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Original Research Article

Energy Performance Optimization of Photobioreactor Façades in Commercial Buildings in Hot-Arid Climates

(Case Study: Commercial Building in Qom, Iran)

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Abstract

Problem statement: Over recent decades, environmental crises driven by escalating greenhouse gas emissions have increasingly steered the attention of architects and urban planners toward sustainable design and energy-efficient strategies. Among the emerging innovations in this domain is the integration of microalgae-based photobioreactors into building façades.

Research objective: This study aims to evaluate the change in annual energy consumption intensity (kWh/m²) of a commercial building located in the hot-arid climate of Qom by applying a photobioreactor façade system and comparing its performance with that of a reference glass façade.

Research method: The study adopts a descriptive–analytical approach supported by energy simulation. After reviewing theoretical foundations, relevant photobioreactor technologies, and international case studies, a representative commercial building was modeled. Its annual energy consumption under four façade configurations—single glazing, double glazing, single-skin photobioreactor, and double-skin photobioreactor—was simulated using DesignBuilder software and Qom's climatic data. Additionally, a sensitivity analysis was conducted on microalgae suspension transparency, the ventilation rate within the cavity of the double-skin system, and window thermal transmittance.

Conclusion: The simulation results demonstrate that replacing conventional glazing with photobioreactor panels—particularly the double-skin configuration—significantly reduces annual energy consumption, decreasing from 272. 58 to 175. 88 kWh/m². The double-skin system also moderated thermal variations across different orientations. Sensitivity analysis indicates that the energy performance of the double-skin photobioreactor façade is predominantly influenced by microalgae suspension transparency and cavity ventilation rate, whereas variations in the window U value had minimal effect on overall energy consumption. The findings are specific to the climatic conditions of Qom and the modeling assumptions applied in DesignBuilder; therefore, further research is needed to evaluate applicability in other climatic contexts.

Keywords: *Bioclimatic Design, Photobioreactor Façade, Hot-arid Climate, Commercial Building, Thermal Comfort.*

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Introduction

Buildings and urban infrastructure are significant energy consumers throughout their lifecycle, including both construction and operational phases. Global climate change and rising temperatures have further intensified building energy demands, leading to a surge in cooling requirements in many parts of the world (Bazazzadeh et al., 2021). According to the International Energy Agency (IEA), the building sector accounts for an average of 30% of global energy consumption and 26% of greenhouse gas emissions (Largest sectors in final consumption in Iran, 2023). Consequently, recent research has focused on developing computational approaches to understand and mitigate energy consumption within the built environment (Taylor & Bergés, 2014). Developing precise models to predict building energy performance is essential, as it leads to reduced operational costs and enhanced sustainability. Innovations in this industry must be designed not only to minimize energy use during operation but also to mitigate the overall environmental footprint of buildings.

To date, various strategies have been proposed to curb energy consumption. Passive design, such as optimizing building envelope parameters and window-to-wall ratios, can reduce energy consumption by up to 33% (Gondal et al., 2021). Specific technologies, such as underfloor air distribution (UFAD) and the use of double-glazed windows, have shown promising results in improving energy efficiency (Akram et al., 2022). Since the majority of thermal loss occurs through the building envelope (Chayaamor-Heil&Hannachi-Belkadi,2017),leveraging these surfaces is crucial for energy conservation. In this context, the integration of innovative envelopes—specifically microalgae-based bio-facades—has emerged as a pioneering solution. Utilizing microalgae photobioreactors (PBRs) in building facades provides shading and thermal insulation, which effectively reduces thermal loads and subsequent energy demand (Yaman et al., 2021; Negev et al., 2019). Recent modeling studies indicate that microalgae facades are capable of nearly eliminating cooling demand and substantially reducing heating demand in warm climates (Girard et al., 2023; Martokusumo et al., 2017). This research investigates the impact of photobioreactor panels on reducing annual energy consumption and improving thermal comfort in commercial buildings located in hot-arid climates.

Literature Review

Research on the integration of microalgae into building envelopes indicates that this technology can significantly reduce energy consumption and carbon emissions while providing complementary environmental benefits, such as carbon dioxide (CO_2) sequestration and biomass production. At a practical level, a case study of a commercial building in Giza demonstrated that replacing traditional facades with photobioreactor panels could reduce electricity consumption by 45–50%. This system also showed moderate social acceptance (50–60%), although concerns regarding initial costs and maintenance remain (Hanafi, 2021). From an economic perspective, comparing PBR facades with photovoltaic (PV) cells reveals that while PV systems have a shorter payback period (16 years compared to 24 years), PBR panels are more profitable in the long term and offer superior environmental advantages, particularly in water-scarce regions (Biloria & Thakkar, 2020). Feasibility studies further suggest that envelope-integrated PBRs enhance daylight transmission, shading, thermal performance, and indoor air quality, alongside their potential for biofuel production (Kim, 2013). A significant body of research focuses on cooling load reduction and climatic impacts, emphasizing improved comfort in hot-dry and Mediterranean climates (Negev et al., 2019; Yaman et al., 2021). PBR facades have been shown to significantly outperform single and double-glazed systems, with their efficiency being highly sensitive to aperture size and algae density (Talaei et al., 2022). Furthermore, validated modeling suggests that cooling demands can be almost eliminated in certain scenarios (Girard et al., 2023). In the Iranian context, reviews of bio-based envelopes indicate that algae-integrated facades perform optimally on sunfacing orientations in hot climates; however, challenges such as increased building dead loads and complex maintenance procedures persist (Bastanfard, 2018). Additionally, the application of microalgae shading systems in Tehran has demonstrated effective radiation moderation and improved indoor comfort (Ghaemi, 2021).

Moreover, adaptive facades can reduce the carbon footprint of construction by minimizing mechanical components, weight, and building height (Borschewski et al., 2023), while green walls significantly lower cooling loads during extreme heat (Ramadhan & Mahmoud, 2023). Other studies have focused on optimizing parameters such as lighting, hydrodynamics, mixing, and scalability (Zhaoetal.,2022;Shankaretal.,2022),aswellasevaluating typologies (Sukačová et al., 2021) and integration with double-skin facades (Elmalky & Araji, 2023). Research has also expanded into carbon capture capabilities (Haghir et al., 2020; Villalba et al., 2023), advanced climatic simulations (Pozzobon, 2024), and functional applications such as domestic hot water supply and enhanced lighting (Nguyen et al. 2025).

Despite promising evidence regarding energy efficiency and carbon footprint reduction, there remains a critical need for quantitative assessments within specific Iranian climatic contexts, as well as analyses of life cycle assessments (LCA), maintenance costs, water consumption, and real-world user acceptance. By focusing on local climatic conditions and employing a computational modeling framework, this study seeks to investigate the impact of this technology on energy reduction within a localized and adapted context.

Theoretical Framework

- **Carbon-neutral fuels**

Carbon-neutral fuels are energy carriers that do not result in a net increase of atmospheric CO_2 over their life cycle. More precisely, the CO_2 released during consumption is offset by the CO_2 absorbed during the production phase (Li et al., 2022). Three primary pathways are identified:

a. Biofuels, which rely on the balance between carbon uptake and release during biomass growth.

b. Synthetic fuels, produced from electrolytic hydrogen and captured carbon dioxide (Janaki et al., 2024).

c. Renewable electricity–based pathways, in which hydrogen is generated via renewable energy and subsequently used directly in fuel cells or converted into biofuels (Galimova et al., 2023).

Despite their significant potential, challenges such as the need for efficient catalysts, dedicated infrastructure, and high production costs continue to hinder large-scale deployment (Myers, 2022).

- **Energy optimization in commercial buildings**

The building sector accounts for a substantial share of global energy consumption—approximately 40% worldwide (Akram et al., 2022). In commercial buildings, heating, ventilation, and air-conditioning (HVAC) systems typically represent the largest portion of energy use (Pease et al., 2021).

Effective optimization frameworks include:

a. Integrated energy design in early project stages, supported by energy modeling to compare alternative scenarios (Ali et al., 2021).

b. Multi-objective optimization, considering energy demand, economic cost, and environmental impacts simultaneously (Jun & Fei, 2024).

c. Data-driven and AI-based adaptive control systems, which adjust operations according to climatic conditions and occupancy patterns (Sonta et al., 2021).

In Iran, where electricity generation heavily depends on natural gas, reducing building electricity demand effectively translates into lower gas consumption and reduced greenhouse gas emissions (IEA, 2022).

- **Microalgae facades**

Integrating bio systems into building envelopes—commonly referred to as living architecture—has emerged as an effective strategy for reducing energy loads and improving environmental quality. Living facades (composed of plants or microorganisms) provide not only physical benefits such as shading, insulation, and moisture exchange but also offer the potential for biomass production and carbon sequestration (Salisbury et al., 2023).

Microalgae photobioreactors, representing the new generation of living facades, have been reported to reduce heating and cooling loads, generate biomass, and lower greenhouse gas emissions (Talaei & Prieto, 2024). Due to their rapid growth rate and high photosynthetic efficiency, microalgae are strong candidates for active building facades.

Optimal microalgae growth depends on several parameters, including light intensity and photoperiod, temperature (typically 20–30°C depending on the species), nutrient availability, pH (commonly between 7–9), CO_2 concentration, salinity, and controlled mixing and aeration (Wang et al., 2012; Zhang et al., 2022; Gouveia, 2011). Species selection is performed based on biomass yield, environmental tolerance, and the intended end product (Hosseini Tafreshi & Shariati, 2009; Pistocchi et al., 2024).

- **Cultivation systems and building integration**

Photobioreactors —whether tubular, flat-plate, columnar, helical, or biofilm-based— provide stable and controllable growth conditions and exhibit lower contamination risks and performance fluctuations compared to open-pond systems (Sukačová et al., 2021). Key design criteria for façade-integrated PBRs include:

a. Light management (intensity, distribution, and prevention of light oversaturation),

b. Thermal management, considering that up to 95% of absorbed radiation may be converted into heat, which necessitates efficient heat dissipation and potential heat recovery,

c. Mass mixing to avoid sedimentation and dark zones,

d. CO_2 supply, often provided through return air from HVAC systems, alongside nutrient distribution pathways and maintenance accessibility (Sedighi et al., 2023; Yaman et al., 2021).

The choice between flat-plate and tubular PBR configurations is typically guided by factors such as daylighting conditions, temperature control, and architectural integration requirements (Arora et al., 2024).

Research Methodology

This research is categorized as applied in terms of its objective and descriptive-analytical in terms of its nature. The primary aim is to investigate the impact of microalgae-integrated photobioreactor (PBR) facades on the reduction in energy consumption in commercial buildings. A mixed-methods approach was adopted, encompassing a comprehensive literature review, case study analysis, and numerical modeling using energy simulation software. In the theoretical phase, scientific fundamentals and existing literature were reviewed from reputable sources, alongside climate-responsive design standards and completed projects. Subsequently, international case studies of buildings featuring PBR facades were analyzed to establish the design framework for the baseline model. For the quantitative phase, a commercial building situated in a hot-arid climate (Qom, Iran) was designed and modeled using DesignBuilder software. This software, which utilizes the EnergyPlus simulation engine, enables precise analysis of cooling and heating loads as well as total energy consumption. To isolate the impact of the facade type, four distinct scenarios were defined:

1. Single-pane glazing (Baseline),
2. Double-pane glazing,
3. Single-skin photobioreactor facade,
4. Double-skin photobioreactor facade.

In all scenarios, climatic data, building dimensions, occupancy types, construction materials (for the roof, floors, and walls), and operational schedules were kept constant. This approach ensures that the energy performance variations are strictly attributable to the facade configuration. The primary performance indicators evaluated include annual energy consumption, percentage change relative to the baseline, and the effectiveness of the facade in mitigating greenhouse gas emissions.

- **Field study**

The city of Qom is situated within a distinctly arid and extremely hot desert climate, characterized by very limited annual precipitation 4 (less than 250 mm), extremely high summer temperatures (often exceeding 40°C), pronounced diurnal temperature variations, high rates of evaporation and transpiration, sparse vegetation cover, and shallow, saline soils. These conditions highlight the necessity for climate-adapted architectural design strategies tailored to hot-arid environments.

In such circumstances, recommended design approaches include the adoption of compact and inward-oriented building forms with central courtyards , low-rise structures with a limited number of stories to minimize heat exchange, the use of indigenous materials with high thermal mass (such as adobe and brick), and the application of light-colored surfaces to reflect solar radiation. Openings should be small, restricted, and predominantly oriented along the north–south axis. Traditional architectural solutions also incorporate features such as “orsi ” and lattice windows, shading devices, verandas , and tall openings to moderate direct sunlight penetration and enhance natural ventilation during hot periods. Collectively, these strategies enhance thermal comfort, reduce energy consumption, and increase the building’s overall adaptability and resilience to harsh environmental conditions.

- **Site and project description**

The study site, covering an area of 3,650 m², is located in Qom City, within Neighborhood Four of Pardisan Town, along Abutalib Boulevard. The plot has approximate dimensions of 60 × 60 meters and is oriented with a rotation of about 15 degrees toward the southeast. The surrounding land uses and urban context of the site, according to the detailed urban development plan, are illustrated in Fig. 1, while its current physical condition is presented in Fig. 2.

In the design of this commercial building located in a hot-arid climate, principles of climate-responsive architecture were employed with the aim of optimizing energy consumption, ensuring occupants’ thermal comfort, and mitigating adverse environmental impacts. The overall building form was selected as a square geometry, a configuration traditionally observed in the vernacular architecture of Iran’s hot and arid regions. This compact form, characterized by a low surface-to-volume ratio, effectively reduces heat exchange with the surrounding environment and prevents unnecessary energy loss (Fig. 3).

The architectural design of the photobioreactor (PBR) façade was conceived based on the simultaneous pursuit of two primary objectives: first, to establish a passive system capable of effectively contributing to the reduction of building energy consumption, and second, to maintain the spatial quality, aesthetic appeal, and structural integrity of the façade. To achieve these goals, several key design principles were considered,

Fig. 1. Site Location. Source: Source: Authors.

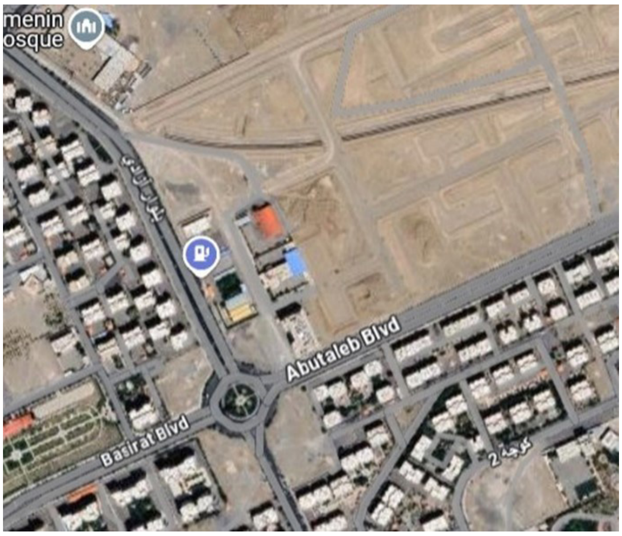

Fig. 2. Existing Site Condition. Source: maps.google.com

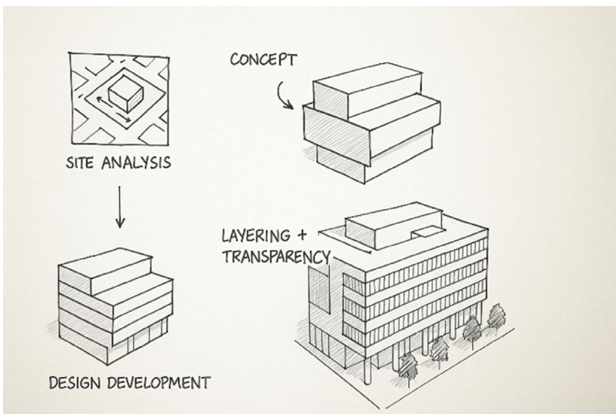

Fig. 3. Concept Sketch. Source: Authors.

including harmonization with the building's façade modulation, adaptability to climatic conditions, ease of maintenance and repair, and compatibility with interior daylighting requirements. In selecting the overall form and arrangement of the PBR panels, an effort was made to strike a balance between the bioreactive performance of the photobioreactor and the architectural imperatives of the façade. Instead of employing complex or movable systems, flat-plate panels with a regular and modular arrangement were utilized, allowing for straightforward integration into the commercial building's façade structure. The specific system implemented in this project is a flat-plate photobioreactor. Detailed plans and other design documents are presented in Fig. 4.

- **Modeling and software parameters**

To accurately assess the impact of integrating photobioreactor (PBR) panels into the building façade on energy performance, energy simulations were performed for the third floor, which serves a commercial function. Given the extensive floor plan and to achieve higher precision, the energy analysis of the interior zones was conducted separately for the four cardinal orientations (North, South, East, and West); this approach allows for a detailed investigation into how geographical orientation influences the system's efficiency (Fig. 5).

Within the simulation framework, four distinct exterior wall configurations were evaluated. To isolate the effects of the façade type, all other building elements—including the roof, floor, internal partitions, and HVAC systems—were kept constant across all scenarios. This ensures that the obtained results are solely attributable to variations in the exterior façade design. The key modeling parameters are detailed in Table 1. The weather data file used in this study is of the TMYx type, compiled based on climatological data from 2009 to 2023. A TMYx file represents a synthetic year, constructed by selecting individual months from historical records whose climatic patterns most closely correspond to the long-term average for each location. The dataset was obtained from the reputable OneBuilding website and corresponds to WMO Region 2 – Asia: Iran (2025).

Weather data file were imported directly and unaltered into the simulation software—without any preprocessing, smoothing, additional averaging, or structural modification. Therefore, all analyses and results presented in this research are entirely based on the raw TMYx data .Given the relatively large project footprint and the need for precise comparative assessment, each façade orientation (north, south, east, west) was modeled independently. The study space is located on the third floor of the commercial complex. The main simulated zone follows the operational parameters defined by ASHRAE Standard 90 for commercial spaces: working hours from 09:00 to 21:00, mechanical heating and cooling systems, and inclusion of lighting and electrical equipment loads.

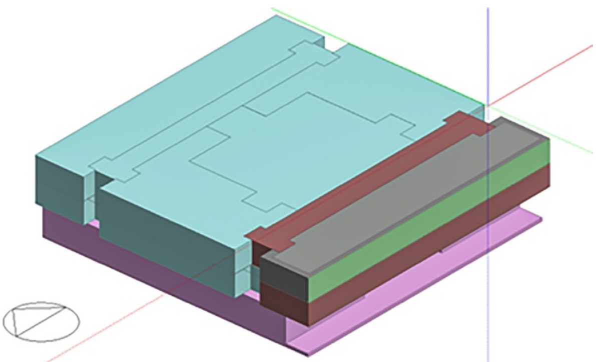

Fig. 5. Modeling in DesignBuilder. Source: Authors.

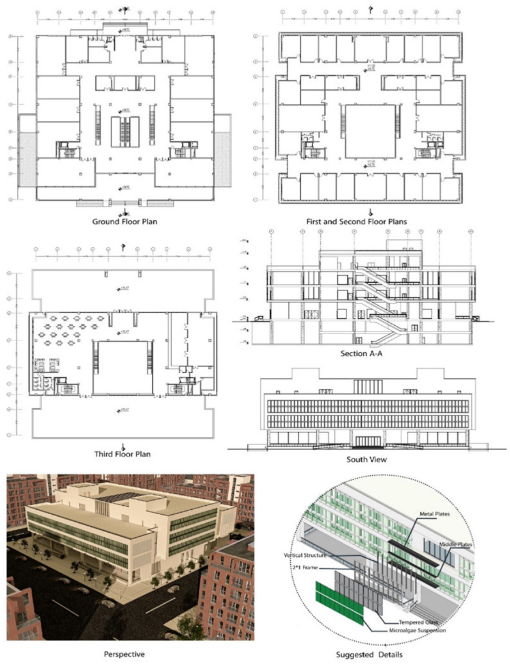

Fig. 4. Architectural Plans and Design. Source: Authors.

Table 1. Key Modeling Parameters. Source: Authors.

Location	Material Name	Thickness (m)	U-Value (W/m²·K)
	Materials (Thermal Transmittance Coefficient)		
External Wall	Lightweight concrete block with exterior brick and interior gypsum plaster	0.3	0.351
Internal Wall	Clay block with gypsum plaster	0.2	1.59
Roof	Concrete roof with polystyrene insulation	0.35	0.486
-	Activity	-	-
Space Type	Commercial Space	-	Value
Activity Pattern	Occupancy Rate	Persons per 100 m²	16
	Operating Hours	-	09:00–22:00
Environmental Temperature Control	Heating	-	20
	Heating Setback	-	13
	Cooling	-	26
	Cooling Setback	-	32
-	Openings	-	-
Dimensions	Window-to-Wall Ratio	Percent	70
	Window Height	m	2
	Sill Height / Distance from Floor	m	0.4
-	HVAC System	-	-
System Type	Four-pipe fan coil unit (heating-cooling)	-	-
Ventilation	Mechanical	-	-
Infiltration Rate	ACH	-	0.475
Operating Schedule	Cooling	First six months of the year, 08:00–23:00	
	Heating	Second six months of the year, 08:00–23:00	
	Mechanical Ventilation	Every day, 08:00–22:00	

Adjacent spaces were modeled as adiabatic volumes, meaning spaces without thermal exchange to ensure boundary condition integrity. The main zone dimensions were specified as 60 meters in length, 10 meters in width, and 4 meters in height. The external walls (except the façade under study), along with the roof and floor assemblies, were modeled with standard thermal insulation to obtain an accurate evaluation of the façade's effect on building energy consumption and to ensure scientific validity in comparative analysis. The overall heat transfer coefficients (U-values) of the façade system in four design scenarios, as derived from simulation outputs, are presented in Table 2.

In the single-glazed façade scenario, a simple single-pane glass window was modeled, covering approximately 70% of the wall surface area—equivalent to roughly 25% of the floor area of the analyzed zone. In the double-glazed façade scenario, the frame specifications and opening dimensions remained constant, with only the transparent section replaced by a double-glazed unit featuring an air gap of 13 mm between the glass panes. The photobioreactor (PBR) façade consists of glass panels mounted within metal frames. Since the software DesignBuilder does not natively recognize the biological or thermophysical properties of microalgal suspensions, their thermal characteristics were defined based on values extracted from previous studies. According to Fu et al. (2021), the thermal conductivity of a microalgae suspension at ambient temperature is approximately 0. 55 W/m·K. Similarly, research by Verso et al. (2019) reported that the solar absorption coefficient of microalgal cultures ranges between 0. 70 and 0.85, indicating that 70–85% of incident solar radiation is absorbed.

To represent this material within the simulation, it was modeled as an equivalent water-based medium with a thickness of 7 cm, density of 1,050 kg/m³, thermal conductivity of 0.55 W/m.K, solar absorptance of 0.7, and specular reflectance of 0.5. Other main simulation parameters are summarized in Table 1.

The double-skin façade configuration comprised PBR panels as the external skin (covering 100% of the wall area), an intermediate ventilated cavity of 0.70m width, and an inner layer consisting of a brick wall combined with glazed openings covering 70% of the internal wall surface. To ensure appropriate thermal and airflow performance of the double-skin façade, air circulation vents were incorporated every 4 meters at both the top and bottom of the façade to facilitate natural ventilation within the cavity.

Findings and Discussion

- **Impact of façade systems on energy consumption**

The simulation results reveal that the choice of façade system has a significant influence on determining building energy performance. Overall, advanced façade technologies—such as algae photobioreactor systems and double skin façades—demonstrated notably higher efficiency in reducing energy consumption, particularly on the southern and eastern orientations. This enhanced performance is primarily attributed to their superior capacity for solar energy absorption and storage, as well as their improved thermal insulation characteristics.

In contrast, conventional single layer glass façades exhibited significantly higher energy demand due to increased thermal losses. The integration of a double skin photobioreactor façade reduced the average annual energy consumption from 272.58 kWh/m² to 175.88 kWh/m². A detailed summary of the simulation outcomes is provided in Table 3.

According to Table 3, the double-skin photobioreactor façade exhibited the lowest energy consumption among all façade configurations. On average, its energy consumption was approximately 35% lower than that of the conventional single-layer glass façade.

A comparative analysis of the results, along with the calculation of energy variations across different orientations, revealed that the double-skin photobioreactor façade showed the smallest variation in energy consumption among the various orientations. This indicates enhanced thermal stability across different orientations.

Furthermore, a more detailed comparison of the reduction in energy consumption for each geographical orientation demonstrated that this façade system has the greatest impact on reducing energy consumption on the southern façade of the building. The detailed results of energy consumption reduction are presented in Table 4.

The simulation results indicate that the differences in thermal transmittance (U-value) among the four façade scenarios are not sufficient on their own to explain the substantial variation in energy consumption. This is primarily because the U-value represents only the conductive heat transfer through the envelope, whereas in hot and arid climates, the dominant portion of cooling and heating loads arises from solar radiation and radiative heat gains.

Therefore, even when the photobioreactor façades do

Table 3. Energy Consumption Simulation Results (kWh/m²). Source: Authors.

Direction	Double-Skin PBR	PBR	Double-Glazed Glass	Single-Glazed Glass
North	178.5	199.86	240.65	250.14
South	179.18	215.79	292.64	305.31
East	172.37	201.91	261.29	270.52
West	173.47	196.72	255.34	264.34

Table 4. Energy Use Reduction (%). Source: Authors.

Orientation	Double-Glazed Glass	PBR Facade	Double-Skin PBR
North	3.8	20.1	28.65
South	4.13	29.35	41.3
East	3.41	25.39	36.28
West	3.41	25.57	34.38
Average	3.69	25.1	35.15

not exhibit a significantly lower U-value compared to conventional double glazing, they considerably limit heat transfer into the interior space due to their markedly reduced solar heat gain coefficient and the absorption of a large portion of incident solar radiation by the microalgae-containing fluid. This mechanism is clearly reflected in the simulation outcomes as a notable reduction in overall energy consumption.

- **Impact of façade design on thermal comfort**

To evaluate the thermal comfort conditions of indoor spaces, the Predicted Mean Vote (PMV) index identified as a principal indicator in ASHRAE Standard 55 was employed. This index, developed by Fanger, represents the average thermal sensation of occupants on a scale ranging from − 3 (cold) to + 3 (hot). The optimal comfort range is defined between −0. 5 and +0.5, while the acceptable range extends from − 1 to +1.

In this study, to assess the thermal comfort performance of the proposed design scenarios, PMV values for the southern façade were extracted from the simulation software for four design alternatives. The results are presented as monthly graphs in Fig. 6.

The analysis of the PMV index revealed that the type of façade plays a critical role in determining annual thermal comfort conditions. The conventional single-glazed façade generated the highest levels of discomfort, providing virtually no periods within the desirable comfort range. Replacing it with double glazing resulted in moderate improvement; however, its performance during summer remained inadequate.

The single-skin photobioreactor façade offered noticeably better conditions, particularly in winter, with more than 40% of the hours falling within the comfort zone. The best performance, however, was achieved by the double-skin façade with an external photobioreactor layer. Through its combined effects of shading, controlled solar absorption, and an insulating air cavity, this configuration provided the highest thermal stability and the lowest discomfort levels, indicating substantial potential for reducing both heating and cooling energy demands.

- **Model validation**

Given that the photobioreactor façade technology has thus far been implemented in other regions like the BIQ building in Hamburg, Germany, a direct comparison between the findings of this research and real-world data from these projects was not feasible due to substantial differences in climate, building function, and operational patterns. Therefore, the simulation model was validated using reference scenarios and internationally recognized standards. To this end, all models were developed in DesignBuilder using the EnergyPlus engine and were defined based on the default parameters of ASHRAE Standards 55 and 62.1.

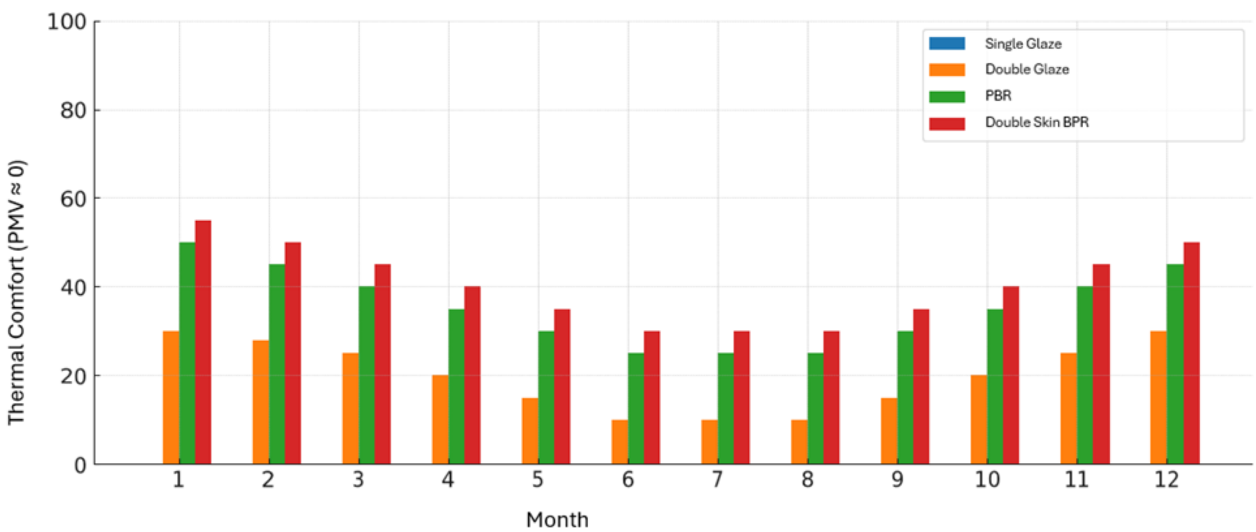

Fig. 6. Annual Thermal Comfort Chart. Source: Authors.

Operational conditions, ventilation rates, internal loads, and occupant schedules were all configured according to the software's predefined templates.

Additionally, to ensure the reliability of the energy simulation model, the results were compared with a reputable reference study on microalgae windows. The reference study, titled "Algae Windows: A Novel Approach Towards Sustainable Building Design and Energy Conservation" (Nguyen et al. 2025), simulated the thermal performance of a conference room in Vietnam measuring 14 × 6 × 3. 5 meters under three window scenarios: single glazing, double glazing, and microalgae glazing.

First, the geometry of the model—including wall dimensions and orientation, as well as the number, position, and size of the windows (10 windows, each measuring 1. 5 × 1. 3 meters)—was precisely reconstructed in DesignBuilder in accordance with the reference study. Subsequently, the thermal and optical properties of the envelope elements, including the U-values of the walls, roof, and floor, as well as the U-values and visible transmittance of the three window types, were applied exactly as reported in the article.

Operational settings—including the number of occupants (11 persons at 70 W sensible heat per person), lighting and equipment loads (7 W/m²), infiltration rate (05 ACH), comfort temperature range (25–26°C), and system operating hours (6:00 to 17:00)—were also matched with the reference model. Annual simulations were then performed for the three window scenarios, and annual cooling loads were extracted. According to the reference study, the annual cooling loads for single glazing, double glazing, and microalgae glazing were 30,820. 1 kWh, 29,322. 9 kWh, and 27,118. 7 kWh, respectively. The corresponding results obtained from this study's simulations were 28,792. 8 kWh, 27,339. 1 kWh, and 26,597. 9 kWh. To assess simulation accuracy, two error indices—NMBE and CV(RMSE)—were calculated. The NMBE value was −0.0509, indicating a slight negative bias, meaning the model's predictions were, on average, marginally lower than the actual values. The CV(RMSE) was found to be 0.0570, reflecting the standard deviation of the error relative to the mean of the observed data.

- **Sensitivity analysis of key design parameters**

To evaluate the robustness of the simulation outcomes with respect to underlying design assumptions, a sensitivity analysis was conducted on the energy performance of the double-skin photobioreactor façade. The analysis focused on three key parameters: (1) the transparency of the microalgae suspension, (2) the cavity ventilation rate between the two skins, and (3) the U-value of the glass panels.

- **Sensitivity to Microalgae Suspension Transparency**

The sensitivity analysis revealed that variations in the concentration of the microalgae suspension throughout its growth cycle have a noticeable impact on the annual energy consumption of the case-study building. In the energy model, the suspension layer was represented as an equivalent 7-cm-thick water layer with a density of 1050 kg/m³ and a thermal conductivity of 0.55 W/mK. The three growth phases—initial cultivation, mid-growth, and harvest phase—were modeled solely through adjustments to the effective optical properties of the photobioreactor layer. The solar absorptance coefficient was set to 0.55, 0. 70 (base case), and 0.85, respectively. During the initial cultivation stage, corresponding to low microalgae concentration and high suspension transparency, increased solar transmission through the façade led to higher annual cooling loads. Consequently, annual energy consumption reached approximately 183.9, 186.4, 179.3, and 182. 1 kWh/m²·year for the north, south, east, and west façades, respectively representing an increase of approximately 3–6% compared to the base case. In contrast, during the harvest phase, increased biomass concentration and reduced transparency limited solar transmission into the building and enhanced the façade's shading effect. As a result, annual energy consumption decreased to approximately 174.9, 173.8, 167.2, and 166. 5 kWh/m²·year for the north, south, east, and west orientations, respectively, corresponding to a reduction of about 1–5% relative to the base scenario.

Overall, the findings indicate that transitioning from the initial cultivation phase to the harvest phase can result in a 5–7% variation in annual building energy consumption. This sensitivity is more pronounced in façades with greater solar exposure, particularly the east and west orientations.

- **Sensitivity to Cavity Ventilation Rate**

To assess the influence of cavity ventilation between the two façade skins, the base case ventilation rate was set at 0. 5 ACH, representing minimal ventilation through lower and upper openings.

Two additional scenarios with ventilation rates of 1 ACH and 5 ACH were then analyzed. The results showed that increasing ventilation from 0.[5] to 1 ACH reduced total energy consumption by 1.81% (north), 3.07% (south), 1.34% (east), and 4.38% (west). When ventilation was increased to 5 ACH, energy consumption decreased by 5.47% (north), 8.52% (south), 3.76% (east), and 12.02% (west).

Seasonal load analysis further indicated that while increasing cavity ventilation slightly intensified heating demand during the cold season, the substantial reduction in cooling loads during the warm season dominated overall performance, leading to a net reduction in annual energy consumption.

- **Sensitivity to Glass Thermal Transmittance (U-value)**

The sensitivity analysis of the glass panel's thermal transmittance demonstrated that even a relatively large variation (±20%) in the U-value of both glass layers resulted in only minor changes in overall building energy performance. Under this variation, the equivalent U-value of the photobioreactor panel changed from approximately 3. 05 W/m²K to a range of 2.98–3. 10 W/m²K. Consequently, the overall U-value of the double-skin façade varied only slightly—from the base value of 1. 05 W/m²K to approximately 1.04–1. 06 W/m²K. This change—less than 1% in the total façade U-value—is largely attributable to the significant thermal resistance provided by the 70-cm cavity layer. As a result, the impact on annual building energy consumption remained limited to only a few tenths of a percent.

Therefore, the findings suggest that in double-skin photobioreactor façades, energy performance is relatively insensitive to variations in glass U-value. Instead, parameters such as cavity ventilation rate and the solar absorption and transmission characteristics of the photobioreactor layer play a far more dominant role in determining overall building energy performance.

- **Economic analysis**

Despite the environmental advantages and the positive impacts of photobioreactor systems on building façades, the large-scale adoption of this technology is feasible only if it also proves economically viable. The construction cost of a closed algae façade system at the building scale is estimated at approximately 1,800 to 1,900 USD per square meter, while annual operation and maintenance expenses range from 260 to 285 USD per square meter. Consequently, the short-term economic justification of this system remains limited, and its primary value lies in long-term environmental benefits, including reduced CO_2 emissions and improved building energy performance.

Current economic assessments are largely based on experimental or simulation data, and variations in energy prices and government subsidies in Iran create a larger gap between investment costs and payback periods compared to other countries.

The economic evaluation in this study was conducted using capital budgeting methods, specifically the Net Present Value (NPV) indicator and simple payback period analysis. The key assumptions used in the calculations are summarized in Table 5.

According to the collected data, the annual revenue generated from energy savings in the first year of operation is estimated at 3,412,536,000 IRR (equivalent to approximately 2,622 USD). This indicates that even with substantial energy savings, the system faces a significant operational deficit during the first year. Assuming a 30% annual growth rate in energy-saving revenues over 20 years, the cumulative income is projected to reach approximately 1.652 million USD. In contrast, the initial capital investment required for façade implementation and subsequent maintenance amounts to about 3.387 million USD.

These results demonstrate that, despite considerable growth in energy savings, the system is unable to recover its initial capital investment within a 20-year horizon under current energy pricing conditions in Iran. Therefore, achieving full economic feasibility would require either a significant reduction in capital costs or the inclusion of supplementary revenue streams and additional economic benefits, such as biomass sales or environmental credits.

- **Biological considerations and maintenance**

Given the hot and arid climate of Qom, the selection of microalgae species was based on key criteria, including heat tolerance, salinity tolerance, and optimal pH range. Accordingly, Chlorella vulgaris and Dunaliella salina were chosen as the hypothetical microalgae species for the façade system. Their relevant biological parameters are presented in Table 6 (Wolkers et al., 2011).

The maintenance and replacement strategy for the photobioreactor units was developed based on a modular design approach, allowing each panel to be serviced independently without disrupting the operation of the overall façade system. Routine maintenance procedures include monitoring panel transparency, controlling microalgae growth, inspecting potential leakages, and performing both internal and external cleaning operations, most of which can be conducted without dismantling the panels. In the event of system failure or panel malfunction, the affected unit can be locally isolated from the circulation loop and subsequently repaired or replaced if necessary. This approach minimizes system downtime and, through the implementation of preventive maintenance practices, helps preserve both the operational lifespan of the system and the energy performance of the façade.

Conclusion

The findings of this research demonstrate that façade type has a substantial influence on building energy performance and indoor thermal comfort. The simulation results indicate that the double-skin photobioreactor façade achieved the highest level of performance across all orientations, consistently outperforming conventional façade systems, including single and double glazing. For example, on the southern façade, annual energy consumption decreased from 305. 31 kWh/m² for a single-glazed façade to 179. 18 kWh/m² with the photobioreactor double-skin system, corresponding

Table 5. Assumptions of economic analysis. Source: Authors.

Parameter	Value
Annual Energy Consumption Reduction	97 kWh/m²
Usable Building Floor Area	7000 m²
Facade Area	1632 m²
Commercial Electricity Tariff (Base)	5040 Rials (0.0038 USD)
Initial Investment Cost (per m² of facade)	1850 USD
Annual Operation & Maintenance Cost (per m²)	275 USD
Annual Electricity Price Escalation Rate	30%
Discount Rate (Cost of Capital)	25%
Analysis Lifetime	20 years

Table 6. Growth Assumptions of the Proposed Algae Species. Source: Wolkers et al., 2011.

Parameter	Chlorella vulgaris	Dunaliella salina
Maximum growth rate (day^-1)	1.5	1.2
Optimal light intensity (μmol m^-2 s^-1)	200	150
Optimal temperature (°C)	25	30
Water requirement (L/g)	2	3
CO2 requirement (mol/g)	0.02	0.03

to a 41.3% reduction. Similar reductions were observed for the northern, eastern, and western orientations, with savings of 28.65%, 36.28%, and 34.38%, respectively, compared to single glazing. Overall, the double-skin photobioreactor façade reduced annual energy consumption by an average of approximately 35% relative to a conventional single-glazed façade. This reduction—equivalent to about 97 kWh/m² annually—translates into an avoidance of approximately 46.56 $kgCO_2/m^2$ of emissions per square meter of building floor area. The sensitivity analysis revealed that the energy performance of the double-skin photobioreactor façade is strongly influenced by the transparency of the microalgae suspension and the cavity ventilation rate. In contrast, variations in the window U-value had a negligible impact on overall energy use. From a thermal comfort perspective, the results showed that the double-skin photobioreactor façade provided the highest number of comfort hours by combining effective shading, controlled solar absorption, and the insulating capacity of the air cavity. In comparison, single- and even double-glazed façades failed to maintain acceptable comfort conditions during a significant portion of the year.

Overall, the study concludes that the double-skin photobioreactor façade not only significantly enhances building energy performance by reducing annual energy demand but also enhances indoor environmental quality and thermal stability. These findings highlight the potential of advanced façade technologies as key strategies for sustainable building design, particularly in hot and arid climates. Future research should incorporate life-cycle assessment, advanced economic evaluation, daylighting performance analysis, and visual comfort studies to facilitate broader implementation of this façade system in real-world building projects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Endnotes

1.The Process of Capturing and Storing Atmospheric Carbon Dioxide
2.The Total Amount of Greenhouse Gases (Including Carbon Dioxide and Methane) That Are Generated by Our Actions
3.A Systematic Analysis of Environmental Impact Over the Course of The Entire Life Cycle of a Product, Material, Process, or Other Measurable Activity
4.Heating, Ventilation, and Air Conditioning
5.Schedules Are Used in DesignBuilder to Define: Occupancy Times. Equipment, HVAC Operation. Heating and Cooling Temperature Setpoints
6.An Open Space Surrounded by Walls or Buildings
7.Stained Glass Sash Windows
8.A Roofed Platform Along the Outside of a House, Level with the Ground Floor
9.Typical Meteorological Year Extended

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