Multi-objective evolutionary optimization of bacterial cellulose-based composite glazing for thermal, daylight, and energy consideration

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Abstract. Glazing elements are critical components of building envelopes as they regulate the admission of direct and indirect sunlight, thereby reducing the energy demand of buildings by improving daylight performance and thermal comfort. While recent literature presents various applications of advanced glazing technologies, it is crucial to explore alternative sustainable materials that can respond to environmental conditions while enhancing the performance of buildings. Among biobased materials, bacterial cellulose (BC) stands out due to its unique properties, such as high tensile strength, elasticity, absorbency, and moderate transparency. This study investigates the integration of BC-based composite glazing into the facade of an architectural design studio. A multi-objective optimization, combining daylighting and energy simulations, was employed to optimize the transparency, size, and placement of the glazing elements. The results show that BC-based glazing improves the uniformity of daylight distribution, reduces glare risk, and slightly decreases the building's annual heating and cooling loads compared to the base case. This study demonstrates the potential of bio-based composite glazing as a sustainable alternative for building envelopes, emphasizing circularity and low-energy strategies, by highlighting the synergy between building science, computational design, and biology in driving the transition toward a more resilient built environment.

1. Introduction

The building envelope is one of the most influential architectural design components, acting as a mediator between indoor and outdoor environments [1]. It plays a decisive role in ensuring indoor thermal comfort, controlling humidity, reducing noise, and ultimately lowering the energy demands of buildings [2,3,4]. The envelope consists of various elements, including walls, roofs, windows, doors, and foundations, collectively determining a building's performance. Among these, glazing elements are particularly important due to their direct impact on daylight access and solar heat gains [5]. Glazing systems, if poorly designed, can result in significant thermal discomfort, glare, and increased dependency on mechanical heating, ventilation, and air conditioning (HVAC) systems [6]. As the building sector is one of the most energy-intensive sectors globally, representing approximately 30% of global energy use [7], improving the performance of envelope systems is essential.

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Conventional glazing systems, widely used in contemporary buildings, are often based on petroleum-derived materials such as plastics, chemical coatings, and synthetic polymers. Although significant advancements such as low-emissivity (Low-E) coatings, smart windows, and photovoltaic (PV) glazing have been achieved [8,9,10], these technologies primarily aim to enhance energy efficiency without adequately addressing the broader issue of environmental sustainability. Moreover, the reliance on synthetic materials raises concerns about embodied energy, carbon footprint, and end-of-life recyclability. Therefore, exploring alternative, bio-based materials has emerged as a promising pathway for balancing energy performance with environmental responsibility [11,12].

Bio-based materials offer significant advantages due to their renewability, biodegradability, and unique mechanical and optical properties. In recent years, materials such as aerogels [13,14], phase-change materials (PCMs) [15], nanocellulose [16], and natural dyes have been studied for potential use in glazing systems to improve thermal insulation and daylight control. Among these alternatives, bacterial cellulose (BC) has drawn increasing attention due to its exceptional properties, including high tensile strength, flexibility, hydrophilicity, and optical tunability [17]. BC is synthesized by various bacteria, especially *Acetobacter xylinum*, and has demonstrated promising applications in biotechnology, biomedical engineering, and, recently, material science for sustainable design [18].

Despite the material's versatility, the integration of BC into architectural glazing systems is still underexplored. Existing research has yet to fully address its potential for improving daylight performance, thermal comfort, and operational energy reduction within buildings. Furthermore, the implementation of bio-based materials within multi-objective optimization frameworks for architectural design remains limited, preventing the exploitation of their full capacity.

Given the growing need for sustainable and adaptable building systems, this research investigates the feasibility of BC-based glazing elements as substitutes for conventional glazing components. The primary aim of this study is to develop and evaluate a bacterial cellulose-based composite glazing element to enhance thermal, visual, and energy performance in an educational building context. Specifically, this study focuses on optimizing Spatial Daylight Autonomy (sDA) and minimizing annual heating and cooling loads through an integrated simulation and optimization process. The proposed BC-based composite glazing system is incorporated into the facade of an architectural design studio, where it is subjected to detailed daylight and energy performance simulations.

2. Methodology

The methodology of this study combines physical material formulation and advanced computational simulations to evaluate and optimize multiple performance objectives. This research explored BC biofilm as a glazing element to improve thermal comfort, reduce excessive illuminance, and lower operational energy consumption within an educational building context. To this end, a BC-based composite glazing system was integrated into the facade of an architectural design studio in an educational building in Izmir, Türkiye. The objectives were defined as maximizing Spatial Daylight Autonomy (sDA) and minimizing the annual heating and cooling loads of the space. The optimization process involved generating a wide range of possible design solutions. Each design was evaluated through objective functions representing thermal and visual performance criteria. A multi-objective evolutionary optimization approach was employed to address these objectives simultaneously.

2.1. Implementation of bc-based composite glazing

Multiple material formulations for BC biofilms are available in the literature, often modified to enhance specific properties such as tensile strength, transmittance, or colour. This study followed the production protocols described by De Filippis et al. [18] and Domskiene et al. [19] without further modification. The BC biofilm was cultivated in a 1 L water-based medium, supplemented with 4 grams of green tea (infused for 10 minutes at 100°C), 100 grams of sucrose, and 30 ml of fermented liquid for acidification. Subsequently, 90 grams of pre-produced BC biofilm pieces were added to the medium. The culture was grown under static conditions at 20 ± 2°C and 65 ± 5% relative humidity for 34 days. After harvesting,

the biofilm underwent pretreatment and sterilization and was applied to a double-glazed window with a thickness of 1 mm.
After harvesting, the biofilm was pretreated and sterilized (Figure 1). The physical production was solely intended for property measurements, such as optical transmittance using a lux meter (Unit UT383 Mini) equipped with photoelectric sensing technology. This device converts light intensity into electrical signals, processes the data, and displays the results on the's LCD screen.

These measured values were then used in the simulation model, where the BC-based glazing was digitally integrated into the building facade to evaluate its daylighting and energy performance.

2.2. Performance-based simulation and optimization

First, a base case model of the architectural design studio was created to evaluate its existing daylight and energy performance. The building was three-dimensionally modeled using Rhino/Grasshopper, with performance simulations conducted using Honeybee v1.3.0 and Ladybug v1.3.0 for daylight analysis and OpenStudio and EnergyPlus for thermal simulations. This model incorporated material inputs of the building envelope, including walls, ceilings, roofs, slabs, and windows, along with occupancy schedules, lighting, equipment loads, natural ventilation, HVAC systems, and the surrounding context. Regional weather data (.epw) was utilized to run annual simulations. In the second stage, the BC-based composite glazing was digitally integrated into the simulation model. The properties of the physically produced BC biofilm, such as optical transmittance, were applied to the glazing material. The final transmittance of the BC-implemented glazing was found to be 50%, while the base case glazing had a transmittance of 80%. The daylight and energy performance of the building were re-simulated to assess the impact of the BC glazing. Finally, a multi-objective optimization was conducted using Octopus, a genetic algorithm integrated into Grasshopper. This optimization focused on two key variables: glazing transmittance and the window-to-wall ratio (the size and placement of windows). The transmittance range of the composite glazing was defined between 40% and 60%. The model was subsequently simulated through the optimization algorithm to evaluate its annual daylight and energy performance, measured in illuminance (lux) and energy consumption (kWh).

3. Results and Discussion

3.1. Base case results

The base case model's daylight and energy performance was initially assessed using Honeybee. Radiance and OpenStudio were employed as the simulation engines for daylight and thermal analysis, respectively. Spatial Daylight Autonomy (sDA), a climate-based daylight performance metric, was selected as the primary indicator. The thresholds of 500 lux and 2000 lux, along with the 50% temporal threshold, were established based on commonly accepted practices in the literature. These thresholds represent adequate and excessive daylight levels, respectively, ensuring consistency and comparability across studies [21].

The simulation results indicate that the model achieves $sDA_{500,50\%} = 59.1\%$, meaning that at least 500 lux of illuminance is available in 59.1% of the analysis area for at least 50% of the occupied hours throughout the year (typically the time between sunrise and sunset) (Figure 2).



Figure 1. The production of a simple BC biofilm

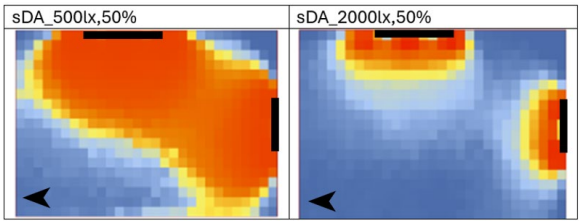


Figure 2. Annual daylight autonomy results for base case model

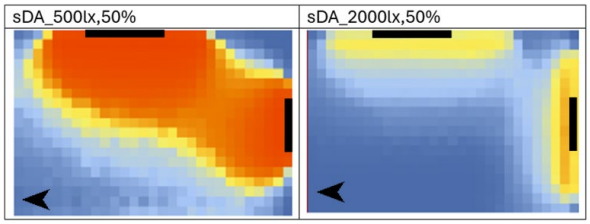


Figure 3. Annual daylight autonomy results for BC-based composite glazing

This value exceeds the minimum threshold set in this study, which is $sDA_{500,50\%} \geq 50\%$, indicating an acceptable overall daylighting level. However, daylight distribution within the space was found to be inhomogeneous. The studio exhibited over-illuminated zones near the windows and under-illuminated areas towards the back, leading to visual discomfort for the occupants. Moreover, second analysis revealed that illuminance levels exceeding 2000 lux occurred in 13.6% of the analysis area for at least 50% of the year, which poses a significant visual comfort concern. Addressing both the uneven daylight distribution and excessive illumination was, therefore, a key objective in the subsequent optimization process.

In addition to daylight analysis, thermal simulations were performed to estimate the building's annual heating and cooling loads. According to OpenStudio outputs, the annual heating and cooling demands were calculated as 7,909,507 kWh and 1,114,731 kWh, respectively, corresponding to 12,554 kWh/m² for heating and 1769 kWh/m² for cooling. The simulations show that the building consumes considerably more energy for heating than for cooling, which may be attributed to the building's location, climate conditions, and the limited insulation capacity of the existing windows. This imbalance underlined the necessity of improving the glazing system, which was addressed during the multi-objective evolutionary optimization stage.

3.2. BC-based composite glazing Performance Results

This section presents the daylight and energy performance assessment of the BC-based composite glazing digitally integrated into the existing windows of the studio. The window dimensions and positions were preserved, and only the glazing material was replaced with the BC-based composite. The purpose of this analysis was to evaluate the performance of the composite glazing without applying any window-related optimization; instead, its as-measured properties were directly introduced into the simulation model. The simulations were conducted following the same methodology as the base case. The results indicate that the studio achieves $sDA_{500,50\%} = 42.5\%$, meaning that 42.5% of the space receives at least 500 lux of illumination for at least 50% of the year. Excessive illumination risk was evaluated separately by identifying areas exceeding 2000 lux of illuminance for more than 50% of the occupied time. The BC-based glazing exhibited a transmittance of 50%, which is lower than that of the existing glazing. As a result, the reduced transmittance led to a lower sDA value compared to the base case. However, this reduction simultaneously decreased excessive illumination and improved the uniformity of daylight distribution within the studio (Figure 3). Specifically, the area exposed to illuminance levels exceeding 2000 lux was reduced to 9.8% of the analysis area, improving occupant visual comfort.

Annual thermal simulations were also performed to determine the heating and cooling demands of the building with the BC-based composite glazing. The heating and cooling loads were estimated at 7,850,275 kWh and 1,073,628 kWh, respectively, corresponding to 12,460 kWh/m² for heating and 1704 kWh/m² for cooling. The improved insulation capacity of the composite glazing slightly reduced both heating and cooling demands compared to the base case. However, its relatively low transmittance also limited daylight availability. Therefore, further optimization of the glazing properties is necessary to balance daylight performance and energy efficiency, which constitutes the focus of the next stage of the study.

3.3. BC-based composite glazing optimization results

The optimization process was conducted using Octopus, a multi-objective optimization algorithm implemented within the Grasshopper environment. The algorithm was executed over the course of one week to generate a comprehensive set of design alternatives. Upon completion, the optimization results were visualized on a three-dimensional Pareto-front, where solutions were evaluated based on two conflicting objectives: maximizing Spatial Daylight Autonomy (sDA) and minimizing annual thermal loads. Since increasing one objective often resulted in the deterioration of the other, careful selection of Pareto-optimal solutions was essential.

Table 1 and Table 2 summarize the optimization results. One of the best-performing solutions achieved an sDA of 51.4%, satisfying the target threshold while reducing excessive illumination compared to the base case. This solution was obtained with a BC-based composite glazing transmittance optimized to 55%. The window sizes were also adjusted to 14.4 m² for the east facade and 13.2 m² for the south facade. The results suggest that the algorithm consistently favored increasing the glazing transmittance and the window-to-wall ratio to enhance daylight performance. While this led to an 8.5% reduction in sDA compared to the base case, it also resulted in a more comfortable daylight distribution with more visually comfortable illuminance levels. This optimized scenario's annual heating and cooling loads were estimated at 7,901,827 kWh and 1,068,273 kWh, respectively, representing a slight reduction compared to the base case model. The optimization improved daylight uniformity and reduced excessive illuminance, although the trade-off between increased daylight autonomy and higher heating and cooling loads remained partially unresolved. Several key insights emerged from the optimization process:

- Increasing window sizes improves sDA but leads to higher heating and cooling loads due to increased infiltration and heat loss, particularly in cold seasons.
- The selected BC-based composite glazing is characterized by moderate transmittance and reduced heating/cooling demand. However, its reduced transmittance limits daylight penetration and solar heat gain, creating a trade-off between energy performance and visual comfort.
- The findings highlight the importance of optimizing the glazing properties and window configurations before implementation. Applying such composite glazing without prior performance evaluation may not be suitable for all climates or building types.
- Despite the slight reduction in sDA compared to the base case, the optimized model achieved better daylight distribution and significantly reduced excessive illuminance, results in better visual comfort.
- The optimization process also revealed that increasing the window-to-wall ratio, particularly on the south-facing facade, is beneficial in regions with high solar exposure and lower latitudes. This strategy helps balance daylight performance and energy consumption while preventing excessive illuminance and overheating.

Table 1. Optimized variables and objectives of Pareto-front solutions.

Case	Window surface (m²) East/South | Total	Glazing transmittance (%)	sDA (%)	(%)[1]	Heating load (kWh)	Cooling load (kWh)	Total thermal load (kWh)	(%)[2]
Base Case	12.6/8.4 | 21	75	59.9	-	7,909,507	1,114,731	9,024,238	-
BC-based composite glazing	12.6/8.4 | 21	50	42.5	-17.4	7,850,275	1,073,628	8,923,903	1.11
Pareto-front genome (1)	14.4/13.2 | 27.6	55	51.4	-8.5	7,901,827	1,068,273	8,970,100	0.59
Pareto-front genome (2)	14.2/12.8 | 27	54	53.1	-6.8	7,907,283	1,182,737	9,090,020	-0.72
Pareto-front genome (3)	13.9/13.5 | 27.4	56	54.6	-5.3	7,912,372	1,192,837	9,105,209	-0.89

%[1]: Difference in SDA compared to the base case; %[2]: Difference in total thermal load compared to the base case.

Table 2. Annual energy consumption and daylighting results for base case, BC-based composite glazing, and pareto-front genome (1).

Data Input	Annual heating energy consumption (kWh/m²)	Annual cooling energy consumption (kWh/m²)	Heat gain from windows (kWh/m²)	Infiltration heat gain (kWh/m²)	Heat removal from windows (kWh/m²)	$sDA_{500,50}$ (%)
Case model	7,909,507	1,114,731	18,233	522	2383	59.9
BC-based composite glazing	7,850,275	1,073,628	17,837	495	2265	42.5
Pareto-front genome (1)	7,901,827	1,068,273	18,021	502	2402	51.4

Overall, the optimized BC-based glazing configuration demonstrates that achieving acceptable daylight and energy performance is possible while incorporating a more sustainable material into the building envelope.

4. Conclusion

This study demonstrates the potential of BC-based composite glazing when digitally applied to an architectural studio's south and east facades, focusing on its impact on energy consumption and daylight performance (Table 2). By optimizing window-related variables, the study revealed the effectiveness of this glazing system within the specific building and climatic context. Future research could extend these findings by investigating the performance of BC-based glazing in diverse climatic regions and orientations and through alternative biofilm production methods. Furthermore, this study highlights the interdisciplinary synergy between building science, computational design, and biology. Integrating knowledge from these fields provided valuable insights for developing sustainable building envelope solutions, emphasizing circularity and the potential reduction of embodied and operational energy. By encouraging material reuse and energy efficiency, these strategies contribute to the transition toward a more resilient and regenerative built environment.

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