

Original Research

Algae Windows: A Novel Approach Towards Sustainable Building Design and Energy Conservation

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Abstract

This study introduces an innovative approach, harnessing photobioreactors (PBRs) as algae windows to optimize energy efficiency and environmental protection in building design. The integration of microalgae cultivation systems into windows presents a promising avenue for multifaceted benefits, encompassing energy savings, improved indoor daylight levels, hot water production, and carbon sequestration. This research work presents a comprehensive exploration of this cutting-edge concept by employing simulations and analyses. It delves into various facets, including energy performance, cooling loads, daylight distribution, and hot water generation. The model room equipped with algae windows demonstrates substantial reductions in cooling energy consumption due to the shading effect of the algae. The daylight analysis underscores how algae windows can effectively illuminate spaces while minimizing the need for artificial lighting. Furthermore, the study reveals the potential for these windows to harness solar energy for hot water production, offering a dual-purpose solution. Despite the promise, this work acknowledges the existing challenges associated with technology adoption, encompassing technical, economic, and regulatory barriers. It underscores the critical role of governments in promoting favorable regulations, incentivizing investments, and raising public awareness to accelerate the uptake of algae windows. Algae windows present a holistic solution by simultaneously mitigating energy consumption, reducing carbon emissions, and improving indoor environments. This research serves as a foundation for future studies, encouraging further investigations into the viability and scalability of algae-integrated building systems.

Keywords: Autodesk Ecotect, cooling load, LEED standard, algae window, energy saving

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Introduction

The largest energy consumption in buildings typically stems from HVAC systems, specifically heating, ventilation, and air conditioning. The cooling load, crucial for maintaining comfortable indoor conditions, consists of internal and external heat gains [1]. Internal heat gains include factors like people, lights, and equipment, while external heat gains encompass solar radiation through windows, infiltration, ventilation, and heat conduction through building envelopes. Notably, approximately 75% of the total cooling load arises from heat loss through the building envelope, with windows contributing the highest proportion, potentially accounting for up to 60% of a building's energy consumption [2]. Architects strive to develop envelope materials to reduce energy usage.

In recent years, buildings have increasingly integrated renewable energy generators like solar panels and wind turbines to cut energy costs and lessen reliance on fossil fuels. However, these technologies alone may not fulfill a building's energy needs. Photobioreactors (PBRs), particularly algae windows, emerge as a promising solution to mitigate building energy consumption [3]. Algae cultivated within PBRs absorb sunlight for photosynthesis and can be harvested for valuable biomass used for bio oil, biogas, or nutrient supply [4]. Algae windows, a specialized type of PBR integrated into building facades, offer benefits such as reduced heat loss, natural light provision, and renewable energy generation. Consequently, algae windows contribute to both improved building aesthetics and reduced greenhouse gas emissions [5].

Algae, known for their high efficiency in converting solar energy into biomass, offer several advantages over conventional biofuels derived from edible feedstock. Algae's high oil content makes it an excellent source of clean, sustainable bio-oil, suitable for powering various transportation vehicles [6]. Moreover, algae's ability to absorb CO₂ during growth makes them promising candidates for biofuel production and carbon capture, aiding in environmental preservation. Several studies have explored the potential of algae-based technologies for building applications. For instance, researchers have developed algae-based air purification systems capable of significantly improving air quality, especially in highly polluted urban environments. Energy simulation studies comparing different window types have consistently demonstrated the superior energy-saving performance of algae windows. Additionally, economic analyses suggest that algae building technologies, such as closed tubular photobioreactors, offer favorable returns on investment compared to traditional solar PV systems [7]. Martin Kerner et al. [8] claimed that the whole year's heat production efficiency is nearly 38%, which can meet about 59% of the total heat demand of a building. Moreover, the surplus heat can be stored in the soil below the building and used in the winter. In theory, algae can convert solar energy into biomass with

an efficiency of up to 9%. This is at least three times higher than the efficiency of C4 plants, which are the most efficient type of land plant. Algae can also absorb large amounts of CO₂, up to 1.8 kg of CO₂ per 1 kg of biomass. This makes algae a promising candidate for biofuel production and carbon capture [9].

Recently, there have been several studies on PBR for building [10]. For instance, a team of researchers developed an algae-based air purification system in Warsaw, one of the most polluted cities in Europe. The algae-based air purification system consists of 52 large reactors that can hold a total of 520 liters of *Chlorella vulgaris* algae culture. This amount of algae culture can filter 200 liters of polluted air per minute. The surrounding air quality was monitored using sensors. The researchers reported that the system has the potential to absorb nitrogen and fine particulate matter (PM2.5) up to 97% and 75%, respectively. In particular, the PM2.5 concentration dropped by 83% and remained within the recommended zone of the World Health Organization. M. Talaei et al. [11] conducted an energy simulation study for buildings in Mashhad, Iran. Researchers compared three types of windows: single glass, double glass, and water windows. The authors found that the algae window had the best energy savings performance. The algae density had a small effect on energy consumption. Nimish Boloria et al. [12] analyzed the cost and profit of algae building technologies and solar PV panels. A case study at a building at the University of Technology Sydney, Australia, was conducted. The closed tubular photobioreactors were used for the algae system. Additionally, the use of a closed tubular photobioreactor system increases the return on investment and has a quicker payback time as compared to a solar PV system. Cervera Sardá et al. [13] examined the study of using algae windows for building façades. The study obtained good results for energy conservation, CO₂ mitigation, and the ability to produce biomass. Ghada Mohammad Elrayyes [4] stated that the application of algae windows is an effective option for green energy because of its potential to absorb CO₂, purify water, and generate oxygen. For this reason, it can considerably reduce the electricity bill of a building and improve air quality by absorbing CO₂ and generating oxygen in the building. Yaman et al. [14] studied the use of building-integrated photobioreactors (PBRs) in Izmir, Turkey. To investigate the performance of an algae window on the south side of a building, a simulation was carried out. The results showed that this type of façade could significantly reduce the number of uncomfortable hours in the building. Additionally, the excess daylight was cut down due to the high concentration of algae inside the window. The study found that there was no significant difference between a 100% PBR façade and an 80% PBR façade, except for a partial improvement in daylight illumination.

To evaluate personality traits that are attributed to microalgae façade. Kathryn Warren et al. [15] conducted a survey of 40 randomly selected architecture students.

The students were assigned to stay in a room with a microalgae façade, and their emotions were studied using questionnaires. The study found that people who lived in an algae envelope were more creative and produced better work than those who stayed in a normal room. Martokusumo et al. [16] studied an ongoing building in Bandung, Indonesia, which is a historic location. The building has glass windows on the west and east sides. The authors investigated three types of windows: brise-soleil, horizontal fixed shading device, and algae photo-bioreactor. The experiment was carried out for the final type. During the investigation of each type of façade, parameters such as indoor and outdoor temperature differences, daylight level, and the amount of oxygen generation were obtained. It was reported that algae windows are able to reduce the Solar Heat Gain Coefficient (SHGC) and indoor temperatures. Jo et al. [17] also suggested that green algae windows can be integrated with artificial light-emitting diodes (LED). With this integration, LED lights can change color in response to environmental conditions, including weather and time of day. This approach has the potential to enhance energy savings and the aesthetic appeal of buildings. Joud Al Dakheel et al. [18] found that active shading systems, such as smart glazing, kinetic shading, and algae façades, can potentially reduce energy consumption by 10-50%. However, the algae window is still a developing technology because it needs further investigation to reduce factors including investment costs, maintenance expenses, and labor costs for specialized installation. Heru W. Poerbo et al. [19] studied the design of the ITB Innovation Park, a new building in Bandung, Indonesia. It was found that the building-integrated microalgae photobioreactors (BIMPs) have not yet been included in the Green Building regulation in Bandung city (Indonesia) because these are a relatively new technology. However, this approach is able to cut down energy consumption and boost indoor air quality. In a recent study, Chew K.W et al. [20] stated that integrated photo-bioreactors in buildings can play a crucial role in green energy applications. This is attributed to their ability to convert CO₂ to oxygen and harvest biomass. However, some challenges, such as the cost of production and maintenance expenses, need to be tackled, and further research is still being done.

N.A. Ardiani et al. [21] discussed the design of a photobioreactor for building façades using Sketup software. In this design, acrylic molding and pipes were chosen to replace the conventional panel photobioreactor. Algae culture flows from the top of the pipes and fills them, then returns to a 2000-liter pond in the basement via pipes at the bottom. At the pond, there are four types of pipes connected to it: pipes connecting to building-integrated photobioreactors, oxygen pipes that transfer oxygen produced in the pond to the building, nutrient pipes, and pipes for harvesting biomass or cleaning. Researchers assume that their renovation has some benefits, such as a low risk of leaking and a lower

likelihood of algae death. Soowon Chang et al. [22] developed a simulation framework using BIM (Building Information Modeling) to evaluate the feasibility of algae façades in different buildings. The framework comprises three main components: (1) integration of algae façades as library components in BIM; (2) use of a system dynamics model (SDM) to model closed-loop energy and waste streams; and (3) retrieval of data in BIM for the SDM.

To contribute to the application of algae façades, this research work developed a model of a conference room in a resort in Phan Thiet with dimensions of 14 m x 6 m x 3.5 m. Three types of windows were compared, including single glazing, double glazing, and algae windows (microalgae photobioreactors). The aspects of the windows that were evaluated included energy savings, daily lighting, and energy savings for hot water utility from the microalgae photobioreactors.

Methodology

Basic Theory

To calculate the heat conductivity Q (W) through the envelope of the building, the Equation (1) is used:

$$Q = U \times F \times (t_{\text{ex}} - t_{\text{int}}) \quad (1)$$

Where U represents the total heat transfer coefficient of the envelope material (W/m².K), F is the area of the envelope (m²) and t_{ex} and t_{int} are the outdoor temperature and indoor temperature (°C), respectively.

To reduce heat conduction through building envelopes, such as walls and windows, the U -factor should be low. The U -factor of window glazing can be calculated according to Equation (2) in ASHRAE [23].

$$U = \frac{1}{\frac{1}{h_{\text{ex}}} + \frac{1}{h_{\text{int}}} + \frac{t_{g1}}{1000.K_{g1}} + \frac{t_{gw}}{1000.K_w} + \frac{t_{g2}}{1000.K_{g2}}} \quad (2)$$

Where:

h_{ex} and h_{int} are convection coefficients of outdoor and indoor, respectively (W/m².K).

K_{g1} , K_w , and K_{g2} are the thermal conductivity of glass layer 1, water (algae culture), and glass layer 2, respectively (W/m.K). t is the thickness of each layer (mm).

The thermal conductivity of glass is approximately 1 W/m.K. In a study by Negev et al. [3] there was almost no difference between the thermal conductivity of pure water and algae culture. The authors recommend using 0.64 W/m².K for algae culture, which is about 10% higher than pure water, because of the natural convection of water between two glass panes. Natural convection is caused by the temperature difference between the water and the glass surface.

In addition to heat conduction through the building envelope, radiation also contributes to the cooling load of a building. Sunlight carries energy that penetrates through the glass of a building, raising the temperature inside the room. This one can be prevented and limited by using glazing with a low SHGC (solar heat gain coefficient), which is the ratio of the amount of radiation energy that passes through the glazing to the amount of radiation energy that strikes the glazing surface. Therefore, a lower SHGC means less radiation will pass through the pane [24].

Daylight level is a crucial factor in determining the illumination within a room. Higher daylight levels indicate ample natural light, reducing reliance on artificial lighting and promoting energy conservation. However, it's important to note that this can also elevate room temperatures [11]. Thus, when designing a building, selecting the right Visible Transmittance (VT) for glazing is essential to balancing lighting and thermal considerations.

The coefficient of performance (COP) is used to estimate the energy consumption of an air conditioner. COP is the ratio of the cooling capacity of an air conditioner to the electricity demand of the compressor. Therefore, the higher the COP, the lower the energy consumption can be achieved [25]. However, the COP of an air conditioner is affected by a number of factors, such as the indoor and outdoor temperatures, the efficiency of the compressor, and the cleanliness of the indoor and outdoor units. In Equation (3), COP is the ratio of the cooling capacity of the air conditioner (Q_o in watts) to the energy input (N in watts). Normally, the cooling capacity of the air conditioner is equal to the cooling load of the building.

$$\text{COP} = Q_o / N \quad (3)$$

In this study, it was assumed that a hot water supply was needed. When the algae culture absorbs sunlight, the temperature of the culture will increase. To avoid the death of *Chlorella vulgaris* algae, the temperature of the algae culture should be lower than 38°C [26]. Another fluid was used to cool it to keep it at such a temperature that it could be utilized for water heating. The temperature that is also suitable for people to take a shower is from 40°C to 42° [27]. Therefore, in this study, a hot water system can be used to utilize the heat generated from cooling the algae culture, and a heater will be used if a higher water temperature is needed. The efficiency of converting sunlight energy to heat in a photobioreactor is about 38% [8], which is the ratio of useful energy (Q_{usef} in W) to incident solar radiation on the surface of the equipment (Q_{rad} in W), so if there is incident solar radiation, the useful energy of a hot water system can be determined using Equation (4).

$$\eta = Q_{\text{usef}} / Q_{\text{rad}} \quad (4)$$

Methodology

The methodology of this study was to use Ecotect Autodesk to develop a conference room model with three different types of glazing: single glazing, double glazing, and algae windows. This software has been used to analyze environmental conditions such as solar radiation, daylight level, etc. [28]. The cooling load, energy consumption for air conditioning, and daylight were then analyzed to evaluate the efficiency of each type of glazing. Additionally, the energy savings for hot water production that could be achieved by using algae windows were also analyzed. The steps of the study were as follows:

Step 1: Design the model of the conference room.

Step 2: Determine some crucial parameters for three kinds of glaze (single glaze, double glaze, and algae window) which comprise the U-factor and Visible Transmittance (VT).

Step 3: Run a simulation of Ecotect to find out the cooling load, daylight, and luminance of the room.

Step 4: Calculated energy savings for hot water production when harnessing the algae window's heat release.

Step 5: Economic analysis.

The case study is a conference room located in Mui Ne, Phan Thiet, Vietnam. This area is famous for its sunny beaches and numerous resorts. Algae windows are a good fit for this type of resort because they allow people to feel close to nature with the green of the algae. In this study, the algae chosen for the windows is *Chlorella vulgaris*, which has a spherical cell shape [29]. This is a freshwater algae with a green color, but it can also live in salt water. When living in salt water, its growth rate is lower than in freshwater. However, it can tolerate salinity up to 45 g/l. Under these salty conditions, the total lipid content increases from 11.5% to 16.1% [30]. This type of algae is used for biodesalination and biofuel production [31]. Therefore, when used as building-integrated microalgae photobioreactors, it can be used to produce biomass and oil.

The model of the room, its orientation, and the sun's orbit are shown in Fig. 1.

The conference room has dimensions of 14 m x 6 m x 3.5 m. The main door (2.2 m x 1.3 m) faces east (90°), and the two long walls face south (180°) and north (0°). There are five windows on each side of the room, each measuring 1.5 m x 1.3 m. The windows make up almost 20% of the wall area. In the case of algae windows, the solar heat gain coefficient (SHGC) decreases as the concentration increases. This means that less solar radiation will pass through the window, and the visible transmittance (VT) will also decline. Therefore, *Chlorella vulgaris* with a concentration of 20% was chosen ($U = 5.1 \text{ W/m}^2\cdot\text{K}$, $\text{SHGC} = 0.4$, $\text{VT} = 0.45$), as it has the highest VT coefficient of all the remaining concentrations. The higher the VT, the better the daylight and illuminance will be, and the less artificial light will be needed. In terms of single glaze,

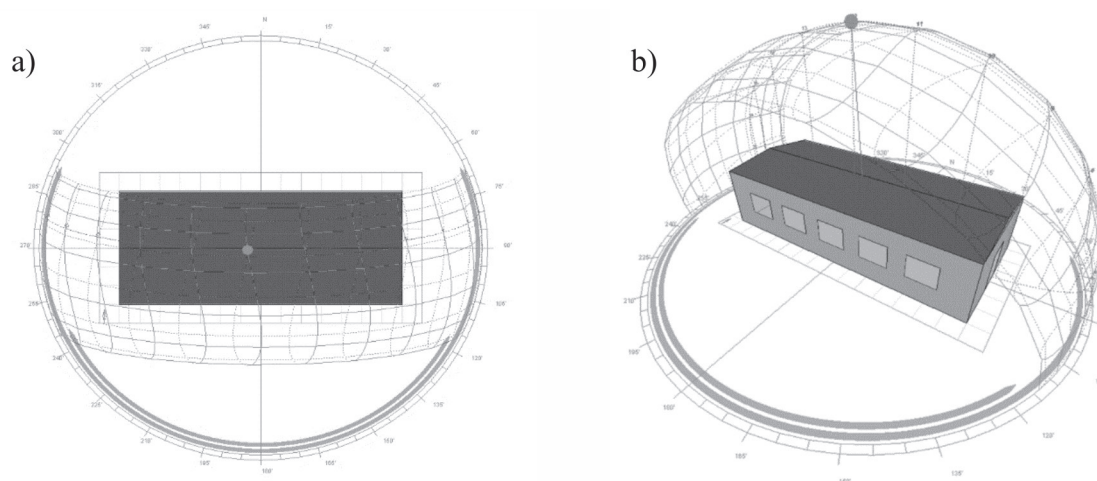


Fig. 1. The model of simulation and sun's orbit a) the plan view of the model and b) the perspective view of the model.

it has U-factor ($5.8 \text{ W/m}^2\text{.K}$), SHGC (0.9), and VT (0.86), and for double glaze, U-factor, SHGC, and VT are $3.12 \text{ (W/m}^2\text{.K)}$, 0.81, and 0.76, respectively [3].

In addition to the material properties of glazes, energy simulations also require the properties of other materials, such as walls ($U = 2.62 \text{ W/m}^2\text{.K}$), roofs ($U = 0.836 \text{ W/m}^2\text{.K}$), and slabs ($U = 0.8 \text{ W/m}^2\text{.K}$). These properties are available in the Ecotect library.

In this energy simulation, there are 11 people sitting in the room. The heat emission from each person in sedentary conditions is 70 W. The internal heat gains (for lighting and small power loads) are 7 W/m^2 . The infiltration rate is 0.5 air changes per hour (ach), which is considered to be well-sealed conditions. The temperature setting is from 25 to 26 degrees Celsius, and the operation hours are from 6 am to 17 am.

Results and Discussion

In this simulation, weather data from the Joint Research Center (JRC) was used, including local temperature, humidity, solar radiation, and other factors. The JRC provides data and environmental knowledge to support EU policies and combat climate change. By using the METEOSAT satellite, weather data covering Europe, Africa, and Asia is collected [32]. These data are widely used by simulation experts around the world.

Cooling Load of the Room and Energy Consumption

The cooling load in this simulation is calculated based on the total operation time in a year. The peak load that occurs at a specific moment in the year will be used as the cooling capacity of the air conditioner. The peak load for single glazing is 15,455 watts. This is also the highest cooling load. The second highest cooling load is for double glazing, at 14,640 watts. Algae windows experience the lowest cooling load, at 13,838 watts.

The total cooling load for each type of window for months in a year is illustrated in Fig. 2.

For the single glaze and double glaze, the cooling load peaks in May, with April as being the second highest. However, for algae windows, the cooling load is slightly lower in May than in April, or it peaks in April. These months have the highest radiation and outside temperature, which significantly contributes to the cooling load. The lowest cooling load is in December due to the lowest temperature. It is clear that single glaze has the highest cooling load, followed by double glaze, and then algae windows. This is because single glaze has the highest U-factor and SHGC, allowing more heat to pass through. The cooling load is strongly dependent on the U-factor, as shown in Equation (1). In addition to the U-factor, single glaze also has the highest SHGC, allowing more radiation energy to pass through.

According to Fig. 2, the room using single glazing has the highest annual cooling load, at 30,820,088 Wh. The next highest is double glazing, at 29,322,906 Wh. The lowest annual cooling load is for algae windows, at 27,118,662 Wh. Although algae windows have a higher U-factor than double glaze, their cooling load is lower because their SHGC is two times lower than that of double glaze. In other words, Vietnam is located near the equator, so radiation is very high, which significantly contributes to the cooling load. The solar radiation element that accounts for cooling load for each type of glaze is shown in the tables below.

According to Table 1, solar radiation passes through the glazing from 6:00 am to 17:00 pm, with the highest intensity occurring from 11:00 am to 14:00 pm. In general, the total solar cooling load is lowest in April and May and reaches a peak in January and February. As shown in Fig. 1a), the sun's altitude is highest in April and May, so solar radiation is concentrated on the roof, not on the two sides of the room. In January and February, the sun is positioned in the south, so sunlight is focused on the sides, resulting in a higher solar radiation load in these months.

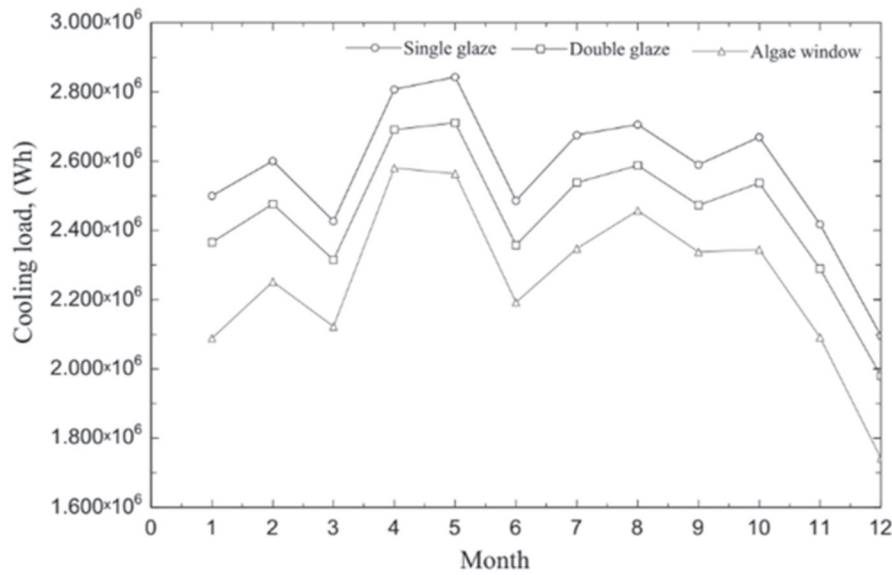


Fig. 2. Cooling load of room during months.

Of the three types of glazing, single glazing has the highest solar radiation load, followed by double glazing and algae windows. Algae windows have the lowest solar radiation load because they have the lowest SHGC. This means that sunlight is less likely to penetrate the window and raise the temperature. In other words, if a building or room has a lot of windows, the cooling load using algae windows will be significantly reduced.

In this study, the coefficient of performance (COP) of the air conditioner is chosen as 3, which is a popular value for air conditioners. Using Equation (3), the annual energy consumption for the air conditioner when using three types of windows, namely single glazing, double

glazing, and algae windows, is 10,273,362.67 Wh, 9,774,302 Wh, and 9,039,554 Wh, respectively.

According to Decision No. 1062/QĐ-BCT [33], issued on May 4, 2023, by the Ministry of Industry and Trade, the average electricity price in Vietnam has increased by 3% to 2,746 VND/kWh (0.11 USD/kWh). The main reason for the increase is the rise in the price of coal, natural gas, and crude oil on the world market. These fuels are used to generate electricity in Vietnam. The annual energy cost was computed based on the air conditioner’s electricity consumption and electric price. The results show that single-glaze windows cost \$1130, double glaze windows cost \$1075, and algae windows cost \$994.35. This means that algae windows

Table 1. Solar radiation load for different walls.

Walls	Hour	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
		(Wh)											
Single glaze	6	0	0	0	6	18	15	5	0	0	0	0	0
	7	340	511	374	243	216	249	228	210	382	620	837	726
	8	1188	1102	673	690	445	494	527	411	823	977	1121	848
	9	1664	1627	1141	1015	1354	1253	1329	1406	1192	1514	1502	1506
	10	2138	1923	1507	1171	1333	1501	1544	1150	1283	1830	1865	2068
	11	2345	2105	1707	1146	1357	1655	1750	1022	1528	2058	2095	2294
	12	2400	2156	1768	1218	1408	1618	1797	1253	1408	2064	2095	2218
	13	2409	2093	1785	1132	1485	1630	1734	1134	1505	1891	1981	2131
	14	2228	1977	1562	1117	1284	1512	1625	1183	1325	1726	1773	1873
	15	1857	1712	1259	1007	1266	1270	1523	1172	1039	1350	1415	1469
	16	1361	1342	936	855	1066	1033	1104	918	735	738	1002	1007
	17	676	819	501	524	631	697	792	561	396	67	0	9

Table 1. Continued.

Double glaze	6	0	0	0	5	15	12	4	0	0	0	0	0
	7	271	406	297	193	172	198	181	167	304	493	666	577
	8	945	877	535	548	354	393	419	327	654	777	892	674
	9	1323	1294	908	807	1077	997	1057	1118	948	1204	1195	1198
	10	1700	1529	1198	932	1060	1194	1228	915	1021	1456	1483	1645
	11	1865	1674	1358	911	1080	1316	1392	813	1215	1637	1666	1824
	12	1909	1715	1406	969	1120	1287	1429	996	1120	1641	1666	1764
	13	1916	1664	1420	901	1181	1296	1379	902	1197	1504	1575	1695
	14	1772	1572	1242	889	1022	1203	1292	941	1054	1373	1410	1489
	15	1477	1362	1002	801	1007	1010	1211	932	826	1074	1125	1169
	16	1083	1067	745	680	848	821	878	730	584	587	797	801
	17	538	651	399	417	502	555	630	446	315	53	0	7
Algae window	6	0	0	0	1	4	3	1	0	0	0	0	0
	7	79	119	87	56	50	58	53	49	89	144	195	169
	8	276	256	156	160	104	115	123	96	191	227	261	197
	9	387	378	265	236	315	291	309	327	277	352	349	350
	10	497	447	350	272	310	349	359	267	298	426	434	481
	11	545	490	397	266	316	385	407	238	355	479	487	533
	12	558	501	411	283	327	376	418	291	328	480	487	516
	13	560	487	415	263	345	379	403	264	350	440	461	496
	14	518	460	363	260	299	352	378	275	308	401	412	435
	15	432	398	293	234	294	295	354	273	242	314	329	342
	16	317	312	218	199	248	240	257	213	171	172	233	234
	17	157	190	117	122	147	162	184	131	92	15	0	2

can save up to 12% (or \$135.65) compared to single-glaze windows and up to 7.5% (or \$80.65) compared to double-glaze windows. In other words, algae windows are the most cost-effective option, followed by double-glaze windows and single-glaze windows. Therefore, if a room has a large number of algae windows, the cost savings will be significantly greater than if other types of glazes were used. This is because algae windows have a low solar heat gain coefficient (SHGC), which means that they allow less solar radiation to pass through them than other types of windows. As a result, rooms with a lot of algae windows will require less energy to cool, which will lead to lower energy bills.

Daylight Analysis

When considering sustainable and energy-efficient design, daylight analysis should be considered. Daylight analysis determines how much light penetrates a room, and designers base their decisions on this parameter to install artificial light to meet operation demand. Therefore, natural light can be utilized effectively to

reduce energy for artificial light. Cutting down on energy leads to lowering greenhouse gas emissions associated with electricity generation. In addition to cost saving and lowering greenhouse gasses, exposure to natural light can improve our mood and increase productivity. Leadership in Energy and Environmental Design (LEED standard), which is the world’s most widely used green building rating system, requires the percentage of time that a space receives enough daylight to perform visual tasks without electric light. LEED requires a minimum of 55%, 75%, or 90% of the time, depending on the type of building. The required level of daylight illuminance is 300 lux, and this is also the minimum value that must be met when simulating daylight levels in a building [34].

To simulate daylight levels, Ecotect utilizes the concept of “design sky illuminance”, which is obtained through a static analysis of outdoor illuminance levels. The desired light levels will be met at least 85% of the time over the period from 9 am to 5 pm during the entire year. In this simulation, “from model latitude“ mode was chosen for the design sky illuminance calculation.

After calculations, the average daylight level in a room with single glazing is the highest, at 1137.96 lux. This is followed by double glazing at 1053.5 lux and algae windows at 791.7 lux. This indicates that illuminance is strongly correlated with visible transmittance (VT). This finding is entirely in line with LEED standards. However, the new LEED criteria (LEED v4) recommend that windows should be temporarily closed when more than 2% of the daylight level in space exceeds 1000 lux of direct sunlight. Moreover, the direct sunlight illuminance of 1000 lux must not be exceeded for more than 250 hours per year for more than 10% of the area [35]. With the new LEED standard, in this case, single-glaze and double glaze windows allow too much daylight in, which leads to higher energy consumption. Algae windows are therefore a good option in this case, as they can reduce daylight levels while still providing adequate light for occupants. However, it is important to note that these results are based on simulations, and the actual value is likely different from the result of the simulation. Moreover, if a building or room has a high window-to-wall ratio (WWR), *C. vulgaris* with a 30% concentration (SHGC = 0.33, VT = 0.3) or a 40% concentration (SHGC = 0.2, VT = 0.17) [3] can be used to reduce energy usage. However, daylight-level simulation should be conducted to ensure that the required daylight level is still met. The daylight level using the algae window is displayed in Fig. 3.

Fig. 3 shows the daylight level in different parts of a room. The brighter the square, the higher the daylight level at that location. The brightest areas are near the windows, with approximately 1200 lux. However, about 10% of the positions have an illuminance of 1000 to 1200 lux, which meets the LEED standard criteria. From the two long sides to the center of the room, the daylight level gradually decreases. Some areas near the two long sides have a high daylight level because there

are windows there. Conversely, the daylight level is low on the two short sides because there are no windows. However, the illuminance is sufficient for office work (300 to 500 lux) [36]. Generally, the higher the daylight level, the more accurate office workers can be, and it should be between 500 and 800 lux [37]. Therefore, in this design, the illumination using algae windows is suitable for office work and also avoids using too much energy.

Hot Water Production

When sunlight hits an algae culture, the solar energy is absorbed, causing the temperature to rise gradually. To prevent the algae from dying, the temperature must not exceed 38 degrees Celsius, so the algae must be cooled. The energy emitted in this process can be used to heat water for a hot water supply, saving energy. In addition, this temperature is suitable for taking a bath. To calculate energy savings, the solar radiation that strikes the vertical algae window must be investigated, as shown in Fig. 4.

It is evident in Fig. 4 that a south-facing wall receives significantly more solar radiation than a north-facing wall throughout the year. This is because the sun is in the south for most of the year in the Northern Hemisphere (as shown in Fig. 1). In other words, the north-facing wall only receives solar radiation during the summer months. In the summer months, the sun's altitude is high, and its path tends to move north, so the solar radiation is lower on the south-facing wall than on the north-facing wall. However, from September to March, the sun's path returns to the south, leading to higher values on the south-facing wall than on the north-facing wall during those months.

Using Equation (4), the solar radiation in each direction (kWh/m^2) in Fig. 3, the total area of windows

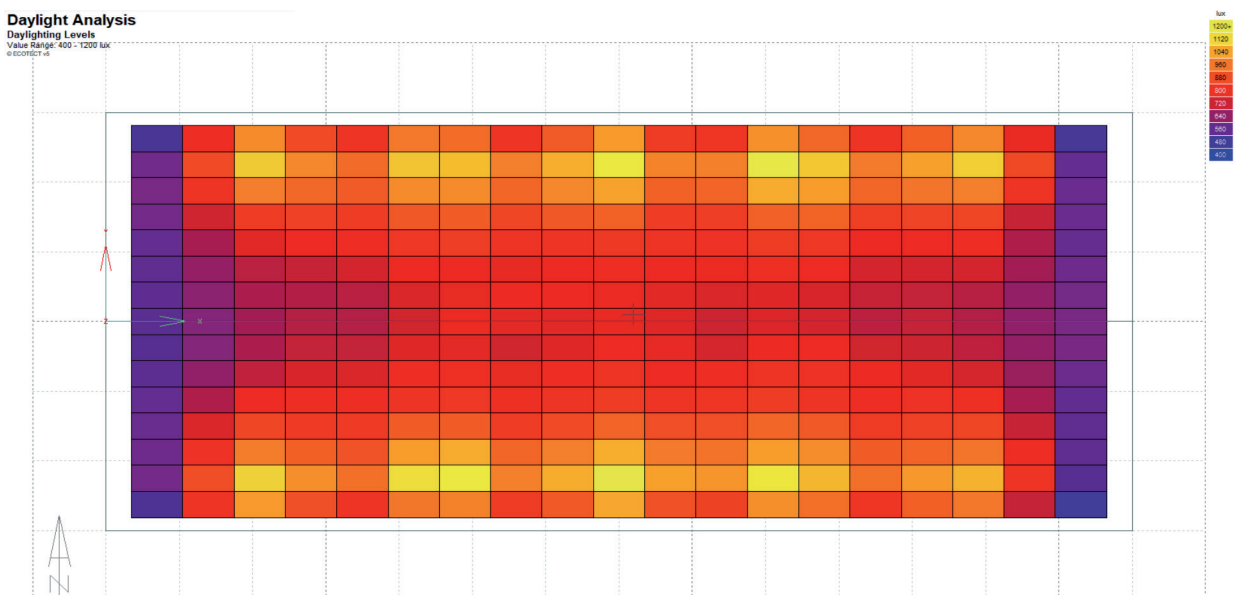


Fig. 3. The daylight level at different parts of a room.

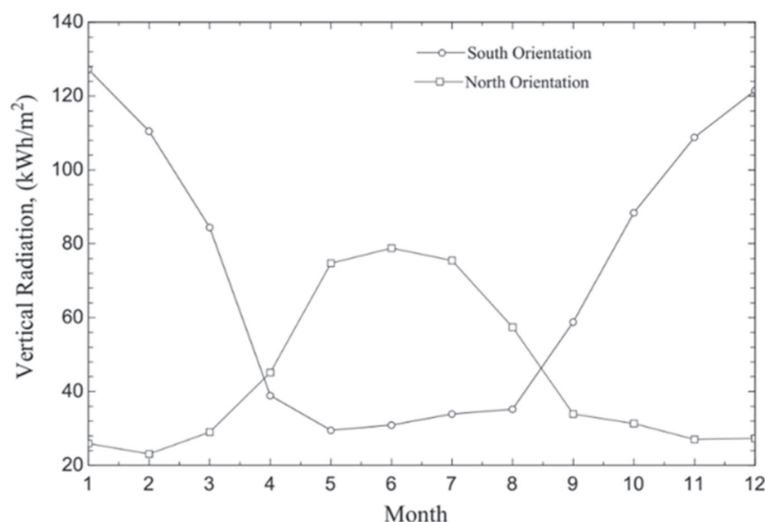


Fig. 4. Vertical solar radiation in the South and North walls.

(m²), and a solar efficiency of 38% [8], the energy savings for hot water supply in south-facing windows and north-facing windows for the entire year are 3216 kWh (USD 353.7) and 1960 kWh (USD 215.6), respectively. Therefore, with a total of 10 windows in both orientations, the energy saving cost is USD 569.3 per year. In other words, the cost of energy savings for hot water is dramatically higher than the cost of energy savings for cooling.

Table 2 compares different studies on the use of photobioreactors (PRBs) as algae windows. The table shows that the energy saving potential of algae windows is promising, with some studies reporting that the energy savings are up to 80%. This study is also in line with the results evaluated in published works and further suggests that algae windows are a viable technology for reducing energy consumption and greenhouse gas emissions [38, 39].

Environmental Protection

The applicability of algae windows not only provides eco-friendly energy, but they also contribute to the reduction of greenhouse gasses, making them a carbon-neutral energy solution for environmental protection. From an environmental perspective, there are apparent advantages on account of reduced energy consumption, improved energy efficiency, on-site biomass production, thermal generation, biofuel manufacturing, and wastewater treatment. These structures provide advantages of a low carbon economy via lowered energy, operational, and tax expenditures, thereby resulting in mitigated overall life cycle costs and rising rental returns without compromising occupancy rates. Moreover, these innovations hold significance in the realm of net zero energy, on account of which they excel in enhancing building energy efficiency, generating renewable energy, and optimal air quality.

Specifically, numerous studies indicate that the

algae window for improved temperature control can bring significant mitigations in energy consumption with over 33% fuel and around 10% electricity [40]. Moreover, buildings integrated with microalgae systems may recycle building waste into valuable resources as well as reach self-sufficiency in power and water, which simultaneously deal with air pollution and wastewater treatment. A case in point is that buildings integrated with microalgae in Hamburg, Germany [41]. The energy efficiency and resident satisfaction of this building are further meliorated by aspects such as geometric design, microalgae cell concentration, and color changes affected by environmental conditions. The effectiveness of the photosynthetic performance of microalgae enclosures contributes to energy savings by mitigating the demand for heating, cooling, and artificial lighting, leading to decreased CO₂ emissions and improved indoor air quality. This potential technology may reap the benefits of a low-carbon economy. The effective and large scale installation results in the economic viability of algae-integrated buildings.

Another example is a skyscraper powered by microalgae systems called One World Trade Center in the US. The building could potentially mitigate energy consumption yearly (arising from heating, cooling, lighting, and ventilation) by approximately 20%, leading to considerable expense savings of more than one million US dollars a year and a return on investment of 7 years. Such significant energy conservation also correlates with an average mitigation of 6 thousand tons of CO₂ emissions. Together with the positive influence on CO₂ reduction through energy savings, these innovative buildings are able to sequester more than 7 thousand tons of CO₂ a year, consuming at a rate of 5 g/ft². Potential profits from the trade of biomass or high value bioproducts, in addition to the utilization of building waste, could help offset energy expenses. By maximizing growth conditions and operational modes, the potential daily productivity ranges from 1 to 5 grams

Table 2. Published studies related to algae window.

Reference	Location	Panel size (m)	PBRs function	Orientation	Research content	Results
[38]	Hamburg	2.5×0.7×0.08 129 flat panel	Shading, Thermal usage, Biomass	Southwest Southeast	Experiment on <i>C. vulgaris</i>	<ul style="list-style-type: none"> - Heat efficiency for hot water production is 38% - Converting light to biomass efficiency is 10% - Heat generation of 150 kWh/m² per year.
[3]	Tel Aviv, Israel	15%, 30%, 45%, 60%, 75%, 90%	Shading	North, East, South, West	<ul style="list-style-type: none"> - Determine experimentally the U-factor, SHGC, and VT of <i>C. vulgaris</i> and <i>Chlamydomonas</i> algae window with different concentrations. - Simulate energy consumption 	<p>At maximum concentration, the energy savings of using an algae window can be up to 20 kWh/m².year in the south, 8 kWh/m².year in the east, 14 kWh/m².year in the west, and 18 kWh/m².year in the north compared to using single glass.</p> <ul style="list-style-type: none"> - When outside temperature increases, PBR can regulate indoor temperature. - Algae window can reduce 90% daylight, but its illuminance is still at an acceptable level. - Algae windows can reduce energy consumption. - Oxygen production can be 4.83 ml/hour/l microalgae culture (chlorella).
[16]	Bandung, Indonesia	0.7×0.6×0.05	Shading	-	<ul style="list-style-type: none"> - Energy simulation for building. - Experiment for algae window for outdoor and indoor temperature difference, illuminance, and Oxygen release. 	<ul style="list-style-type: none"> - The light intensity in the door of an algae window glazing and an Orosi window are approximately equal. - Humidity increased from 25% to almost 70% with the algae window. - Nearly 500 ppm of CO₂ can be absorbed using an algae window.
[38]	Iran	0.30×0.30×0.45	Shading	-	<p>Compare the performance of algae window glazing and typical Iranian Orosi window using simulation and experiment.</p>	<ul style="list-style-type: none"> - Reduce water usage by up to 80% and save up to 80% energy consumption
[39]	Paris	10000 ft ²	Shading Biofuel production, Waste water treatment.	-	Experimentally developed microalgae	<ul style="list-style-type: none"> - Save up to 12% energy consumption for cooling compared to single glaze. - Produce 329.84 kWh/m².year at South facing and 201.2 kWh/m².year at North facing. - Reduce daylight level from outside.
Current study	Phan Thiet province, Vietnam	1.5x1.3x0.2 10 windows	Shading Hot water production.	South North	<ul style="list-style-type: none"> -Energy, daylight simulation based on <i>C. Vulgaris</i> 20%. -Hot water production based on solar efficiency of 38% 	<ul style="list-style-type: none"> -Reduce daylight level from outside.

per square foot. Applying this technology results in the mitigation of greenhouse gas emissions. Integrating this technology in an office building with an average size (100 feet in width and length and 65 feet in height) could reach the sequestration of CO₂ from 17 to just above 80 metric tons, generate dry biomass up to 50 metric tons, and generate biofuel up to 7 thousand gallons. In practice, the commercial expense of eliminating CO₂ is likely to be between 500 and 1700 dollars per ton. The cost savings from the applicability of this technology could amount to as much as 145 thousand dollars a year. Additionally, the use of algae windows could have positive effects on wastewater treatment. When integrated with wastewater treatment processes, algal culture may eliminate phosphorous and nitrogen at an efficient rate of 80% to 100% [41].

Some Current Barriers and Potential Regulations for the Utilization of Algae Windows

While providing numerous merits, utilizing algae integrated structures is still an emerging technology. Several technological, economic, environmental, social, and regulatory shortcomings should be overcome before these technology systems can be widely applied. Many scholars will raise questions related to sustainability and customer satisfaction related to its guarantee of sequestered energy efficiency and effective CO₂ elimination over a long period of time, address concerns related to thermal insulation, monitor variations in indoor color because of changes in algae culture density, prevent discoloration, reconsolidate the durability of algae against climate change, and solve maintenance, construction, and operational expenses. Furthermore, potential adverse environmental influences arising out of the generation of toxins and odors by harmful algae need to be carefully examined. Generally, all of these barriers are exposed due to the lack of investment in research, the governmental regulations, and the relatively high cost of management and operation. More specifically, the number of cases of algae integrated into buildings in reality is limited. Therefore, studies on tracking and reporting the environmental performance and longevity of this technology pose challenges. The Return on Investment (RoI) remains uncertain because the lifespan of applying this technology is at least 25 years [42]. The initial operational costs and ongoing maintenance of algae cultivation within buildings are high and require significant time for management. This results in investors and researchers being hesitant when the time to achieve profitability is too lengthy. Additionally, there are concerns about potential pollutants from certain algae species producing toxins or releasing harmful volatile organic compounds [43]. Users need to pay more expenses for the assessment of risks and adverse impacts on human health resulting from damage or leakage and then the development of preventive strategies. Legal regulations to promote the utilization of this technology in architecture and environmental protection within

some developed countries remain restricted and in some cases, even absent in developing countries like Vietnam.

Limitations

The research reveals several limitations. Firstly, the technology under study is novel and not widely recognized or adopted in Vietnam. Consequently, the study couldn't be conducted on real buildings and relied solely on simulations from experiments conducted in developed nations. Secondly, variations in external factors such as weather and infrastructure among countries, notably Vietnam with its tropical equatorial climate, hinder the comparability of research results regarding temperature and building structure. Thirdly, Vietnam's environmental and investment policies haven't adequately assessed the risks and benefits of this emerging technology, thus impeding financial support from the government and investors.

Governments worldwide are currently emphasizing environmental protection, particularly through the integration of green technologies in urbanization processes. The incorporation of algae into buildings holds promise for achieving zero-emission structures, environmental conservation, and improved quality of life. Consequently, governments are urging research funding to evaluate the long-term effectiveness of these technologies while addressing associated societal risks, especially concerning environmental and human health. Moreover, governments need to establish conducive conditions for businesses and investors to adopt these technologies through policy incentives and regulatory frameworks.

Enhancing regulations and enforcement within environmental protection laws is imperative, particularly in monitoring toxins and contaminants from algae that may pose health risks. Public awareness campaigns focusing on the value of algae and its application in green urban development are essential. Algae windows, for instance, offer energy-saving benefits, carbon sequestration, and wastewater treatment capabilities, enhancing their appeal and potential public acceptance [43].

Financial incentives such as carbon credits and the development of value-added products can further drive the advancement of this technology. Governments should facilitate businesses in utilizing algae technology for manufacturing biomass and bio-products, offering tax incentives to enhance operational efficiency and profitability, thus contributing to the development of a low-carbon economy.

Conclusions

A model of a conference room using photobioreactors (PBRs) as algae windows was created. Energy, daylight simulation, and hot water production calculations were

performed. Algae windows were used in a resort in Phan Thiet province because their green color made tourists feel closer to nature. The *C. vulgaris* 20% window parameter was chosen because this type of algae is suitable for marine water, has a green color, and produces high yields. Algae windows have the potential to significantly reduce solar radiation that passes through them. The higher the concentration of algae, the lower the solar radiation cooling load, which will also lead to a lower cooling load and energy consumption. However, it is important to consider the room's lighting to avoid insufficient daylight. The study found that using algae windows instead of single glazing can result in a 12% reduction in cooling energy costs. Additionally, hot water production can be saved by 329.84 kWh/m².year for south-facing windows and 201.2 kWh/m².year for north-facing windows. These energy savings can be significant for businesses, as hot water energy is essential. Biomass can also be collected for electric generators. Overall, using a photobioreactor as a window can effectively reduce energy consumption and protect the environment, as algae can absorb CO₂ and release oxygen. To optimize this technology and implement it in practice, countries need to enhance public awareness of the role of algae in environmental protection. Simultaneously, supportive policies and incentives for investors and businesses should be developed and implemented properly, depending on the capacity of every state. Legal regulations should also establish responsibilities for users of this technology to mitigate potential risks that could negatively impact communities, especially human health.

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Conflict of Interest

The authors declare no conflict of interest.

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