Exploration in Using Algae to Enhance Indoor Environment in the Tropical Climate

ISMAIL, Muhammad Azzam and MUSTAFA AL-OBAIDI, Karam <http://orcid.org/0000-0002-4379-6964>

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Muhammad Azzam Ismail
Centre of Building, Construction and Tropical Architecture
Faculty of Built Environment, University of Malaya
Kuala Lumpur, Malaysia
e-mail: ma.ismail@um.edu.my

Karam Mustafa Al-Obaidi
Department of the Natural and Built Environment
Faculty of Social Sciences and Humanities, Sheffield Hallam University
Sheffield, United Kingdom
e-mail: k.al-obaidi@shu.ac.uk

***Abstract*—This paper discusses an exploration in algae application as a sun shading device for buildings. Four basic algae photobioreactors were constructed to investigate the effectiveness of Chlorella species to reduce direct sunlight transmission and solar heat gain in the Tropical climate of Kuala Lumpur. From the experiment, algae flat panel photobioreactor with direct carbon dioxide supply manage to reduce up to 44.9% of heat gain due to solar radiation on average. The overall solar transmission was also reduced to only 25% on average. These indicate that algae have the potential to be used as sun shading material for buildings.**

Keywords-component; algae; photobioreactor; daylighting; heat gain

I. INTRODUCTION

In 2013, the Bio Intelligent Quotient (BIQ) building was unveiled in Hamburg during the International Building Exhibition (IBA). It was designed and built as a showcase apartment building that produces its own energy source through photosynthesis by algae which is cultivated in 129 SolarLeaf flat photobioreactor (PBR) panels installed on the façade of the building as a second building skin [1]. These flat panel PBRs feeds the algae with carbon dioxide (CO_2) that is collected from the fermentation of algae harvested earlier in the cycle in the same closed loop system [2]. Bubbles of CO_2 can be seen bubbling in the panels, stimulating the algae to conduct photosynthesis and absorb solar radiation. In turn, the algae grew and the PBR panels' color changed from light to dark green then the algae are harvested and pumped to the biogas chamber within the same building for fermentation, production of CO_2 and burning for energy to constantly supply the residential units with hot water and heating [3]. It was estimated that the efficiency of this system in converting solar radiation into biomass is at 10% and into heat at 38%. Comparatively, the efficiency of PV systems is 12-15% and solar thermal systems are 60-65% [1], [4]. Furthermore, algae does not require fresh water, can be cultivated in non-arable land (or closed-system PBRs at the BIQ building) without affecting crop based food commodities [5].

This building shows that algae can directly contribute towards self-sustaining buildings thus, showing the way for a novel approach in generating renewable energy and having reduced impact on the environment by diverting CO_2 from being released into the environment towards photosynthesis by algae to produce O_2 [6][7]. Previous research found that the CO_2 fixation rate four different species of algae including Chlorella vulgaris, Scenedesmus Obliquus, Chroococcus sp. and Chlamydomonas sp. increases when constantly supplied with CO_2 [8]. Furthermore, another research found that CO_2 fixation rate increases by 95% when an open raceway pond is covered with a transparent cover under intermittent CO_2 supply [9], [10], proving that cultivation of algae under controlled environment such as at the BIQ building will lead to reduced environmental impact. The question right now is, will it work in the constantly hot and humid Tropical climate?

In the tropics, buildings must perform differently from those in cold climates whereby they have to keep the heat out and maintain comfortable indoor temperatures. Past studies determined a range of acceptable indoor temperature depending on the building context in line with The American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) standard and the Predicted Mean Vote (PMV) model to achieve thermal comfort [11]. Other studies highlighted that heat gain in buildings can be caused by daylighting through fenestrations [12], [13]. Evidently, large fenestrations particularly on the Eastern and Western facades of buildings in the tropics allows too much daylight to enter the building thus, heat gain [14]. In order to mitigate this incidental heat gain, daylighting is supplied in a diffused manner through light troughs, light shelves, light ducts and optical fiber [15], [16]. Alternatively, various coatings such as Kristalbond [17] are used besides low emissivity/electrochromic glass, double/triple glazing and sun shading devices are used to reduce the transmission of energy through glass into the building [18], [19].

Notwithstanding the singular benefits of these building elements in reducing heat gain, a bio skin (algae cultivated in flat photobioreactor panels at the BIQ building) such as presented earlier produces energy for the occupants' consumption while generating own supply of CO_2 to cultivate the algae. However, empirically it is not made apparent how the PBRs affect the indoor environment in terms of direct sunlight transmission (daylighting) and heat gain (indoor temperature). Therefore, this paper explores this possibility but in the hot and humid climate of Kuala Lumpur instead.

II. PHOTOBIOREACTOR DESIGN

The designers of the SolarLeaf system determined that it was suitable and effective to implement flat panel PBR at the

BIQ building [1][4]. Novel PBRs were designed and tested by Pagliolico et al. [5] and by Kim [5]. However, conventionally algae can be mass-produced at different yield or productivity rates in open ponds, raceway ponds, closed-loop tubular PBRs, and flat panel PBRs [7]. Algae cultivation in open and raceway ponds is susceptible to changes in surrounding climatic conditions while tubular and flat panel PBRs provide controlled environments for high quality algae cultivation due to better exposure to light and CO_2 [10], [20], [21], [22], [7], [5].

Open raceways involves less amount of investment and management but yield less amount of volumetric productivity [5]. The same study also found that vertical plate PBR is greater than that of tubular PBRs by a factor of 1.67 [5].

III. Research Methodology

A. Experiments

This study was designed to investigate the effects of microalgal growth on daylight transmission and heat gain. Parameters of algae cultivation including daylighting, CO_2 supply, and oxygen (O_2) production were investigated. These variables were assessed to find out the overall effect on daylight and heat transmissions. In order to achieve this, a small algae growth experiment was carried out according to established parameters and procedures as presented and discussed in previous researches.

B. Experiment Parameters

Parameters that need to be considered for this experiment are type of culture, light, temperature, mixing, pH level, salinity and culture vessel properties. From previous researches, suitable species for cultivation is mainly green algae such as Nanochloropsis and Chlorella. Nanochloropsis are mainly cultivated for biofuel as it is very rich in oil content [7], [9], [23]. Chlorella instead, is a unicellular green alga and grown as food source due to its relatively high photosynthesis rate of 8%, compared to sugarcane [24]. For this experiment, the unicellular Chlorella sp. was selected for its ability to grow fast and not for biofuel production.

Energy from daylight is needed by the algae to convert CO_2 into organic compounds like sucrose and starch that will help algae to grow [5], [7]. The light intensity of between 1,000 to 10,000 lux is needed to limit ultraviolet light exposure that can prohibit algae growth. So, the experiment was conducted outdoors without direct exposure to the sun.

Temperatures below 16^oC slow algae growth, while temperatures higher than 35^oC are lethal for algae [5]. Wang *et al*. [25] highlighted that the temperature in a closed PBR can reach 10^oC to 30^oC higher than the ambient temperature thus, cooling mechanism is required. However, this study only used small PBRs which are located outdoors with exposure to prevailing winds for cooling. The average diurnal outdoor temperature difference was 8.4^oC near the experiment location at Subang Airport prevented overheating in the PBRs.

Mixing or bubbling of CO_2 is necessary in this experiment to avoid thermal stratification and to make sure all cells of the algae population can absorb nutrients, CO_2 and light equally and to improve gas exchange between the air and culture medium [7]. This process was carried out daily and gently as algae cannot tolerate vigorous mixing.

In addition, algae must be grown in water with pH value controlled between 7 and 9 to avoid the collapse of growth culture as cellular processes may be disrupted [25].

From previous researches, it was found that algae are usually tolerant to instability in culture medium salinity and survive well in lower salinity level such as sea water [25] which was used in this experiment.

Lastly, the culture vessel must be non-toxic, sterilized, can be cleaned easily, and can provide large surface to volume ratio [26]. Most tubular PBRs are constructed with borosilicate glass but for this experiment, a more cost-effective acrylic panels were constructed and used instead.

C. Materials Needed

Material needed to construct the basic flat panel PBRs for this experiment were acrylic panels, yeast, sea water, plastic tubes, and water bottles. In order to monitor the experiment, a solar transmission and power meter model SP2065 (to determine solar radiation) as well as a solar spectrum meter SS2450 to determine daylight transmission level (as shown in Figure 1) were used.

Figure 1. Readings taken using solar spectrum meter

D. Experimental Procedure

- Four transparent acrylic flat panels with dimension of 210mm x 290mm x 20mm were constructed to act as the algae cultivation containers.
- A sample of algae in sea water from a local public university marine research center was acquired.
- The sample was further diluted with 2 liters of sea water to avoid self-shading (since the cell density was low, the incident light intensity was almost equal to the intensity experienced by the algae in the apparatus).
- First panel was left empty as the control sample, the second panel was filled with 0.64 liters of sea water, while third and fourth panels were filled with 0.64 liters of diluted Chlorella sp. The fourth panel was connected

to a bottle with 250ml of water filled with 55g of yeast which act as the source of CO_2. Each panel was labelled as Panel A, B, C, and D respectively.

- All panels were placed at the level 4 balcony of a university building facing South East in order to get indirect exposure of sunlight for optimum growth as shown in Figure 2.
- The panels were observed for one week. Transmission of ultraviolet (UVA) energy, visible light or the portion of the sun's spectrum that human eyes can see, and overall solar transmission within the range of 300-1,700nm which includes UV, visible light and infrared energy through the panels were measured every hour between 10:45 am and 5:45 pm daily to cover various daylighting conditions using a solar spectrum meter to ensure accuracy.
- Solar radiation level was measured at 5:00 pm daily using the solar transmission and power meter at a minimum distance of 18" from the acrylic flat panel PBRs according to the manufacturer's requirements to ensure that readings were not affected by surrounding daylight as the experiment was not done in an enclosure.
- Readings were then tabulated and analyzed.

Figure 2. From the right is Panel A, Panel B, Panel D and Panel C

IV. Result, Data Analysis and Discussion

The experiment conducted within this study is a preliminary study for a much larger study that will utilize a full-scale flat panel PBR fitted to window in a building to determine similar effects of algae in PBRs on daylighting and heat gain. Preliminary findings are presented and discussed in the following sections.

A. *Analysis of Chlorella sp. in filtering solar transmission by getting data using Solar Spectrum Meter*

Table I shows the percentage of various light transmission through each panel. Panel A contained only air. Hence it has the highest point of solar transmission, second highest of UVA transmission and visible light at 58% and 85% respectively. Panel B contained only sea water and has the highest transmission of UVA and visible light at 71% and 92% respectively while the overall solar transmission is second highest at 68%. Panel C which was filled with Chlorella sp. has very low transmission of UVA, visible light and overall solar transmission level at 17%, 49%, and 42% respectively. Lastly, Panel D filled with Chlorella sp. and supplied with CO_2 produced by yeast has the lowest UVA, visible light and solar transmission at 9%, 26%, and 25% respectively.

Solar transmission includes UVA, visible and infrared energy. Based on Table I, Panel A has highest overall solar transmission and second highest of UVA and visible light transmission which means except from infrared energy, Panel A which is an empty clear panel was able to reduce UVA and visible light. This is caused by the air gap in the panel which allowed double reflection of UVA and visible light by acrylic panels on both sides of the container.

Panel B which was filled with seawater allowed more UVA and visible light to transmit through by not allowing for double reflection by the acrylic panels but reduced the overall solar transmission due to its density as compared to air in Panel A.

Panel C containing Chlorella sp. allowed low transmission of UVA, visible light and overall solar transmission which proved that Chlorella sp. is a good filter for daylight. The existence of Chlorella sp. in seawater helped to block sunlight from penetrating through Panel C and D and its thermal mass also helped to prevent the rise of temperature in these panels. The transmission rate of UVA and visible light also reduced greatly as compared to Panel A and B. Sunscreen pigment in Chlorella sp. known as *mycosporine* has great effect on absorbing UVA to reduce the photoinhibition process.

Panel D filled with Chlorella sp. and connected to a CO_2 reactor to increase the algae growth rate proved to restrict more UVA, visible light and overall solar transmission than any other panels. At high levels and long-term exposure, UVA is harmful to health as it can cause skin cancer thus, reduced penetration of UVA through Panel D is a positive finding.

TABLE I. Percentage of UVA, Visble Light and Overall Solar Transmission Through Each Panel

Date/ Time	Transmission percentage	Panel A	Panel B	Panel C	Panel D
17/4/18	UVA (%)	58	75	17	7
5:00 pm	Visible light (%)	85	92	45	22
	Overall solar transmission (%)	80	67	39	22
18/4/18	UVA (%)	58	77	17	8
5:00 pm	Visible light (%)	85	92	50	25
	Overall solar transmission (%)	80	69	43	25
20/4/18	UVA (%)	58	61	17	11
5:00 pm	Visible light (%)	84	91	52	30
	Overall solar transmission (%)	80	69	44	29
Average readings	UVA (%)	58	71	17	9

	Visible light (%)	85	92	49	26
	Overall solar transmission (%)	80	68	42	25

Nevertheless, readings over the one week period could have improved if the culture medium in each panel were stirred and mixed continuously as highlighted earlier. This caused sedimentation in Panel C and D and a slight increase in UVA, visible light and overall solar transmission near to the end of the experiment period.

B. *Analysis of Chlorella sp. in Filtering Solar Radiation by Getting Data Using Power Meter*

Figure 3 shows the average solar radiation against time on the first day of experiment for all flat panel PBRs in study. During the experiment, the highest surrounding solar radiation reached 112 W/m² on average at 12:45 pm. While the lowest surrounding solar radiation was 14.6 W/m² at 5:45pm. It is clear that the amount of solar radiation is directly linked to the amount of surrounding solar radiation and there are clear reductions in solar radiation from Panel A to C while readings between Panel C and D are almost identical because algae in Panel D have not grown more than in Panel C despite the direct CO_2 supply. The maximum reading for Panel A, B, C, and D is 87.6 W/m², 68.6 W/m², 62.2 W/m² and 62.2 W/m² respectively. Meanwhile, the minimum reading for Panel A, B, C, and D is 12.8 W/m², 9.8 W/m², 9.8 W/m², and 9.0 W/m² respectively.

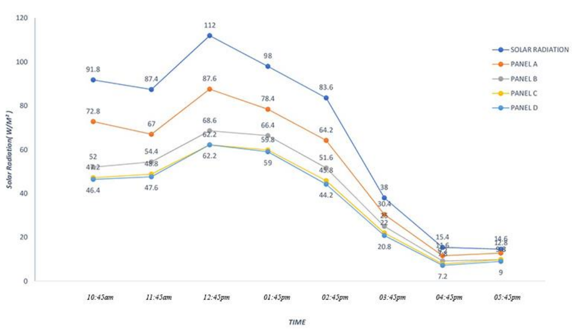

Figure 3. Average solar radiation transmission against time on the first day of experiment for all flat panel PBRs

TABLE II. AVERAGE DAILY SOLAR RADIATION OVER FIVE DAYS OF EXPERIMENT

	Solar radiation (W/m2) / percentage of reduction (%)				
Panel/Day	1	2	3	4	5
Surrounding solar radiation	69.3 (100)	61.3 (100)	59.0 (100)	89.3 (100)	59.3 (100)
A	58.9 (15.0)	46.1 (24.8)	47.9 (18.8)	66.1 (26.0)	46.5 (21.6)
B	47.9 (30.9)	36.4 (40.6)	39.0 (33.9)	52.5 (41.2)	34.9 (41.1)
C	42.9 (38.1)	33.0 (46.2)	33.5 (43.2)	46.8 (47.6)	33.5 (43.5)
D	41.5 (40.1)	33.0 (46.2)	33.0 (44.1)	44.8 (49.8)	33.0 (44.4)

Consistently, the difference in solar radiation through Panel C and D is marginal over the five day experiment period as shown in Table II and the drop in solar radiation transmission through the panels between A, B, and C (D is almost identical to Panel C as mentioned earlier) is significant. The surrounding solar radiation reached the maximum point of 89.3 W/m² on the fourth day and its minimum point of 59.0 W/m² on the third day.

Although almost identical to Panel C, the solar radiation penetration reduction percentage for Panel D is still the lowest. It is projected that the difference between Panel C and D should be more apparent over an extended period of experiment as the cultivated algae grows. Chlorella sp. in Panel D should grow more than in Panel C as it received direct CO_2 supply as presented earlier.

The Chlorella sp. was bought from a local marine research center and was cultivated in two of the four flat panel PBRs for 5 days to complete this experiment. This microalgal species growth rate in Panel D increased even when the surrounding day time temperature hovered around 30°C with the provision of CO_2. At the same time, the recorded average light intensity was 7,920 lux which is below the maximum allowable of 10,000 lux for optimum algae growth. However, the pH level of the culture medium used in Panel C and D remained between 10 to 10.5 and exceeded the tolerable pH levels of between 7 and 9. This could be caused by the pH of the sourced water or even the amount of CO_2 and O_2 in the culture medium. Despite this setback, it is proven that Chlorella sp. is suitable to be grown in the Tropical climate in flat panel PBRs and can be used as sun shading material to reduce heat gain in buildings.

According to the analysis, the effectiveness of algae to reduce heat gain in buildings is strongly affected by the surrounding environmental factors especially the presence of direct sunlight and high temperatures. From the experiment, results showed that Panel C and D filtered more overall solar transmission (which includes UVA, visible light, and infrared energy) and solar radiation in comparison to air gap and seawater in Panel A and B respectively.

TABLE III. DAILY HIGHEST OUTDOOR TEMPERATURE RECORDED AT SUBNAG AIRPORT OVER THE EXPERIMENT PERIOD [27]

Date	17/4/18	18/4/18	19/4/18	20/4/18	21/4/18
Highest temperature	93.2F (1500)	95.0F (1400)	91.6F (1400)	91.4F (1300)	93.2F (1400)
Diurnal difference	17.1F	18.9F	16.0F	15.8F	16.6F
Thunderstorm occurrence	4:00-8:00 pm	3:00-11:00 pm	4:00-6:00 pm	2:00-11:00 pm	2:00-5:00 pm

However, sedimentation of Chlorella sp. in Panel C and D occurred on the fifth day of experiment and increased the amount of solar radiation and solar transmission. The algae started to produce biomass at that moment. This experiment was carried out passively without any mechanism and could not cultivate the Chlorella sp. over an extended period. Within the five days of experiment, the weather was not ideal for the growth of algae due to thunderstorm in the evenings and less exposure to the sunlight due to the haze thus, the accuracy of results is reduced. Furthermore, more care is needed to control the pH level of used culture medium and water. Nevertheless, the data is reliable where the outcome is positive because the data showed that the algae panel filtered the solar radiation and overall solar transmission in comparison to other panels without Chlorella sp.

V. Conclusion

Despite external environmental factors that influence algae growth and the need for an experiment over an extended period for consistency and accuracy, the experiment showed that cultivated algae with direct CO_2 supply in flat panel PBRs helps to reduce heat gain caused by solar radiation by up to 44.9% on average. Similarly, the overall solar transmission also reduced on average to only 25%. Therefore, algae have high potential as sun shading material and can effectively limit heat gain in buildings to achieve indoor thermal comfort.

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