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EFFECTS OF PHOTOBIOREACTOR FAÇADES ON THERMAL AND VISUAL PERFORMANCE OF AN OFFICE IN IZMIR

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ABSTRACT

Due to the increasing environmental awareness, the tendency to develop sustainable buildings has also increased interest in using renewable energy or energy-efficient technologies in recent years. Integrating a photobioreactor, an innovative building element on the façade, has received attention as an alternative approach to renewable energy systems for its potential to reduce the carbon footprint and energy consumption of a building without compromising thermal and visual comfort. This study aims to improve the performance of the building by using a façade integrated photobioreactor system. Implementing photobioreactors on the building façades raises the following benefits a) regulating the indoor temperature swings and improving thermal comfort, b) blocking the excess daylight thanks to the increasing concentration during the algae growth, c) reducing the energy consumption of the building, and d) producing energy from the harvested biomass (algae). The photobioreactor is integrated into the south façade of an existing office building in Izmir and comprises two glasses and a growth medium of photosynthesizing microalgae between the glasses. The method is simulation-based optimization that maximizes useful daylight illuminance and minimizes thermal comfort violation and energy use intensity. The performance of the existing building was compared with two photobioreactor alternatives. Rhino Grasshopper software with the Octopus plugin was used for the optimization study. The optimization results show that the photobioreactor integrated façade system performed better than the currently used one. The photobioreactor integrated façade can reduce the number of uncomfortable hours during the year. For the investigated photobioreactor configurations, there was no significant difference between 100% photobioreactor façade and 80% photobioreactor façade, except for partial improvement in daylight illumination.

Keywords: Multi-objective optimization, Microalgae photobioreactor, Building performance, Thermal-visual comfort

1. INTRODUCTION

The design decisions made in the early design phase of the buildings significantly affect the daylight, comfort, and energy performances. In addition, taking various precautions against problems that may arise in the future is possible. The building envelope is directly in contact with the outdoor environment and is responsible for an average of 75% heat gains and losses [1]. Especially the window element usually has an overall heat transfer coefficient of typically five times greater than the other components in the building envelope. Hence, these transparent surfaces cause 60% of the total energy consumption of buildings [1]. Thus, it is crucial to choose the window element correctly, but multiple parameters need evaluation to improve the building’s performance.

The properties of the building envelope components determine the building's performance. The trends and thoughts of architects in buildings working with algae can help form an idea of the requirements and possibilities needed in the architectural design of such buildings. It can bring different perspectives on different subjects, such as biomass production with algae grown inside, contributing to the thermal energy balance with solar energy gains, and lighting with a change in light transmission depending on time. In this direction, researches show that using microalgae, an innovative alternative to envelope components, will enable buildings to be more sustainable and contribute positively to the energy

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balance. Kim [2] examined the PBR's daylight considering the thermal and structural performances by proposing a microalgae façade panel comprising two zones (algae and vision zone). She concluded that algae façade systems could visibly improve buildings' thermal and daylight performance. Decker et al. [3] showed that microalgae growth and daylight penetration are interdependent, and various culture densities can affect indoor daylight intake. Lo Verso et al. [4] used PBR as a shading element and analyzed the daylight performance in an outdoor working area under PBR shade with DIVA-for-Rhino software. In that study, the illumination values changed for different light transmittance values. The authors changed the light transmittance by adjusting the biomass density in the culture medium circulating inside the panels. Cervera Sardá and Vicente [5] stated that by adding PBRs to buildings, the microalgae absorb the sunlight by photosynthesis, lower the temperature via the shading effect, and increase the energy savings because the microalgae growth medium increases the acoustic and thermal insulation performance of the façade and mainly contributes to temperature reduction. Negev et al. [6] studied the effects of PBRs on the energy consumption of buildings in the Mediterranean climate and showed that including windows in the building façade, mostly in west and south orientations, provides energy savings compared to single and double-glazed windows.

Studies on the effect of one parameter on a PBR façade element are present; however, studies optimizing PBR façades for high daylight performance and low energy usage are quite limited. Köktürk et al. [7] investigated the useful daylight illuminance (UDI) and energy use intensity (EUI) values in a hypothetical office space in the Ankara climate, depending on the window-to-wall ratio (WWR) and algae concentration variables for the north and south directions. There are no other simulation-based studies on this subject in Turkey. In addition, although there are some studies where these innovative systems present PBR façades as an energy-friendly alternative to traditional window systems, there is no attempt to optimize their thermal comfort performance. This study aims to investigate the effects of the thermophysical and optical properties of a PBR façade on energy consumption, daylight illumination, and thermal comfort in an office room in İzmir. This study examines the main design parameters of the PBR integrated façade such as WWR, algae concentration, wall type and thickness, insulation material thickness, and heating-cooling set point. The objectives of the simulation-based optimization are to reduce EUI and thermal comfort violation (TCV) and to increase the UDI.

2. MATERIALS AND METHODS

The current research uses different tools holistically to evaluate the dynamic thermal and visual behaviors of existing office space in İzmir. Building geometry comprises multiple areas created by Rhinoceros software, then converted to thermal zones in Grasshopper. The validation of the energy simulation was performed according to the criteria defined by ASHRAE [8] by comparing the indoor temperature results from the simulation with measured temperatures to prove the validity.

After validating the simulation, a single zone for a PBR was created in two different ways. In the former, as in Negev et al.'s [6] study in the literature, the PBR is 100% filled with a growth medium. In the latter, the PBR has a 20% air gap and 80% microalgae growth medium following realistic working principles (Figure 1).

Daylight simulation is the next stage. The lighting schedule obtained from the daylight simulation model is integrated with the energy simulation. EnergyPlus/Openstudio engine evaluated the energy performance, while Radiance/Daysim engine simulated the daylight performance. UDI, TCV, and EUI metrics were calculated during the simulations. Optimization was carried out on Rhino Grasshopper software using the Octopus plugin. Optimization objectives are related to daylight, energy, and thermal comfort and enable the analysis of the relationship between building design variables and performance metrics. In optimization, the design variables and ranges are set as follows. The window types are PBRs that are prepared to depend on the algae concentration with an increase of one day. Window to wall ratio has been adjusted from 10% to 95% in increments of 5%. Wall types are brick and aerated concrete. Both wall thickness and insulation material thickness differ. While cooling set points varied from 23.5°C to 27° with 0.5°C increments, heating set points varied from 18°C to 23.5°C.

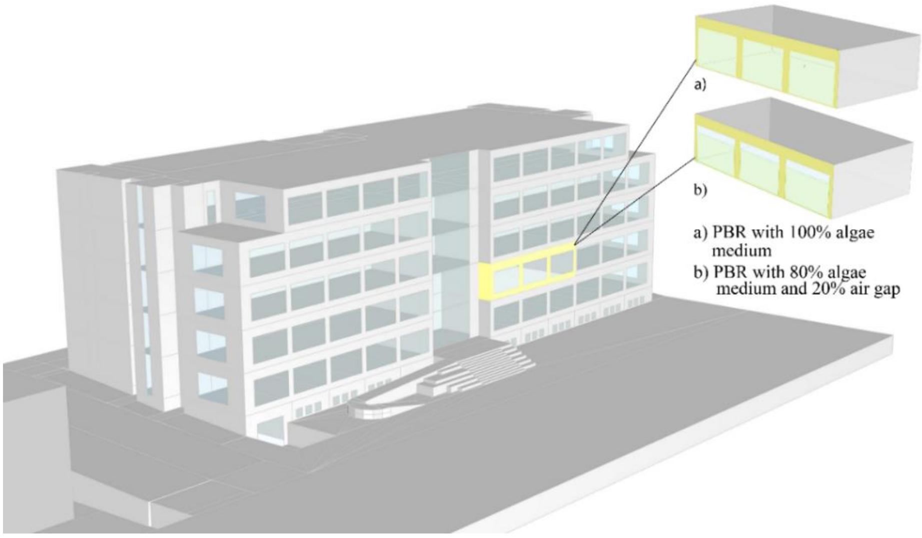

Figure 1. Façade alternatives

3. RESULTS AND DISCUSSIONS

The building model has two different PBR façade element modeling proposals (as seen in Fig. 1). The solutions obtained by optimizing the existing building and the alternatives to improve this façade are compared and evaluated in terms of the thermal and visual comfort performance parameters.

3.1. Photobioreactor Façade Fully Filled with Growth Medium

The independent variables in the analyzes were PBR-related design variables (WWR and window type), temperature control settings (heating - cooling set points), the wall type-thickness, and the thickness of the insulation material used in the wall. By calculating the fitness function in the solutions obtained at the end of the optimization, balanced solutions were obtained between daylight, energy, and thermal comfort performances. Optimization results are given in Table 1. Table 1 shows that the UDI changes in the range of 51.81% to 65.12%. It should be noted that UDI is only affected by window type and WWR. At the same time, the WWR should be adjusted depending on the algae concentration. It has been observed that as the algae concentration increases, the amount of light entering decreases, so the WWR increases to provide the UDI. The optimal results have a WWR varying between 15% to 25% in the PBR with algae concentration on the first day, and this ratio varied between 20-30% in PBR with algae concentration on the 2nd day. As the algae concentration increases inside the PBR, the light entering the indoor space decreases because of the increasing shading effect. As a result, the UDI reduces; that is, PBRs with high light transmittance were more common in optimization.

The relationship between the UDI value and the energy used for lighting shows that as the UDI decreases, there is a reduction in the use of daylight in the space. According to this reduction, the energy consumption for artificial lighting increases. This result has been provided by the integration of lighting control systems as well as WWR and algae concentration parameters.

EUI is affected by all parameters, and EUI values change between 544.05 and 1094.86 kWh/m^{2}y. In all optimum solutions, the wall type is only autoclaved aerated concrete (AAC). The wall thickness varied. In the same way, the thickness of the insulation material is also found in different thicknesses. Wall type-thickness and insulation thickness are less effective on the EUI than the other parameters. The cooling setpoint was constant at 23.5°C for each optimal case. Except for one case, the heating set point was identical to the cooling set point. Increasing the heating setpoint from 23°C to 23.5°C in the same configuration improved the TCV, but it increased the energy consumption for heating.

It is necessary to be careful in window designs, as the heat brought into the room by the solar radiation from the windows can cause overheating during summer, decrease indoor thermal comfort, and increase cooling energy consumption. This means that more air conditioning systems consume more energy to bring indoor temperatures to comfortable levels. As the window sizes increase, the cooling loads also increase, and in the Izmir climate, where cooling is dominant, window sizes are generally small. Similar results were found in terms of WWR in studies conducted in the Mediterranean climate in the literature. Acar et al. [9] found the optimal WWR of the Mediterranean climate building as 18.6% and 30.2% for buildings in the cold climate in the optimization they made for the Mediterranean climate and cold climate separately. Goia [10] optimized the WWR in the building envelope in different European cities and reported that the WWR of south-facing windows in Rome and Athens was 20%. However, a lower limit should be set on window widths in climates where cooling is dominant. Because although small dimensions improve thermal performance, they may not provide sufficient lighting.

The window's solar heat gain coefficient value is important to examine the effect of the window type on the energy performance. When the algae concentration increases, the energy used for heating increases in the same configuration, and the energy used for cooling decreases. Heat gain is an essential parameter in the cooling load calculations. PBR types with solar heat gain coefficients of 0.5 and 0.67 were optimal in the Mediterranean climate. This situation is similar to the optimization results made by Badeche and Bouchahm [11] in a city in Algeria with a Mediterranean climate. In that study, the solar heat gain coefficient of the window was found to be optimum between 0.5 and 0.7.

In the results, TCV values are below 10%, which is the ASHRAE recommended value. According to the table, WWR and heating set points must be proper to improve thermal comfort. Unless those parameters are adjusted correctly, more energy will be used to provide comfortable indoor conditions. The increase in algae concentration in the same configurations also increases thermal comfort.

Table 1. Alternative 1- Pareto optimal solutions

Window-to-wall ratio (%)	Window Types	Wall Types/ Thickness (cm)	Insulation Thickness (cm)	Cooling Set Point (°C)	Heating Set Point (°C)	UDI (%)	EUI (kWh/ m²y)	TCV (%)	Cooling (kWh/ m²y)	Heating (kWh/ m²y)	Lighting (kWh/ m²y)	Fitness Function
20	1st day	AAC 25	12	23.5	23.5	60.57	740.46	5.74	667.99	65.57	6.90	64.27
20	1st day	AAC 25	7	23.5	23.5	60.57	740.99	6.06	668.40	65.69	6.90	63.92
25	1st day	AAC 25	12	23.5	23.5	65.12	912.99	8.81	828.08	78.60	6.17	61.50
25	1st day	AAC 25	12	23.5	23	65.12	868.94	10.67	784.12	78.71	6.17	61.11
25	1st day	AAC 25	7	23.5	23.5	65.12	913.43	9.39	828.50	78.77	6.17	60.89
20	1st day	AAC 25	8	23.5	23.5	60.57	671.44	12.63	598.82	65.72	6.90	59.70
15	1st day	AAC 25	12	23.5	23.5	51.81	569.41	3.91	507.95	52.88	8.58	59.39
25	2nd day	AAC 25	7	23.5	23.5	60.51	919.87	5.27	836.00	77.09	6.77	58.04
25	2nd day	AAC 25	8	23.5	23.5	60.51	920.44	5.74	836.44	77.23	6.77	57.52
20	2nd day	AAC 25	12	23.5	23.5	54.62	745.55	4.04	673.57	64.27	7.72	56.94
30	2nd day	AAC 25	10	23.5	23.5	64.08	1094.54	6.89	998.39	89.96	6.19	55.22

3.2. Photobioreactor Façade Air Defined Above The Growth Medium

An examination of the optimal solutions is in Table 2. Window type and WWR were similar as in Alternative 1. WWR varies between 15% and 30% in both PBR with algae concentration on day one and PBR with day two algae concentration. When examining the solution with the highest UDI value (70.16%) among the optimum solutions, it has the biggest WWR and PBR with the highest algae concentration. However, since the energy consumption of this solution is too high, it was well below the desired value in the fitness function calculation. Although the daylight and thermal performance of the building meet the desired values, the energy consumption is not at the desired level. These cases show that as the WWR increases, energy consumption increases to provide thermal comfort in the interior. When looking at the solution with the lowest EUI (399.17 kWh/m^{2}y) and TCV (2.69%) among the optimal solutions, it could not provide the desired value in UDI due to its low WWR. As a result, small window sizes minimize energy consumption, while larger window sizes maximize visual comfort. As can be seen, the sizing of the window reveals contradictions between the two performances. Hence, determining the design according to the fitness function makes it possible to make better choices.

The ideal heating-cooling set point values were both 23.5°C. When the wall type is examined, while the aerated concrete option is common in the first alternative, the brick with a higher thermal capacity has emerged in the second alternative. When considering the wall thickness, options with less thickness are seen compared to the first alternative. While insulation thicknesses vary between 3 cm and 10 cm, the most common choice is 3 cm of the rockwool.

Table 2. Alternative 2- Pareto optimal solutions

Window-to-Wall ratio (%)	Window Types	Wall Types/ Thickness (cm)	Insulation Thickness (cm)	Cooling Set Point (°C)	Heating Set Point (°C)	UDI (%)	EUI (kWh/ m^{2}y)	TCV (%)	Cooling (kWh/ m^{2}y)	Heating (kWh/ m^{2}y)	Lighting (kWh/ m^{2}y)	Fitness Function
20	1st day	AAC 10	4	23.5	23.5	62.18	739.85	6.38	666.98	65.65	7.23	67.07
20	1st day	Brick 17.5	3	23.5	23.5	62.18	741.43	7.44	668.07	66.13	7.23	65.93
25	1st day	AAC 17.5	3	23.5	23.5	65.72	911.87	10	827.23	78.71	5.94	64.76
25	2nd day	Brick 25	8	23.5	23.5	62.96	916.90	6.25	832.32	77.55	7.03	63.98
20	2nd day	Brick 17.5	3	23.5	23.5	58.72	744.63	4.78	672.13	64.76	7.74	62.92
25	2nd day	Brick 25	3	23.5	23.5	62.96	920.14	7.79	934.94	78.16	7.04	62.31
15	1st day	Brick 17.5	8	23.5	23.5	54.96	569.18	4.33	507.77	52.90	8.56	61.69
30	2nd day	Brick 25	5	23.5	23.5	65.37	1092.26	9.17	995.72	90.65	5.89	60.45
30	1st day	Brick 17.5	5	23	23.5	65.99	1032.55	15.26	934.92	92.18	5.45	56.70
15	2nd day	Brick 15	8	23.5	23.5	50.97	571.82	3.62	510.78	52.01	9.04	55.79
10	1st day	Brick 15	7	23.5	23.5	44.43	399.17	2.69	347.93	40.52	10.72	50.41
95	9th day	AAC 10	5	23.5	23.5	70.16	4038.38	11.15	3763.50	269.3	5.53	-8.78

3.3. Comparison of Photobioreactor Façade and Existing Building

Comparisons of two alternative PBR façades and the existing building are in Tables 3 and 4. Examining optimal solutions indicates similarities between alternative façade proposals regarding WWR and window type. For PBR with day one algae concentration, the WWR ranges between 15-30% for both façade proposals. On the other hand, there are different optimal values for PBR with algae concentration on the second day. Among the options balanced with the fitness function, the UDI decreased in the best choice of Alternative 1 compared to the current situation, while the UDI improved in Alternative 2. In other words, the position where the WWR is 20% is not a good option in terms of UDI in Alternative 1 compared to the current situation. In comparison, splitting the PBR in Alternative 2 with the definition of air above the growth medium allows more light to pass indoors, therefore showing better results than in Alternative 1 in terms of UDI.

EUI optimization shows very similar results in the cases of Alternative 1 and Alternative 2 with the same configuration. When the energy usage density of the existing building is examined, the total EUI value per m^2 was found to be 1751.22 kWh/m^{2}y. Both façade proposals provided improvements ranging from 37.48% to 67.48% and 37.63% to 67.50%, respectively, compared to the current situation.

TCV values are below 10% in all proposals. While the number of uncomfortable hours during the year is 14.70% in the current situation, the number of uncomfortable hours decreases by 2.07-10.79% in Alternative 1, which is full of growth medium. The improvement varies between 0.44-11.21% in the façade proposal, which is 80% full.

Table 3. Comparison of Alternative 1 and existing building

Window-to-wall ratio %)	Window types	UDI (%)	Improvement (%)	EUI (kWh/m^{2}y)	Improvement (%)	TCV (%)	Improvement (%)
20	1st day	60.57	1.14	740.46	57.72	5.74	8.96
20	1st day	60.57	1.14	740.99	57.69	6.06	8.64
25	1st day	65.12	3.41	912.99	47.87	8.81	5.89
25	1st day	65.12	3.41	868.94	50.38	10.67	4.03
25	1st day	65.12	3.48	913.43	47.84	9.39	5.31
20	1st day	60.57	1.14	671.44	61.66	12.63	2.07
15	1st day	51.81	9.90	569.41	67.48	3.91	10.79
25	2nd day	60.51	1.20	919.87	47.47	5.27	9.43
25	2nd day	60.51	1.20	920.44	47.44	5.74	8.96
20	2nd day	54.62	7.09	745.55	57.43	4.04	10.66
30	2nd day	64.08	2.37	1094.54	37.50	6.89	7.81
30	1st day	66.26	4.55	1086.82	37.94	12.15	2.55

Table 4. Comparison of Alternative 2 and existing building

Window-to-wall ratio (%)	Window types	UDI (%)	Improvement (%)	EUI (kWh/m^{2}y)	Improvement (%)	TCV (%)	Improvement (%)
20	1st day	62.18	0.47	739.85	57.75	6.38	8.32
20	1st day	62.18	0.47	741.43	57.66	7.44	7.27
25	1st day	65.72	4.01	911.87	47.93	10	4.74
25	2nd day	62.96	1.25	916.90	47.64	6.25	8.5
20	2nd day	58.72	2.99	744.63	57.48	4.78	9.98
25	2nd day	62.96	1.25	873.21	50.14	8.88	5.89
25	2nd day	62.96	1.25	920.14	47.46	7.79	6.99
15	1st day	54.96	6.75	569.18	67.50	4.33	10.46
30	2nd day	65.37	3.66	1092.26	37.63	9.17	5.63
30	1st day	65.99	4.28	1032.55	41.04	15.26	0.44
15	2nd day	50.97	10.74	571.82	67.35	3.62	11.21

4. CONCLUSIONS

Simulation-based optimization studies, which provide fast and accurate design guidance to architects, are frequently used to improve the benefits of buildings and seek a balance between conflicting building performance goals. Hence, this study investigated the effect of a nature-based PBR element on the building façade regarding the energy consumption and thermal-visual comfort of an office building. This study analyzed two different PBR façade models for the south façade of an existing office building in İzmir. Optimization results of the proposed PBR integrated façade systems generally showed a better performance than the current design. The shading effect of the algae medium in the PBR filtered out excess daylight; thus, it minimized the visual comfort problems that may occur because of sunlight. Hence, the amount of energy required for lighting reduces. The PBR façades also regulated the temperature distribution in the interior, consequently improving the thermal comfort conditions. In summary, integrating an innovative system such as PBR into the building envelope positively impacts building performance, and it will be an important step towards achieving the goals for a more sustainable built environment. Evaluating the contribution of the effects of the PBR system in the future is possible by examining the cost, life cycle analysis, and environmental performance, besides looking at thermal and visual performances.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

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