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Design and Construction of a Novel Gravity Fed Algal Photobioreactor for Sustainable Algal Biofuel Production.

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Abstract*-The need of alternative fuel sources is emerging day by day. Fossil fuels are depleting rapidly and the consequence of using these fuels on the environment is dreadful. In these circumstances, algae come up with a lot of potentials to serve as an important source of alternative fuel which can contribute to protecting the environment. It has numerous applications. But one critical challenge it comes up with is its low production rate with respect to the huge demand. Although algae can grow in any aquatic environment with very little or no supervision, for mass level production it becomes a quite difficult job. Closed photobioreactor provides a good medium for algal growth over other mediums of cultivation such as open raceway ponds. But a photobioreactor requires a considerable amount of energy and a close maintenance of the system. This report illustrates the aspects of a simpler closed photobioreactor system with very little power consumption. A gravity fed photobioreactor was designed and constructed and its performance was evaluated. In this system of capacity 140 liters, the maximum pumping power required for the flow of the culturing medium is only 23 Watts which is merely almost the power consumption of a small light bulb. A good mixing characteristic is achieved by the free force of gravity without any external stirring effort or pumping action. The design provides means of photo penetration from either side of the system. In the experiment, Chlorella sp. was used as an algae sample for the performance evaluation of the photobioreactor. It was found that after 7 days of observation algal cell density increased from 80560 cells/ml to 2024360 cells/ml. The dry mass obtained after this period was 1373.16 g. The estimated crude oil production from the amount of dry mass obtained from 7 days 444.8 ml.*

Keywords: Biofuel, Alternative, Photobioreactor, Renewable, Algal, Energy

1. INTRODUCTION

1.1 Energy Situation of The Current World

The climatic change and environmental impacts due to excessive use of fossil fuels are clearly visible. Day by day the rate of our consumption of fossil fuels has increased drastically. Following graph can clearly present the world energy consumption increment over the years [1].

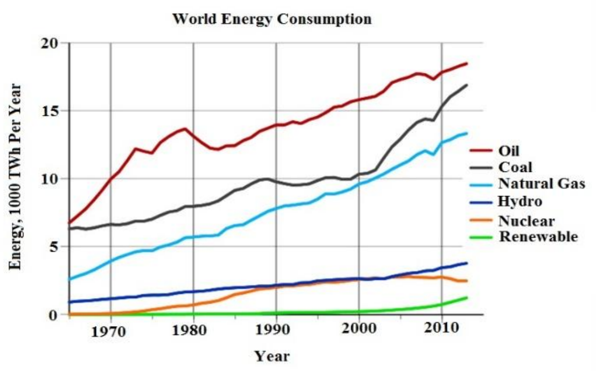

Fig 1.1: Energy Consumption vs. Year Graph

With the increasing demand, we are depleting non-renewable resources. Oil and natural gas storage on the Earth have been estimated to be depleted in 40 and 64 years, respectively [2]. From another table, we can see the probable estimation of fossil fuels in Reserves-to-production ratio or RPR [3].

Table 1.1: Estimation of Major Fossil fuels in RPR

Fuel	Unit of Measure	Reserves	Annual Usage (2005)	RPR (years)
Oil	Trillions of barrels	1.2-2	0.03	40-80
Coal	Billions of tons	998	6	164
Natural Gas	Quads	6370	108	59

The main drawback of fossil fuels is environmental pollution. Carbon dioxide, a greenhouse gas emitted during the consumption of fossil fuels, is considered to be one of the main causes of global warming. Excessive emission of pollutant particles and sulfur dioxide, the reason of acid rain, are also some unavoidable problems. For above mentioned reasons renewable energy sources are the solutions to the current energy crisis situation of the world. The World is gradually inclining to this type of energy and from 2000 to 2008, uses of renewable energy increased by 20.6% [5].

1.2 Algae as an Alternative Energy Source

Algae are emerging to be one of the most promising long-term, sustainable sources of biomass and can produce oils for fuel, food, feed, and other co-products. It has the potentiality due to its high mass production rates and oil contents. The yield of algae biomass per acre is three to five times greater than from typical crops [6]. Algae can be classified into three major groups- macro algae, cyanobacteria and microalgae and among them, microalgae have unique biological properties like high growth rate, flexible production methods and high lipid contents. The majority of microalgae biomass is made up of proteins, carbohydrates, and lipids. In general, algae biomass contains 20-30% carbohydrate, 10-20% lipid, and 40-60% protein [7]. Certain species have been found to contain up to 77% of total dry weight (DW) of biomass as lipids and 80% of which are neutral lipids [8]. Lipid is very attractive in biofuel production due their high energy density and easy upgrading to bio-diesel.

1.3 Algae Cultivation in Closed System

For large-scale production of microalgae, algal cells are continuously mixed to prevent the algal biomass from settling down and nutrients are provided during daylight hours when the algae are reproducing. This mixing process also helps to get sufficient amount of sunlight, CO2 and helps to mix up the nutrients necessary to make a favorable condition for algal growth. Numerous ways and techniques are there to produce mass level of algae. Among them algae-photobioreactor is a closed system which provides a controlled environment and enables high productivity of algae. Many unique photobioreactors have been developed which has their own advantages and disadvantages. Tubular, Helical, Airlift and Flat panel are the common photobioreactors. A common problem that we found about all these sources is that a huge amount of energy is required for the pumping action. These systems also require high initial and maintenance cost. Thus a simpler gravity fed photobioreactor system is proposed in this work that requires less pumping action and is simple at the same time. In this system the flow of algae or water is done by the help of gravity hence it requires a small electric pump.

1.4 Objectives

1)To design and construct of a photobioreactor that consumes minimal energy.
2)To evaluate the performance of the constructed photobioreactor.

2. DESIGN

2.1 Design considerations For Algal Growth

Numerous aspects influence the growth rate and lipid content of algae. The reaction driving the initial conversion of sunlight into stored energy is photosynthesis. Therefore, all of the components involved in photosynthesis contribute to growth. The primary factors that affect algae growth are-
(a)Lighting: An optimal photobioreactor should have good photosynthetic surface area. Solar radiation should be distributed uniformly over the total photosynthetic area and dark zone should be reduced as much as possible.
(b) Mixing: Mixing improves productivity by increasing the frequency of cell exposure to light and dark volumes of the reactor and by increasing mass transfer between the nutrients and cells.
(c) CO_2 Consumption: Like light, water algae consume CO_2 for its photosynthesis process. CO_2 can be supplied through air pump or by mixing the right amount of carbonic acid with nutrients.
(d) O_2 Removal: The combination of intense sunlight and high oxygen concentration results in photo-oxidative damage to algal cells. The Proper amount of aeration area is required to transfer gasses among them so that O_2 doesn't accumulate.
(e) Temperature: Research has found that the optimum temperature of algal growth is 30^0 C [8].
(f) Nutrient Supply: To increase growth rate algae require more than the reactants in the photosynthesis reaction. Two major nutrients are nitrogen and phosphorus, which both play a role in controlling growth rates and lipid production.

2.2 Design Calculation

The main criterion of our design is to minimize the total amount of energy requirement. In order to reduce the pumping power, we envisioned a system where the flow of culturing medium is not by the power of the pump like conventional systems but by gravitational force. The schematic diagram of the system is shown in the figure. From the figure, it can be observed that a drum is elevated to a height to get the advantage of the gravitational force. 8 plastic containers or bottles are placed below it so the flow of the culturing medium can occur without any external force. A reservoir is used to store and supply water to the pump. The pump is used only to lift the water from the reservoir to the drum.

Few assumptions are made based on the availability and cost of the materials in the local market. After performing a market analysis the considerations of the system made are stated below.

1. The drum is 16.5 inches in diameter and 70 Liters of capacity so that it can store enough water that is necessary for the required gravitational force.
2. The total portion of the system from the drum to the reservoir which includes pipes, plastic containers and the reservoir are transparent so that sunlight could easily penetrate through them.

3. The plastic containers or bottles are 6 inches in diameter. Any larger bottle can generate dark zone. Dark zone is the phenomenon where sunlight cannot penetrate to the algae which are in the middle because of the thick layer of algae on the outside.
4. The capacity of each bottle and the reservoir is 4 Liters and 35 Liters respectively. Total of 8 bottles are used so that the combined capacity is 68 Liters which is almost equal to the capacity of the drum.

The drum is elevated to a height of 72 inches to provide enough gravitational force.

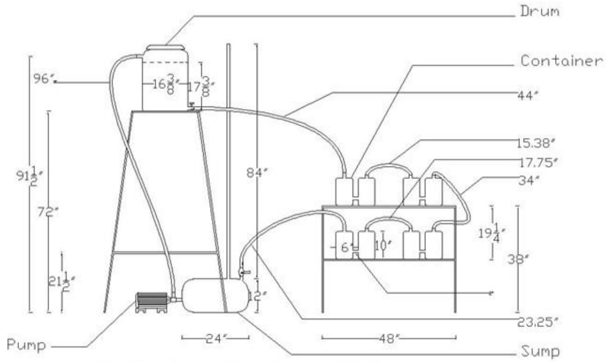

Fig 2.1: Theoretical Design of Photobioreactor

If we consider the system for 65 liters filled drum then the water height h in the drum can be found from the following relation…

$$\frac{\pi}{4}d^2h\rho = 65\ kg$$

Where diameter of drum, $d = 16.71\ inch = 16.71 \times 0.0254\ m$

Density of water, $\rho = 1000kg/m^3$

$$h = \frac{65}{\frac{\pi}{4}(16.71 \times 0.0254)^2 \times 1000}m$$

$$h = 0.442\ m$$

Now applying Bernoulli's equation [9] in figure 2.2-

$\frac{P_1}{\omega} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\omega} + \frac{v_2^2}{2g} + z_2$ (Equation 2.1)

Where,

$P_1 = 0$ $P_2 = \frac{mg}{\pi DL}$

where,

D= diameter of drum & $L = Z_1$

$V_1 = 0$

Z_2=0.5 inch= 0.013 m

Z_1=Water height in Drum, h= 0.442 m

$\omega = 9.81 \times 1000 kN/m^2$

Now putting the values in equation 2.1

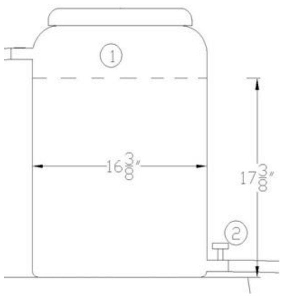

Fig 2.2: Mathematical Diagram

$$0 + 0 + 0.442 = \frac{\frac{65 \times 9.81}{\pi \times 0.424 \times 0.442}}{9.81 \times 1000} + \frac{v_2^2}{2 \times 9.81} + 0.013$$

$$v_2^2 = (0.442 - 0.111 - 0.013) \times 19.62$$

$$\therefore v_2 = 2.5\ m/s$$

Area of the connection at point 2,

$A = \pi/4\,(3/4 \times 0.0254)^2 = 2.85 \times 10^{-4}$

So discharge at point 2,

Q= V×A= 2.5×2.85× 10^{-4} m^3/s = 42.75 liters/min

Now if the total head loss in the PBR is h_f then applying Bernoulli's equation [9] from point 2 to 3 in figure 2.3 is..

$\frac{P_2}{\omega} + \frac{v_2^2}{2g} + z_2 = \frac{P_3}{\omega} + \frac{v_3^2}{2g} + z_3 + h_{loss}$ (Equation 4.2)

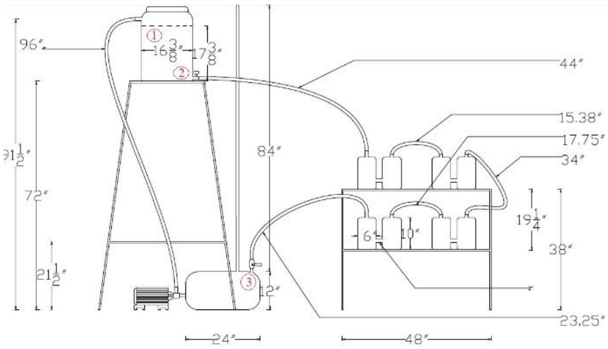

Fig 2.3: Mathematical Diagram

For design consideration let the mean velocity be 60% of the initial velocity,

$$\bar{v} = 0.6 \times 2.5$$

$$\therefore \bar{v} = 1.5\ m/s$$

Now we calculate the head losses in the photobioreactor. Head loss due to friction: Firstly we consider the total water flow passage as an equivalent system of pipe of diameter 1 inch and length L. The total water flow passage also includes the flow inside bottles.

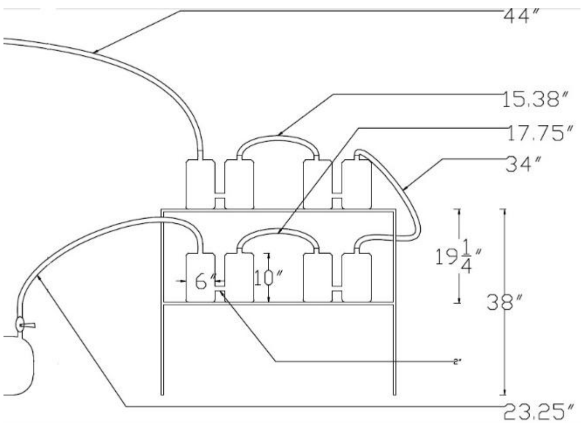

Fig 2.4: Mathematical Diagram

From the equation of equivalent pipes [9] in figure 2.4-

$$\left(\frac{L}{D^5}\right)_{Equivalent} = n \times \left(\frac{L}{D^5}\right)_{\text{Bottles}} + \left(\frac{L}{D^5}\right)_{\text{Pipes}}$$

$$\frac{L}{1^5} = 8 \times \frac{9}{3^5} + \frac{44 + 1 + 15.375 + 1 + 34 + 2 + 17.75 + 1 + 23.25}{1^5}$$

$$L = 0.296 + 139.375$$
$$\therefore L = 139.671\ inches = 3.54\ m$$

From Darcy-Weisbach equation, head loss due to friction,

$$h_f = \frac{4fL\bar{v}^2}{D \times 2g}$$

Where $f = 0.015$, for plastic pipes. [10]

$$h_f = \frac{4 \times 0.015 \times 3.54 \times 1.5^2}{.0254 \times 2 \times 9.81}$$
$$h_f = 0.96\ m$$

Head loss at the entrance: We know the head loss at the entrance is given by, $h_{ent} = 0.5 \times \frac{v_{ent}^2}{2g}$

$$h_{ent} = 0.5 \times \frac{2.5^2}{2 \times 9.81}$$
$$h_{ent} = 0.16\ m$$

Head loss at exit: We know the head loss at the exit is given by,

$$h_{exit} = \frac{\bar{v}^2}{2g}$$
$$h_{exit} = \frac{1.5^2}{2 \times 9.81}$$
$$h_{exit} = 0.115\ m$$

Head loss at the unions: 16 unions were used in the portion of the system considered. The head loss at the unions,

$h_{unions} = 16 \times k \times \frac{\bar{v}^2}{2g}$

Where $k = 0.08$ for unions [47]

$$h_{unions} = 16 \times 0.08 \times \frac{1.5^2}{2 \times 9.81}$$
$$h_{unions} = 0.15\ m$$

Head loss at the valves: Two different valves were used in the portion of the system considered. Head loss in both of them is calculated.

Steel gate valve: $h_{gate} = k \times \frac{\bar{v}^2}{2g}$

Where $k = 0.19$ for steel valves; [47]

$$h_{gate} = 0.19 \times \frac{1.5^2}{2 \times 9.81}$$
$$h_{gate} = 0.02\ m$$

Plastic ball valve: $h_{ball} = k \times \frac{\bar{v}^2}{2g}$

Where $k = 0.29$ for ball valves; [11]

$$h_{ball} = 0.29 \times \frac{1.5^2}{2 \times 9.81}$$
$$h_{ball} = 0.03\ m$$

Head loss due to bending: We know the head loss due to bending is given by, $h_{bend} = k \times \frac{\bar{v}^2}{2g}$

Where $k = 4.49$ for all the bends; [11]

$$h_{bend} = 4.49 \times \frac{1.5^2}{2 \times 9.81}$$
$$h_{bend} = 0.515\ m$$

Total head loss**,**

$$h_{losses} = h_f + h_{ent} + h_{exit} + h_{unions} + h_{gate} + h_{ball} + h_{bend}$$
$$h_{losses} = 0.96 + 0.16 + 0.115 + 0.15 + 0.02 + 0.03 + 0.515$$
$$\therefore h_{losses} = 1.95\ m$$

Applying Bernoulli's equation [9] from point 2 to 3 point in figure 2.3 is

$$\frac{P_2}{\omega} + \frac{v_2^2}{2g} + z_2 = \frac{P_3}{\omega} + \frac{v_3^2}{2g} + z_3 + h_{loss}$$
$$0.111 + \frac{2.5^2}{2 \times 9.81} + 1.5367 = 0 + \frac{{v_3}^2}{2 \times 9.81} + 0 + 1.95$$
$$\therefore v_3 = 0.56\ m/s$$

The area of flow at point 3 is the same as previous,

$$\therefore A = 2.85 \times 10^{-4} m^2$$

So the discharge at point 3 is given by,

$$Q_3 = A \times v_3$$
$$Q_3 = 2.85 \times 10^{-4} \times 0.56$$
$$Q_3 = 1.61 \times 10^{-4} m^3/s$$
$$Q_3 = 9.66\ Litres/min$$

This is the maximum allowable discharge of the pump. The pump must have a discharge of 9.66 Liters/min otherwise, the sump will create a vacuum.

Now from the laws of affinity (when impeller diameter is constant) [11], we know

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

For a typical 0.5HP pump, we know that a maximum discharge of 21 Liters/min occurs when the impeller rotates at 2850 rpm. Now from the affinity equation,

$$\frac{21}{9.66} = \frac{2850}{N_2}$$

$N_2 = 1310\ rpm$. Again from the affinity law (when impeller diameter is constant) [12] we know that,

$$\frac{P_1}{P_2} = (\frac{N_1}{N_2})^3$$
$$\frac{0.5}{P_2} = (\frac{2850}{1310})^3$$
$$P_2 = 0.049\ HP$$
$$P_2 = 36\ Watts$$

So this is the power of the pump required for the continuous flow of circuit. If the pump runs with more power than the calculated value a vacuum will generate in the reservoir. This may damage the vessel. So the pump should not run at more than the calculated speed. Again, if the pump runs slowly than the calculated value water will be stored in the reservoir. This will result an excessive pressure in the reservoir which may also damage the vessel. So the pump speed should be close to the calculated value for the optimum result.

2.3 Practical Readings

Based on the design a system was constructed and various parameters were determined. They are mentioned in the table below.

Table 4.1: Practical Data

Parameters	Measurements
Drum Discharge	43 liter/min
Sump Inlet	9.23 liter/min
Lowest Impeller Speed	1126 rpm

Lowest Power Required	23 watt
Pump discharge	8.3 liter/min

From the table, it can be seen that the flow rate at sump inlet is 9.23 Liters/min. the pump is running at 1126rpm which gives a discharge of 8.3 liters per minute. This is close to the sump inlet.

2.4 Total Energy Analysis

In the system, there are two devices that consume electric power. They are

a) A centrifugal pump which consumes maximum 23 watts in our system.
b) An air pump which consumes 8 watts.

So the total energy consumption of the system is (23+8) or 31 watts.

3. CONSTRUCTION

3.1 Main Components of The System

The main components of our design are following:

a) Drum: Circumference 52.5in, Diameter 16.71in, Height 24in.
b) Plastic containers: Circumference 18.7in, Diameter 6in, Height 10in.
c) Reservoir: Length 24in, Width 12in, Height 12in.
d) Pump: Discharge Height 14m, Discharge 21liter/min, Power 0.5HP, Speed 2850 RPM.
e) Regulator: This was made with a resistor, a potentiometer and a polyester capacitor. It can reduce the speed from 2850 rpm to 1126 rpm.
f) Air Pump: Power 8watts.
g) Valves: Gate and ball valves.
h) Elevated Platform: Bench (24×24) in^2 , Base (33×33) in^2 , Height 72in
i) Steel Shelf: Length 48in, Width 15in, Height 38in.

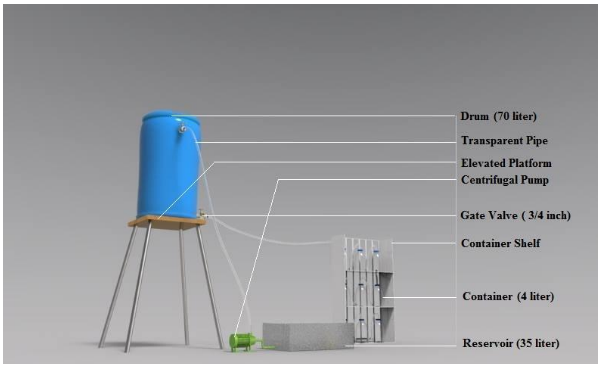

Fig3.1: Model of Gravity Fed Photobioreactor

3.2 Assembly:

Firstly two holes were made in each plastic container, drum and the reservoir at a precise position and in perfect shape for the insertion of the union connections. Then the unions were attached to the containers. Then the pipes were cut according to the design consideration. Two small holes in the shape of the outlet pipes of the air pump were made in the top of the drum. A safety ventilation passage was made on top of the reservoir to avoid squeeze of reservoir and containers. For this a whole was made on the upside of the reservoir and another union was attached to it. A large pipe of length 6 feet was attached to that union. This will also release the trapped air in the system and free the space for water. This was the initial preparation for the system assembly.
For the final assembly, the drum was placed on the elevated bench. Four containers were placed on each rack. The reservoir or sump was placed on the floor as shown in the diagram. Then precisely cut pipes were used to connect the components. The pipes were connected from one union to the next union in the way that maximum turbulence can be created for mixing. Clamps were used on each end of the pipe to strongly seal the connections. The total system was set up as shown in the figure.

Fig 3.2: Constructed Gravity Fed Photobioreactor

The pump was connected to the regulator. The regulator is used to synchronize the flow rate in the sump and the discharge rate of the pump. From calculation, we found that the maximum allowable rpm of the pump for equal discharge as the sump was 1310 rpm. The regulator was able to reduce the rpm of the pump to 933 which was permitted by the design. The air pump was included to the design to supply air in the drum continuously. The outlet's pipes of the air pump were fitted through the holes made on the top of the drum.

3.3 Methodology

The algae along with the culturing medium were deposited in the drum. Because of the free force of the gravity, the culturing medium would flow through the plastic containers and be stored in the reservoir. Then after turning on the pump, water will flow back to the drum from the reservoir. Thus, the circuit completes. The nutrient medium was also deposited in the drum. They have mixed with the water automatically because of the constant flow of water. After applying the medium, it was stirred manually also for better mixing. Both the valves are fully open during the flow. The algae receive sunlight in the plastic containers. The large ventilation pipe in the sump acts as a temporary reservoir when the pump is stopped for some reason. It also helps to reduce the pressure of the sump.

4. PERFORMANCE STUDY

Initially, 1200 ml sample of a density 469956 cells/drop was mixed with 140 liters of water. Then the density became 4028 cells/drop in the system. The cells were counted with the help of microscope which magnification was set to 40×10 times. The average growth rate was recorded for 7 consecutive days and plotted in a graph.

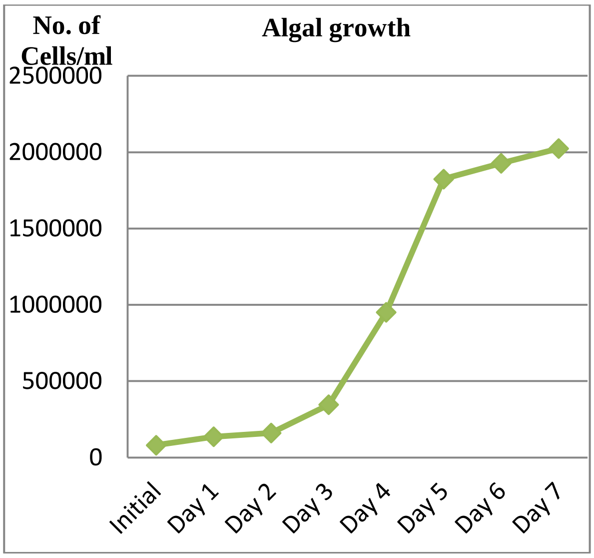

Fig 4.1: Curve of Algal Growth (Density vs Time)

After analyzing the cell density of 7 consecutive days and initial cell density it was seen that algae density increased from 4028 cells/drop to 101218 cells/drop in that period.

After harvesting the following data was obtained from the biomass.

Table 4.1: Experimental readings of the biomass

Property	Measurement
Maximum thickness of the layer	1.5 mm
Wet mass of the algae	99.8 g
Dry mass of algae	39.233 g

It was found that the amount of crude oil obtainable from the dry mass of *Chlorella sp.* is 36% [13]. So we can estimate that the amount of crude oil that can be obtained from 39.233g dry algae is (0.36 × 39.233g) =14.12g or (14.12×0.90)= 12.708ml from one container. If we consider uniform growth in the total system, then crude oil obtainable from the total system is $(\frac{140}{4} \times 12.71)$mL or 444.8mL.

5. RESULT AND DISCUSSION

5.1 Result

- The minimum power consumption of pump was reduced to 23 Watt and discharge to 8.3liter/min.
- After observation of 7 days in our controlled environment, it was found that algae density increased from 4028 cells/drop to 101218 cells/drop or 80560 cells/ml to 202436 cells/ml.
- The amount of dry biomass obtained from 99.8 g wet mass is 39.233 g. The estimated crude oil from the total system after 7 days of operation is 444.8 ml.

5.2 Discussion

Because of the absence of a proper aeration system algae flocculated on the body of the containers which created a dark zone on the bottles. The algal density did not reach its prime condition because of it. Proper sunlight which is one of the key ingredients of algal growth was not available during the experiment because of the weather condition. Fluorescent bulbs could have been used to minimize this limitation. But that would add to the maintenance cost of the system. The material of the photobioreactor was not satisfactory because they were not intended for withstanding high stress and load of water. The system would have run more efficiently if bending of the pipe were reduced by using the more flexible pipe. But flexible pipes are generally not transparent. So, to maximize the photo penetration area comparatively rigid-transparent pipes were used.

6. CONCLUSIONS

An energy efficient gravity fed algal photobioreactor was constructed in this project. Its performance was evaluated in terms of algal growth rate. It was found that the growth of the algae was 101218 cells/drop from an initial value of 4028 cells/drop after seven days of observation which is satisfactory under the circumstances. The dry mass obtained from the system after 7 days is 1373.155 g. The estimated crude oil obtainable from the system is 444.8 ml/ 7 days. The total system can easily be integrated anywhere and a cost-effective solution to the rising demand of fossil fuel may come forward.

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8. NOMENCLATURE

Symbol	Meaning	Unit
d	Diameter	(m)
h	Height/Head	(m)
ρ	Density	(kg/m^3)
ω	Specific weight	(kN/m^2)
P	Pressure	(N/m^2)
g	Acceleration of gravity	(m/s^2)
z	Distance from datum	(m)
v	Velocity	(m/s)
L	Length	(m)
K	Resistance Coefficient	Dimensio-nless
A	Area	(m^2)
Q	Discharge	(m^3/s)
N	Rotating speed	(Revolution/min)
P	Power	(watt)