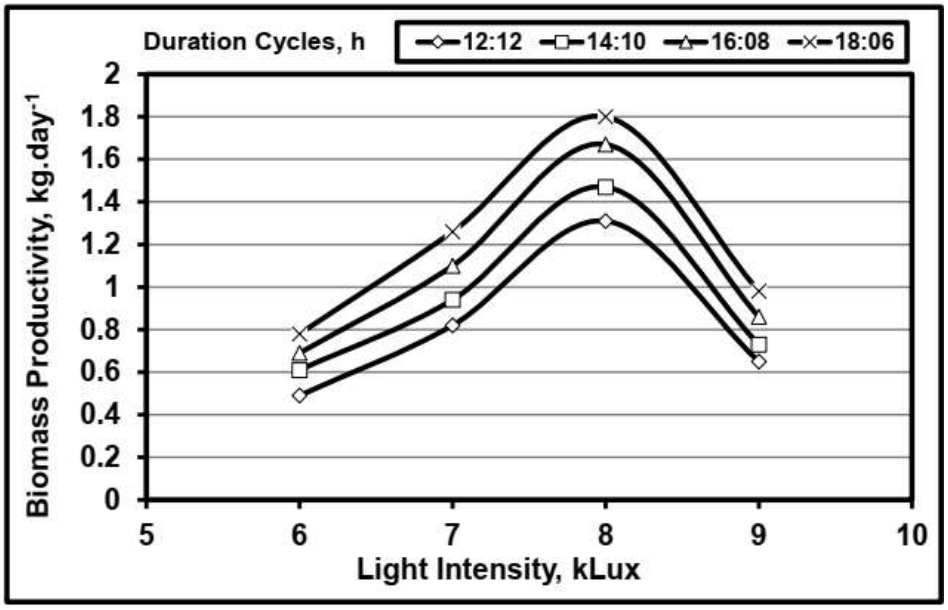


Fig. 4: Effect of light intensity and duration cycle on productivity.

Results show that increasing light intensity from 6 to 8 kLux measured at different light/dark duration cycles of 12:12, 14:10, 16:8 and 18:6 h, increased biomass productivity from 0.49 to 1.31, from 0.61 to 1.47, from 0.69 to 1.67 and from 0.78 to 1.80 kg.day^{-1} respectively. Any further increase in light intensity more than 8 up to 9 kLux measured at the same previous duration cycles decreased biomass productivity from 1.31 to 0.65, from 1.47 to 0.73, from 1.67 to 0.86 and from 1.80 to 0.98 kg.day^{-1} respectively.

Among light intensity 6 and 8 kLux, results indicated that the highest biomass productivity was 1.80 kg.day-1, any further increase in light intensity the biomass productivity will decrease. When the light intensity reaches the saturation level, the microalgae growth will be inhibited by increasing light (photoinhibition) and will be lost. Moreover, when the light intensity is lower the proper level to balance the periodic maintenance the growth rate will be limited by photo-limitation as well as the algae culture will collapse.

Lipid productivity

Influence of light intensity on lipid productivity at different light/dark duration cycle is given in Fig. 5. The obtained results show that increasing light intensity from 6 to 8 kLux measured at different light/dark duration

cycles of 12:12, 14:10, 16:8 and 18:6 h, increased lipid productivity from 118 to 314, from 146 to 353, from 166 to 401 and from 187 to 432 g.day^{-1} respectively.

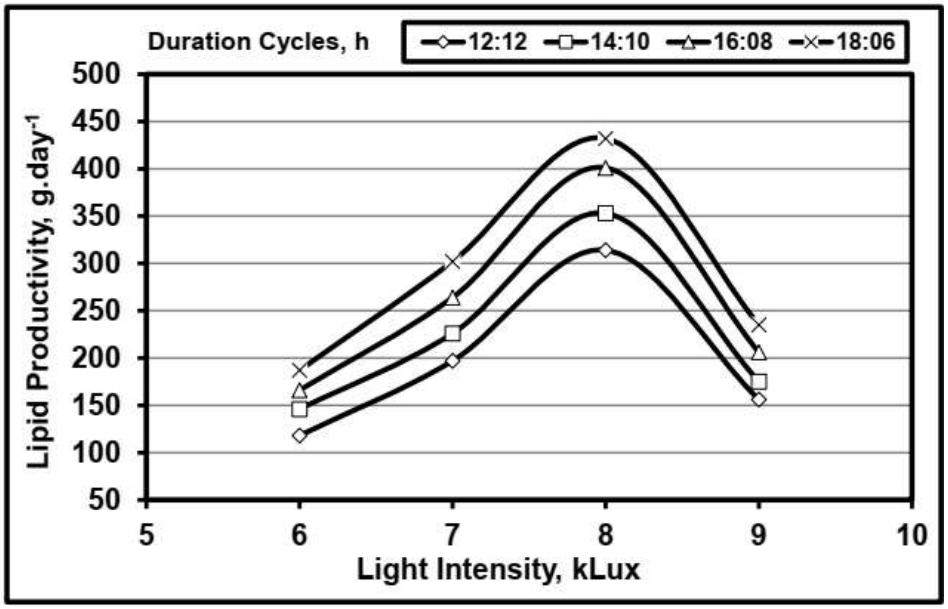


Fig. 5: Effect of light intensity and duration cycle on lipid productivity.

Any further increase in light intensity more than 8 up to 9 kLux measured at the same previous duration cycles decreased lipid productivity from 314 to 156, from 353 to 175, from 401 to 206 and from 432 to 235 g.day^{-1} respectively.

Higher values of light intensity more than the optimum value tend to decrease lipid productivity because the increase in light level inhibited the algae growth faster which decreases biomass concentration and amount of the lipid cells. Lower values of light intensity less than the optimum value tend to decrease lipid productivity for reduction in cell concentration which subject the algae culture to the inappropriate lighting requirements during growth period that tends to decrease lipid production.

Carbon capture efficiency

The obtained values of carbon capture efficiency as a function of light intensity and light/dark duration cycle is shown in Fig. 6. It was evident that carbon capture efficiency values were 63.40, 71.20, 80.80 and 87.10% under duration cycles of 12:12, 14:10, 16:8 and 18:6 h, respectively at light

intensity of 8 kLux. It was noticed that efficiency values were 23.70, 29.50, 33.40 and 37.80% measured under the same previous duration cycles respectively and at constant light intensity of 6 kLux. Experimental results indicated that the highest carbon capture efficiency was reached 87.10% under duration cycle of 18:6 h and light intensity of 8 kLux.

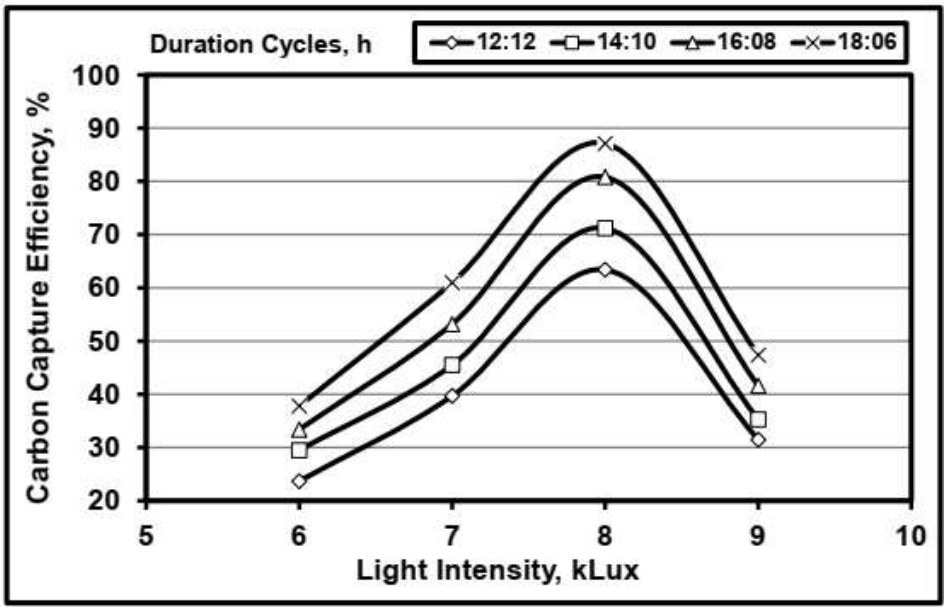


Fig. 6: Carbon capture efficiency as a function of light intensity.

Higher values of light intensity more than the optimum value tend to decrease carbon capture efficiency because of the decrease the algae growth rate that reaches the saturation state and the algae culture will collapse, synchronously

On the other hand, the lower values of light intensity less than the optimum value tend to decrease carbon capture efficiency due to the decrease in both weight and size of algae cells causing less amount of carbon capture. Where weight of carbon capture is 50% dry weight of algae biomass.

Energy balance of algae production system

Biomass derived from algae yields heating value of 39.5 MJ/kg for dried biomass with 10% moisture content. It has sufficient energy density to make an applicable alternative to petroleum diesel.

The energy balance concept of renewable energy generation is a notable factor to estimate whether the system provided can be applied or not.

Representative values of both energy production and energy consumption versus light intensity at different light/dark duration cycle is given in Fig. 7. The results show that increasing light intensity from 6 to 8 kLux measured at different light/dark duration cycles of 12:12, 14:10, 16:8 and 18:6 h, increased energy production from 1.29 to 3.45, from 1.60 to 3.87, from 1.82 to 4.40 and from 2.05 to 4.74 kWday respectively. Any further increase in light intensity more than 8 up to 9 kLux measured at the same previous duration cycles decreased energy production from 3.45 to 1.71, from 3.87 to 1.92, from 4.40 to 2.26 and from 4.74 to 2.58 kWday respectively.

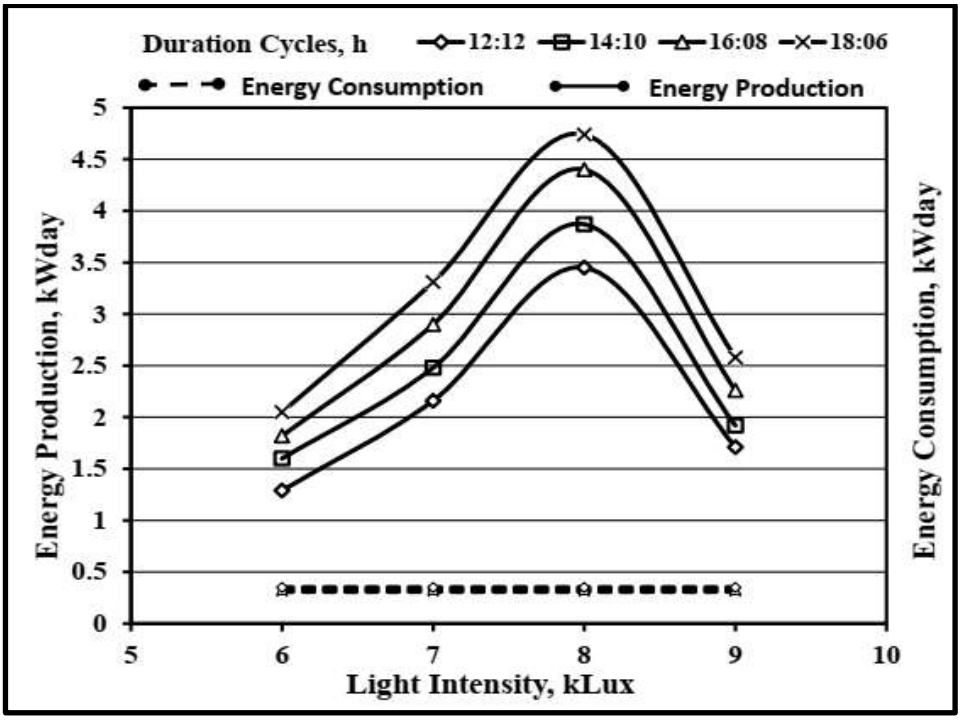


Fig. 7: Effect of light intensity and duration cycle on energy production.

The results obtained show that increasing light intensity increased net energy output up to 8 kLux, any further increase in light intensity up to 9 kLux the net energy output will increase as shown in Fig. 8. Based on these data the net energy output of algae production system reached to 3.16, 3.56, 4.07 and 4.39 kWday under duration cycles of 12:12, 14:10, 16:8 and 18:6 h, respectively at light intensity of 8 kLux. When the net energy output of the algae production system is positive then the designed system be applicable option.

Results obtained suggested that the highest energy production value was 4.74 kWday with a specific power input of 0.35 kWday (power needed for light requirements, culture circulation and gases exchange. Experimental results also show that the optimal conditions for algae cultivation in order to achieve the highest net energy output is 4.39 kWday.

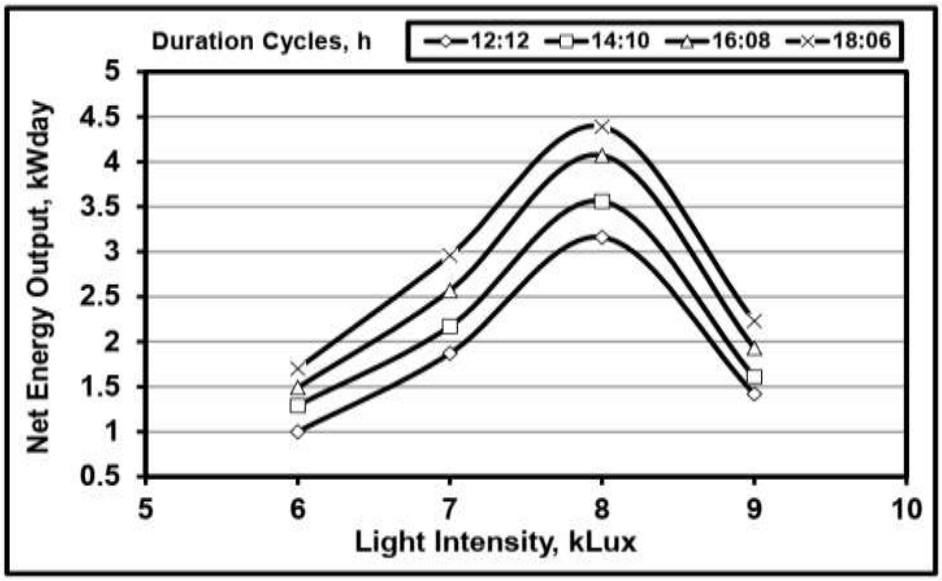


Fig. 8: Net energy output as a function of light intensity.

This parameter is paramount in importance the cell concentration and the higher the biomass productivity of the algae culture up to light intensity of 8 kLux and light/dark duration cycle of 18:6 h based on the obtained results and then net energy output will increase.

4. CONCLUSION

Presently, biofuel with microalgae origin is one of the most important options available for supply by renewable, sustainable, inexpensive and clean energy. A helical-tubular photobioreactor has been designed and evaluated to improve some operating parameters for optimizing both of a biomass productivity, lipid productivity, carbon capture efficiency and energy balance under the different light conditions. White light was provided by LED lamps circuit which is designed and integrated in the cultivation system. The highest biomass productivity and maximum lipid production was obtained under light intensity of 8 kLux and light/dark duration cycle of 18:6 h based on the conducted experimental studies. Maximum value of energy

production reached 4.74 kW with an energy consumed of 0.35 kW per day which reflected the positive effect of energy balance for presented system under the same previous light requirements.

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الملخص العربى

تصميم وتقييم أداء مفاعل حيوي أنبوبي لإنتاج الطحالب

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فى ظل أزمة الطاقة العالمية جذبت الطحالب اهتماماً كبيراً في جميع أنحاء العالم مؤخراً نظراً لإمكاناتها الواسعة للتطبيق في تطوير تكنولوجيا الطاقة الجديدة والمتجددة التى تعد الركيزة الأساسية لدعم التنمية المستدامة طويلة الأجل وتحسين حوكمة منظومة الطاقة في كافة المجالات، والصناعات الغذائية والأدوية الحيوية. تعتبر الطحالب موارد متجددة ومستدامة واقتصادية لتطبيقات الوقود الحيوي ، فهي بديل مثالي للوقود البترولى فيما يتعلق بالتجدد والتكلفة الرأسمالية والمردود البيئى. الطحالب المجهرية الضوئية هي مصدر حيوي وهام لإنتاج المنتجات المرغوبة والآمنة بيئياً بما في ذلك إنتاج الديزل الحيوي كوقود بيولوجي ومستدام من الجيل الثالث. كما تمتلك قدرة كبيرة على تحويل ثاني أكسيد الكربون في الغلاف الجوي إلى منتجات ذات قيمة اقتصادية بما في ذلك الدهون والبروتينات والكربوهيدرات والفيتامينات ومضادات الأكسدة والعديد من المستقلبات الحيوية النشطة. على الرغم من أن الطحالب هي مصادر حيوية للطاقة المتجددة إلا أنه هناك بعض القيود والتحديات التي يجب التغلب عليها لتطوير هذه التكنولوجيا من النطاق المعملى إلى النطاق التطبيقي.

لا تزال الجهود البحثية التي تجمع بين النظرية والتطبيق مطلوبة لتحقيق أقصى استفادة ممكنة لاسيما فيما يتعلق بتصميم وتصنيع المفاعلات الحيوية للتحفيز الضوئي الذى يمثل تحدياً ملحوظاً نظراً للعوامل التي يجب مراعاتها عن كثب فيما يتعلق بمتطلبات الإضاءة. لزيادة إنتاجية الكتلة الحيوية والدهون وتعظيم الطاقة المتولدة على حساب الطاقة المستهلكة.

لذلك، تناولت هذه الدراسة تصميم وتقييم أداء مفاعل حيوي أنبوبي لإنتاج طحلب الكلوريلا فلجاريس بهدف تحسين بعض عوامل التشغيل التي تؤثر على أداء النظام. تضمنت الاعتبارات التصميمية كل من تصميم دائرة التحكم في شدة الضوء ، ونسبة المساحة الضوئية إلى حجم التشغيل ، والطاقة اللازمة لتشغيل كل من مضخة الهواء ومضخة الخلط للوصول إلى أفضل معايير للتشغيل تحت مستويات مختلفة لشدة الإضاءة بلغت (٦ ، ٧ ، ٨ و ٩ كيلولوكس) وفترات الضوء/الظلام بقيمة (١٢:١٢ ، ١٠:١٤ ، ٨:١٦ و ٦:١٨) وتم تقييم أداء المفاعل حيوي بأخذ القياسات التالية: إنتاجية الكتلة الحيوية وإنتاجية الدهون وكفاءة التقاط الكربون وكذلك صافي إنتاج الطاقة (توازن الطاقة). ويعد مقياس توازن الطاقة لأي نظام توليد طاقة عاملاً بارزًا لتحديد إمكانية مدى تطبيقه.

أظهرت النتائج التجريبية أن إنتاجية الكتلة الحيوية والدهون للطحالب بلغت ١,٨٠ كجم/يوم و ٤٣٢ جم/يوم بكفاءة إلتقاط للكربون بنسبة ٨٧٪. كما سجلت النتائج المتحصل عليها أن المفاعل الحيوي قادر على إنتاج ٤,٧٤ كيلووات أي ما يعادل ٤,٣٩ كيلو وات في اليوم من صافي إنتاج الطاقة عند مستوى إضاءة ٨ كيلولوكس خلال فترة الضوء/الظلام بقيمة ١٨: ٦ ساعة.

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