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Bioreactive Skins: Evaluating Microalgae Façade Systems for Thermal and Daylighting Performance in Los Angeles

Yonca Yaman [1], Ayça Tokuç [1, 2], Mehmet Akif Ezan [2, 3], Gülden Köktürk [4], Zeliha Demirel [5], and İrem Deniz [6]

[1] Department of Architecture, Dokuz Eylül University, 35390, İzmir, Türkiye, yaman.yonca@ogr.deu.edu.tr; ayca.tokuc@deu.edu.tr
[2] Energy Research and Application Center (EUAM), Dokuz Eylül University, 35390, İzmir, Türkiye
[3] Department of Mechanical Engineering, Dokuz Eylül University, 35390, İzmir, Türkiye, mehmet.ezan@deu.edu.tr
[4] Department of Electrical and Electronics Engineering, Dokuz Eylül University, 35390, İzmir, Türkiye, gulden.koktuk@deu.edu.tr
[5] Department of Bioengineering, Ege University, 35040, İzmir, Türkiye, zelihademirel@gmail.com
[6] Department of Bioengineering, Manisa Celal Bayar University, 45140, Manisa, Türkiye, iremdenz@gmail.com

Abstract. Façade-integrated photobioreactors are sustainable architectural elements due to their ecological, economic, and environmental benefits. Similar in appearance and application to curtain walls, their applications as green and bioreactive windows seem promising. However, challenges in modeling building physics parameters such as daylighting and thermal control often hinder feasibility studies to research their applicability. This paper aims to propose a methodological framework to evaluate the impact of different microalgae species on occupant comfort when integrated into building façades. The study focuses on Los Angeles climate and investigates the year-round total energy consumption, lighting and thermal comfort performance of two distinct microalgae strains, *Chlorella vulgaris* and *Pseudanabaena sp.* The method involved measuring light transmittance of algal cultures in different concentrations; then using these to calculate solar heat gain coefficients and visual transmittance levels for defining photobioreactor systems for building performance simulation using Grasshopper plugins, Honeybee and Ladybug. Three distinct façade design (FD) scenarios were optimized in terms of algae density, window-to-wall ratio, wall type and thickness, insulation thickness, and heating/cooling setpoints. Results indicate that photobioreactor façades have significant potential to enhance thermal comfort, improve daylighting performance, and reduce energy consumption throughout the year. Viable alternatives exist for both strains; however, their effects differ: *Pseudanabaena sp.* demonstrated 26-44% improvement in mean thermal comfort violation (TCV) across all three façade designs compared to *C. vulgaris*, attributed to its lower solar heat gain coefficient. FD1, consisting solely of algae-integrated windows, showed better thermal comfort while hybrid designs were sensitive to the placement of algae windows. Regarding daylighting, FD3 achieved highest mean useful daylight illuminance (UDI ~47%) for both species, though with greater spatial non-uniformity. Energy performance revealed configuration-dependent optimal species selection. Sensitivity analysis revealed hierarchical parameter influence: cooling setpoint demonstrated dominant effect on both energy and thermal comfort, while window-to-wall ratio (WWR) affected daylighting the most. Optimal solutions for Los Angeles require performance-priority-specific selections: FD1 with *C. vulgaris* (10-15% concentration) for thermal comfort prioritization, FD2 with *Pseudanabaena sp.* (40-50% concentration) for energy optimization, and FD1 for daylighting maximization. This research demonstrates a comprehensive, transferable methodology that enables comparative studies while presenting design guidelines for Los Angeles PBR façade applications.

Keywords. Building energy simulation, building façades, microalgae, thermal comfort, visual comfort

1 Introduction

The building sector accounts for approximately 40% of global energy consumption and contributes significantly to carbon emissions, therefore it is a critical area for climate change mitigation. Building envelopes and especially glazing systems are the most influential elements responsible for direct heat gains and losses to or from the building. Traditional approaches to building envelope design often create trade-offs between daylighting, thermal insulation, and solar heat gain control, and requires innovative solutions that can simultaneously address multiple performance criteria.

Façade-integrated photobioreactors (PBRs) are emerging as a promising solution in sustainable building design, offering multifunctional benefits including dynamic shading, thermal regulation, carbon sequestration, and potential biomass production. Unlike static shading devices or conventional glazing systems, PBR façades can respond to environmental conditions and function as bioreactive building skins, where microalgae cultures modulate solar radiation transmission based on their growth density and concentration.

Despite growing interest in PBR façade applications, significant knowledge gaps persist in understanding how different microalgae species perform across various climate zones and façade designs. Most existing studies have focused on limited species diversity, predominantly *Chlorella vulgaris,* and have rarely provided comprehensive frameworks that simultaneously evaluate thermal comfort, visual comfort, and energy performance [1, 2]. Furthermore, the methodological challenge of accurately modeling PBR optical and thermal properties within conventional building energy simulation tools has hindered systematic performance evaluation [3].

This research investigates two distinct microalgae strains—*Chlorella vulgaris,* which has been comprehensively studied in building façade applications, and *Pseudanabaena sp.*, which has no other published research known to the authors at the time of the study. The study integrates empirical laboratory measurements with computational building performance simulation to quantify impacts on thermal comfort, daylighting quality, and annual energy consumption across three distinct façade design (FD) scenarios in Los Angeles climate conditions. The novelty of this research is comparative performance evaluation of two distinct algae species in façade applications for Los Angeles.

2 Background and literature review

2.1 Photobioreactor façades in building applications

PBRs integrated into building envelopes use biological mechanisms and simultaneously serve multiple building performance functions. PBR façades typically consist of transparent or translucent panels containing microalgae cultures in a liquid growth medium. The operating principle uses photosynthesis, where microalgae absorb light energy and carbon dioxide to produce oxygen and biomass. Thus, PBR's optical properties vary with algae concentration through the growth phase and enable adaptive response to environmental conditions.

Among various documented benefits of PBR façade integration is the exceptional carbon sequestration capacity that significantly exceeds terrestrial plants per unit area. These CO_2 fixation rates can make contributions to building carbon offset strategies. Thermally, algae concentration modulates heat transfer characteristics as a dynamic insulation system. The growth medium provides thermal mass and dampens temperature fluctuations, while increasing biomass amount inside the medium reduces solar heat gain coefficient (SHGC) values. For daylighting, PBRs enable controllable light transmission, where algae growth creates natural shading and reduces glare potential while maintaining daylight access.

2.2 Previous studies on PBR performance and research gaps

Thermal performance investigations have established PBR façades' capability for moderating indoor temperatures. Martokusumo et al. [4] demonstrated that PBR panels achieved 6.4°C temperature difference between interior and exterior compared to 3.4°C for conventional shading devices. Kim's prototype testing [5] revealed that algae zones exhibited significantly higher surface temperatures than windows inside a PBR. Pruvost et al. [6] examined the effects of vertical PBR orientations for building integration, showing that while vertical positioning reduced annual biomass productivity compared to optimal tilting (45°), vertical façades provide more stable year-round performance due to reduced seasonal irradiance variations, making vertical façades more suitable for application. These studies demonstrate PBRs' thermal regulation potential, though systematic comparison across multiple algae species remains limited.

Daylighting and visual comfort research explored PBR façades' optical behavior. Pagliolico et al. [7] investigated five plastic bag PBR prototypes as window shading systems, finding that circular geometries outperformed rectangular designs and that light transmittance control capabilities enabled daylight management. Their simulation (Radiance and Daysim) work demonstrated that PBR systems allowed higher light penetration than conventional blinds but could produce glare concerns without control strategies. Lo Verso et al. [8] studied PBR screens in kindergarten classrooms, reporting that biomass density adjustments enabled light transmittance variations from 0.5 to 2.0, though Italian daylight regulations were not consistently met. Decker et al. [9] examined bio-active façades with rotatable PBR panels, documenting how RGB sensors could track optical density changes throughout growth cycles. These studies both highlight PBRs' potential for dynamic daylighting and reveal challenges in maintaining consistent visual comfort.

Energy simulation approaches have evolved to address the challenge of modeling PBR systems within building performance analysis tools. Negev et al. [10] developed a comprehensive methodology for determining U-value, visible transmittance (VT), and SHGC for algae windows containing *Chlamydomonas reinhardtii* and *C. vulgaris*, establishing calculation procedures based on spectrophotometry measurements and ISO 9050:2003 standards. They proposed using spectrophotometry measurements to characterize optical and thermal properties for building energy simulations. Talaei et al. [2] applied multi-objective optimization to PBR façades in Mashhad, Iran, demonstrating energy savings compared to conventional glazing systems and establishing optimization frameworks for window size and algae density using U-value, VT, and SHGC for *C. vulgaris* defined due to Negev et al. [10]. Recent work has extended these approaches to include lifecycle cost assessment and carbon sequestration quantification [11]. However, comparative studies evaluating multiple algae species across diverse climate zones are scarce, and most investigations focused on a single performance rather than an integrated analysis of multiple performances.

3 Methodology

The methodology is structured into three primary stages (Fig.1). Step 1 focuses on experimental inputs of microalgae production and calculation of optical/thermal properties; Step 2 is the simulation setup to define design variables and running of simulations. Step 3 focuses on identifying Pareto optimal solutions via Octopus and conducting parametric analysis with Colibri, ending with data processing, visualization, and Spearman correlation.

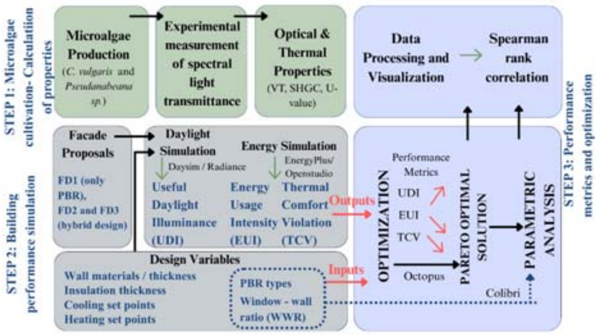

Fig. 1. Methodology

3.1 Microalgae cultivation and selection

Two microalgae species were selected for investigation: *C. vulgaris* and *Pseudanabaena sp.*, obtained from Ege University Microalgae Culture Collection (EGE-MACC). Selection criteria prioritized species capable of cultivation in identical growth medium (BG-11) under controlled conditions, enabling direct performance comparison. *C. vulgaris* represents the most widely studied microalgae for building applications, providing benchmark comparison, while *Pseudanabaena sp.*, a filamentous cyanobacterium, introduces novel optical characteristics not previously evaluated in façade systems. Algae cultures were grown using BG-11 medium in a shaking incubator at 150 rpm, temperature 22±2°C, light intensity 60 μ mol photon $m^{-2}s^{-1}$, under 12:12 hour light:dark cycles for 10 days with an initial inoculum of 10% concentration. The results are for dilutions created concentration ranging from 10% to 100% in 10% increments.

3.2 Experimental measurement of spectral light transmittance

Light transmittance measurements were conducted using Perkin Elmer Lambda XLS UV-VIS spectrophotometer across wavelength range 300-850 nm. Raw transmittance data represents the fraction of incident radiation at a wavelength transmitted through a sample. The measurement range (350-850 nm) encompasses the visible (350-750 nm), and infrared (750-850 nm) spectra, which is relevant for evaluating building thermal (solar heat gain) and visual comfort in the full visible range. For each algae species and concentration, three replicate measurements were performed and averaged to ensure statistical reliability. Baseline transmittance measurements using BG-11 growth medium without algae established reference values.

3.3 Calculation of thermal and optical properties

The overall thermal transmittance or U-value characterizes heat transfer through the complete PBR window assembly. The PBR design consists of two 20 mm plexiglass panels separated by 60 mm of BG-11 cavity. U-value calculation followed ASHRAE 2001 methodology [12]. The adaptation for water-based systems follows [3]. Heat transfer through BG-11 accounts for convection within the liquid. Calculations yielded U-value = 2.14 W/m^2K, held constant year-round in simulations following validation that seasonal variation remained minimal.

Solar Heat Gain Coefficient or SHGC quantifies total solar heat gained through fenestration as a fraction of the incident solar radiation. Following ISO 9050:2003, SHGC comprises two components: directly transmitted solar radiation and inward-flowing fraction of absorbed radiation. Direct transmittance was calculated by weighting measured spectral transmittance against standard solar spectral irradiance per ASTM G173. For inward heat flow, energy balance equations were formulated for each layer (two plexiglass panels, growth medium) accounting for absorption, reflection, and conduction. The equations were solved to determine fraction of absorbed energy flowing inward [10].

Visible Transmittance or VT represents the fraction of visible light (350-750 nm) transmitted through the window system, weighted by the response of the human eye as given in ISO/CIE 10527 [13]. Higher VT values indicate greater daylight transmission, directly influencing daylighting performance and artificial lighting energy requirements.

3.4 Building performance simulation

A representative office space (4.8 m length × 3.2 m width × 3.2 m height) was modeled with south-facing façade (4.8 m × 3.2 m). This orientation maximizes solar exposure in Los Angeles (34.05°N, 118.24°W, Climate Zone 3B) where southern façades receive significant solar radiation year-round. Building construction assumed autoclaved aerated concrete walls with variable insulation thickness, concrete floor slab, and flat roof with insulation. Internal loads included typical office occupancy (10 m^2/person), lighting power density (10 W/m^2), and equipment loads (8 W/m^2).

Three distinct façade designs were investigated (Fig. 2):

Fig. 2. Green in the façade designs show algae while blue shows windows

- Façade Design 1 or FD1 has all PBR glazing across the entire south façade. This scenario maximizes algal coverage, providing maximum biological activity and shading potential but potentially limiting view quality and daylight penetration.
- Façade Design 2 or FD2 is a hybrid design with PBR panels and conventional double-glazed windows to distribute daylight more evenly across the room depth while maintaining partial view access.
- Façade Design 3 or FD3 has alternating PBR panels with conventional glazing, like FD2 with different design.

The simulation platform is Rhinoceros 3D with Grasshopper parametric modeling environment. The Honeybee plugin interfaced with EnergyPlus thermal simulation engine (v9.3) for energy and thermal comfort calculations, while Ladybug plugin provided climate data processing and environmental analysis tools. Daylight simulations were conducted using the Radiance and Daysim engines. The climate data is typical meteorological year (TMY3) weather file for Los Angeles through 2004–2018 years [14]. The four-pipe fan coil and air-cooled chiller system maintained indoor temperature.

3.5 Performance metrics and optimization

Three building performance metrics have competing objectives:
- Thermal Comfort Violation or TCV is the number of annual hours when operative temperature falls outside ASHRAE 55 comfort range (18-26°C) [15]. The target is to minimize TCV.
- Useful Daylight Illuminance or UDI is the percentage of occupied hours when daylight illuminance at a work plane of 0.75 m height falls in 100-2000 lux range. Light less than 100 lux is insufficient, and more than 2000 lux is deemed excessive, and are excluded. The target is to maximize UDI.
- Energy Use Intensity or EUI is the annual energy consumption per unit floor area (kWh/m²/year), including heating, cooling, and artificial lighting. The target is to minimize EUI.

Multi-objective optimization employed the Octopus plugin implementing genetic algorithm (NSGA-II) to identify Pareto-optimal solutions for 30 generations.

Design variables and ranges included:
- Algae concentration: 10-100% (corresponding to measured VT and SHGC values)
- Window-to-wall ratio or WWR: 0.15-0.95 (15-95% glazing coverage)
- Wall thickness: 200-400 mm
- Insulation thickness: 50-200 mm
- Heating setpoint: 18.0-23.5°C
- Cooling setpoint: 23.5-27.0°C

Following optimization, detailed parametric studies using Colibri plugin systematically varied algae concentration and WWR while holding other parameters at optimal values. This analysis revealed sensitivities of parameters and provided insights beyond the discrete solutions. Sensitivity analysis was performed on multi-objective optimization results (n=1,903 iterations across 6 scenarios) using Spearman rank correlation coefficients (ρ) to quantify parameter influence on performance outcomes. Six design variables above were analyzed.

4 Results and discussion

4.1 Thermal and optical properties of microalgae

The U-value remained constant at 2.14 W/m²K for both species, confirming that algae concentration primarily affects radiative rather than conductive heat transfer. This value is between single glazing (typical U = 5.7 W/m²K) and double glazing (typical U = 2.7 W/m²K), providing reasonable thermal insulation while enabling dynamic solar control through concentration variation.

Spectrophotometry measurements revealed distinct optical characteristics of *C. vulgaris* and *Pseudanabaena sp.* across different concentrations (10%-100%). The wavelength-dependent absorption patterns for *C. vulgaris* have absorption peaks at 440 nm (chlorophyll a blue absorption) and 680 nm (chlorophyll a red absorption), and broader near-infrared transmittance beyond 750 nm. *Pseudanabaena sp.* showed similar peaks with an addition of 620 nm (phycocyanin) characteristic of cyanobacteria. As algae concentration increased, light transmittance decreased progressively across all wavelengths, with most dramatic reduction in the visible spectrum (350-750 nm); however, attenuation in the infrared range reduced more gradually (Fig. 3 and Table 1).

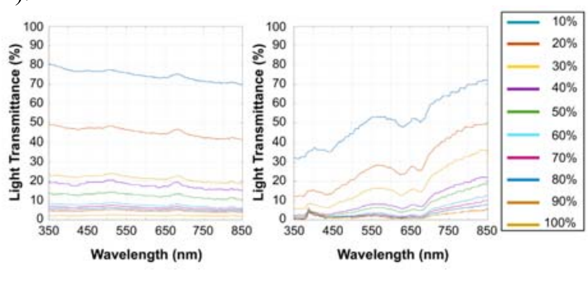

Fig. 3. Measured light transmittance values for *C. vulgaris* (left) and *Pseudanabeana sp.* (right) through the spectrum

4.2 Optimization outcomes

Multi-objective optimization yielded Pareto-optimal solution sets representing trade-offs among TCV minimization, UDI maximization, and EUI minimization.

Table 1. Optical and thermal properties of PBR windows for *C. vulgaris* and *Pseudanabaena sp.* at different concentrations

Algae species	*C. vulgaris*		*Pseudanabeana sp.*	
Algae concentration	VT	SHGC	VT	SHGC
10%	0.52	0.60	0.35	0.44
20%	0.32	0.44	0.18	0.31
30%	0.16	0.30	0.10	0.25
40%	0.13	0.28	0.05	0.21
50%	0.09	0.25	0.04	0.20
60%	0.06	0.22	0.02	0.19
70%	0.05	0.22	0.02	0.19
80%	0.04	0.21	0.01	0.18
90%	0.03	0.21	0.01	0.18
100%	0.02	0.19	0.01	0.18

Analysis of Pareto fronts revealed conflicts between competing objectives, particularly between thermal comfort and daylighting performance. Solutions with excellent thermal comfort typically require high algae concentrations that compromise daylighting. Conversely, solutions optimizing daylighting employ lower concentrations that increase solar heat gain and thermal discomfort. Examination of optimal parameter patterns identified consistent design principles across solutions.

Optimal values for *algae concentration* range 30-45% for both species across most scenarios. Lower bound prevents excessive daylight reduction, while upper bound provides sufficient solar heat gain control. *Pseudanabaena sp.* typically achieves equivalent performance at lower concentrations than *C. vulgaris* due to higher optical attenuation.

4.3 Parametric Analysis

The parametric analysis results presents the impact of different design variables on overall building performance Summarized in Table 2, the minimum, maximum, and mean values are evaluated in the subsequent subsections, for thermal, energy, and daylighting performance.

Table 2. Minimum, maximum and mean results of parametric studies for three façade designs and two algae species

	C. vulgaris			*Pseudanabeana sp.*		
	min	max	mean	min	max	mean
FD1-UDI	6	75	40	6	74	40
FD1-EUI	111	183	147	113	173	143
FD1-TCV	0	31	15	0	22	11
FD2- UDI	19	73	46	19	73	46
FD2- EUI	106	159	132	113	168	141
FD2-TCV	0	46	23	0	26	31
FD3- UDI	23	71	47	23	71	47
FD3- EUI	111	178	144	117	187	152
FD3-TCV	0	45	22	0	30	15

4.4 Thermal comfort performance

The Los Angeles climate's mild winters (mean January temperature 14°C) and hot summers (mean July temperature 24°C) created asymmetric thermal comfort challenges. Cooling loads dominated annual energy consumption, making SHGC reduction through algae concentration beneficial for thermal comfort.

Thermal comfort analysis across the three façade designs reveals that species strongly influence solar heat gain characteristics. *Pseudanabaena sp.* consistently demonstrated superior thermal comfort performance compared to *C. vulgaris* across all three façade designs, probably because of its lower SHGC values, which reduce solar heat gain, especially during Los Angeles' hot summer months.

For FD1 (glazing with 100% PBR), *Pseudanabaena sp.* achieves mean TCV of 333 hours annually across optimal solutions, compared to 469 hours for *C. vulgaris*—representing 29% improvement. FD1 exhibits the best thermal comfort among all three designs for both species, as complete PBR coverage provided consistent solar modulation. The continuous biological shading effect reduces peak cooling loads during summer afternoons. When the glazing ratios are high, higher algae concentrations perform the best (Fig. 4).

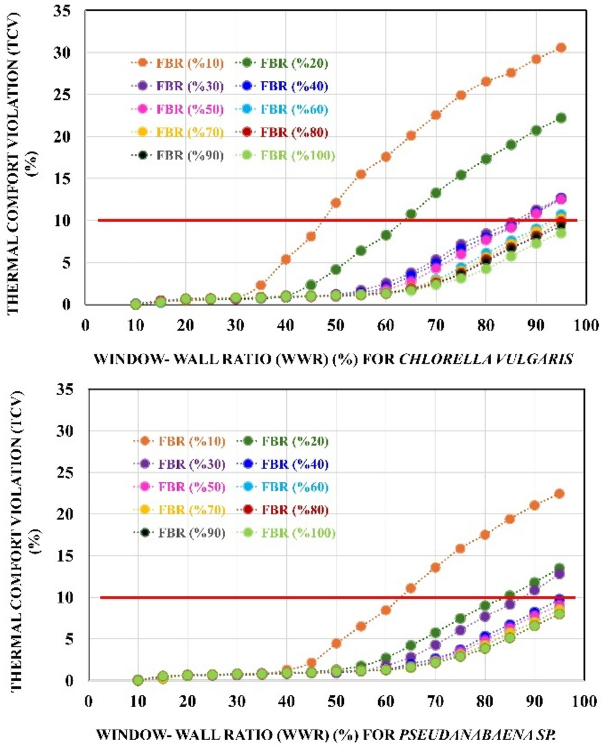

Fig. 4. Parametric study results with Octopus for thermal comfort-WWR in FD1.

FD2 (mixed façade) shows more complex thermal behavior depending on the PBR placement. *Pseudanabaena sp.* achieves 32% better thermal comfort than *C. vulgaris* in this design, with mean TCV of 491 hours versus 720 hours. However, both species perform worse than in FD1, indicating that partial conventional glazing introduces thermal vulnerabilities.

FD3 (mixed façade 2) demonstrates the sensitivity to algae window placement. *Pseudanabaena sp.* has the advantage with an improvement of 33%, though this represents the poorest performance among three designs.

Results confirm that mixed façade designs must carefully consider solar geometry and glazing placement to avoid compromising thermal comfort. While the shading effect of algae integration into the façade increased thermal comfort, this created trade-offs with daylighting performance.

4.5 Daylighting performance

Daylighting performance reveals interactions between algae species, algae concentration levels, and façade window configuration. *Pseudanabaena sp.* demonstrated superior daylighting performance in FD1 and FD2, achieving better results despite having lower VT values than *C. vulgaris*. This contradiction needs to be considered in the context that excessive daylight creates glare issues, while *Pseudanabaena sp.*'s stronger light attenuation prevented over-illumination more effectively.

For FD1, *Pseudanabaena sp.* achieves mean UDI of 40.13% across optimal solutions against 40.41% for *C. vulgaris*. Although mean values are comparable, *Pseudanabaena sp.* shows more consistent performance with narrower range at WWR values around 0.30-0.60. Optimal algae concentrations range 20-40% for both species.

FD2 demonstrates nearly identical UDI values, mean for *Pseudanabaena sp.* is 45.92% while it is 45.95% for *C. vulgaris*. FD2's mixed configuration equalizes daylighting performance between species. The façade configuration performed best for daylighting among all three designs, as this window configuration created favorable illuminance gradients from window wall to back wall, minimizing both over-lit and under-lit zones.

FD3 shows minimal difference between species, with both achieving mean UDI near 47%. The arrangement creates non-uniform daylighting patterns with bright zones adjacent to conventional glazing and dimmer zones behind PBR panels. While the overall UDI scores are the highest, the spatial non-uniformity highlights the trade-off between mean illuminance and distribution uniformity.

Parametric analysis reveals that WWR exerts strongest influence on daylighting performance, as expected (ρ=0.493 average across all scenarios, reaching ρ=0.970 for FD2 and FD3). However, algae concentration shows surprisingly weak correlation with UDI (ρ=0.153 on average). Below 30% concentration, UDI improves with concentration as glare risk decreases. Above 40% concentration, UDI does not change much as neither species provides sufficient daylight penetration. This identifies an optimal concentration range between 20-40% which balances daylight access with glare control (Fig. 5).

The relationship between artificial lighting energy and UDI follows expected correlation. Improved UDI reduces lighting energy by 15-25%, reducing the need for artificial lighting. However, improvements in UDI above 55% yield diminishing savings in lighting energy.

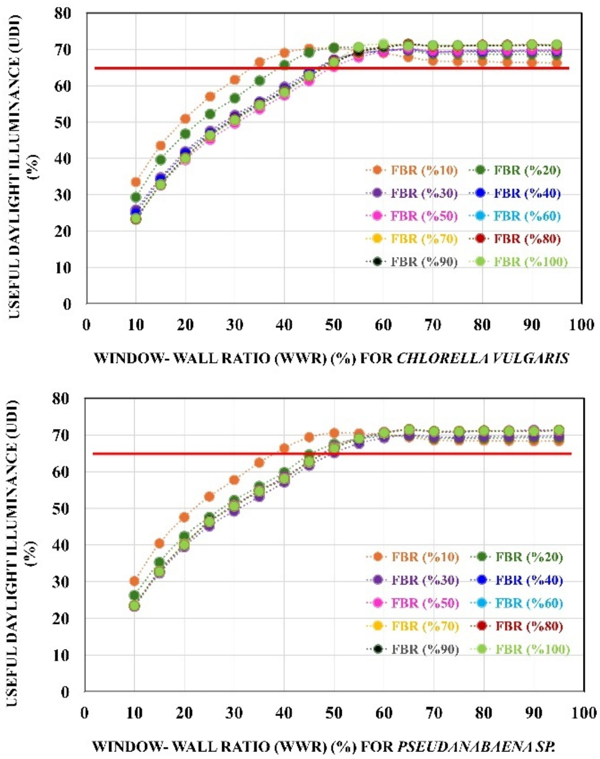

Fig. 5. shows parametric analysis results in FD3 for WWR, the variable that most affects the daylighting results.

4.6 Energy performance

Total energy consumption analysis encompasses heating, cooling, and lighting energy, revealing the relationships between façade configuration, algae species, and EUI. Cooling energy dominates annual energy consumption with 68-75% of the EUI. Given Los Angeles' cooling-dominated climate, solar heat gain reduction is critical for energy performance.

FD1 achieves FD1 achieves mean EUI of 142.96 kWh/m²/year for *Pseudanabaena sp.* and 146.87 kWh/m²/year for *C. vulgaris.* However, FD1 shows significantly higher energy consumption than the initial building performance. Lighting energy is 12-18% higher than hybrid designs, FD2 and FD3. Complete PBR coverage provides consistent solar reduction, lowering cooling loads while increasing lighting loads (Fig. 6).

FD2 demonstrates the most favorable energy performance among all three designs. *Pseudanabaena sp.* achieves mean EUI of 140.50 kWh/m²/year, while *C. vulgaris* achieves mean EUI of 132.43 kWh/m²/year. Surprisingly *C. vulgaris* achieves 9.9% better energy performance than *Pseudanabaena sp.* in FD2 (132.43 vs 140.50 kWh/m²/year), representing the only scenario where *C. vulgaris* outperforms *Pseudanabaena sp.* These results indicate that strategic partial PBR coverage in FD2 optimizes the cooling energy vs. lighting energy trade-off (Fig. 6).

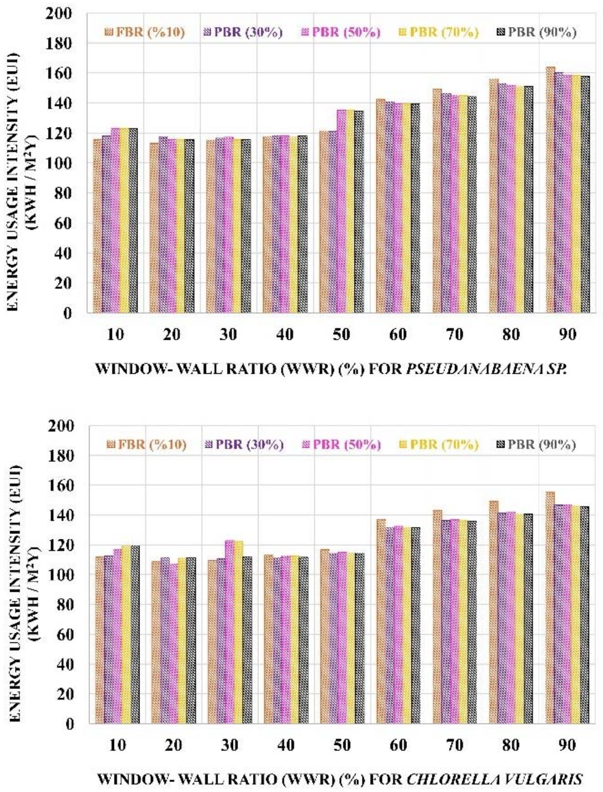

Fig. 6. Parametric analysis results are for *C. vulgaris* and *Pseudanabaena sp.* in FD2.

FD3 fails to reach FD2's energy benefits, with mean EUI of 140.88 kWh/m²/year for Pseudanabaena sp. and 141.72 kWh/m²/year for C. vulgaris. The arrangement's less favorable solar control geometry allows mid-day solar gains through conventional glazing sections, increasing cooling loads without proportional lighting energy reduction. This confirms that façade placement and configuration must align with solar geometry for energy optimization. FD3 shows less energy benefits than FD2.

4.7 Integrated performance analysis

WWR shows a strong but highly configuration and specie dependent influence. For FD3 (both species) and FD2 with *C. vulgaris*, WWR showed a very strong positive correlation with UDI (ρ=0.95 to 0.97), indicating that increased glazing area substantially improved daylight availability. Interestingly, for FD2 with *Pseudanabaena* sp., WWR exhibited a very weak correlation with UDI (ρ=0.15), as daylight performance in this specific scenario was driven almost entirely by Algae Concentration (ρ=0.96). For the FD1 configurations, WWR exhibited strong positive correlations with UDI (ρ=0.71 for *Pseudanabaena* sp. and ρ=0.63 for *C. vulgaris*). Across all scenarios, WWR showed an overall strong positive correlation with UDI (average ρ=0.73) and a moderate positive correlation with EUI (average ρ=0.36), with a weak correlation to TCV (average ρ=0.21).

For *Pseudanabaena sp.*, optimal WWR ranges between 30–50% (FD1), 10–55% (FD2), and 30–40% (FD3) glazing ratio, compensating for lower VT by adjusting glazed area. For *C. vulgaris*, optimal WWR showed different ranges (25–50% (FD1), 35–40% (FD2), and 45% (FD3)), as higher VT provides adequate daylight with varying glazing area. These findings suggest that FD must integrate algae optical properties with glazing area to achieve target illuminance levels.

Optimal wall material thickness and insulation values vary significantly depending on the selected façade type and the target performance scenario. This indicates that rather than uniformly maximizing thermal mass and insulation, the opaque envelope sections of PBR façades must be specifically configured to compensate for the thermal performance of the glazed areas under different design conditions.

Optimal heating setpoints clustered around 20.5°C, while cooling setpoints ranged 23.5-24.5°C. Cooling setpoint demonstrated very strong negative correlation with EUI (average ρ=-0.79, ranging from -0.73 to -0.89) and very strong positive correlation with TCV (average ρ=0.90, ranging from 0.87 to 0.94), indicating a critical trade-off: higher setpoint temperatures (26-27°C) reduce energy consumption but increase thermal discomfort hours, while lower setpoints (23-24°C) maintain comfort at the expense of increased energy use. This finding is particularly significant for Los Angeles' cooling-dominated climate, where cooling accounts for 65-75% of annual HVAC energy consumption.

The choice between façade designs depends on project priorities. Considering balanced performance across all three metrics, optimal solutions for Los Angeles climate employ:

-FD2 with *Pseudanabaena sp.* at 40-50% concentration for energy optimization

-FD1 with C. vulgaris at 10-15% concentration for thermal comfort prioritization

-FD1 with either species for daylighting prioritization

-Optimal WWR for *C. vulgaris* is 25–50% (FD1), 35–40% (FD2), or 45% (FD3); while for *Pseudanabaena sp.*, optimal WWR values changes between 30–50% (FD1), 10–55% (FD2), and 30–40% (FD3)

-Wall material thickness and insulation values vary depending on the selected facade type and the target performance scenario

-Setpoints balancing energy and comfort are 18.0–20.5°C for heating and 23.5-24.5°C for cooling.

5 Conclusions

PBR façades represent promising sustainable building technology offering simultaneous benefits for energy efficiency, thermal comfort, daylighting quality. Literature review reveals three critical gaps that this study addresses. First, algae species in PBR façade research is extremely limited, with *C. vulgaris* dominating investigations while numerous potentially viable species remain unexplored. Our inclusion of *Pseudanabaena sp.* not previously studied in façade applications, expands the knowledge base for species selection. Second, climate-specific performance evaluation has concentrated on European and Middle Eastern contexts, with limited investigation of California Mediterranean climates characterized by mild winters and warm, dry summers—conditions highly relevant for PBR viability. Third, methodological frameworks simultaneously addressing thermal comfort, visual comfort, and energy performance through integrated optimization are rare, yet essential for holistic building performance assessment.

This study utilizes a comprehensive, transferable methodology that addresses these gaps enabling comparative studies across performance criteria, species, and building façade configurations, building a comprehensive knowledge base for PBR façade applications. Limitations include simulation limitations and the focus on performance functions while not considering other potentials like biomass production for energy generation or high-value product extraction. In addition, practical implementation faces technical challenges including maintenance requirements, contamination prevention, nutrient delivery systems, and temperature control in extreme climates. Further studies on life cycle assessment, economic optimization, biomass production and utilization, various PBR control strategies.

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