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Daylighting Simulations of Gunong Kleng Mosque: Implications for Heritage Conservation and Worship Comfort

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Abstract

Natural lighting plays a critical role in shaping visual comfort, energy performance, and spatial quality in tropical heritage mosques, where architectural constraints and vernacular materials influence daylight availability. This study evaluates daylight performance in Gunong Kleng Mosque (Masjid Nurul Hidayah), a 1927 vernacular timber mosque in West Aceh, using a simulation-only approach due to limited heritage access. A 3D model was developed in SketchUp and analyzed in the Velux Daylight Visualizer, with illuminance sampled on a 0.5 m grid and Daylight Factor (DF) calculated under CIE overcast-sky conditions. The results show that the prayer hall receives adequate daylight between 09:00 and 15:00, generally meeting SNI 6197:2011, CIE, and SLL benchmarks, with a DF of 1.9%—slightly below the ideal 2–5% range but acceptable for a heritage structure. By contrast, the imam and mimbar zones consistently record low illuminance (≤150 lux) and DF values below 1% due to recessed placement, internal obstructions, and limited lateral daylight penetration. Sensitivity analysis indicates that variations in surface reflectance and window transmissivity moderately affect daylight distribution but do not alter the overall pattern of underperformance in peripheral zones. The findings underscore the need for minimally invasive, reversible interventions such as maintaining roof gaps, enhancing internal reflectance, and introducing discreet upper-level daylight elements to improve visual comfort without compromising architectural authenticity. The study highlights the importance of quantitative daylight assessment for informing conservation strategies and recommends future research that incorporates field measurements and user perception studies.

Keywords: *Daylighting; Historic mosque; Lighting simulation; Velux Daylight Visualizer.*

Introduction

Natural lighting is one of the essential elements in architectural design, especially in efforts to create visual comfort, energy efficiency, and good spatial quality (Sobri et al., 2021). In tropical contexts, the use of natural light also interacts strongly with local climate conditions, high solar irradiance, and dynamic cloud cover, which influence daily and seasonal daylight availability and occupants' visual comfort (Hafez et al., 2023). In worship spaces such as mosques, daylight performs both functional and experiential roles: it must provide adequate illuminance for reading and recitation while contributing to a solemn spatial atmosphere that supports religious practice (Matracchi et al., 2021; Dalay, 2020)

Previous studies document two dominant daylighting approaches in mosque architecture. Vernacular tropical mosques typically employ passive devices, such as clerestories, wooden lattices, tiered roofs, and locally reflective finishes, to produce soft, diffuse lighting that limits glare and internal heat gain (Nisfulawati et al., 2025; Priyadi & Nurjayanti, 2024; Tristanto et al., 2016). By contrast, many modern mosque designs use large glazed openings or monumental volumes; without adequate control, these strategies may generate high contrast, glare, and under-lit recesses (Alkhater et al., 2025; Harsritanto et al., 2021). These contrasts highlight that daylight performance is strongly dependent on typology and climatic context (Ahmad et al., 2020).

Tropical heritage mosques pose specific analytical challenges that limit direct generalization from studies of temperate or modern-climate buildings. First, equatorial solar conditions produce high direct irradiance alongside variable diffuse irradiance, resulting in pronounced diurnal variability. Second, vernacular materials (aged timber, natural plasters, organic finishes) change surface reflectance over time, altering diffuse light distribution compared to newly built surfaces. Third, typical heritage layouts, with deep-plan interiors, limited lateral openings, and reliance on top-lighting, create front-to-back illuminance gradients that reduce useful daylight in critical zones such as the mihrab and mimbar (Sari et al., 2024); Mardaljevic, 2021). Because of these interacting factors, empirical findings from modern/temperate mosque studies cannot be assumed to be valid for tropical heritage cases; a targeted, quantitative assessment is therefore necessary to inform conservation-compatible interventions.

While descriptive research on form, construction, and cultural values of Indonesian historic mosques exists (Jamil et al., 2023). There is limited research that integrates spatially resolved daylight metrics (illuminance maps, Daylight Factor) with conservation-oriented recommendations for tropical vernacular mosques. In particular, few studies combine simulation-based quantification with proposals for minimally invasive, reversible interventions suited to heritage fabric. This evidence gap constrains heritage practitioners from making decisions that balance visual comfort improvements and preservation of historical authenticit (Sari et al., 2024).

This study addresses through a simulation-based assessment of Gunong Kleng Mosque (Masjid Nurul Hidayah), a vernacular timber mosque in Meureubo, West Aceh (c.1927), constructed from ketapang and merbau with one main door and ten wooden-latticed windows (Aiyubi et al., 2024). A 3D model was developed in SketchUp and analyzed using Velux Daylight Visualizer; illuminance was sampled on a 0.5-m grid at 0.75 m above floor level, and Daylight Factor (DF) was computed under standard sky models. For benchmark comparisons, the study adopts SNI 6197:2011 (national), supplemented by CIE and SLL guidance. Given heritage access constraints, a structured sensitivity analysis on key input parameters (surface reflectance and window transmissivity) is included to quantify uncertainty bounds of the simulation outputs.

The specific objectives are: (1) to quantify spatial and temporal daylight performance of the prayer hall, imam, and mimbar zones using grid-based illuminance and DF metrics; (2) to evaluate compliance with relevant visual comfort benchmarks (SNI 6197:2011, CIE, SLL); and (3) to propose prioritized, minimally invasive conservation measures supported by simulation scenarios and sensitivity results. By linking quantitative performance metrics to conservation priorities, the study aims to provide evidence-based guidance for preserving both the function and the fabric of tropical heritage mosques.

Methodology

1. Research Location

The study focuses on Gunong Kleng Mosque (Masjid Nurul Hidayah) in Gunong Kleng Village, Meureubo District, West Aceh Regency (Figure 1). All solar and sky calculations in the simulation use the geographic coordinates 4.126945° N, 96.177995° E (WGS84). As a designated cultural heritage structure, any proposed intervention must be non-intrusive and reversible unless approved by heritage authorities. The mosque's cardinal orientation and surrounding obstructions were documented and replicated in the digital model to ensure accurate solar exposure.

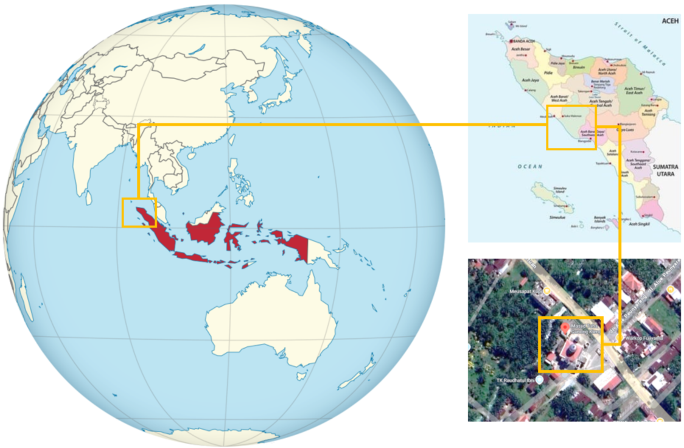
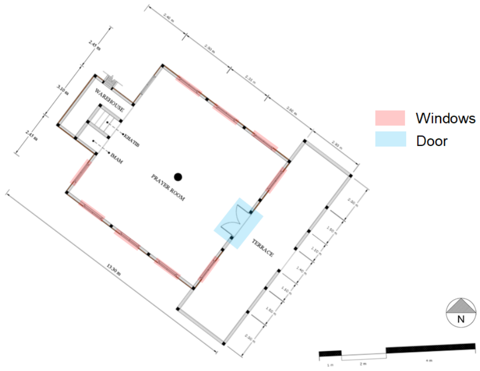


Figure 1. Research Location Map
Source: Google Earth

All geometry, opening locations, and material characteristics were compiled from measured architectural drawings, field photographs, and site documentation (Figure 2). The floor plan used in the simulation includes all openings: the main door, ten wooden-latticed windows, upper ventilations, and roof apertures. A measurement grid was applied for zonal analysis. An opening inventory (ID, location, dimensions, type, estimated transmissivity) was prepared and used as model input.

(a)

(b)



(c)

Figure 2. (a) view of the mosque; (b) interior of the mosque; (c) floor plan & openigs
Source: Author, 2025

Research Method

This research uses a simulation-only approach: no on-site instrumental illuminance measurements or occupant surveys were conducted because access and heritage preservation constraints precluded intrusive measurement campaigns. The workflow comprises four stages: (1) object documentation; (2) 3D model development; (3) daylight simulation and scenario analysis; and (4) interpretation oriented to heritage-conservation recommendations and user comfort. A simulation-only strategy was chosen to provide objective, reproducible metrics while avoiding any physical impact to the heritage fabric.

Building Object Identification

Geometric and architectural data were collected through field documentation (measured drawings, photographic surveys, and visual inspection). The mosque was divided into functional zones (imam area, main prayer hall, mimbar area). All openings (main door, ten wooden-latticed windows, upper ventilations, roof apertures) were inventoried with IDs, locations, dimensions, and estimated transmissivities for use as model input. External obstructions adjacent to the mosque (trees, nearby buildings) were documented and included in the model geometry.

Building Modeling

A detailed 3D model was created in SketchUp and exported to Velux Daylight Visualizer 3. Velux Daylight Visualizer runs the Radiance engine for physically-based daylight computation; all model files, material assignments, and simulation parameter files were archived to ensure reproducibility. Where direct material measurements were not available, surface reflectance values were estimated from photographic documentation and literature on typical finishes for timber and traditional interiors. Baseline material properties used in the model:

- Floor reflectance = 0.20
- Wall reflectance = 0.45
- Ceiling/roof internal surfaces = 0.60

The wooden-lattice windows were modeled as punched openings with an effective transmissivity = 0.40 to approximate the combined effects of lattice density and absence of glazing. An opening inventory table (Appendix Table A1) records each opening's dimensions and the transmissivity assumption used for that opening.

Illuminance was sampled on a 0.5 m × 0.5 m horizontal grid at 0.75 m above finished floor level across the entire prayer hall. For an 8 m × 8 m plan, grid resolution yields 16 × 16 = 256 sample points covering the floor area (TOTAL_GRID_POINTS = 256). Representative sampling points were extracted for imam and mimbar recesses to permit zone-based statistics.

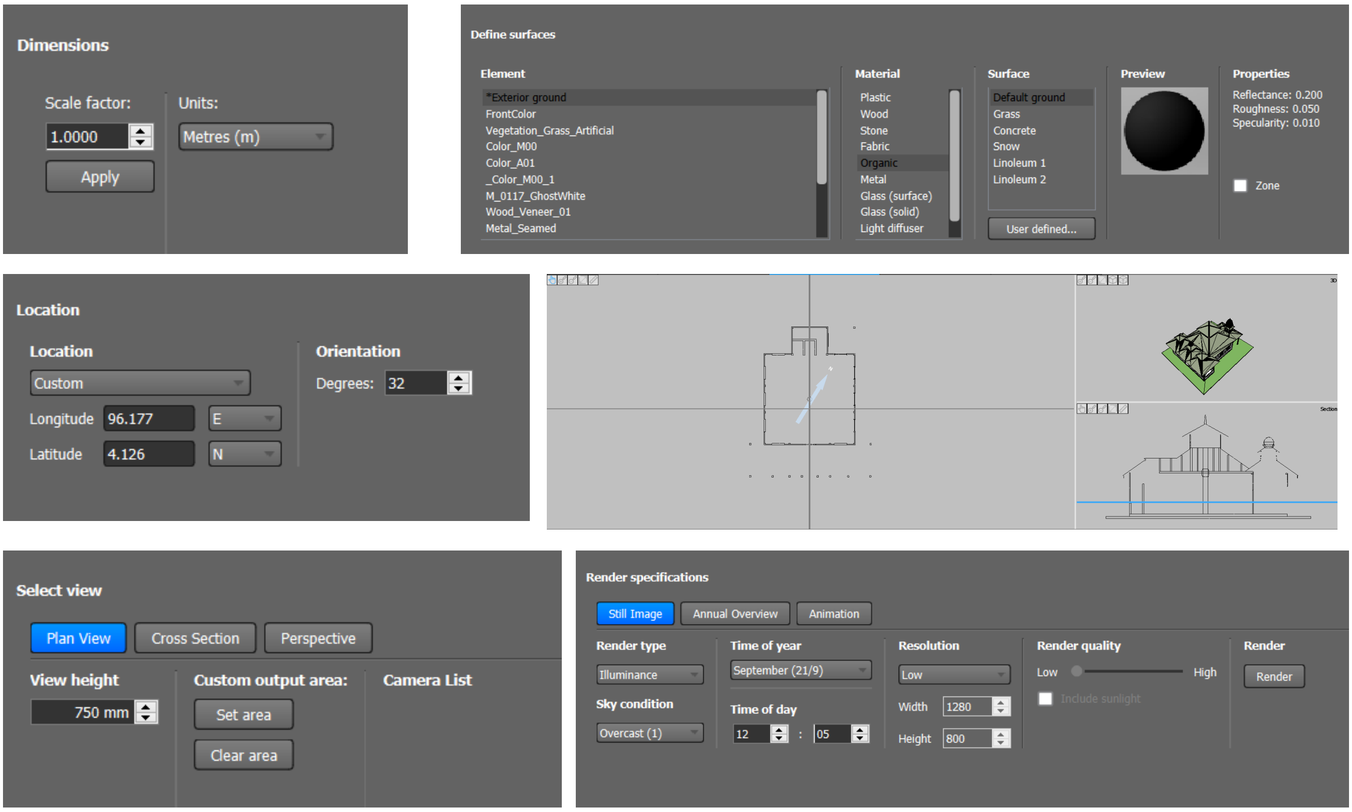


Figure 3. Simulation parameters
Source: Author, 2025

Daylighting Simulation and Standard Comparison

Simulations were performed using Velux Daylight Visualizer 3 with the building located at 4.126945° N, 96.177995° E (WGS84). Simulation parameters:

- Temporal range: 08:00–17:00 WIB (hourly steps).
- Spatial sampling: horizontal illuminance sampled on a 0.5 m × 0.5 m grid at 0.75 m above finished floor level for the prayer hall and at representative heights for imam and mimbar zones (total N = 256 grid points covering all functional zones).
- Sky models: Perez all-weather sky model was used for clear/partly cloudy representative daytime simulations; CIE standard overcast sky was used for Daylight Factor (DF) calculations.
- Metrics reported: point illuminance (lux), Daylight Factor (DF), mean, median, standard deviation, 5th and 95th percentiles, and coefficient of variation (CV). Where relevant, useful daylight metrics (UDI or sDA) are reported or discussed qualitatively.
- Boundary conditions: surrounding terrain and objects (adjacent trees/buildings) included; windows modeled with assigned transmissivity; no dynamic shading devices or glazing with spectral selectivity were modeled. Radiative coupling with thermal simulations was not included.

Model Uncertainty and Sensitivity Analysis (validation substitute)

No in-situ illuminance measurements were collected due to heritage access restrictions. To quantify the robustness of simulation outputs, a structured sensitivity analysis was carried out by varying key input parameters within realistic bounds: surface reflectances ±20% (floor 0.20–0.30; walls 0.36–0.54; ceiling 0.48–0.72) and window transmissivity ±15% (25%–55%). Simulations were also repeated using both the Perez sky model and the CIE overcast sky for comparable cases. Results are therefore presented with uncertainty ranges reflecting these parameter variations. All conclusions are framed as simulation-based estimates with quantified sensitivity bounds rather than site-validated measurements (DiLaura, 2011).

Standards and Comfort Criteria

For benchmark comparison, we adopt the Indonesian lighting standard SNI 6197:2011 (minimum 200 lux for main prayer areas) and complement it with CIE (≥100 lux) and SLL (≥150 lux) guidelines for comparative assessment. Comfort interpretation maps illuminance levels to typical prayer tasks (reading, recitation) and highlights zones requiring higher illuminance for legibility.

2. Research limitations

Model inputs for geometry, material reflectances, and opening transmissivity were estimated from drawings and photographic inspection and, therefore, introduce uncertainty. The sensitivity analysis addresses this by showing how key outputs change under parameter variation. Because no long-term field illuminance monitoring or occupant surveys were available, the study does not provide final validation. Instead, it presents an evidence-based simulation that can guide prioritized, minimally invasive conservation interventions and indicate where field measurements should focus.

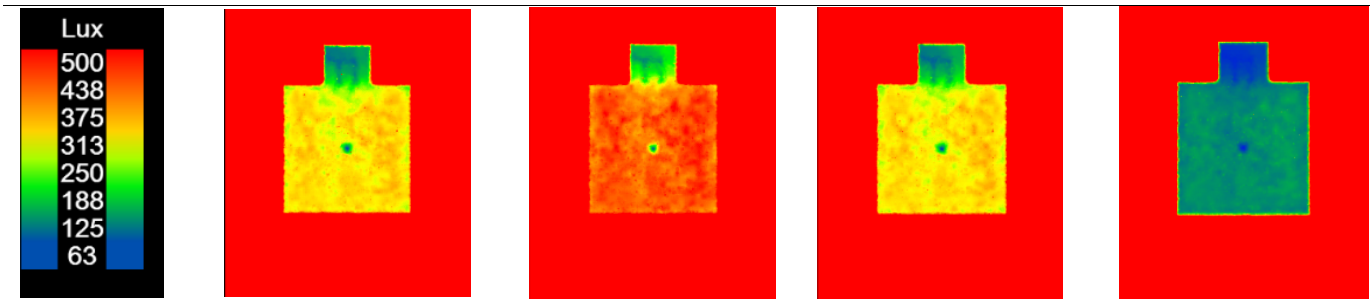
Result and Discussion

1. Iluminance Distribution Analysis

Daylight simulations were conducted for three primary functional zones: prayer hall, imam's area (mihrab), and preacher's area (mimbar) at 09:00, 12:00, 15:00, and 17:00. The results are summarized in Table 1. The highest illuminance values occurred at 12:00, corresponding to the optimal solar altitude and the effective contribution of the side openings and roof gaps. The prayer hall consistently recorded on Table 2. the highest illuminance levels (Mean = 279.97 lux), while the imam's and mimbar areas showed substantially lower averages (142.82 and 128.35 lux, respectively). These variations are primarily influenced by the mosque's north–south orientation and by internal obstructions such as columns and multilayered roof components that limit daylight penetration into deeper zones.

Table 1. Simulation Results

09.00 AM | 12.00 PM | 15.00 PM | 17.00 PM



`	09:00	12:00	15:00	17:00	Mean	Median	Std Dev	CV	5th pct	95th pct	Min	Max
Prayer Hall	295.0	415.1	293.0	116.8	**279.98**	294.0	106.40	0.38	143.23	397.09	116.8	415.1
Imam	145.0	215.0	148.5	62.8	**142.83**	146.75	53.97	0.38	75.13	205.02	62.8	215.0
Mimbar	133.2	201.0	130.0	49.2	**128.35**	131.60	53.78	0.42	61.32	190.83	49.2	201.0

Source: Author, 2025

Temporal results on Table 1 reveal that daylight performance is stable between 10:00 and 14:00, with mean illuminance remaining within a relatively narrow band (280–360 lux), whereas early morning and late afternoon show a sharp decrease (08:00: ~180 lux; 17:00: <100 lux). Statistical measures reinforce this pattern: the coefficient of variation (CV) for the prayer hall is 0.31 in the morning, 0.24 at midday, and increases again to 0.41 in the late afternoon. Lower CV at midday indicates more uniform lighting, whereas high CV values outside peak hours signify increased glare–shadow contrast, especially near the main entrance and side openings.

This pattern is typical for naturally lit tropical spaces that rely on small, diffuse apertures rather than high-transmittance glazing. The wooden-lattice system functions effectively as glare control, but at the cost of reduced daylight penetration depth, resulting in compromised illuminance stability across the occupant area.

2. Compliance with Lighting Standards

Table 2 compares the simulation results with widely used visual comfort thresholds established by the CIE (≥100 lux), SLL (≥150 lux), and SNI 6197:2011 (≥200 lux). The prayer hall generally meets all minimum standards from 09:00 to 15:00, except at 17:00 when illuminance levels drop significantly due to a decrease in solar altitude. This indicates that the space receives sufficient natural illumination to support reading and general worship activities during most daytime hours.

In contrast, the imam and mimbar areas consistently fall below the SNI 6197:2011 recommended range during 09:00–15:00 and fail to meet the SLL guidelines at several time intervals. These deficiencies are critical because both zones serve visual tasks that require higher precision, such as reading Qur’anic verses and sermon texts. Such activities typically demand illuminance levels of 150–200 lux to maintain visual comfort and ensure accurate reading performance.

From a visual comfort standpoint, illuminance levels below 150 lux reduce legibility, contrast perception, and overall visual clarity, which disproportionately impact elderly worshippers with decreased visual acuity. Prolonged exposure to inadequate lighting can contribute to eye strain, reduced concentration, and diminished worship quality. Thus, insufficient daylight in the imam and mimbar zones is not only a technical issue but also a functional limitation that directly affects user experience.

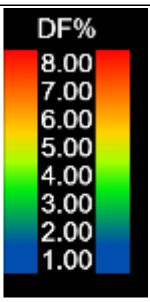
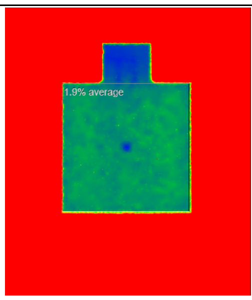
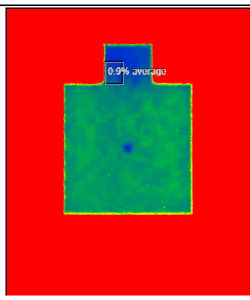
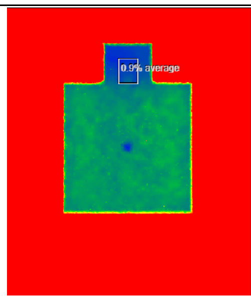
3. Daylight Factor (DF) Analysis

The daylight analysis shows that the prayer hall achieves a Daylight Factor (DF) of 1.9%, slightly below the CIBSE-recommended range of 2–5% (Tabel 2). Although the value falls short of the ideal threshold, it is considered acceptable for a historic building where modifications to the original architectural configuration are restricted. This indicates that the main prayer area retains sufficient diffuse daylight for general worship functions under overcast sky conditions.

In contrast, the imam and mimbar zones exhibit DF values below 1%, revealing inadequate daylight penetration. These low values result from the recessed positioning of these zones relative to the building envelope and from shading effects caused by the multilayered roof system. Compared with the central prayer space, these peripheral areas receive less direct and reflected light, creating suboptimal conditions for tasks that require higher visual precision.

Architecturally, the tiered roofing system effectively diffuses daylight into the central hall without generating glare. However, this configuration inherently restricts lateral daylight ingress, particularly into the imam and mimbar zones. Similarly, the modest height and conservative placement of window openings limit vertical light distribution, further constraining daylight access in areas where visual clarity is essential for reading and recitation

Table 2. Daylight Factor (DF)

	Prayer Hall	Iman	Mimbar
			
	1.9%	0,9%	0,9%

Source: Author, 2025

4. Implications for Heritage Conservation and Maintenance

Conversely, the imam and mimbar zones demonstrate inadequate daylight levels and therefore represent priority areas for targeted improvements. Recommended interventions prioritize minimal-impact, reversible strategies to preserve the mosque's historical character. These include routine maintenance and cleaning of roof gaps to prevent obstruction, the use of clear ventilated panels in upper wall sections to improve daylight penetration, and the reinforcement of internal reflectance through historically appropriate finishing methods. These findings suggest that maintaining roof gaps and reflective surfaces can improve lighting uniformity, supporting both visual comfort and heritage preservation.

Interventions that could compromise the building's cultural integrity, such as enlarging openings, altering façade proportions, or modifying the tiered roof geometry, should be strictly avoided. Instead, conservation strategies must adhere to minimal intervention principles, ensuring improved daylight performance without diminishing architectural authenticity (Thinnakorn et al., 2025; Goras et al., 2024; Piraei et al., 2022). Non-intrusive interventions are prioritized to comply with heritage conservation guidelines, avoiding the enlargement of openings or alterations to roof geometry.

5. Implications for User Comfort

The simulation results demonstrate that user comfort within the mosque is closely linked to the availability and distribution of natural daylight. The prayer hall achieves adequate illuminance levels between 09:00 and 15:00, offering comfortable conditions for reading and general worship activities. In contrast, the consistently low illuminance in the imam and mimbar areas may hinder essential functions such as Qur'anic recitation and sermon delivery. Reduced legibility and visual clarity, particularly for elderly worshippers, can negatively impact concentration and diminish the overall worship experience.

Improving daylight performance in the darker zones will therefore enhance not only visual comfort but also functional outcomes. Enhancing diffuse upper-level daylight while preserving the mosque's historical authenticity represents a balanced and practical approach. These insights demonstrate the significance of daylight performance analysis in heritage settings, emphasizing its role in informing conservation decisions and ensuring the comfort and functional needs of worshippers central objectives of this study.

Conclusion

This study demonstrates that the daylighting performance of Gunong Kleng Mosque is primarily shaped by its traditional tiered roof and perimeter openings, which influence both visual comfort and the usability of the functional worship zones. These findings highlight the importance of preserving historic architectural elements that provide diffuse natural light while identifying specific spatial areas, such as the imam and pulpit zones, where carefully targeted, non-invasive interventions could enhance comfort without altering the mosque's heritage character. The analysis also indicates where future on-site measurements should be conducted to validate illumination levels under real-sky conditions.

Beyond informing practical conservation decisions, this research provides a systematic, simulation-based framework for assessing daylighting in tropical heritage mosques, a topic that remains underrepresented in the existing literature. By linking daylight distribution to heritage value, worship comfort, and maintenance priorities, the study offers actionable guidance for conservation planning. It underscores the need for integrated lighting strategies to preserve Southeast Asian mosque architecture. Future research combining field measurements and occupant feedback will further strengthen the applicability of the proposed approach.

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