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Renewable Energy: Integrated Smart Photobioreactor (PBR) For Mircoalgae Culture Application

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Abstract: In this study, the focus will be on the design and development of a smart photobioreactor (PBR) for microalgae culture with integrated harvesting components meant for renewable energy application. While there are lots of PBR designs have been reported, but the harvesting unit is not integrated in the PBR or built separately/stand-alone. Therefore, the extraction process is not straight-forward and will be a bit complicated during harvesting. Having a stand-alone harvesting unit means it involves more manpower and need to be manually done which is not error proof. In this paper, the idea is to have a PBR that is smartly monitor or control the growth or cultivation of the microalgae at its most optimum growth parameters together with a built-in harvesting system which will collect the output from microalgae automatically and in a closed-loop manner. For this purpose, a prototype of a PBR was built to mimic a relatively real-case growth condition.

Keywords: Photobioreactor; Microalgae culture; Smart; Integrated; Harvesting; Renewable energy.

I. INTRODUCTION

Due to global warming and severe climate changes caused by over burning of the fossil fuels, several alternating energy resources were actively explored as per outlined by Chisti and Ashnani et al. in Fig. 1 below [1].

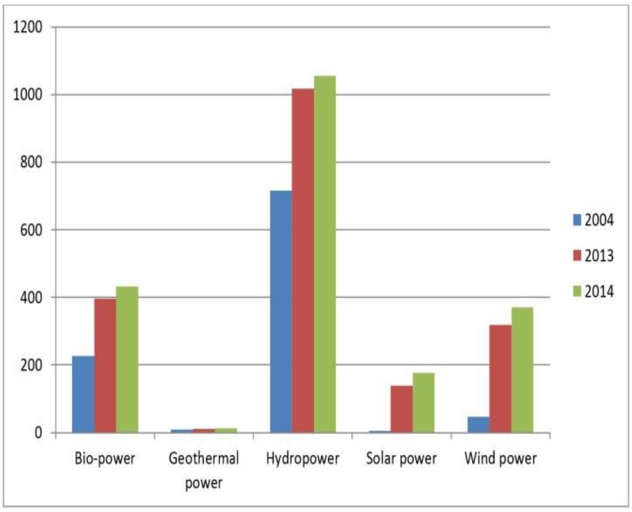

Fig. 1: Development works recorded in various type of renewable energy as per reported in 2004, 2013 and 2014 respectively [1].

As per mentioned in Fig. 1, bio-power which shown second the highest development recorded, has high potential to be used as an alternative renewable energy. Bio-power has bigger advantages compared to hydropower as it is cheaper to implant, small foot print and scalable. Bio-power refers to the ability to convert renewable biomass fuels into heats and/or electricity using certain processes. One example of bio-power is microalgae cultivation. Microalgae has better compatibility and have high potential to be used as bio-power energy resources. There are a lot species of microalgae that are rich in oil contents. It grows rapidly and produces more than oil palm trees. It is also a non-food resource and takes small foot-print for culture [2, 3].

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Microalgae like all plants, uses sunlight for photosynthesis to produce lipids which are the raw materials to make biodiesel from microalgae. The production is more economical and feasible as per first studied by Elrayies and Chisti et al. [4, 5]. Photoperiod and irradiance significantly influence lipid content and the growth in the microalgae culturing.
Microalgae needs to be cultivated in a PBR in the most optimum condition for good biomass production as per mentioned by Kuan and Emma et al. [6, 7]. The PBR process and design need to be studied extensively.

Smart and harvesting components in the PBR will be studied in this project. Currently there is no review or record on the integrated harvesting application in PBR current design. Important parameters are then recorded and analyzed. Towards the end of this project, profiling, analyzing data and validating the performance will be carried simultaneously.

II. LITERATURE REVIEW

A. **Microalgae for energy harvesting**

The uses of microalgae as renewable fuel sources were explored. For energy application, the lipid oils collected from microalgae is used as bio-fuels. Therefore, this process demand for microalgae is called bio-oil. Bio-oil is a clean, safe and green as compared to conventional energy and produces less greenhouse gas emissions that will not affected the global warning or climate change as mentioned by Hui and Teresa et al. [10, 11]. Fig. 2 discusses on the oil yield and land use as compared by Ahmad and Lam et al. between the microalgae and others crop plants [12, 13]. Microalgae are reported to be the best suitable candidate for green energy production with high potential and less land use compare with others.

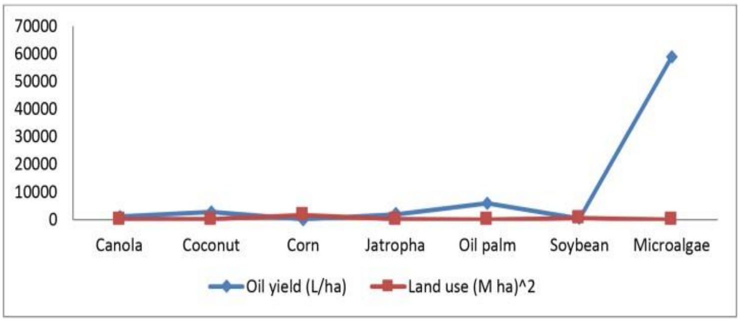

Fig. 2: Comparison an oil yield and land use in plants used as renewable energy sources [12, 13].

Microalgae is considered to be the best candidate as microalgae can be turned into different products and usage as carbohydrates, lipids, proteins and some valuable ingredients that can be found inside the microalgae. Lipids extraction from microalgae biomass can be used to livestock feed. Meanwhile biogas and biodiesel can be converted into different products. Besides, the carbohydrates (cellulose and starch) through fermentation process can transitioned into bio ethanol or sugar source as demonstrated by Yusuf et al. [15].
In addition, protein and fat in microalgae tissue can be applied into food source. This bio-product conversion process from microalgae biomass was reported by Rawat et al. [16]. Not only biogas, biodiesel and bio ethanol, some valuable ingredients found in microalgae are used in the production of cosmetics, human nutrition, fine chemicals and pharmaceuticals as in figure 3 shown.

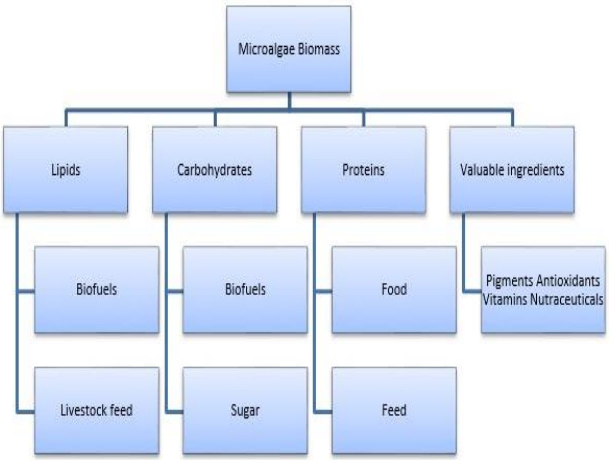

Fig. 3: Various products derived from microalgae biomass that potentially could be used as energy sources [14].

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B. **Type of microalgae**

Extractions of lipids from microalgae are considered as third generation bio-fuels according to the literature. Classifications of microalgae depend on their characteristic and colour. Percentage (%) of carbohydrates, lipids and protein are the three main components used to group microalgaes as per shown in table 1.

Table 1: Classification of microalgae species according to their energy contents [17-28].

Microalgae	Type	Max % of carbohydrate (dry weight)	Max % of lipid (dry weight)	Max % of protein (dry weight)	Relative growth rate	References
Chlorella Vulgaris	Single celled green algae	13	3	46	Fast	[17, 18]
Pyrocystis Fusiformis	Single celled dinoflagelate	13	1-4	23	Slow	[19, 20]
Spirulina	Colonial cyanobacteria	13	8	50	Fast	[21,22]
Nannochloropsis Oculata	Single celled green algae	13	30	25	Very fast	[23, 24]
Isochrysis Galbana	Single celled golden algae	13	23	29	Fast	[25, 26]
Porphyridiumcruentum	Single celled red algae	35	4-14	61	Medium	[27, 28]

C. **Important parameters for optimum growth of microalgae**

Light, temperature, pH and nutrient are the main parameters required for optimum growth of microalgae. These parameters are reviewed extensively as in Table 2. The duration of light illumination exposure should be noted during cultivation for the purpose of photosynthesis. Different light source need to be considered before setting up for microalgae culture. Different species of microalgae needs different exposures as it will directly effecting the growth rate [29]. Temperature control is another important parameter. In any plant cultivation, it requires a range of temperature to grow thrively. Microalgae are not excluded. It grows optimally at around 20-30 °C as shown in fig. 4 respectively. In the case of overheating, it can kill the microalgae cell and vice-versa [30].

pH level (as in fig. 4) is another factor which is very important. The pH level effects growth rate of microalgae. At the same time, too high final pH (pH=11) will have negative effects on the growth of microalgae as reported by Schnurr et al. for another strain of Chlorella Vulgaris. Typically, most option pH level negatives are around 7-11[30]. Nutrient is very important for microalgae culture just like human beings need food for survived. Lack of nutrients will affect the growth of the microalgae. If not properly controlled and maintained [31].

Table 2: Relationship between microalgae and light exposure conditions.

Microalgae	Light conditions	References
Chlorella Vulgaris	Dim light	[29-31]
Pyrocystis Fusiformis	Dim light, indirect lighting, no direct sunlight	
Spirulina	Uses light	
Nannochloropsis Oculata	Dim light, no direct sunlight	
Isochrysis Galbana	Dim light, never direct sunlight	
Porphyridiumcruentum	Dim light, no direct sunlight	

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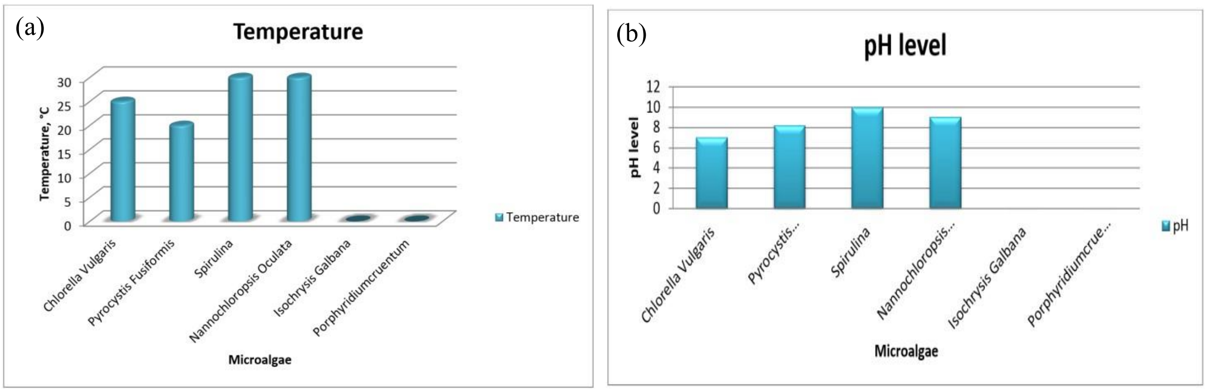

Fig. 4: Important parameters for optimum growth of microalgae where (a) Optimum growth temperature for major species of microalgae as per reported in the literature and (b) Operating pH level for various microalgae species as per reported in the literature [30].

D. **Microalgae cultivation method**

The growth characteristics and chemical composition required depend on the cultivation methods of microalgae. The cultivation method of microalgae can be divided into four major categories: heterotrophic, mixotrophic, phototrophic and photo heterotrophic. Table 3 shows the differences of all four methods of cultivation methods [10]. The first method heterotrophic is the cultivation methods used to solve problem of limited light energy when some of the research that microalgae is growing outdoor. This method is suitable when the organic carbon fed in dark condition to the microalgae, but it has a high contamination risk [32]. Besides, microalgae utilize the organic carbon as energy source and inorganic carbon as carbon source is mixotrophic cultivation. During the photosynthesis, microalgae utilize organic carbon to evolve CO^2 in a respiration process and trap the CO^2 evolved from respiration to use it that early worked by Martin et al. [33].

In addition, Puja et al. showed this one is the most using by the industry for outdoor system because it has small amount of contamination risk from the pathogens. Microalgae that utilize the light as energy source from sunlight and inorganic carbon through photosynthesis for example CO^2 as carbon source to form chemical energy is consider as phototrophic cultivation [34]. Lastly, microalgae utilize the light such as energy source from sunlight and organic carbon as carbon source for photo heterotrophic cultivation. The light and sugars need by microalgae cells to grow at the same time. This method is also less been used because of it high contamination risk and cost, although it is very useful for enhance production of high value metabolites [35].

Table 3: Four types of cultivation methods versus investment fee, reactor scale-up, carbon source, energy source and issues associated with scale-up [10].

Cultivation methods	Heterotrophic	Mixotrophic	Phototrophic	Photoheterotrophic
Investment fee	Medium	High	Low	High
Reactor scale-up	Conventional fermenter	Photobioreactor	Open pond or PBR	Photobioreactor
Carbon source	Organic	Inorganic and organic	Inorganic	Organic
Energy source	Organic	Light and organic	Light	Light
Issues associated with scale-up	Contamination, high substrate cost	Contamination, high substrate and equipment cost	High condensation cost and low cell density	High substrate, equipment cost and contamination
References	[32]	[33]	[34]	[35]

Energy harvesting method talks about the technique for harvesting lipids after the cultivation period of microalgae. The main methods applied in the harvesting system of microalgae include membrane, centrifugation, filtration, flotation and

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sedimentation will be explained and studied extensively [36-42]. Selection of harvesting method depends on the density, size, and the value of the desired products. An overview of membrane materials and membrane processes of interest in microalgae cultivation and processing is provided in the work first reviewed by Bilad et al. [37]. Membrane is a porous sheet that could separate different types on size of materials. In the literature review, membrane is also used to separate lipids and water reported by Rahaman et al. [36]. The microalgae will produce lipids upon culturing in an optimum growth condition. The purposed installed membrane is for the separation of lipids from microalgae. Different species will require different sizes of membrane. In this part, the membrane process been long applied in different stages of microalgae processing and cultivation.

E. **Harvesting methods**

Most microalgae can be recovered from the liquid broth using centrifugation. Centrifugation is another method for harvesting of microalgae biomass, but it is time consuming and costly as compared by Chen and Brennan et al. [38, 39]. In addition, filtration which is a method that operates under pressure or in a vacuum is able to recover relatively large microalgae and it is a high rate method for microalgae harvesting [40].

Another method reviewed is flotation is a separation process in where air or gas bubbles are attached to solid particles and then carry them to the liquid surface. This method is more beneficial and effective than sedimentation with regard to removing microalgae [41]. Sedimentation is commonly applied for separating the microalgae in water and waste-water treatment. In this method, the success of solids removal depends highly on the density of microalgae particles. Christenson et al. found that low density microalgae particle do not settle well and are unsuccessfully separated by this method [42]. The harvest method comparison within the advantages and disadvantages are show in Table 4 respectively.

Table 4: Comparison of the harvesting method [36-42].

Harvest method	Membrane	Centrifugation	Filtration	Flotation	Sedimentation
Advantages	Flexible, multi operation	Reliable, high solid concentration	Reliable, high solid concentration	Proven at large scale	Low cost
Disadvantages	Low selectivity, High	Energy intensive, high cost	Membrane fouling, high cost	Flocculants usually required	Slow, unreliable
Dry solids output concentration	50-90%	12-22%	5-27%	3-6%	0.5-3%
References	[36, 37]	[38, 39]	[40]	[41]	[42]

F. **Microalgae culture: Open system versus closed system**

There are two types of microalgae culturing systems which are open systems refers to cultivated the microalgae outdoor in open area and closed systems refers to cultivated the microalgae indoor in a PBR. Open system permits light passes through directly on surface of culture for photosynthesis reaction. PBR is defined as a reactor or culture system that permits light absorption through the reactor walls which is typically made of transparent material.

Open system for microalgae production is a simple to construct with current technology, but some factors still have to be considered. Due to its limitation such as water losses, contamination, low biomass productivity and this system is not being implemented widely. Closed system (PBR) is more suitable for microalgae cultivation as reported by Svaldenis and Gerardo et al. [40, 41]. The PBR is designed to solve the limitation of the open systems. It has many shapes and sizes based on requirements of microalgae culture and energy harvesting in microalgae. Reducing high rate of water lost due to evaporation, contamination risk and prevents the growth of predators, pathogens, or competitors will kill the crop are the biggest reason that PBR is used for microalgae cultivation. Table 5 showing different reported closed loop PBR reported in the literature versus their respective features [42-49].

Surface to volume ratio refers to capacity of the PBR. This surface volume need to be considered to achieve high efficiency of PBR system, this ratio also plays an important role in PBR design. High productivity and high cell concentration can be achieved by high surface to volume ratio. Culture handling, medium preparation and cost of

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harvesting can be decreased by the high cell concentration. Tubular PBR type is preferable when the design can have near optimum surface to volume ratio since the parameter can be flexible.

Table 5: Different reported closed loop PBR reported in the literature versus their respective features [42-49].

Criteria	Closed Loop Type of Photobioreactor (PBR)				
	Tubular	Flat Panel	Airlift Column	Bubble Column	Stirred
PBR Dimension (L x W x H) cm	10-30cm in ϕ x < 4cm 10-60mm ϕ x > 100ml 32cm x 250cm x 25L	16mm thick plexi-glass alveolar plates	200-400ml x 1000-3000m ϕ 200ml x 1000m ϕ	A height greater than twice the diameter	70-80% fill in liquid
Physical Shape	Tube shape in horizontal or vertical	Box shape in vertical mode	Tube shape in vertical mode	Tube shape in vertical mode	Tube shape in vertical mode
Surface / Volume ratio	High = above 100/m	High	NA	NA	Low
Mixing / Circulation	Recirculation via pumps	Airlift / bubble from bottoms or side	NA	NA	Mechanical agitator
Temperature Control Method	Shading, overlapping and water spraying	Heat exchange coils	NA	NA	Heat exchanger
Gas Exchange	Injection into feed dedicated degassing unit	Open gas exchange at head space	NA	NA	Injection through sparger
Components (Sensor)	Computer simulation	NA	NA	NA	Agitator or impeller
Lighting (Watt)	NA	NA	NA	NA	NA
Growth Time	NA	NA	NA	NA	NA
Harvesting Time	NA	NA	NA	NA	NA
References	[42,43]	[44,45]	[46,47]	[48]	[49]

III. INTEGRATED SMART PHOTOBIOREACTOR (PBR) PROTOTYPE DESIGN

The criteria designs for PBR have to be aimed at increasing areal productivity and volumetric, cost-effectiveness and photosynthetic efficiency of microalgae growth as summarized below. The following will discuss about the important criteria of design such as surface to volume ratio, gas exchange, mixing, circulation, temperature control and others that should be emphasized in developing a suitable or smart PBR system.

i. Gas exchange in the PBR system cannot be ignored. In this part, microalgae needs to absorb sufficient CO^2 and able to remove the oxygen for photosynthesis. There is a method to control and maintain the gas exchange rate. It could be done by air blower which can direct supply the CO^2.
ii. To increase the cell concentration of microalgae, a good mixing process is a must. It is necessary in PBR system for choosing a suitable type of device to mix the culture. Mixing can prevent cell from damage, provide proper irradiance to all cell in culture and supply CO^2 and oxygen removal. Mechanical stirrers not suggest be used due to it hydrodynamic shear stress applies to the cells. Hydrodynamic load that apply to microalgae and cell damage occur when the shear stress is overcritical. Since the microalgae are very fragile, so, the air blower in airlift system is more preferable than water pump.
iii. Circulation system can be an important PBR design issue in terms of power consumption and capital cost. Optimum circulation for microalgae culture is necessary in a PBR. Power requirement for circulation is very dependent on culture velocity, so, velocity minimize will reduce the power consumption. Choosing suitable circulation device also related with the type of microalgae to be cultured. Although the microalgae it is very small, but very fragile. Water pump is not a good choice due to it over critical hydrodynamic load, it will damage the microalgae inside the PBR. Thus, air blower or air compressor for circulation system is more prefer to the microalgae since they cause lower hydrodynamic shear stress than water pump.

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iv. Temperature is one of the design criteria for take note. For different kind of microalgae, it will need different range of temperature control. Not only the closed system will face this kind of problem, although open system need to prevent overheat from direct sunlight exposure. Therefore, several way been used as cooling system for prevent overheat that can kill the microalgae. For example, immersion in water pool, water spraying, fan and shading are the most common techniques to avoid PBR from overheating. One of the suitable methods is fan as cooling system that will use for temperature control. The fan will be activated when the temperature sensor sense is over the temperature setting. This will be more convenient for monitoring and programmable.

Choosing a suitable material for the PBR is seriously important. Materials been used must be low cost, easy to clean, non-toxic to microalgae, high mechanical strength, high stability and high translucence. Table 9 below summarized the comparisons of proposed materials for prototype building.

Table 6: Materials that are compatible to be used for a PBR construction [50, 51].

Material	Glass	LDPE	Acrylic
Material Energy Content (MJ. kg^{-1})	25	78	131
Material Life Span (y)	20	3	20
Material Density ($kg.m^{-3}$)	2470	920	1180
Proposed Wall Thickness (mm)	1.6	0.18	3.0
Energy Content ($MJ.m^{-2}$)	310	40.5	13.5
Life Span Weighted Energy Content ($MJ.jm^{-2}.y^{-1}$)	15.5	1456	72.8
References	[50]	[50]	[50, 51]

Based on the study, acrylic is the most optimum choice for setting/construction of the desired PBR due to it high potential in various requirements.

IV. RESULT & DISCUSSIONS

A. Integrated Smart PBR design layout

Conceptual layout and assembled integrated smart PBR is shown as per Figure 6 respectively. The prototype of PBR is built using acrylic based on research comparison. The diameter of tank is 36 cm and height is 42 cm. The membrane which is the harvesting unit is integrated in the middle of PBR. An air blower was installed and function as a gas exchanger and mixer at the bottom of PBR.

Several sensors were installed and used in this project such as IR, pH, temperature, turbidity and photo-control as part of a smart and integrated PBR. The temperature sensor is connected to a DC fan which functions as cooling system. The temperature sensor is located at the bottom of the reactor. The pH sensor is also located bottom of the reactor. The turbidity, IR and water pump are connecting together for harvesting process and closed-loop processes. The solenoid and flow meter are on automatic mode and thus connected together. The light source (light bulb) connected together with light control system is located in the top middle of the PBR.

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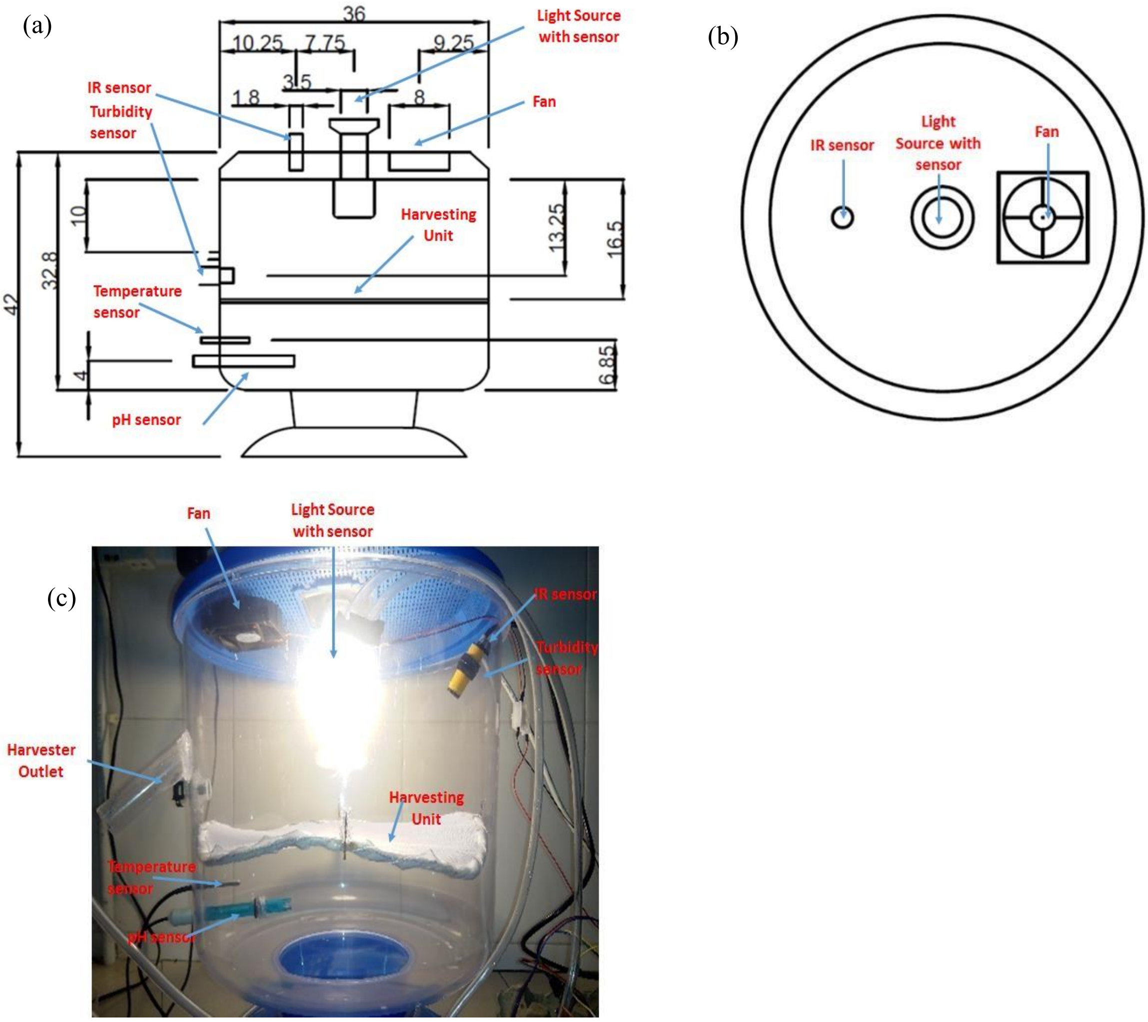

Fig. 5: Conceptual layout design for PBR that is used to conceptual culture Chlorella Vulgaris with all measurements in millimeter: (a) Overall cross sectional view of PBR prototype with tagging showing the sensors location, (b) Sectional Top view and (c) Assembled PBR with integrated harvesting system and installed sensors.

B. Real Time PBR Parameter Monitoring and Closed-loop Control

Integrated monitoring system was developed for light (source of photosynthesis), growth temperature, PBR water level, pH level and lipid-harvester monitoring and controls. Corrective action was automatically carried out should all monitored parameters were deviated from the set-points. Inputs from all the sensors were being fed into a microcontroller. In this study, ARDUINO UNO microcontroller was used and acquired data were subsequently processed and analyzed using Microsoft Excel software. The real time monitoring will display the current time and data from all the sensors. Fig. 6 (a-d) shows example of some real-time monitored parameters.

pH level and temperature control were tested rigorously in evaluating the workability of the closed loop control by the smart integrated PBR system as shown in fig. 6 (e-g) respectively. pH level is monitored and maintained at desired set-point (pH 7). Initial recording yield pH 7 was under normal condition of culture. However, upon adding base solution (NaOH buffer solutions ranging from pH 7 to 9), the pH value increases and the closed system automatically identify this and corrected the pH value to the set-point value by pumping water to dilute the culture solution. This is also true for cases when hydrochloric acid (HCL, pH 3 to 6 respectively) was added. This is highlighted in fig.6(g) respectively Temperature control was illustrated in Fig. 6(h). The set-point for optimum culture is set at 28˚C. In the case of overheating, in-situ fan will be activated to cool down the culture temperature to its optimum value. However, no heater was installed in this project as it is not necessary especially in the hot and humid country like Malaysia.

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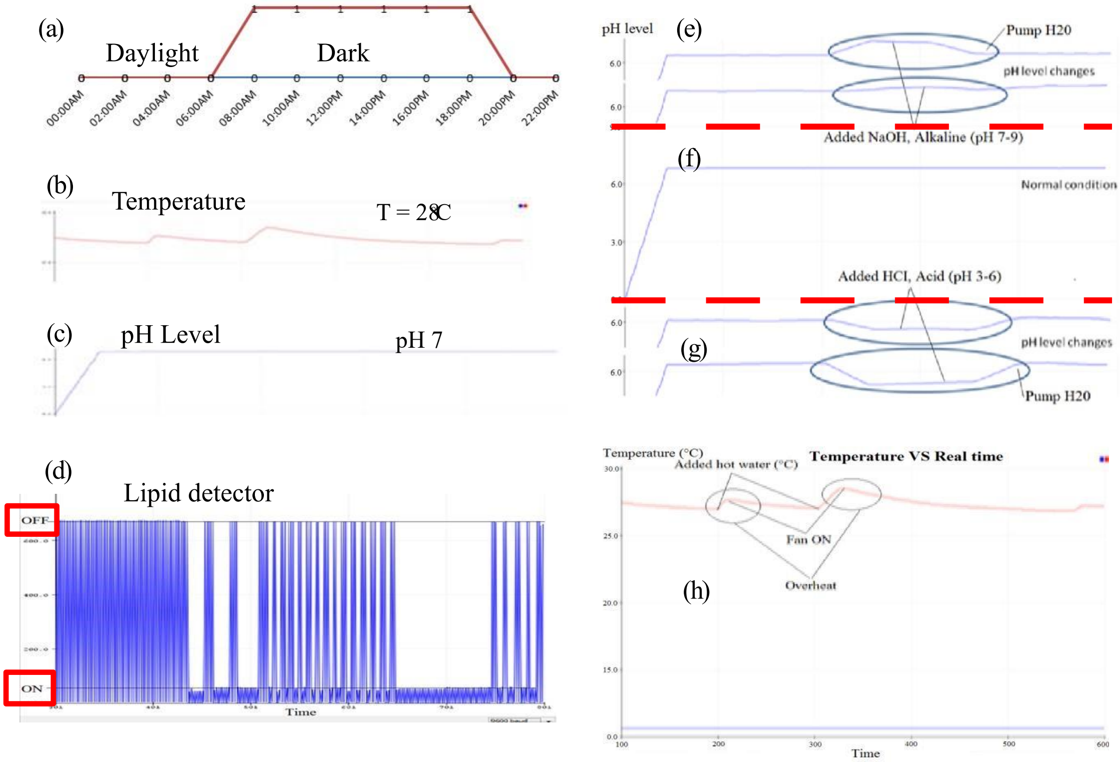

Fig. 6: Snapshots of real-time monitoring via integrated smart PBR system for (a) light (source of photosynthesis), (b) growth temperature, (c) pH level and (d) lipid-harvester and measurement data showing closed-loop control on the pH level in the PBR. The set-point is at pH 7. (e) Corrective action upon adding of NAOH (alkaline solution, pH 7-9), (f) pH level under normal condition and (g) Pumping was initiated upon adding of HCL (acidic solution, pH 3-6) to maintain the culture solution to be pH 7. In addition, temperature control versus time is shown in (h). Hot water was added to mimic temperature deviation from the set-point and cooling fan was observed automatically switched ON to negate this over-heating.

V. CONCLUSION

Prototype of integrated smart Photobioreactor (PBR) was systematically designed and developed for optimum growth condition of the microalgae culture with lipid by-product harvesting component. Real time monitoring and closed-loop control system was developed and tested.

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