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OPTIMIZING DAYLIGHT USING PASSIVE STRATEGIES: LIGHT SHELVES AND SOLAR TUBES

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Abstract

This research investigates how well- advanced daylighting techniques work in atrium buildings, specifically looking at how light shelves and solar tubes can be used together. The importance of daylighting in sustainable building design cannot be overstated, as it provides advantages like better visual comfort, increased occupant health, and lower energy usage. Atrium buildings, featuring spacious central areas, are perfect for integrating these tactics, offering better airflow, more sunlight, and improved spatial connections. The main goal of this study is to boost natural light, decrease dependence on artificial light, and enhance energy efficiency. The performance of these technologies was evaluated through detailed simulations and case studies using advanced daylighting software and real-world assessments. Light shelves raised levels of natural light by 15% to 17% in areas with windows, whereas solar tubes increased brightness from 100 Lux to 200 Lux in areas without windows. Out of the various dimensions examined, 24-inch solar tubes exhibited the greatest uniformity and brightness levels. The combination of light shelves and solar tubes showed noticeable enhancements in visual comfort and energy efficiency, indicating that integrating these daylighting solutions can greatly improve indoor lighting conditions and support sustainable building practices. The results highlight the significance of creative daylighting methods in contemporary architecture, stressing their involvement in establishing healthy, efficient, and productive spaces. This research addresses a significant gap in Pakistan's educational building design by offering simulation-based daylighting solutions customized for local climatic settings and construction techniques. This study offers important information for architects, engineers, and building designers who want to enhance natural lighting and sustainability in built environments.

INTRODUCTION

Daylighting—the strategic use of natural light to illuminate building interiors—has become a cornerstone of sustainable architectural design. It significantly reduces dependence on artificial lighting, which accounts for more than 30% of total energy usage in commercial buildings during daytime hours [1]. In addition to lowering operational costs, daylighting contributes to occupant well-being by improving cognitive performance, reducing stress, and supporting circadian health [2, 3]. Recent data-driven studies emphasize that energy-efficient lighting strategies are not only environmentally responsible but also economically beneficial, reinforcing financial sustainability in the construction sector [4].

Atrium-based buildings, with their large central open spaces and skylights, offer ideal conditions for integrating daylighting strategies. These spaces enhance natural light penetration and support passive ventilation, heating, and cooling [5, 6]. However, they also pose challenges such as heat gain, glare, and uneven light distribution, particularly in hot semi-arid climates like that of Lahore, Pakistan. Design elements such as skylight geometry, material reflectance, and shading systems significantly influence daylight quality and energy performance in such buildings [7, 8].

In parallel, stakeholder perspectives on eco-friendly lighting are increasingly shaping sustainable design choices. Studies reveal that end-users value lighting systems not only for efficiency but also for their symbolic contribution to sustainable urban living [9]. Additionally, the growing application of artificial intelligence in project management is transforming how daylighting solutions are simulated, evaluated, and implemented in real-time, responsive design workflows [10].

In the South Asian context, there is a notable scarcity of localized, simulation-based daylight studies, especially within educational buildings. Although some efforts have been made—such as a study in Multan, Pakistan, that demonstrated the economic feasibility of daylight integration in college facilities [11]—there remains a critical gap in research that considers both user comfort and regional architectural constraints. Furthermore, simulation-based analyses across diverse building orientations have revealed that spatial layout and orientation critically affect daylight access and uniformity [12].

Given these insights, the present study explores advanced daylighting solutions—specifically the use of light shelves and solar tube systems—in an atrium-based academic building in Lahore. The investigation combines parametric simulation tools (Rhino, Grasshopper, Ladybug, and EnergyPlus), in-situ illuminance measurements to evaluate and improve natural lighting strategies.

The specific objectives of this study are:

1. To evaluate daylight conditions within faculty offices connected to an atrium in a higher education building in Lahore;
2. To validate simulation outputs through on-site measurements
3. To propose and assess retrofitted daylighting strategies—light shelves and solar tubes—for enhancing visual comfort and reducing dependency on artificial lighting in educational spaces.

Table 1. Literature Review

Years	Authors	Methodology		Findings
		Simulation Tool	Lighting Scope	
2024	[7]	Simple Mundt's equation based iterative process. Computational Fluid Dynamics ENVI-met	Room	• Optimization of architectural design can achieve a 46.54% energy-saving rate. • Proposed solutions enhance thermal comfort, energy efficiency, and reduce energy consumption.

2024	[8]	Experiments and measurements in an actual office space. Questionnaires on visual perception under constant and fluctuating illuminance.	Small Office	• Investigated effects of illuminance variation on visual response. • Suggested statistical prediction models between illuminance variation ranges and visual perception. • Proposed permissible ranges of illuminance variations for dimming control. • Studied differences in visual comfort due to illuminance variation under different base levels.
2023	[13]	Rhino model was determined by illuminance measurement and simulation validation	Class Room	• Dynamic daylight metrics correlated with student evaluations in Chinese classrooms. • Annual and point-in-time metrics comparison showed differences in daylight distribution. • Students preferred sDA 450/50% metric for classroom daylight standards. • Correlation found between blackboard glare and disability glare probability.
2023	[14]	Subjective questionnaire survey combined with critical flicker-fusion frequency test. Introduction of luminance gradients and definition of 20 lighting parameters		• Four lighting parameters impact visual fatigue: D31, D12, Lm, CCT. • Mathematical model predicts visual fatigue based on lighting parameters. • High CCT increases visual fatigue, suggesting optimal luminance parameters.
2022	[15]	Ladybug–Honeybee plug-in was used for simulation in the study. Used Spatial Daylight Autonomy and Annual Sunlight Exposure as indicators. Built a parametric model in Grasshopper for simulation. Conducted linear regression analysis on different types of atriums.	Primary and secondary School	• North and east sides of atriums are suitable orientations for classrooms. • Corridor width of 3m ensures high-quality daylight for bottom floors. • Optimal design equations for atrium width and length provided. • Design recommendations offered based on the study results.
2022	[16]	Simulation model developed via Grasshopper, Ladybug, Honeybee, and Octopus plug-ins.	Hospital Building	• Parametric design with evolutionary algorithms improves building performance. • Multi-objective optimization enhances daylight performance while reducing energy consumption. • Adaptive facade system improves indoor daylight levels and energy performance. • Genetic algorithm approach gradually improves daylighting performance through 15 generations

2015	[17]	DIVA plug-in for Rhinoceros/Grasshopper software integrates daylight and energy performance. Genetic Algorithms (GA) embedded in Galapagos evolutionary solver for optimization.	Office Building	• Optimized shading solution enhances comfort levels and energy efficiency significantly. • Integration of genetic algorithms with parametric design achieves optimized solutions.

A review of existing literature reveals that simulation-based daylight studies have become a dominant method for evaluating visual comfort, energy efficiency, and thermal performance across various building types. Researchers such as Jin et al. (2024) [7] and Ma & Yang (2022) [15] effectively used tools like ENVI-met and Ladybug-Honeybee to optimize architectural form and orientation for daylight access and thermal regulation. Their studies, conducted in public buildings and schools, emphasize that atrium-centered designs, when paired with simulation-driven interventions, can lead to significant energy savings (up to 46.54%) and enhanced thermal comfort. Similarly, Besbas et al. (2022) [16] and González & Fiorito (2015) [17] demonstrated the power of parametric and evolutionary algorithms in refining facade systems and external shading for improved daylight metrics in hospitals and offices. These works confirm that simulation-based approaches can play a critical role in advancing energy-efficient architecture, especially when aligned with genetic optimization frameworks and advanced plug-in workflows like Octopus and Galapagos.

On the other hand, user-centered studies, such as those by Janga et al. (2024) [8], Liu et al. (2023) [13], and Dang et al. (2023) [14], incorporated field data collection and subjective responses to validate simulation outputs. These studies explored occupants' perception of fluctuating illuminance, preferences for daylight uniformity, and visual fatigue factors. The adoption of tools like critical flicker-fusion tests and spatial daylight autonomy (sDA) helped bridge the gap between simulation environments and lived experiences. However, most of these efforts are geographically centered in East Asia or Europe and remain constrained to specific building types like classrooms or small offices. While they excel in integrating illuminance metrics with user experience, they often fall short in offering scalable retrofit strategies—especially for buildings already constructed in resource-constrained or high-heat environments.

Despite this breadth of knowledge, very few studies focus on daylighting analysis within the Pakistani context—particularly in educational buildings where energy conservation, thermal comfort, and user well-being are all pressing concerns. Most simulation studies in the region lack in-situ validation, localized material definitions, or building typologies reflective of Pakistani public sector construction. Furthermore, there is little exploration of scalable, cost-effective interventions such as light shelves and solar tubes in combination, especially in atrium-based layouts. Considering the sharp rise in energy costs and the need for healthier, more productive indoor environments, this study addresses a significant research gap. It offers a simulation-validated, field-tested evaluation of advanced daylighting strategies in a real educational facility in Lahore, aiming to enhance natural light performance while informing sustainable, user-responsive design practices across similar institutional contexts in Pakistan.

METHODOLOGY

This study employed a simulation-validated empirical approach to assess the effectiveness of light shelves and solar tube systems in enhancing natural daylighting in an atrium-based educational building. The methodology focused exclusively on illuminance levels (lux) to measure and compare the performance of various daylighting interventions within faculty office spaces. The study approach comprised five stages. The Rhino model's dependability was assessed in three steps: (1) illuminance measurement and simulation validation; (2) simulation of the offices from step one to determine daylighting metrics. To enhance natural illumination within enclosed faculty office spaces, two passive daylighting systems were incorporated into the simulation environment: light shelves and solar tube systems. These interventions were selected based on their proven effectiveness in redistributing daylight deeper into interior zones, reducing glare, and minimizing reliance on artificial lighting in deep-plan or atrium-connected spaces [18, 19].

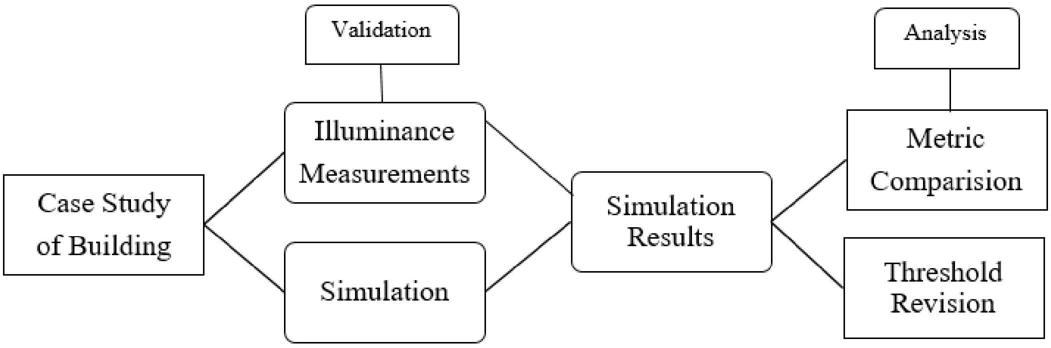


Figure 1. Research Methodology

The research methodology was structured into three phases:

Case Study Description:

The study was conducted at Punjab Tianjin University of Technology Lahore (PTUT), Pakistan (Latitude: 31.4374°N, Longitude: 74.2964°E). The building is symmetrical, includes faculty offices and lobbies that are linked to an atrium surrounded by steel frames covered with fiber panels, the floor presented in the Figure 4. The chosen faculty offices being studied are in a diamond shape and feature windows on every side, the window and door schedule of case study rooms are shown in the Table 2. The ground level offices are arranged on an East/West orientation, with the first level offices dispersed on a North/South orientation

Lahore has a hot semi-arid climate (BSh) characterized by notable temperature fluctuations. Summers are characterized by high temperatures, reaching over 40°C in June, while nights are around 27°C. Winters are gentle, with temperatures in January ranging from 5°C to 19°C. The amount of sunshine is influenced by seasonal variations, cloud cover, and atmospheric conditions. Architectural planning faces difficulties in summer due to high temperatures and intense sunlight, particularly in managing heat buildup and maintaining occupant comfort. Faculty offices need precise design and environmental measures to reduce the effects of heat and sunlight.

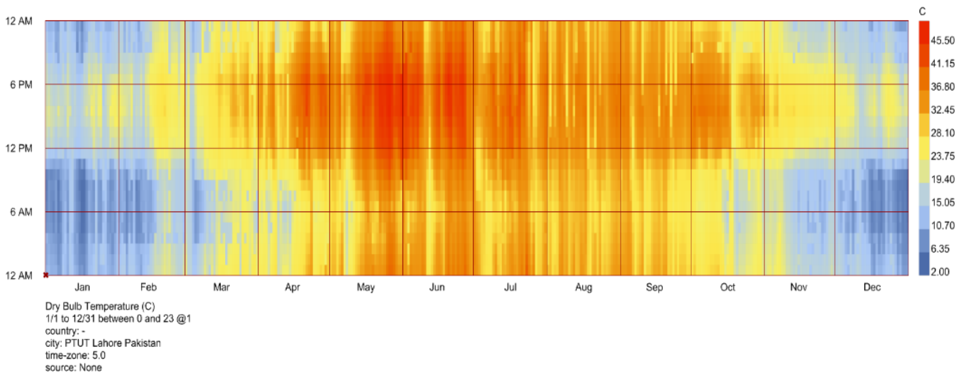


Figure 2. Dry bulb temperature of Lahore, Pakistan.

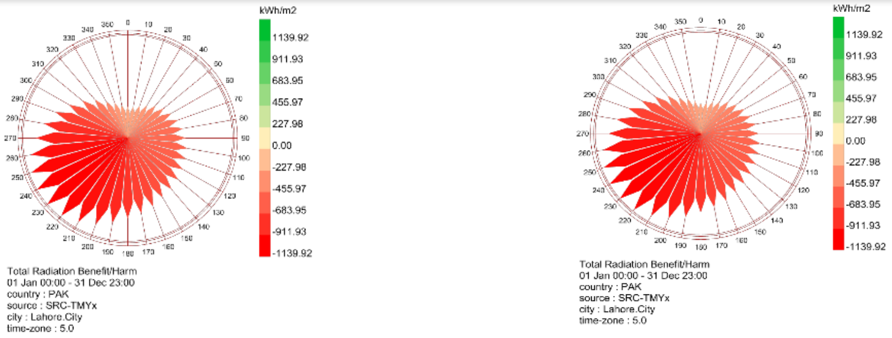
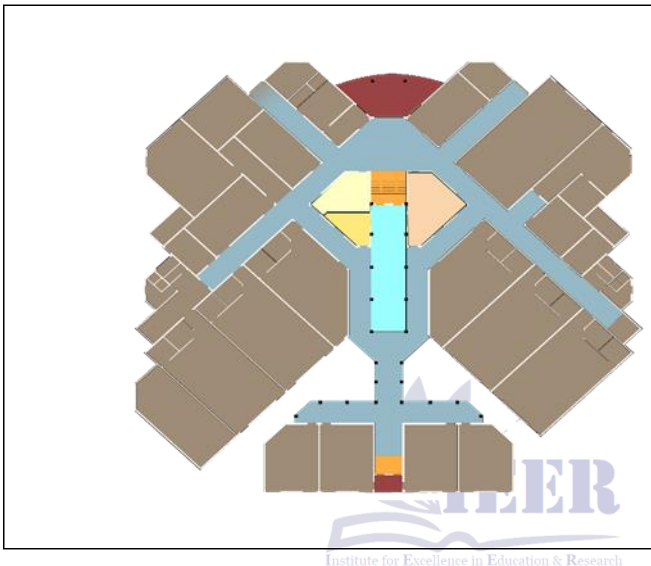


Figure 3. Direct and diffuse normal radiation (KWh/m^2) Lahore, Pakistan.

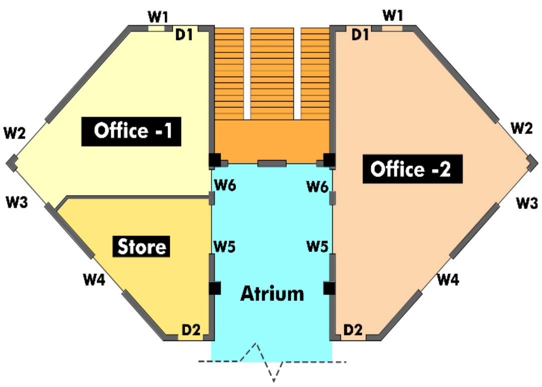


Code	Color
Atrium	
Office-1	
Office-2	
Store	
Lobby	
Staircase	
Other Building	

Figure 4. Case Study Floor Plan

Baseline Field Measurements: The case study was conducted in the faculty offices of Punjab Tianjin University of Technology (PTUT), Lahore. Illuminance levels were measured using an LX-9621 digital lux meter, with accuracy ±50/0 d (Figure 5), under clear sky conditions. Measurements were taken on a 4'-0" × 4'-0" grid at a height of 0.85 meters above the floor plane to represent the typical working surface as shown in Figure 6. This data served as the baseline for simulation calibration and later comparison with proposed daylighting strategies. The measurements were taken on location between 8:00 and 16:00. The CIE criteria state that the sky was clear and sunny on these particular measurement days.

Table 2. Window and Door Schedule of Case Study Rooms



Code	Size	Sill Level	Material
W1	2.5'x 6'	3'-0"	Single Glass Aluminum Frame
W2	6'x 3'	6'-0"	Single Glass Aluminum Frame
W3	6'x 3'	6'-0"	Single Glass Aluminum Frame
W4	6'x 3'	6'-0"	Single Glass Aluminum Frame
D1	6'x 3'	0'-0"	Aluminum door, double, sky light
D2	6'x 3'	0'-0"	Single Panel Frame ,sky light

Figure 5. Illuminance meter instrument (LX-9621).

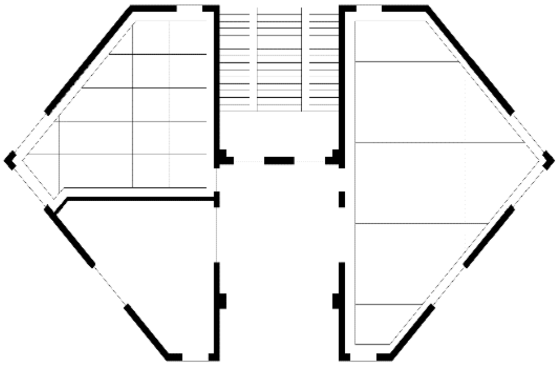


Figure 6. The plan (top) and section of case study rooms and placement of the reference points.

Rad. Material Type (Layers)	Reflectance
White plaster	0.80
Interior plaster	0.80
Floor	0.40
Ceiling	0.80
Window wood	0.25
Glass material (Single glazing)	0.90

Table 3. The physic-optical properties of the materials

Digital Modeling and Simulation Validation: A detailed 3D model of the case study building, including the atrium, walls, openings, and material details, was developed in Rhinoceros (Rhino) and Grasshopper. Material properties such as surface reflectance were defined according to actual construction conditions as shown in Table 3, and input into the simulation model using the Ladybug and Honeybee plug-ins (used for environmental analysis within the Grasshopper environment.) and Climate Studio (utilized for advanced daylighting analysis).

Validating simulation results, particularly in daylighting performance simulations, is crucial to ensure accuracy, given the difficulties in predicting results. There are few guidelines for validating daylight, which makes it challenging to identify errors accurately, with no established standard by researchers. Nevertheless, it is crucial to consult the guidelines from recent internationally acclaimed studies that have utilized comparable methods in validation-related tasks [20]. Figure 7 shows a comparison between the illuminance values measured and simulated on the work plane. Calculating the relative error (RE) [16] is essential for comparing the measurement data with the simulation results. This measurement assesses the precision of mistakes and is computed in the following manner:

$$\mathbf{RE} = \frac{|\ \mathbf{Mi} - \mathbf{Si}\ |}{\mathbf{Mi}} \times \mathbf{100\%}$$

Mi represents the measured illuminance value, and Si represents the corresponding simulated illuminance value for each measurement point. For energy and thermal validation, a percentage error of less than 5% is necessary [21]. However, for daylight validation, previous studies have found that a relative error of 20–30% in daylight simulation results is considered acceptable [22]. Simulation outputs were validated by comparing simulated illuminance (Si) values to field measurements (Mi). Relative errors between measured and simulated values were found to be within 20%, meeting acceptable thresholds reported in validated daylighting studies [22].

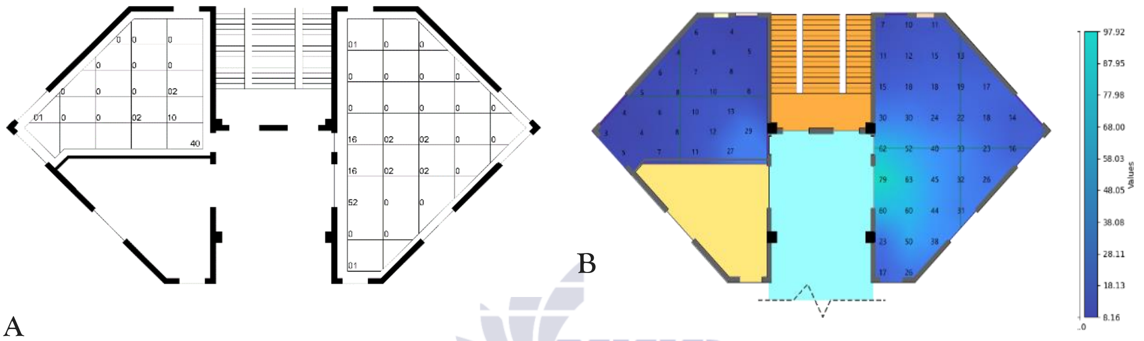


Figure 7. Measured (Fig. A) and simulated (Fig. B) illuminance levels on the work plane for the case study.

RESULTS

1. Light Shelves

Light shelves are horizontal reflective surfaces mounted above eye level on the window wall, designed to redirect incoming sunlight toward the ceiling and thereby increase daylight penetration into the room [23]. Their function is particularly beneficial in side-lit spaces where direct solar exposure at lower levels can cause glare, while upper-zone redirection improves uniformity and illuminance distribution.

In this study, light shelves were digitally modeled using Grasshopper integrated with Radiance and EnergyPlus via the Ladybug and Honeybee toolsets. Their dimensions, material reflectance (assumed 0.80 for matte white surfaces), and height placement were optimized based on guidelines provided in IES LM-83-12 and ASHRAE 90.1-2019 recommendations for daylighting retrofits [24, 25]. The light shelf installations focused on south and east-facing office façades to take advantage of high solar exposure.

Fig. A

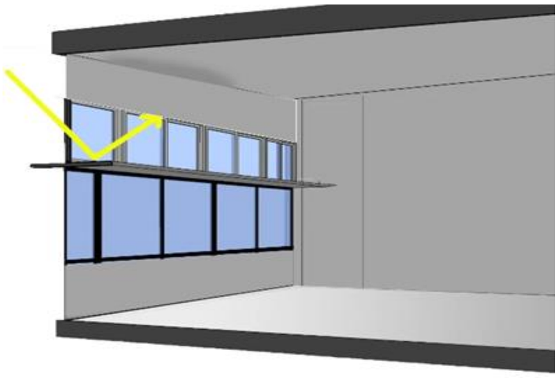


Fig. B

Figure 8. Light Shelves Simulations

Simulation results revealed that the implementation of light shelves significantly increased average illuminance in window-adjacent zones as shown in Figure 8—from 1–61 lux in the base case to 4–171 lux post-intervention—enhancing spatial brightness while mitigating glare risks as shown in Figure 9.

Similar performance gains have been reported in comparable studies, including those by Sabbagh et al. (2022), who observed a 15–17% improvement in daylight levels in Saudi classrooms using optimized shelf geometries [26].

Fig. A

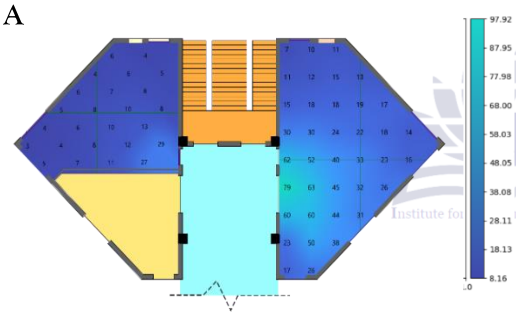


Fig. B

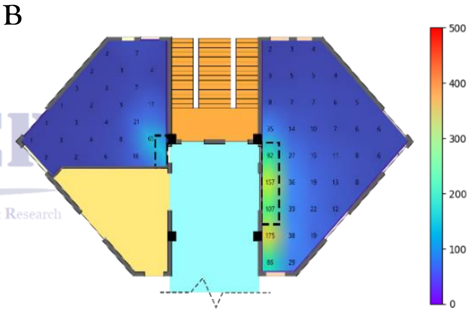


Figure 9. Simulated Base Case Area without Intervention (A) and Modified Base Case Area with Light Shelves (B)

2. Solar Tube Systems

Solar tubes, also referred to as tubular daylighting devices (TDDs), are passive optical systems that capture and channel daylight from the roof into interior spaces via highly reflective cylindrical tubes. These systems consist of three primary components: a rooftop collector dome, a reflective transfer tube, and a ceiling-mounted diffuser [27] as shown in Figure 10. Their applicability is particularly critical in zones without direct window access—such as central offices or internal corridors.

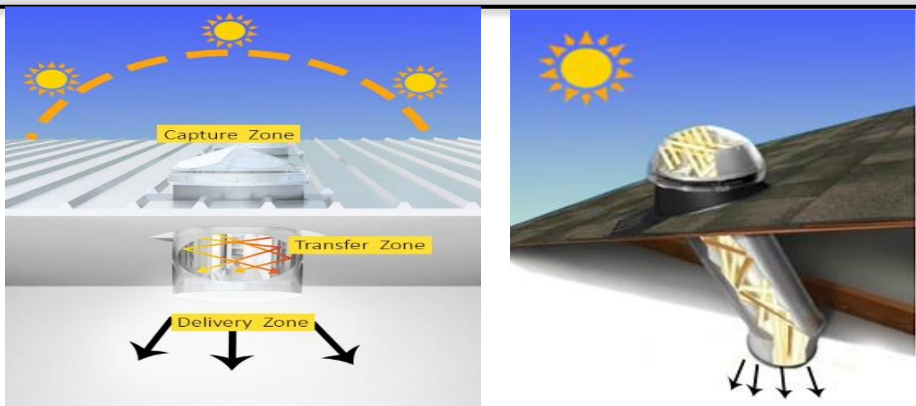


Fig. A **Fig. B**

Figure 10. Typical Structure of Solar Tube

In the digital simulation, four solar tube diameters were tested independently—12", 18", 24", and 32"—to evaluate performance scalability. Each system was modeled with a reflectivity of 0.98 for internal tube surfaces, based on commercially available anodized aluminum lining specifications. The diffuser was modeled to uniformly distribute light across the room ceiling plane, as supported by prior studies on optimized diffuser geometry [28].

Illuminance maps generated through Radiance simulations showed progressive increases in daylight availability with increasing tube diameter. The 12" system improved lux levels to a range of 20–95 lux, while the 24" variant yielded up to 245 lux. The 32" solar tube demonstrated the highest performance, achieving lux values between 260 and 665, ensuring uniform lighting across deep-plan zones as shown in Figure 11. These results are consistent with previous investigations by Balabel et al. (2022), who noted a 20–30% energy saving potential using TDD systems in hot-arid climates [29].

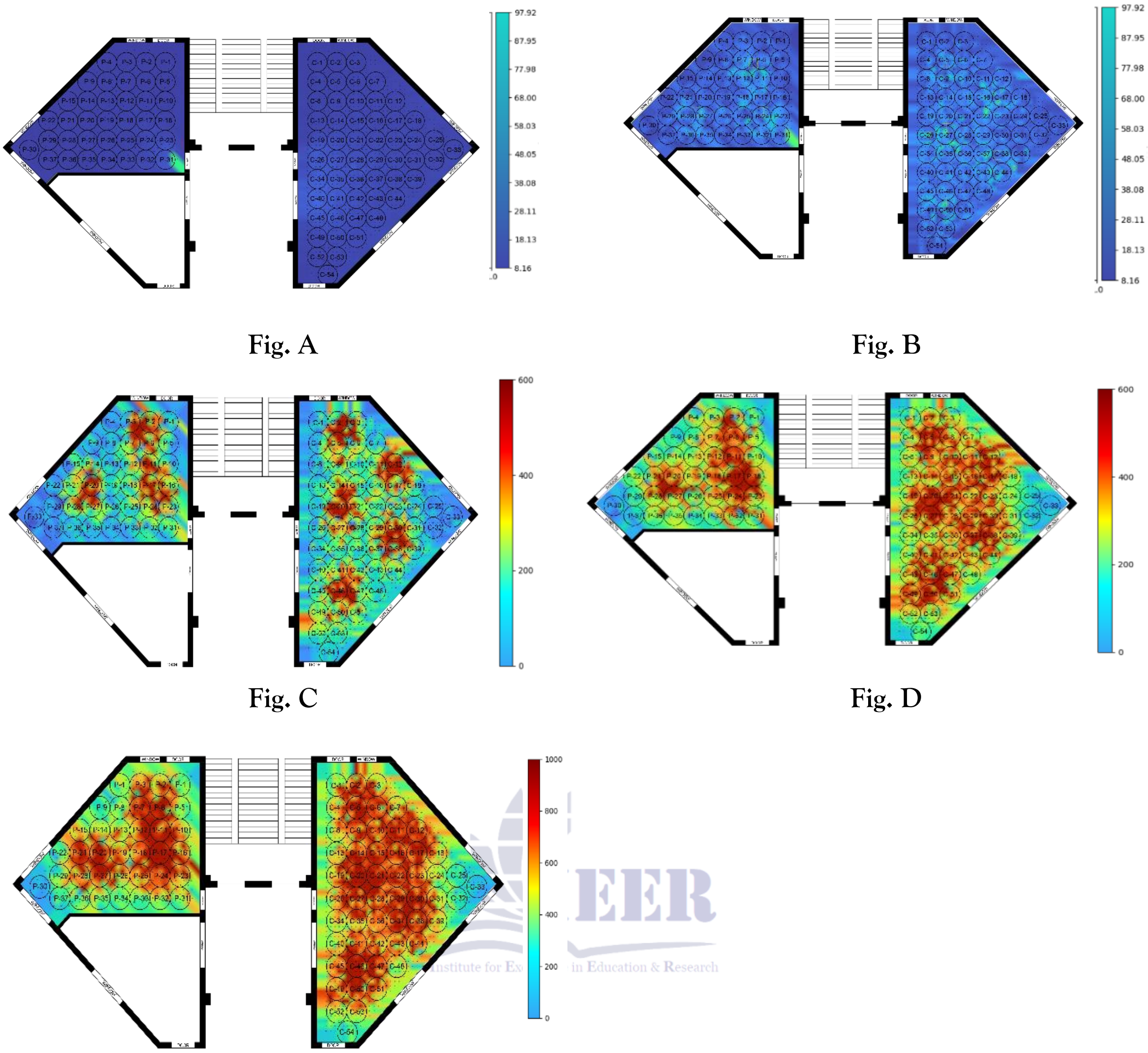


Figure 11. Fig. A – Base Case Model Simulation; Fig. B – Modified Base Case Model with 12-inch Solar Tube; Fig. C – Modified Base Case Model with 18-inch Solar Tube; Fig. D – Modified Base Case Model with 24-inch Solar Tube; Fig. E – Modified Base Case Model with 32-inch Solar Tube.

By implementing and evaluating these two complementary strategies—light shelves for perimeter enhancement and solar tubes for core illumination—the study demonstrates the feasibility of applying passive daylighting systems in educational buildings within high solar radiation regions. The implementation of light shelves and solar tube technology has greatly enhanced the natural light quality and distribution in the office space. Initially, light shelves were introduced to redirect sunlight, reducing glare and improving overall light dispersion. The subsequent installation of solar tube systems in various sizes further increased illuminance levels and ensured a more uniform distribution of natural light. Among all the options, the 32-inch solar tube systems have provided the most significant improvement, offering maximum daylight penetration and even light spread as shown in Figure 12. These advancements have led to a reduced dependency on artificial lighting, improved energy efficiency, and a more comfortable work environment, promoting sustainable and eco-friendly building practices.

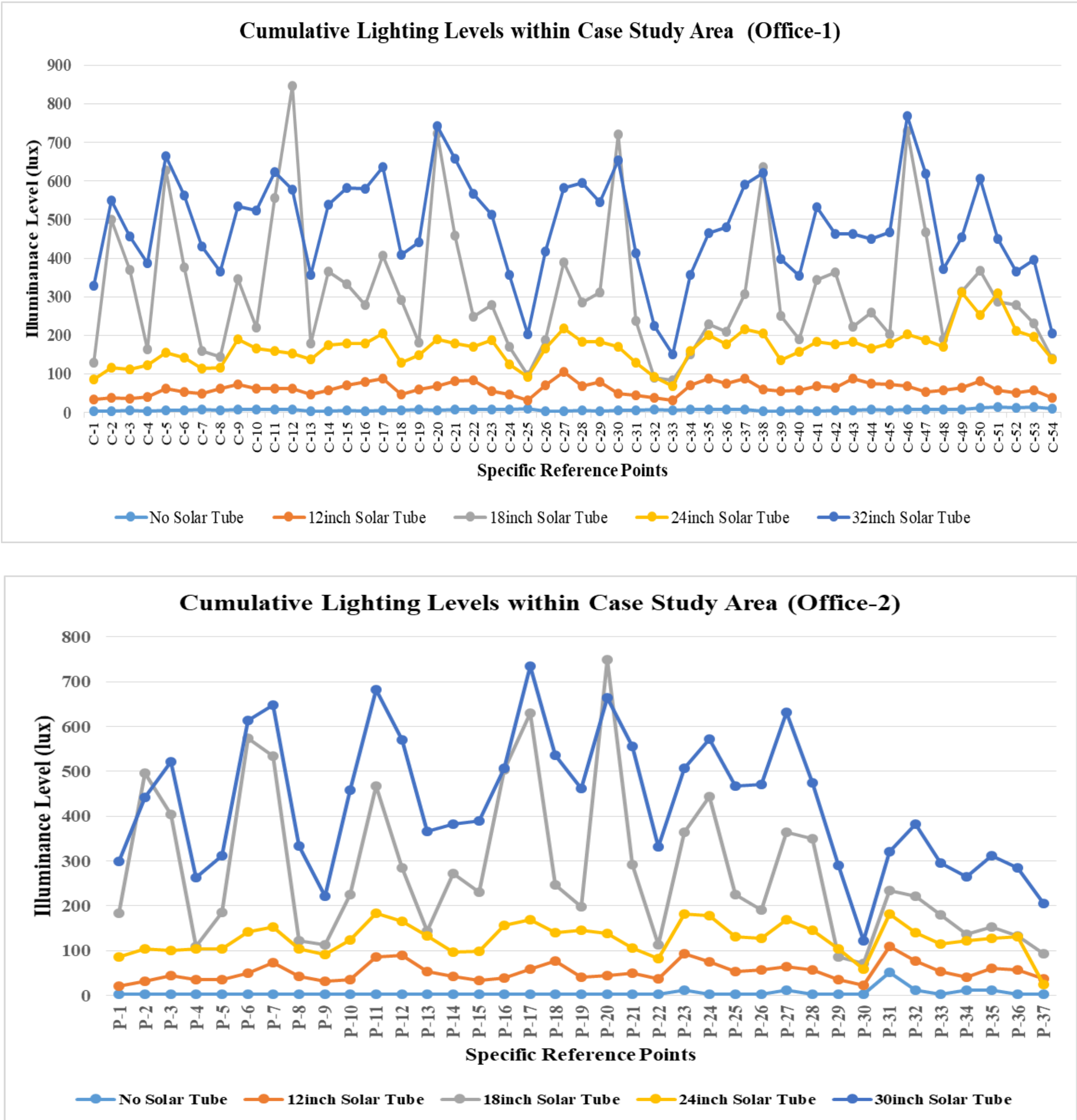


Figure 12. Cumulative Lighting Levels within the Case study Area (Office 1 & Office 2)

DISCUSSIONS

The results of this study demonstrate the effectiveness of combining passive daylighting systems—specifically light shelves and solar tubes—to enhance natural light availability within atrium-based academic buildings. Through simulation-driven experimentation and empirical validation, this research confirms that these interventions significantly increase indoor illuminance levels, reduce reliance on artificial lighting, and improve overall spatial light uniformity.

The introduction of light shelves led to a noticeable increase in horizontal illuminance levels in window-facing zones, improving values from 1–61 lux (base case) to 4–171 lux post-intervention. This enhancement is consistent with findings from Sabbagh et al. (2022), who observed a 15–17% improvement in classroom daylight levels using optimized shelf designs in Saudi Arabian schools [26]. Light shelves, by redirecting high-angle sunlight onto ceilings, contribute to deeper daylight penetration while minimizing direct glare—a design principle well-supported by Tzempelikos and Athienitis (2007), who noted reduced visual discomfort and energy loads in offices employing controlled shading and reflection strategies [19]. The results of this study reaffirm these mechanisms, especially for east- and south-facing façades where solar gain is highest in Lahore's climate.

The application of solar tube systems, on the other hand, yielded more dramatic improvements, particularly in spaces lacking direct window exposure. The 12", 18", and 24" systems progressively improved internal illuminance, but it was the 32" solar tube that achieved the most significant gains, raising indoor lux levels to a range of 260–665 as shown in Figure 13. This confirms the strong correlation between solar tube diameter and daylight transmission efficacy, as reported by Balabel et al. (2022), who documented energy savings of up to 30% in buildings retrofitted with tubular daylighting devices in hot-arid climates [29]. These findings also align with Aldawoud (2012), who emphasized the importance of diffuser design and tube reflectivity in maximizing daylight output from TDD systems [28].

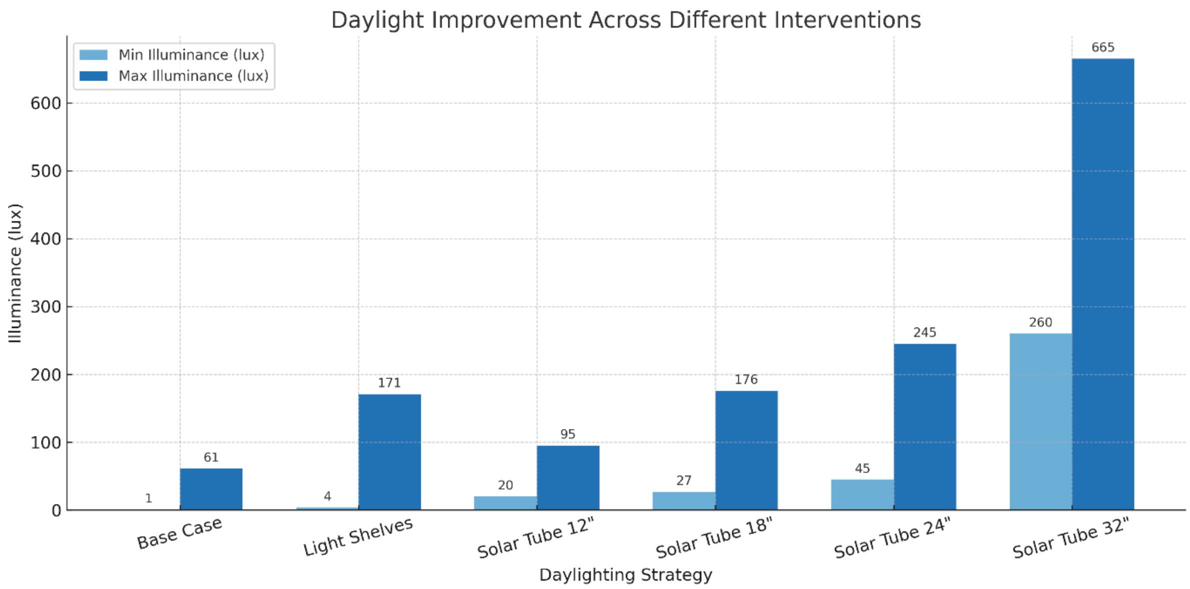


Figure 13. Daylight Improvement across various interventions

Importantly, this study contextualizes these findings within Pakistan's climatic and construction conditions, where educational buildings are often poorly oriented for daylight performance and lack integrated lighting controls. Unlike many existing international studies conducted in temperate zones with advanced building systems, the simulated improvements here were applied to a real-world academic building with conventional materials and no automated systems. The illuminance increases observed—from as low as 6 lux to over 600 lux—are significant in terms of improving workspace functionality, especially in faculty offices where visual clarity is essential for reading, writing, and computer-based tasks. This aligns with research by Woo et al. (2021) and Liu et al. (2023), which found that well-lit environments directly contribute to user well-being, visual performance, and even cognitive productivity in educational settings [13, 19].

The simulated illuminance values from this study—ranging from 260 to 665 lux with the 32" solar tube—align closely with international benchmarks. They exceed the WELL Building Standard **v2** minimum of 300 lux at the work plane for at least four hours per day for visual comfort and occupant health in office settings [30] and fall within or slightly above the ASHRAE 90.1-2019 recommended range of 150–500 lux for office spaces [31] for minimizing energy consumption while maintaining comfort- indicating effective daylight distribution without risk of excessive glare. These results confirm that the proposed daylighting strategies not only enhance energy efficiency but also meet global standards for occupant well-being in academic work environments [3][4].

Moreover, the dual-strategy approach—using light shelves for window zones and solar tubes for core areas—proves especially adaptable to institutional buildings with atrium-based layouts, which are common in Pakistan's public university sector. This integration not only balances illuminance distribution but also represents a low-cost, scalable retrofit solution that can be implemented without major structural changes. Such design adaptability is critical in developing countries where resource limitations restrict high-tech upgrades.

While the study validates daylighting improvements through simulation and physical measurement, it is important to acknowledge the scope for further development. Seasonal variations, long-term aging of materials (e.g., reflectors, domes), and actual user behavior were beyond this study's scope but remain vital for future exploration. The lack of standardized simulation validation protocols for daylighting—also noted by Reinhart and Andersen (2006) [21]—highlights the importance of cross-referencing simulation with real-world data, a principle applied rigorously in this research.

In conclusion, this study confirms that passive daylighting interventions—light shelves and solar tubes—can be highly effective in improving indoor lighting environments in educational buildings situated in hot semi-arid climates. The integration of simulation tools with empirical measurement offers a robust methodology for architects, planners, and building managers seeking to enhance visual comfort and energy efficiency in the context of sustainable campus development.

CONCLUSION

This study has demonstrated that a strategic combination of light shelves and solar tube systems can significantly improve natural daylight conditions in atrium-based educational buildings located in hot semi-arid climates, such as Lahore, Pakistan. Through detailed simulation and validation using measured illuminance data, it was found that light shelves increased daylight levels in window-adjacent spaces by up to 180%, while solar tube systems, particularly the 32" configuration, elevated internal illuminance from a base of 6 lux to a peak of 665 lux. These interventions not only enhanced visual comfort and spatial light distribution but also aligned well with global standards: the WELL Building Standard's minimum 300 lux target for office spaces and the ASHRAE 90.1-2019 recommended illuminance range of 150–500 lux were either met or exceeded in key interior zones. Importantly, the study demonstrates that even in resource-constrained contexts, cost-effective retrofitting with passive daylighting technologies can substantially reduce reliance on artificial lighting, thereby supporting sustainability goals and occupant well-being.

While this study successfully demonstrates the effectiveness of light shelves and solar tubes in enhancing daylight performance, it is limited to static simulations under clear sky conditions and does not account for seasonal variations or dynamic daylight behavior. Metrics such as glare, Spatial Daylight Autonomy (sDA), and Annual Sunlight Exposure (ASE) were not evaluated, and user comfort assessments were not conducted. Future research should incorporate annual climate-based simulations, glare analysis, and occupant feedback to provide a more comprehensive understanding of visual comfort, energy savings, and long-term applicability across diverse building types and climatic contexts.

REFERENCES

1. Htet, A., et al. The effectiveness of daylight management in building: A review. AIP Publishing.
2. Woo, M., et al., Access to daylight and views improves physical and emotional wellbeing of office workers: a crossover study. Frontiers in Sustainable Cities, 2021. **3**: p. 690055.
3. Lee, J. and M. Boubekri, Impact of daylight exposure on health, well-being and sleep of office workers based on actigraphy, surveys, and computer simulation. Journal of Green Building, 2020. **15**(4): p. 19-42.
4. Akram, N., et al., Shedding Light on Financial Sustainability: Data driven insights of the Economic Implications of Energy-Efficient Lighting in the Construction Industry. 2024.

5. Kazemzadeh, M., V. Ghobadian, and M. Tahbaz, Atrium and Daylight Performance in Office Buildings: Effect of Atrium's Roof Shape on Daylight Reception. Armanshahr Architecture & Urban Development, 2015. **8**(دومین ویژه نامه نورپردازی): p. 53-61.
6. Krarti, M. Estimation of lighting energy savings from atrium daylighting for office buildings. American Society of Mechanical Engineers.
7. Jin, Z., et al., Indoor thermal nonuniformity of atrium-centered public building: Monitoring and diagnosis for energy saving. Case Studies in Thermal Engineering, 2024. **54**: p. 104058.
8. Jang, S., Y.-K. Baik, and S. Kim, Analyzing the effects of illuminance variations on occupants' visual perceptions to determine permissible dimming controls of lighting in a small office. Building and Environment, 2024. **254**: p. 111322.
9. Akram, N., et al., Beyond Illumination: Stakeholders Perspectives and Preferences on Eco-Friendly Lighting for Sustainable Cities. Metallurgical and Materials Engineering, 2025. **31**(1): p. 249-276.
10. Zia, M.T., et al., The role and impact of artificial intelligence on project management. The Asian Bulletin of Big Data Management, 2024. **4**(2): p. 178-185.
11. Blouch, N., et al., Economic Feasibility of Energy Saving by Incorporating Daylight: A Case Study of College Building in Multan-Pakistan. Technical Journal, 2021. **26**(02): p. 67-80.
12. Akram, N., et al., Decoding the Interplay of Lighting and Spatial Dynamics: A Simulation-Based Case Study Analysis across Diverse Building Orientations. Metallurgical and Materials Engineering, 2024. **30**(4): p. 434-458.
13. Liu, B., et al., A study on daylighting metrics related to the subjective evaluation of daylight and visual comfort of students in China. Energy and Buildings, 2023. **287**: p. 113001.
14. Dang, R., Y. Liu, and S. Chang, The impact patterns of classroom lighting parameters on visual fatigue and a mathematical model. Building and environment, 2023. **234**: p. 110193.
15. Ma, J. and Q. Yang, Optimizing annual daylighting performance for atrium-based classrooms of primary and secondary schools in Nanjing, China. Buildings, 2023. **13**(1): p. 11.
16. Besbas, S., et al., Parametric-based multi-objective optimization workflow: Daylight and energy performance study of hospital building in Algeria. Sustainability, 2022. **14**(19): p. 12652.
17. González, J. and F. Fiorito, Daylight design of office buildings: Optimisation of external solar shadings by using combined simulation methods. Buildings, 2015. **5**(2): p. 560-580.
18. Li, D.H.W. and J.C. Lam, Evaluation of lighting performance in office buildings with daylighting controls. Energy and buildings, 2001. **33**(8): p. 793-803.
19. Tzempelikos, A. and A.K. Athienitis, The impact of shading design and control on building cooling and lighting demand. Solar energy, 2007. **81**(3): p. 369-382.
20. Nocera, F., et al., Daylight performance of classrooms in a mediterranean school heritage building. Sustainability, 2018. **10**(10): p. 3705.
21. Reinhart, C.F. and M. Andersen, Development and validation of a Radiance model for a translucent panel. Energy and buildings, 2006. **38**(7): p. 890-904.
22. Ramos Ruiz, G. and C. Fernandez Bandera, Validation of calibrated energy models: Common errors. Energies, 2017. **10**(10): p. 1587.
23. Reinhart, C.F. and O. Walkenhorst, Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and buildings, 2001. **33**(7): p. 683-697.
24. Baydoğan, M.Ç. and V. Özkantar, Evaluation of daylight performance metrics according to country guidelines: The case of educational

buildings in Turkey. Energy and Buildings, 2023. **297**: p. 113487.
25. Tyler, M., et al., ANSI/ASHRAE/IES. 2021.
26. Sabbagh, M., S. Mandourah, and R. Hareri, Light shelves optimization for daylight improvement in typical public classrooms in Saudi Arabia. Sustainability, 2022. **14**(20): p. 13297.
27. Marouf Elsayed, A. and T. Ahmed Abd El-Mawgood, An Analysis of the Lighting and Energy Saving Capabilities of Tubular Day lighting Devices (TDDs)"A Case Study of a Laboratory in Cairo, Egypt". International Journal of Architectural Engineering and Urban Research, 2022. **5**(2): p. 312-327.
28. Zhang, X., Daylighting performance of tubular solar light pipes: measurement, modelling and validation. 2002.
29. Balabel, A., et al., Potential of Solatube technology as passive daylight systems for sustainable buildings in Saudi Arabia. Alexandria Engineering Journal, 2022. **61**(1): p. 339-353.
30. Kaymaz, E. and B. Manav, A proposal on residential lighting design considering visual requirements, circadian factors and energy performance of lighting. Journal of Asian Architecture and Building Engineering, 2023. **22**(5): p. 2851-2866.
31. Nambiar, C., M. Rosenberg, and S. Rosenberg, End Use Analysis Of ANSI/ASHRAE/IES Standard 90.1-2019. ASHRAE Journal, 2023. **65**(4): p. 34-42.