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Energy Efficient Buildings with Algae

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Abstract. The biggest part of the energy consumption of buildings is for thermal comfort. Awareness on climate change and concerns about the depletion of natural resources made the necessity to use renewable energy sources in buildings evident. In this context, microalgae have high surface efficiency and consume inorganic carbon, thus enabling carbon-neutral operation. They can be integrated into building façades with photobioreactors to reduce energy demands. This paper aims to clarify and discuss the role of microalgal technologies in energy-efficient architecture. The thermal performance and energy generation properties of microalgae façades are comprehensively reviewed. The results show that microalgae provide dynamic shading and thermal insulation, thus have the potential to significantly reduce the thermal load and energy demands of buildings and increase the building performance. Consequently, besides the thermal performance of microalgae façades, evaluation of daylight, lighting, environmental and cost performance, technical applicability and aesthetics are necessary.

1. Introduction

Today, the construction sector accounts for 36% of total energy use and 40% of energy-related CO_2 emissions [1]. The buildings cause a significant amount of greenhouse gas emissions during the construction process, and their usage, especially during the air conditioning and ventilation of buildings [2]. To reduce energy consumption in building construction and operation is important for a low carbon future. This situation leads architects and engineers to design more energy-efficient buildings. Energy-efficient buildings are "buildings that need less energy with the precautions taken during the design phase, meet the energy they need from renewable sources and make minimum emission by using the energy in the most efficient way" [3].

Energy efficiency measures reduce the amount of energy consumed while maintaining or improving the comfort level in the building. Especially, façades have critical importance in reducing heating-cooling loads and optimizing thermal comfort. They serve as an insulation layer for the building thus help with energy saving [4]. While applications using solar and wind to generate renewable energy is common in buildings, the conversion of biomass produced by photosynthetic plants into bioenergy is one of the new approaches to renewable energy sources. Building-integrated microalgae photobioreactors (PBRs) have the potential to contribute to the reduction of a building's carbon footprint and fossil fuel consumption. The use of a building façade as a microalgae production area plays an important role in using the produced biomass for the energy required for the building's needs [4].

Arazi and Shahid [5] and Pruvost et al. [6] state that there could be “symbiosis” between a building and PBR, and mutual benefit will be obtained for both algae growth and building performance through this

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symbiosis. They also emphasize that with the exchange between PBRs in the integration of PBRs, the high capital and operating costs required for PBRs will be reduced, expenses like glazing will be shared, and the thermal function of buildings will improve. Adding PBRs to buildings significantly reduces the thermal loads, energy, and heating requirements of the building. Evaluation of architectural application of the final products obtained as a result of the bioprocessing of microalgae show that biomass can be converted to biogas for use in the existing infrastructure and the architectural structure for hot water, and partially obtaining electricity [7].
A well-integrated building and PBR couple is beneficial to energy saving, particularly by increasing thermal efficiency [8]. A frequently claim is that PBRs provide some improved indoor air quality and purify polluted air and wastewater besides thermal benefits [3, 7, 9, 10, 11]. This study investigates the potential effect of algae PBRs on the thermal balance of the building. In this context, this paper evaluates and discusses the data on the "Thermal performance" of PBR façades.

2. Methods

In recent years, various approaches have been produced by architects and designers to integrate microalgae with architecture. Most of the studies are unrealistic but consist of futuristic ideas that present the potential of microalgae. Yet, there are also some projects and prototypes that provide a more realistic role to the implementation of microorganisms in buildings. This paper outlines case studies to explain the thermal performance of façades in the integration of PBR systems into the architectural discipline. First, literature about building-integrated microalgae PBRs is reviewed. The review covers scientific articles, web sources, and thesis studies. This work focuses only on PBRs integrated into building façades, and urban scale PBR implementations or individual installations are excluded. The content is limited to flat plate panel PBR studies, and other types of PBR geometries are not included. A total of 25 projects are found in the published literature and outlined on a World map, as seen in Figure 1. All the points in Figure 1 show these 25 projects. However, as the focus of the paper is primarily on thermal performance, other issues such as daylighting, economics, and technical integration of PBR façades are disregarded. Thus, only eight case studies numbered in Figure 1 that provide sufficient data on the thermal performance of flat-panel PBRs are examined in detail. The results are tabulated and discussed according to the thermal functions of the PBR façades.

3. PBR case studies on the thermal performance of buildings

3.1 Bio-Intelligent Quotient (BIQ)

The BIQ building is the world's first pilot project to exhibit a PBR façade. It is a part of the International Building Exhibition in Hamburg. The idea of creating a self-sufficient and sustainable structure was put forward during the design of the building. A total of 129 PBRs with dimensions of 2.5 m x 0.7 m x 0.08 m were installed on the south-west and south-east faces of the four-storey residential building to form a secondary façade [12]. PBRs basically carry out two processes: converting light into heat and converting light into biomass [13]. Since PBRs act like thermal solar collectors, they produce the heat used to warm the building. The thermal energy produced is used in heating the building and preheating the domestic hot water. Excess heat is drawn off by heat pumps and stored in geothermal boreholes under the building [14]. Algae density, harvesting of biomass, and keeping the temperature level constant are controlled by the building management system (BMS). The PBR system produces 150 kWh/m^2 of thermal energy and 30 kWh/m^2 of bioenergy. In addition, the system transformation efficiencies of the bioenergy and the thermal energy are determined to be 10% and 38%, respectively [13].

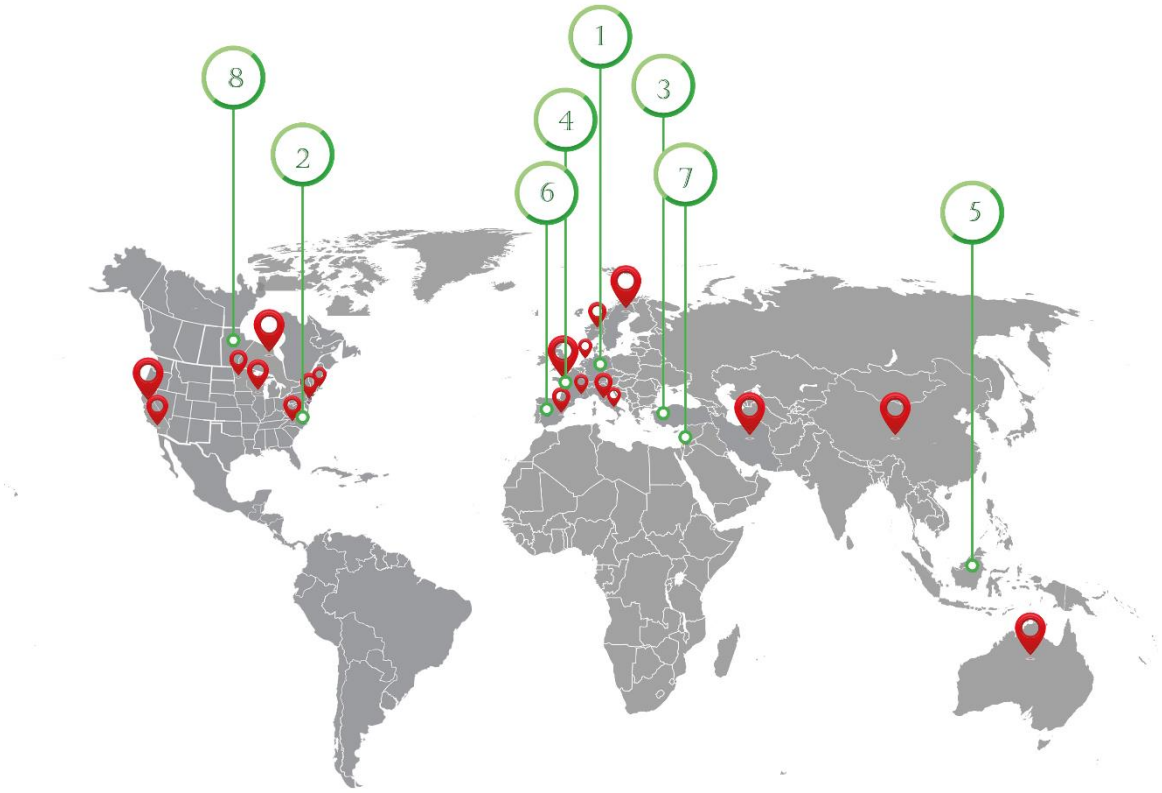


Figure 1. Mapping of building integrated photobioreactor literature. Selected cases are: 1. Bio-Intelligent Quotient (BIQ), 2. A Feasibility Study of an Algae Façade System, 3. Optimization of bioreactor panel thermal transmission, 4. The symbiosis of microalgae-photobioreactor façade, 5. ITB Innovation Park, 6. Case Studies on the Architectural Integration of PBR in Building Façades, 7. Algae window, and 8. Symbiosis optimization of building envelopes and micro-algae photobioreactors

3.2 A Feasibility Study of an Algae Façade System

Kim [2] conducted a feasibility study to examine the performance characteristics of algae façade systems via simulation and experimental works. The façade system consists of a vision zone and an algae-growing zone. The vision zone allows viewing, daylighting, and ventilation when required. The algae zone is a place where the algae culture grows.

A 60 x 60 cm panel and indoor environment were prepared to determine the internal surface temperature. The thermography technique was used to assess the thermal performance. Tests were performed by using the FLUKE thermography system on a sunny winter afternoon. The preliminary thermography data showed that the temperature during winter in the vision zone is 20.5°C, while algae zone is 27.7°C. This showed that the overall heat transfer coefficient (*U-value*) of the vision zone is higher than the algae zone.

3.3 Optimization of bioreactor panel thermal transmission

Umdu et al. [15] determined the overall heat transfer coefficient (*U-value*) of PBRs for different parametric values. They used the experimental design method to evaluate the heat transfer behavior of panel PBRs. 13 different PBR were designed with different PBR inner depth, air layer, and PBR wall thicknesses. The panel with the highest *U*-value has PBR inner depth is 30 cm and is without air layer has, while panel bioreactor with the lowest PBR wall thickness with the the smallest *U*-value has the highest air layer thickness. Results show that there is a significant interaction between *U*-value and the design parameters, such as PBR inner depth, air layer, and PBR wall thicknesses. Generally, the *U*-value

decreases by increasing the design factors. The authors also emphasized that integrating PBRs into the façade provides an effective insulation

3.4 The symbiosis of the microalgae-photobioreactor façade

Pruvost et al. [6] investigated integrating PBR into the south-facing façade of plant for biomass production. They compared the values obtained from vertical, horizontal and inclined installation of microalgae culture systems with conventional systems. They evaluated the 0°, 45°, and 90° positioning of PBRs for France. Since vertical PBRs collect less light in summer, 45° inclination PBRs offer 20% higher productivity than vertical PBRs. In PBRs with 45° inclination, biomass efficiency of *Chlorella vulgaris* in optimum ambient conditions fluctuates throughout the year, while constant productivity has been observed for vertical PBRs throughout the year.

Pruvost et al. [6] also suggested a symbiotic relationship between the building and algae and that energy exchanges between building and PBRs can regulate thermal loads of both subsystems. PBRs can reduce the thermal load on the building by filtering sunlight. They can also be used to heat the building with excess thermal energy in the growth medium. The thermal mass of the building also has the benefit of PBRs at very low temperatures, such as preventing slowing of biomass growth and loss of productivity. Considering the annual energy consumption, for five situations, 90° PBR (without symbiosis), 45° PBR (without symbiosis), 90° PBR (50% of symbiosis), open pond, 90° (100% of symbiosis), and 45° (100% of symbiosis) the least energy consumption is the one with 100% symbiosis at 45° of inclination [6].

3.5 Institut Teknologi Bandung (ITB) Innovation Park

Martokusumo et al. [16] studied usage and performance of algae on the building façade. The aim of their research is to evaluate and compare the performance of three different façades systems: (1) transparent brise-soleil, (2) fixed horizontal shading element, and (3) a PBR. The performance of each façade design is evaluated by considering the interior temperature and total energy consumption. A PBR prototype, which was conceptually proposed to be applied to the ITB Innovation Park building, was also produced. In the first stage of the research, the façades for the transparent brise-soleil and a fixed horizontal shading device were simulated by using Open Studio-Energy Plus software. In the second stage of the work, experimental measurements were conducted. The temperature measurements and simulations showed a difference between indoor and outdoor environments as 3.412°C for brise-soleil, 3.52°C for the fixed horizontal shading device, and 6.447°C for PBR. The results show that the PBR can regulate the indoor temperature when the outdoor temperature is higher. According to the temperature differences, the energy consumption for cooling using PBR is significantly less than the other two façade systems.

3.6 Case studies on the architectural integration of PBR in building façades

Sarda and Vicente [17] stated that with the addition of PBRs to the buildings, microalgae absorb the sun by photosynthesis, reduce the temperature via the shading effect, and the microalgae water environment increases the thermal mass of the façade and thermal regulation. Sarda and Vicente [17] conducted an economic feasibility study and examined the energy efficiency of PBRs. They analyzed the PBR façade theoretically and compared it with the façade systems formed with different walls. They observed that decreasing the heat transmittance provided significant energy savings in comfort demand in all situations studied. The energy-saving of the buildings increased, especially regarding temperature regulation.

3.7 Algae window

Negev et al. [4] examined the integration of microalgae with façades through a window element. They investigated the effect of various transparent façade element performance variables (types of algae, concentration, and window size) on the reduction of a building's energy consumption. The effect of growing two microalgae strains (*C. vulgaris* and *Chlamydomonas reinhardtii*) on heat transfer and light transmittance was investigated in the Algae Window. They measured the visible transmittance and solar heat gain coefficient of the algae window at different concentrations for two microalgae strains. According to the results, for both algae strains, as the algae concentration increases, the heat transfer

coefficient decreases. According to algae strains, at 100% concentration, there is less light transmission for *C. vulgaris* than *Chlamydomonas reinnhardtii*, which leads to lower energy gains.
They simulated the Algae window under Israeli climate conditions. They observed that the energetic performance of the water with 0% algae concentration is better than a single-glazed window unit. But a double-glazed unit has a better performance when it is compared with the base case algae window, with no algae concentration. Different results were obtained in different window sizes for four orientations. The highest energy-savings were achieved in the south and west directions due to receiving more solar radiation. The authors concluded that the algae window has the potential to increase energy efficiency in the building under Mediterranean climate conditions.

3.8 Symbiosis optimization of building envelopes and micro-algae photobioreactors

Araji and Shahid [5] made an optimization study to use microalgae on building façades. Their study analyzed a PBR's performance in terms of energy production. They developed a mathematical model that examines the net energy of a building in terms of its geometry, energy generation capacity, and consumption. Using this model, they analyzed the relationship between building height and energy consumption.. Evaluation parameters are types of algae, photosynthesis time, and panel inclination. The choice of algae strain affects the overall performance of the system due to different chemical properties leading to different ranges of productivity levels. Also, the optimal value of residence time depends on the location and orientation of the building, time of the year, and solar intensity. According to results, using *C. vulgaris* at an inclination of 75° shows a 28.7% productivity increase compared to *Dunaliella tertiolecta* at 90°. For *C. vulgaris* the residence time is 1.3-days, and the energy obtained by positioning it at 75° is 76 kWh/m^2-year. Besides, for *D. tertiolecta,* the residence time is four days, and the energy obtained in its positioning at 90° is 40 kWh/m^2-year.

4. Thermal performance of the photobioreactor façades

When PBRs are applied to building façades, façades gain new functionality. In addition to providing a connection between outdoor and indoor spaces, the use of renewable energy is expanded by providing a new production area for bioenergy, thus buildings become both more energy efficient and sustainable. Building-integrated PBRs can meet the thermal needs of buildings by acting as (i) thermal insulation, (ii) shading, (iii) solar collectors for hot water production, and (iv) light-to-biomass converters. Studies on the thermal performance of PBRs in the literature are summarized in Table 1, while the primary parameters that affect the heat-transfer-related functions of PBRs are detailed below.
Using microalgae PBRs on building façades can provide effective insulation, and help to obtain the thermal comfort required for building occupants. A number of studies concentrated on the *U*-value of flat plate PBRs. In these studies, the heat transfer behavior of PBRs was examined by evaluating different factors. Umdu et al. [15] show that the thermal behavior of PBR design changes depending on different parameters. Higher air layer thickness has given the most effective thermal insulation values. Then, they state that the thickness of the PBR material and PBR depth were also effective, respectively. Similarly, Cervera Sardá and Vicente [17] report that the PBR material, PBR thickness and air layer thickness parameters affect the *U*-values. Kim [2] stated that the U-value of the flat-plate microalgae façade is different when there is growing medium and algae growth inside the PBR. She concluded that the algae zone has lower heat transmittance than the vision zone. Thus, algae culture density is a significant parameter on thermal insulation. Similarly, Negev et al. [4] calculated that the thermal behavior of algae density of culture is comparable with single and double glazed units. According to their evaluations, the concentration and types of algae are also important factors.

Table 1. Summary of studies on the thermal performance of PBRs in the literature.

Reference	Location	PBRs function	Panel size (m)	Orientation	Type of microalgae	Methods	Results
[13]	Hamburg Germany	Shading, Thermal collector, Biomass production	2,5×0,7×0,08	Southwest - Southeast	*C. vulgaris*	Real-Scale Experimental	The efficiency of the heat produced by PBRs is 38%, while the efficiency of converting light into biomass is 10%.
[15]	North Carolina, ABD	Thermal insulation	1,52× 3,66	-	*C. vulgaris*	Simulation and Experimental (Thermography-based thermal testing +FLUKE)	The *U*-value of panel PBR can be compared to a Low-E coated insulated glass unit. The *U*-value of the vision zone is higher than the algae zone.
[14]	İzmir, Turkey	Thermal insulation	0,75×1,14 ×(0,06-0,2) m	-	*N. occulata sp*	Evaluation of PBR's *U*-value according to reservoir, air layer, and reservoir wall thickness	There is an important interaction between all main factors and the *U*- value. The thickness of the air layer affects the *U*-value the most.
[6]	Nantes, France	Solar Thermal Collector Biomass production	-	South	*C. vulgaris*	Theoretical study, simulation, Mathematical model	The symbiosis between microalgae, PBR, and building can significantly reduce energy demands for microalgae culture compared to individual PBR.
[16]	Bandung, Indonesia	Thermal insulation	0,7×0,6×0,05	East-west	*Chlorella*	Simulation (Open Studio-Energy Plus) and Experimental	When the outdoor temperature is higher, the PBR can regulate the indoor temperature. The cooling energy is significantly less in PBR use than the other two façade systems.
[17]	Spain	Thermal insulation Shading	-	-	-	Theoretical study, simulation (C3X software)	Integrating PBR into the façade can increase energy savings potential
[4]	Israel	Thermal insulation	-	East-west north-south	C. *vulgaris, Chlamydomonas reinhardi ti*	Simulation (Open Studio-Energy Plus)	The energetic performance of the base PBR case is less than the double glazed windows and better than the single glazed windows
[5]	Canada	Biomass production	-	-	*C. vulgaris D. tertiolecta*	Mathematical Model	While the 1.3-day residence time of C. vulgaris, energy production at 75° is 76 kWh/m^2-year, the energy obtained by D. tertiolecta's residence time for 4 days at 90° is 40 kWh/m^2-year

The use of PBR as a shading element in the façade both provides a decrease in solar heat gain and protects the façade from solar exposure. The microalgae medium can replace mechanical shading devices by acting as a shading screen to adjust the thermal regulation of the building. By absorbing light through photosynthesis, the microalgae grow, and the density of culture increases. Negev et al. [4] observed that as the concentration of algae used increased, the heat solar heat gain coefficient decreased, and when compared with each other, it was observed that *C. vulgaris* has less light and heat transmission compared to *Chlamydomonas reinnhardtii*. In the BIQ building, PBRs consist of two hollow glass layers and the layer in which the microalgae fluid circulates [14]. They stated that the density of algae is effective in shading. When there is more sunlight, the algae grow faster and provide more shading for

the building. A high-density culture within the PBR-based façade can prevent solar and light penetration into the building. In addition, the density of solar radiation varies depending on the climatic conditions, geography and orientation, which are other factors that affect shading. Cervera Sardá and Vicente [17] stated that with the addition of PBRs to the buildings, microalgae absorb the sun by photosynthesis, and reduce the temperature thanks to the shading effect. When Martokusumo et al. [16], compared the use of three different façade systems as shading elements, they reported that algae can regulate the temperature difference between the indoor and outdoor environment by absorbing the solar rays. They also stated that the PBRs placed on the west façade protected from excessive solar rays.

PBRs can meet the thermal needs of a building by acting as solar collectors. Depending on the inclination of the panel, the PBR geometry and the climatic conditions, the heat generated in a PBR changes. BIQ building generates 150 kWh/m^2-year of energy from heat [13]. The conversion factor of light to heat in the PBRs is 38%, while solar thermal systems usually operate with 60-65% efficiency. The heat generated from the bioreactor façades (6000 kWh/year) can supply for four apartments. In the BIQ building, the system is kept under controlled against overheating, the excess temperature is balanced with heat exchangers to prevent algae damage. The heat absorbed by the heat exchangers can be used for different functions such as hot water generation and building heating. The excess heat can be stored in the geothermal boreholes under the building with the help of heat pumps. It is then sent back to the building when necessary. Also, overheating in PBRs can be conmtrolled by transferring the hot culture to the colder parts of the façade. Similarly, Pruvost et al. [6] stated that the excess heat produced in the summer can be stored and used to heat the building in winter.

It is important for buildings that algae biomass can be stored and then used in energy and heat production. Factors such as climatic conditions of the area where the building is located, solar radiation intensity, PBR material, PBR size and orientation are effective in biomass productivity. BIQ building generates 30 kWh/m^2-year of energy from biomass [13]. When PBRs and photovoltaic panels are compared in terms of the efficiency of converting light into biomass, PBRs have an efficiency of 10% while PVs have an efficiency of 12-15%. There are also studies examining the effects of algae types and panel inclination on biomass production. When algae types are compared in terms of their production efficiency, different results are obtained due to their different chemical properties. Since the positioning of PBRs at different angles change the amount of light captured depending on the seasons, the obtained biomass efficiency differs. According to results, using *C. vulgaris* at an inclination of 75° shows a 28.7% productivity increase compared to *Dunaliella tertiolecta* at 90°. Pruvost et al. [6] calculated that in PBRs with 45° inclination, the biomass efficiency fluctuates throughout the year, while they observed constant productivity for vertical PBRs.

Energy efficiency would increase with the optimization of the factors discussed above. While PBR material, size, building window-wall ratio, types of microalgae, and culture medium density are effective in thermal insulation, PBR size, orientation, surface area to volume, and density of culture medium are effective in shading. In the production of biomass for energy conversion, type of microalgae, the surface to volume ratio, inclination degree, orientation, material thickness, building aspect ratio, and the climatic conditions of the region are important.

5. Conclusion

The building sector is known to be one of the sectors with the greatest impact on global warming. Therefore, making the buildings both energy-efficient and sustainable by implementing new solutions is the main aim of many researchers worldwide. The use of living organisms in buildings can increase their passive and active roles in energy saving and production. This paper extensively reviewed the thermal functions and energy production of flat panel PBRs for developing energy-efficient buildings; thus, it created a resource for the following studies. The integration of PBRs with exterior façades increases the passive energy-saving capacity due to absorbing the solar rays into a water reservoir, providing shading, thermal insulation, and thermal energy storage. In addition, it produces biomass by photosynthesis. Thus, the use of microalgae on the building façade inherently encompasses all the features in the definition of an energy-efficient building. In future studies, other performances such as daylight and lighting performance, environmental performance, technical applicability, cost, and aesthetics will also be examined in order to better understand the performance of microalgae façades.

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