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A Study on Pendant and Blackboard Asymmetric Lens LED Luminaires for Optimal Illumination in Classrooms

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Abstract: This study examines the transformative impact of integrating pendant asymmetric lens (PAL) and blackboard asymmetric lens (BAL) LED luminaires to enhance classroom lighting, with the goals of replicating the ambient effects of natural daylight and promoting energy efficiency. This research focuses on improving the quality of learning environments through uniform, soft, and diffused lighting, which mimics sky-like illumination while adhering to sustainable energy practices. Advanced asymmetric lens LED luminaires are employed to achieve optimal lighting distribution, as indicated by luminous intensity distribution curves. Comparative analyses in diverse educational settings reveal significant improvements in ceiling illuminance, ranging from 935 to 1000 lx, and workspace illuminance from 660 to 720 lx, with reduced glare (UGR < 10). This results in bright, visually comfortable spaces conducive to learning. Additionally, the PAL and BAL solutions outperform conventional lighting systems like stretched ceilings and lightboxes by maintaining clear overhead spaces, eliminating shadows, and offering cost-effective solutions. This successful integration demonstrates a notable advancement in the development of energy-efficient, visually comfortable educational environments, contributing to the goals of sustainability and improved well-being for both students and teachers.

Keywords: asymmetric lens; illuminance uniformity; glare free; shadow free; sky-like ceiling; LED luminaire; classroom lighting

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Citation: Giang, D.T.; Duong, P.H.; Quan, N.V.; Trang, T.N.T.; Khanh, T.Q. A Study on Pendant and Blackboard Asymmetric Lens LED Luminaires for Optimal Illumination in Classrooms. *Sustainability* **2024**, *16*, 10015. https://doi.org/10.3390/su162210015

Academic Editor: Chiara Burattini

Received: 10 October 2024
Revised: 7 November 2024
Accepted: 14 November 2024
Published: 16 November 2024

1. Introduction

Recent studies underscore the importance of optimized lighting in educational settings, with modern approaches focusing on enhancing both cognitive and emotional well-being. Contemporary lighting designs aim to emulate natural daylight conditions, promoting visual comfort and minimizing glare, particularly in learning environments that benefit from "sky-like" illumination [1]. Human-centric lighting solutions are increasingly implemented to support circadian rhythms and improve visual comfort through indirect, uniform lighting distribution, thereby creating a balanced and shadow-free atmosphere [2,3]. These advancements align with 21st-century pedagogical needs, where lighting plays a critical role in supporting student focus and overall classroom experience.

Classroom lighting in tropical regions poses unique challenges not typically encountered in more temperate environments. Ceiling fans, while essential for air circulation, can cause disruptive rotating shadows when combined with conventional overhead lighting, resulting in uneven light distribution. Efforts to lower lights and counteract these shadows often inadvertently lead to increased glare and a reduced uniformity of illumination. Additionally, the strong contrast in luminance between the ceiling and light fixtures can create visual discomfort, and many lighting solutions fail to adequately illuminate blackboards, often not meeting the 500 lx standard, which is defined by European lighting standards like EN 12464–1:2021 [4].

The adverse effects of classroom lighting, such as glare induced by conventional fluorescent lights and their associated 100 Hz flicker, have been shown to significantly impact both students' comfort and performance. Winterbottom and Wilkins (2009) [5] noted these issues, with illuminance levels often exceeding recommended standards and causing significant glares. Kent et al. (2020) [6] further explored how ceiling fan-induced visual flicker, particularly from opaque blades, can detrimentally affect task performance and increase discomfort, a problem less pronounced with transparent fan blades.

Higher horizontal illuminance levels have been linked to increased subjective alertness as indicated by Duijnhoven (2018) [7], and de Vries (2018) [8] noted that room appraisal is significantly influenced by wall luminance, with optimal levels being around 72 cd/m^2 for improved environmental perception. Toftum et al. (2018) [9], Golasi et al. (2019) [10], and Yang et al. (2020) [11] further explored the interplay between correlated color temperature (CCT), thermal comfort, and perceived brightness within classroom settings.

A study by de Vries et al. (2021) [12] reveals that a strategic increase in indirect lighting coupled with a uniform distribution across the ceiling enhances perceived brightness and attractiveness, emphasizing the significance of well-considered lighting design in educational spaces for both aesthetics and practicality.

Ye et al. (2020) [13] demonstrated that a 90° lighting distribution angle achieves the maximum uniformity and an acceptable unified glare rating (UGR) of less than 19, suitable for classrooms. Yet, despite these advancements, such as the deployment of large LED lightboxes to curb glare, rotating shadows from ceiling fans continue to challenge the efficacy of lighting in active learning environments.

Building on foundational work in optics and lighting design by Fang et al. (2013) [14] and Lai et al. (2016) [15], Zhu ZM et al. (2017) [16] investigated the use of off-axis surfaces to enhance rectangular illumination and improve lighting distribution. Babadi et al. (2020) [17] investigated both symmetric and asymmetric freeform lenses to achieve consistent classroom lighting. Sorgato et al. (2019) [18] delved into wavefront tailoring for extended light sources, and Li et al. (2021) [19] optimized double freeform surfaces for substantial ray bending.

Building upon the research of Giang et al. (2020) [20] and Kang et al. (2020) [21], this work presents the development of a novel pendant asymmetric lens (PAL) LED luminaire designed to address specific lighting challenges in tropical classroom settings. This solution not only ensures even lighting distribution but also eliminates the discomfort caused by glare and moving shadows. This approach, emphasizing indirect lighting, aligns with the aesthetic and functional goals for educational spaces, promoting an optimal learning environment by enhancing both visual comfort and energy efficiency.

Moreover, the integration of the adaptable CCT feature, aligned with circadian rhythms, into the PAL LED system enhances the health and well-being of both teachers and students, reflecting modern standards for environmental and sustainability practices, as underscored by House (2021) [22] and Ticleanu (2021) [23].

The remainder of this paper is organized as follows: Section 2 details the design method used to develop the PAL and BAL LED luminaires. Section 3 presents the simulation and real-world performance results of the luminaires in classroom settings. Section 4 discusses the lighting calculation results, while Section 5 provides an in-depth discussion of the findings and implications. Finally, Section 6 offers conclusions and suggests potential directions for future research.

2. Design Method

Figure 1 outlines the design and optimization process for the luminaire system. The process starts with defining lighting objectives (design methodology), followed by distribution curve design and ray tracing simulation to create the initial model. The design is iteratively refined until it meets ideal distribution criteria, then proceeds to luminaire fabrication. In lighting simulation, height and arrangement are optimized for uniform illuminance, with adjustments as needed to meet uniformity targets. The process concludes with installation and testing and evaluation and results to verify performance standards.

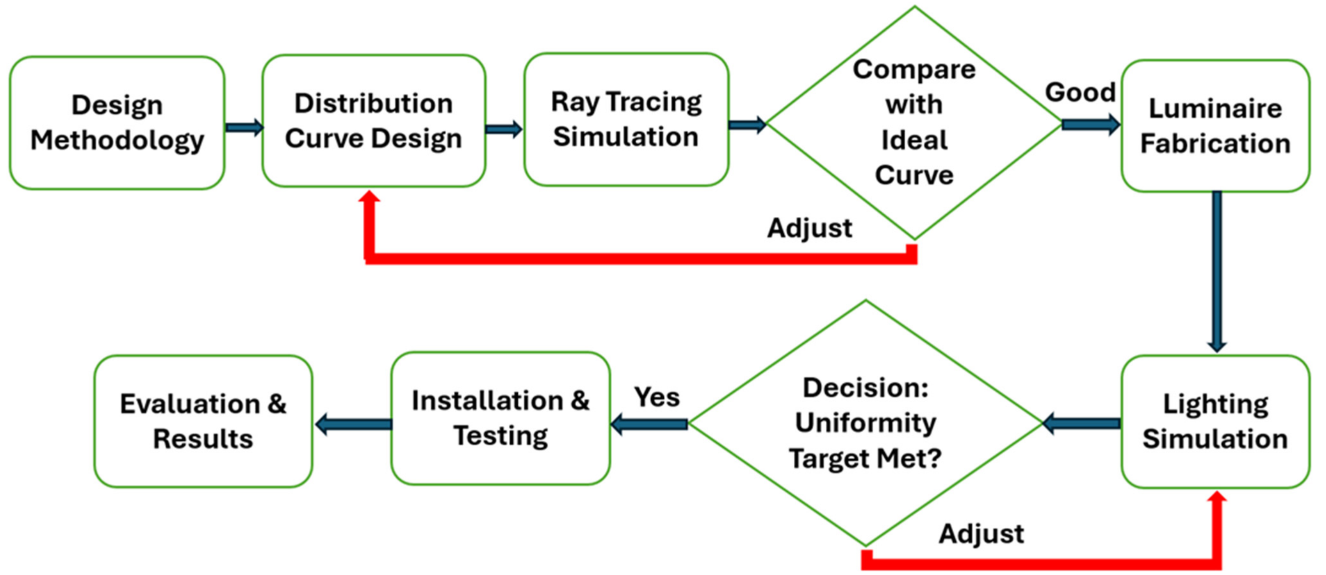

Figure 1. A flowchart illustrating the luminaire design and optimization process.

To ascertain the quality of classroom lighting, parameters such as illuminance uniformity (U_o) and UGR must be comprehensively assessed. The UGR value, indicative of glare levels, should ideally be below 19, with illuminance exceeding 300 lx, and U_o greater than 0.6 to ensure a productive learning environment [23].

A typical classroom space, measuring 8.4 × 6.6 × 3.8 m (length × width × height), was chosen for simulation. The objective was to utilize the uniformly painted white ceiling as a large, secondary light source, effectively eliminating the common problems of glare and shadow under controlled conditions, as classrooms are equipped with curtains to minimize direct solar beams. As shown in Figure 2a, a 3 × 5 grid of luminaires was strategically positioned for indirect ceiling lighting, supplemented by three additional luminaires dedicated to blackboard illumination. Considering the arrangement where the length of luminaire rows is significantly longer than the distances between them, the concept of linear illuminance (measured in lm/m) was adopted to simplify our 3D model into a 2D representation, rather than using the conventional area-based illuminance (measured in lm/m^2). It was postulated that if a logistic-shaped linear illuminance is emitted by each row of luminaires, the sum of these distributions (I1 + I2 + I3) would yield a constant illuminance between them, as depicted in Figure 2b.

This design ensures a linear illuminance distribution that is integral for achieving ideal classroom lighting by arranging light sources at specific points (e.g., P1 at 1.4 m) to foster a logistic intensity distribution. This approach is engineered to emulate the even, diffused spread of daylight, enhancing the learning atmosphere. The mathematical formulation for the linear illuminance distributions, as seen from the left and right sides of the installation position P1, is as follows:

For the left-hand-side segment, ranging from $x = -2x_o$ to P1, the linear illuminance contributed by the first luminaire row I_L is expressed by the following equation:

$$\mathrm{I_L}(x,\ \mathrm{P1}) \ = \ \frac{\mathrm{I_m}}{1 + e^{-k(x + x_o - \mathrm{P1})}} \tag{1}$$

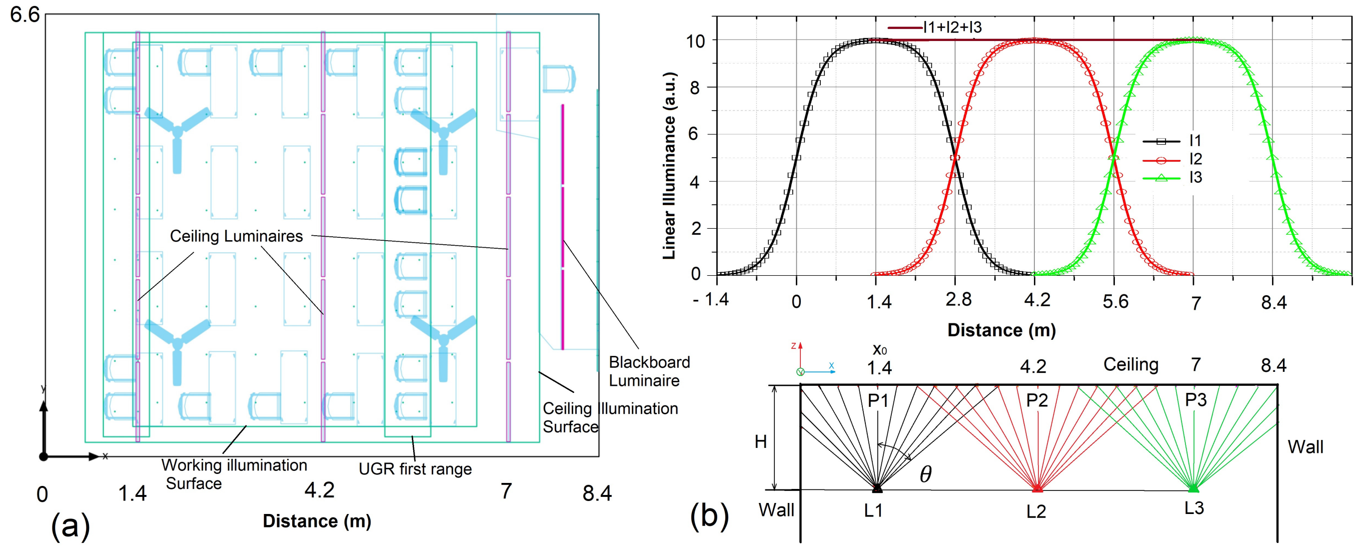

Figure 2. The ideal classroom lighting layout and intensity distribution: (**a**) shows the strategic placement of fifteen innovative PAL LED luminaires in the ceiling and three BAL LED luminaires above the blackboard for enhanced visibility, and (**b**) shows the installation positions P1 = 1.4 m, P2 = 4.2 m, and P3 = 7 m for the luminaire rows L1, L2, and L3, along with the individual and combined light intensity distributions I1, I2, and I3 for each row.

Correspondingly, on the right-hand side, from P1 to the end of the luminaire's influence at $2x_o$, the intensity $\mathrm{I_R}$ is given by the following equation:

$$\mathrm{I_R}(x, \mathrm{P1}) \ = \ \frac{\mathrm{I_m}}{1 + e^{k(x - x_0 - \mathrm{P1})}} \tag{2}$$

In these equations, $\mathrm{I_m}$ denotes the peak linear illuminance achievable by the luminaire. The parameter k represents the logistic growth rate, which defines how quickly the light intensity transitions from its lowest to highest value. A k value of 6 was selected to concentrate light effectively within the target area.

The angular intensity distribution $D(\theta)$ in our model is described by the ratio of the logistic intensity to the change in angle $\Delta\theta$:

$$D(\theta) \ = \ \frac{\mathrm{I}(x)}{\Delta\theta(x)} \ = \ \frac{\mathrm{I_m}}{\left(1 + e^{-k(x - x_0)}\right)\Delta\theta(x)} \tag{3}$$

where θ is the angle between the light ray and the vertical axis, as shown in Figure 2b:

$$\theta(x) \approx arctan\left(\frac{x}{\mathrm{H}}\right) \tag{4}$$

here, H is the distance from the light source to the ceiling, and Δx is the change in distance.

To approximate the change in angle $\Delta\theta$ as a function of a small change in the horizontal distance Δx, we use the following:

$$\Delta\theta(x) \approx \frac{d\theta}{dx}\Delta x \ = \ \frac{d}{dx} arctan\left(\frac{x}{\mathrm{H}}\right) \approx \frac{1}{\mathrm{H}\left(1 + \frac{x^2}{\mathrm{H}^2}\right)}\Delta x \tag{5}$$

This equation assumes small increments in $x(\Delta x)$. This equation is simplified to emphasize uniformity in lighting, crucial for creating an optimal learning environment, by positioning P1 at zero.

The mathematical equations provided describe how light is distributed across the classroom to achieve uniform and effective illumination. The entire classroom, including the ceiling and work surfaces, is ensured to be bright and evenly lit by carefully positioning the lights and using specially designed lenses. This approach mimics natural daylight, reducing shadows and glare and creating a comfortable and productive learning environment.

3. Ideal Simulated and Real AL LED Luminaires

3.1. Double-Sided PAL LED Luminaire

In Figure 3, the ideal luminous intensity distribution curves are depicted, $D(\theta)$, in both polar and rectangular coordinate systems. These curves, represented in black, were derived from the intensity distributions $I(x)$ specified by (1) and (2), with a logistic growth rate $k = 6$ and for a height $H = 0.42$ m, applying (3) and (4). Notably, the depicted luminous intensity distribution curves demonstrate an exceedingly narrow distribution angle at half maximum (approximately 15°), posing a substantial design challenge for lens developers, especially when striving for a system with a primary lens for simplicity. The intensity peaks of these curves are prominently observed at approximately ±70 degrees, indicating the primary directional angles for maximum lighting distribution from each luminaire. This configuration helps ensure balanced illumination across the classroom, as these angles direct light to cover a wide area effectively.

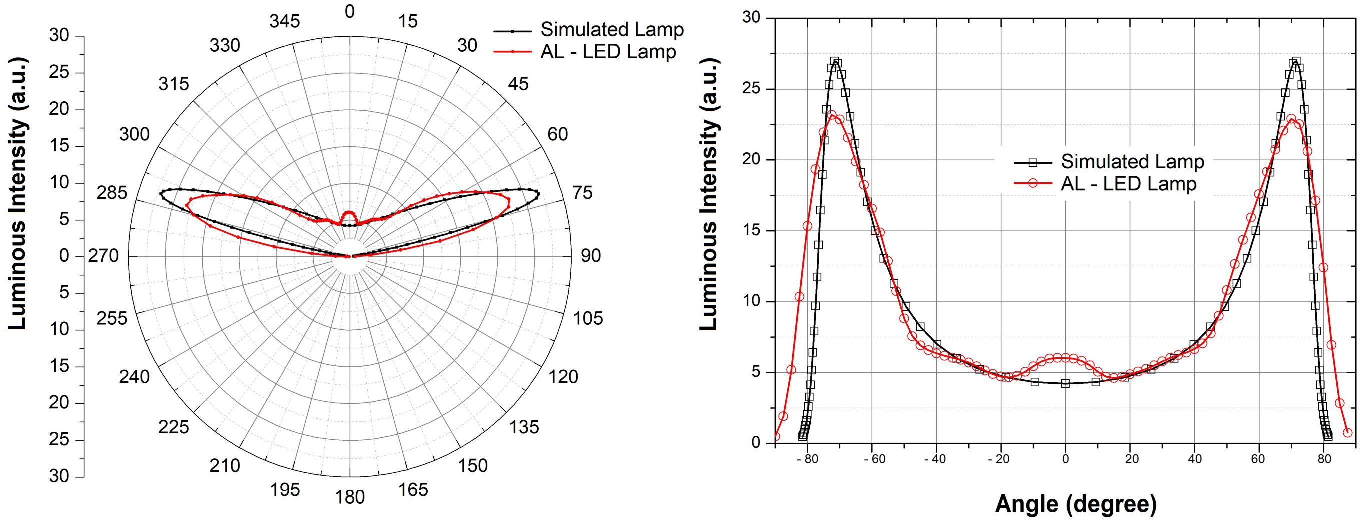

Figure 3. Luminous intensity distribution curve contrast: Displayed are the ideal simulated distributions (black curves) alongside the real distributions from custom-designed PAL LED luminaires (red curves), in both the polar (**left**) and rectangular (**right**) views. These comparisons will underpin further discussion on the design and structural principles behind the PAL LED luminaires.

The red curves in Figure 3 illustrate the realized luminous intensity distribution for custom-designed PAL LED luminaires. The design process began with several lens configurations using computer-aided design software SolidWorks 2016 (Dassault Systèmes, 10 Rue Marcel Dassault, 78140 Vélizy-Villacoublay, France), which then progressed to combining two asymmetric lenses (ALs) with LED strips in a pendant format, all subjected to detailed ray tracing simulations. Refinements to the lens profile and inclination angles were informed by these simulation outcomes. This paper discusses one PAL LED design in detail, highlighting its practical application.

In Figure 4a, the sectional architecture of the realized PAL LED luminaire, embedded with an AL, is showcased. This AL is fine-tuned for efficacy within double-sided pendant fixtures. Observing the cross-section perpendicular to the lens axis, the AL displays an innovative asymmetric contour: a semi-circular arc transitions into strategic linear segments, sculpting the asymmetry. Internally, it segments into dedicated zones, yielding a lens that combines convergent and diffusion segments for controlled light spread. An inclination angle of 66°, defined by the orientation of the LED surface normal relative to the vertical axis, was identified as the ideal value for achieving the optimal light distribution.

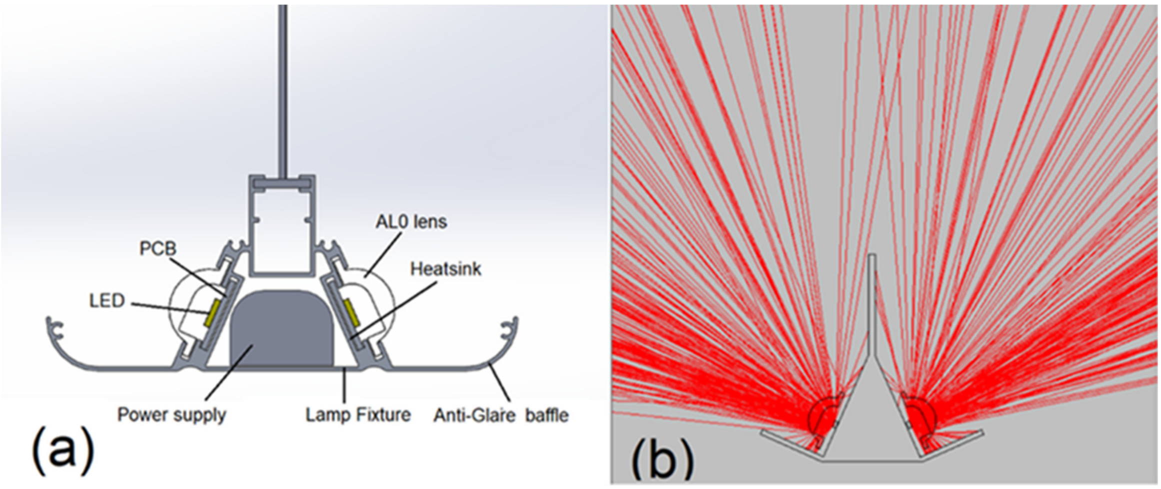

Figure 4. (**a**) The cross-sectional design of the PAL LED luminaire, highlighting the AL configuration; (**b**) a ray tracing visualization demonstrating the PAL LED luminaire's targeted light refraction and uniform distribution.

For practical implementation, a double-sided LED luminaire with dimensions 1200 × 82 × 32 mm (L × W × H) was engineered. It integrates straightforward manufacturing techniques, using aluminum for the heat sink and extruded plastic for the lens. The luminaire operates at a wall plug power of 36 W and outputs 3400 lm using LED chips. The ray tracing visualizations in Figure 4b, performed using TracePro 7.3.4 (Lambda Research Corporation, 25 Porter Road, Littleton, MA 01460, USA), confirm that the refracted light focuses around a ±70° angle, which is indicative of the luminaire's efficiency in lighting distribution.

3.2. Blackboard Asymmetric Lens LED Luminaire

The BAL LED luminaire, displayed in Figure 5a, integrates AL technology tailored for single-sided applications. The luminous intensity distribution follows a similar mathematical approach to (2), with the angular intensity distribution also derived from the logistic intensity and angle variation as per (3) and (4).

The optimum inclination angle for the LED surface normal relative to the vertical axis is set at 66° when utilizing LED chips. A linear BAL LED luminaire was manufactured with dimensions 1200 × 30 × 57 mm (L × W × H), which, at a modest power consumption of 18 W, delivers a luminous output of 1700 lm. The ray tracing simulations in Figure 5b exhibit a focal convergence at approximately 70°, indicative of a balanced light spread. The colors are used solely for visualization purposes to differentiate individual light rays within the optical path and do not indicate specific wavelengths or intensities.

Figure 5c,d offer insight into the blackboard surface's linear illuminance and the polar luminous intensity distribution, respectively. This figure is essential for evaluating the uniformity and effectiveness of luminous intensity distribution, specifically over the blackboard area. The luminous intensity distribution curve is a critical parameter for in-depth analysis and can be both predicted through simulation and validated through goniophotometer measurements. These findings are formatted into IES files for a detailed assessment and applied in the luminaire design and for the lighting design using measured IES files.

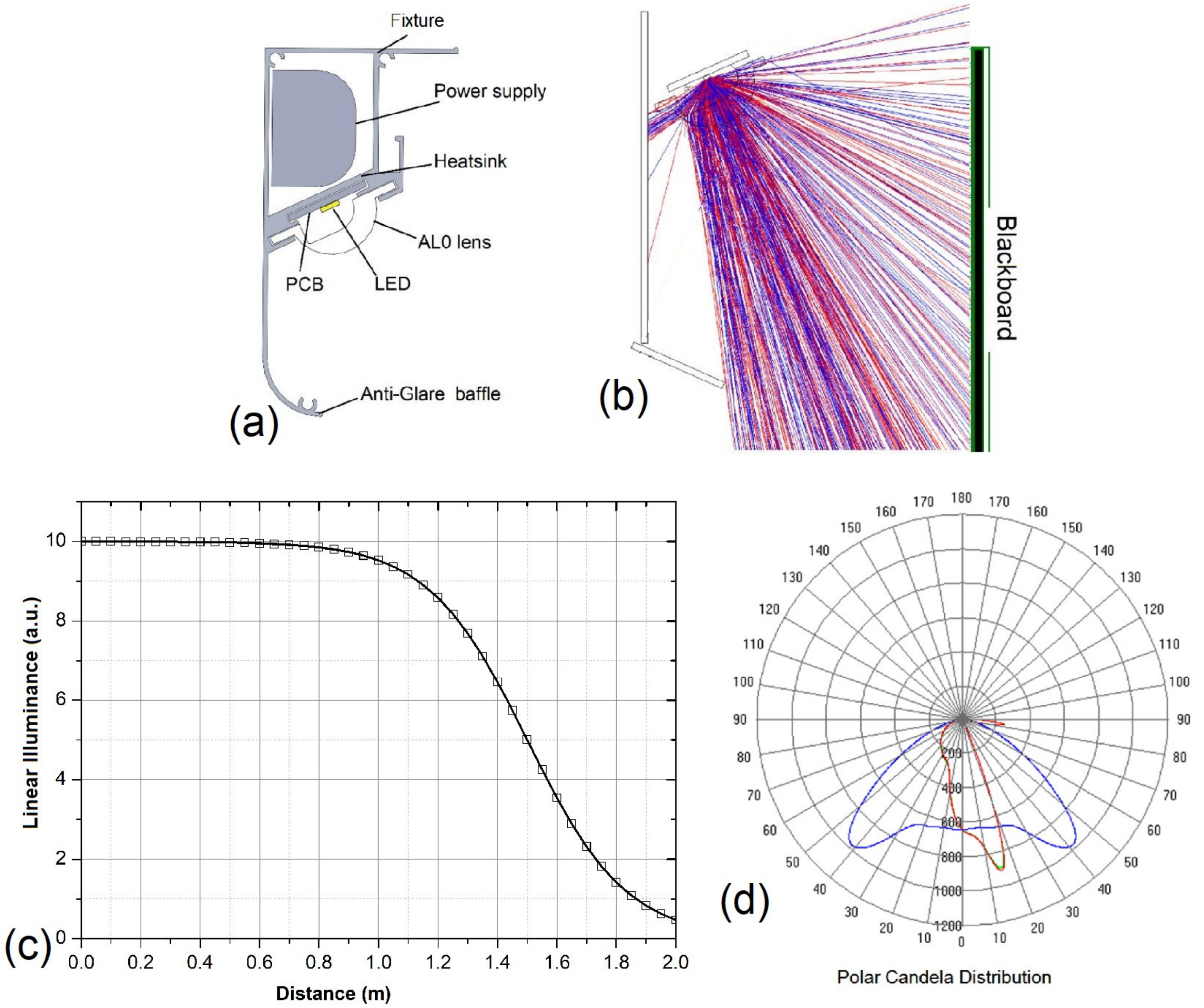

Figure 5. (**a**) A cross-sectional view of the BAL LED luminaire with the distinctive AL design; (**b**) a ray tracing visualization demonstrating the asymmetric light distribution of the BAL LED luminaire; (**c**) a graph showing the linear illuminance distribution on the blackboard surface; (**d**) a polar plot of the luminous intensity distribution demonstrating the asymmetry in the light spread.

4. Lighting Calculation Results

Table 1 compiles the simulated parameters of the luminaires, elucidating a shift from traditional fluorescent to contemporary LED lighting systems, which marks an advancement in terms of luminance, energy efficiency, and uniformity in luminous intensity distribution.

Typical values were employed for straightforwardness in the selection of classroom parameters, including dimensions 8.4 × 6.6 × 3.8 m (Length × Width × Height) and corresponding reflectance values for the ceiling, walls, and floor, which are 85%, 70%, and 50%, respectively. It is important to note that daylight contribution was excluded from this simulation due to its variability over time and changes in external conditions. However, opting for high reflective factors for the floor and walls is not merely common practice but also recommended, as higher reflectance contributes to increased overall luminance, aiding student alertness and visibility throughout the day, as emphasized by de Vries (2018) [8].

Table 1. Luminaire parameters.

The Type of Luminaire	FL	TLED	PAL LED	BAL LED
Length (m)	1.2	1.2	1.2	1.2
Luminous Flux (lm)	3960	3400	3400	1700
Power (W)	80	36	36	18
CCT (K)	6500	6500	6500	6500
CRI	70	85	85	85
Lighting Mode	Direct	Direct	Indirect	Indirect

Table 2 outlines the simulation results for eleven diverse lighting arrangements within a conventional classroom, utilizing the five lighting systems detailed in Table 1. Four ceiling fans were included in the model, each with a half-meter space from the fan blades to the ceiling, to simulate a typical classroom environment. These simulations disregarded the influence of natural daylight and considered the interplay of artificial light with the room's surfaces and furnishings.

Table 2. This table compares various lighting scenarios, illustrating the performance of different luminaire types and configurations in simulated and practically realized forms.

Ceiling Luminaire Arrangement	3 × 4 FL	3 × 4 TLED	3 × 4 PAL LED			3 × 5 PAL LED					7 × 2 PAL LED	
Lighting Scenario	S1	S2	S3	S4		S5	S6	S7	S8	S9	S10	S11
	Simulated		Simulated		Real	Simulated					Simulated	
Mounting height H (m)	0.6	0.6	0.4	0.6	0.6	0.2	0.3	0.42	0.5	0.6	0.42	0.6
Work Ill. $\overline{E}_{work}$ (lx)	290	604	680	667	690	716	722	722	721	717	683	675
Work unif. U_{work}	0.80	0.85	0.87	0.87	0.89	0.86	0.86	0.84	0.84	0.84	0.86	0.84
Ceiling Ill. $\overline{E}_{ceiling}$ (lx)	108	217	1000	935	NA	1182	1124	1062	1063	1000	1026	966
Board Ill. $\overline{E}_{board}$ (lx)	384	550	1147	1135	1296	1081	1079	1071	1063	1054	1034	1029
Board unif. U_{board}	0.64	0.76	0.82	0.82	0.7	0.83	0.83	0.82	0.82	0.83	0.82	0.82
Glare 1st range UGR_1	21.6	20.6	<10	<10	NA	<10	<10	<10	<10	<10	<10	<10
Glare last range UGR_2	19.2	20.6	<10	<10	NA	<10	<10	<10	<10	<10	<10	<10
Fan blade shadow	No	No	No	No	No	No	No	No	No	No	No	No
Object shadows	Yes	Yes	No	No	No	No	No	No	No	No	No	No
Energy density (W/m^2)	11	8.8	9.6	9.6	9.6	10.6	10.6	10.6	10.6	10.6	10.3	10.3

The UGR was calculated for the positions of both students and teachers, though for brevity, Table 2 reports only the UGR for students at the front and rows of the classroom. The UGR values listed are the maximum encountered from any horizontal viewing direction around the classroom at a standard desk height.

The simulations serve as a crucial tool for assessing and ensuring visual comfort and minimizing the glare impact for occupants across different classroom lighting designs. A comparison was conducted between computed illuminances without daylight and measured illuminances using curtains to minimize outside light (less than 4 lux).

5. Discussion

5.1. Traditional Classroom Lighting Using Fluorescence Lamp (FL) and Tubular LED (TLED) Light Sources

Traditional lighting scenarios S1 and S2 employ 12 pendant FL or TLED luminaires, typically arrayed in a 3 × 4 grid within tropical educational environments, as shown in Figure 6a. In the diagram, pink represents the lighting fixtures, blue denotes classroom objects, and green outlines the simulated calculation area.

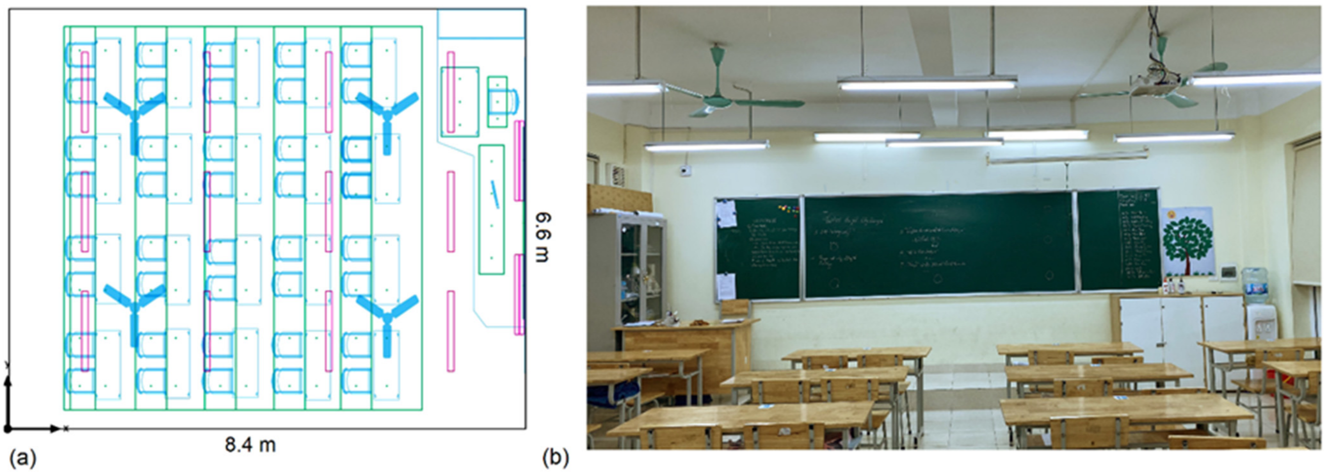

Figure 6. (**a**) A traditional classroom lighting setup featuring a 3 × 4 grid arrangement of twelve 36 W TLED luminaires suspended from the classroom ceiling and two 18 W TLED luminaires specifically positioned to illuminate the blackboard; (**b**) a real classroom image.

In these settings, ceiling fans, indispensable for ventilation, often create disruptive shadows when combined with standard overhead lighting. The luminaire placement strategy beneath the ceiling fans, at 0.6 m from the ceiling, as depicted in Figure 6b, attempts to alleviate these shadow effects. However, this low-hanging position leads to increased glare towards students, notably when looking towards the blackboard, which can hinder their visual comfort.

The UGR values of 21 and 20 for scenarios S1 and S2, respectively, as indicated in Table 2 of the simulation outcomes, do not align with the acceptable limits given in international and national lighting standards. Although scenario S2 provides sufficient illuminance at the working surface and blackboard with acceptable uniformity, it fails to overcome the challenge of glare and residual shadows effectively.

The traditional approach, while common, falls short in addressing the intricate balance required between adequate illumination, energy efficiency, and visual comfort, highlighting the necessity for innovative lighting designs that cater to contemporary educational requirements.

5.2. Optimal Classroom Lighting with PAL and BAL LED Luminaires

The optimal classroom lighting scenario leverages the design principles exhibited in scenarios S5 through S9, varying the luminaire mounting heights for ideal distribution. As shown in Figure 7a, the deployment of 15 PAL LEDs combined with 3 BAL LEDs supersedes traditional FL or TLED solutions. This upgrade eradicates the common classroom nuisance of shadows from ceiling fans and furniture.

Carefully calibrated at a mounting distance of 0.42 m, both PAL and BAL LEDs distribute light efficiently, effectively transforming the ceiling into a secondary light source akin to the skylight. Such a deliberate design surpasses standard classroom lighting requirements, furnishing a uniformly lit space devoid of glare and productive for an educational setting.

Figure 7b captures the classroom's new ambiance, a testament to the successful application of advanced lighting design that fosters focus and well-being in academic settings. A strategic mounting distance of 0.42 m for both PAL and BAL LED fixtures was chosen to maximize the efficiency and distribution of light, thereby improving the overall lighting quality within the classroom. The result is a brightly illuminated ceiling that mimics the appearance of a natural skylight, enhancing the visual environment for educational activities without the need for specialized solutions like transparent fan blades. In this context, the term 'appearance of a natural skylight' refers to achieving omni-directional, shadow-free distribution and broad light coverage.

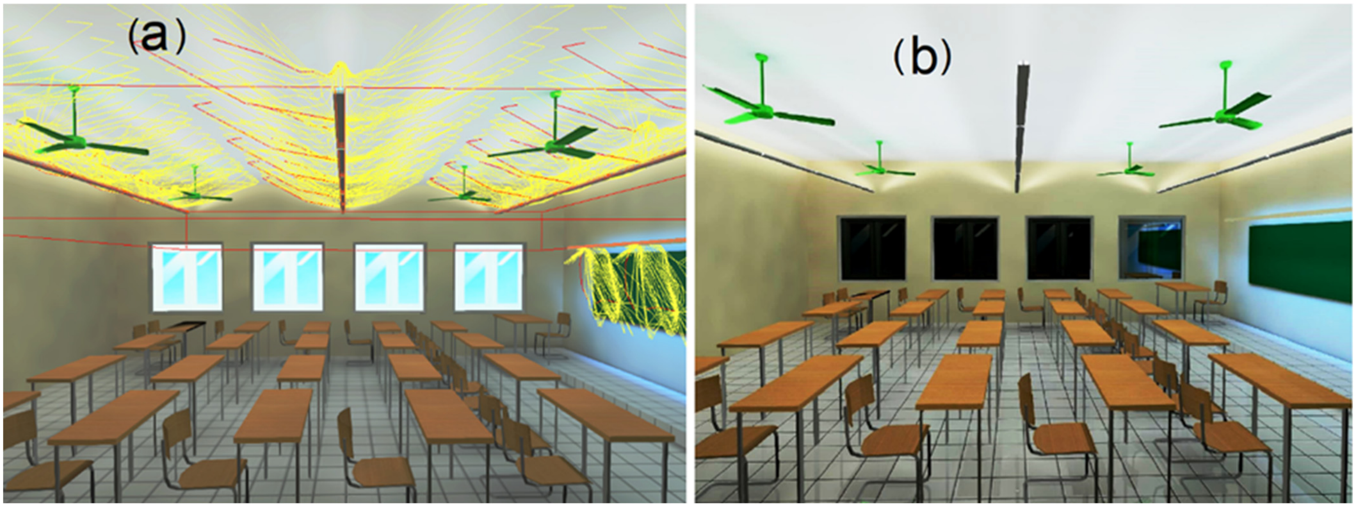

Figure 7. (**a**) A ray tracing visualization of the optimum lighting configuration employing 15 PAL LEDs and 3 BAL LEDs, offering a modern twist to traditional classroom illumination; (**b**) the resultant classroom ambiance, free from shadows cast by ceiling fans, tables, and chairs, emulates the diffuse and even quality of natural daylight.

This innovative lighting design not only meets but exceeds the typical classroom lighting standards, ensuring that all students experience consistent, glare-free illumination productive for learning. The transformation of the classroom lighting, as shown in Figure 7b, illustrates the successful application of these modern lighting principles, achieving an ambient space that supports academic focus and well-being.

Figure 8 showcases color illumination maps for an exemplary classroom lighting scenario labeled as S7. In Figure 8a, the ceiling illuminance ($\overline{E}_{ceiling}$) reaches 1062 lx, with an average luminance of approximately 230 cd/m^2.

In Figure 8b, the illumination map reveals that working surfaces such as desks and tables are well lit at an $\overline{E}_{work}$ of 722 lx. Moreover, the excellent uniformity (U_{work} = 0.84) contributes to an evenly lit space that maintains an efficient total lighting power density of only 10.6 W/m^2, which includes the blackboard lighting. These levels of illumination and uniformity, which bolster the room's perceived brightness and appeal, corroborate the insights from de Vries et al. (2021) [12].

Figure 8c highlights the blackboard's illuminance, reaching an outstanding $\overline{E}_{board}$ = 900 lx, which not only exceeds the EN 12464–:2021 recommendation of 750 lx but also showcases good uniformity (U_{board} = 0.7). Enhanced lighting such as this can significantly improve students' visual clarity, engagement, and alertness during class, which aligns with the findings of de Vries et al. (2018) [8]. However, it should be noted that maximizing the impact of this elevated illuminance is dependent on the surface's reflective capacity. Considering the blackboard's reflectance at about 9%, the resultant luminance is roughly 27 cd/m^2, below Vries's optimal recommendation for active learning (>72 cd/m^2). To address this, a transition to matte whiteboards with black markers is proposed to increase vertical luminance, thereby elevating both visual perception and alertness among students.

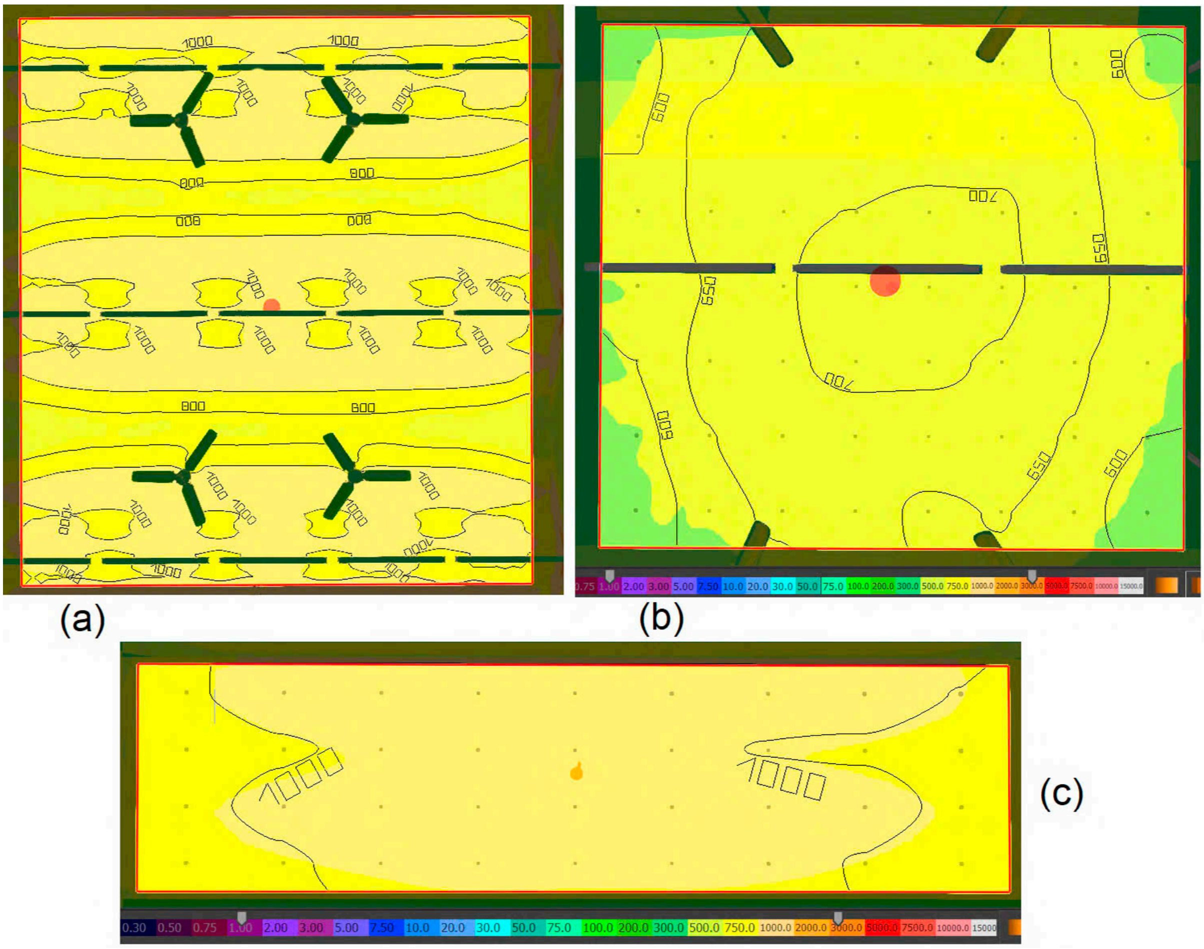

Figure 8. Color illumination maps for ideal classroom lighting scenario S7: (**a**) shows the illuminance on the ceiling, reflecting a secondary light source concept; (**b**) illustrates the illuminance on working surfaces; (**c**) shows the significantly improved illumination on the blackboard, promoting better visibility and student engagement.

This lighting approach also eliminates direct glare, resulting in very low UGR values (<10) from every angle. This full indirect lighting method establishes a discernible association between perceived brightness and room attractiveness for certain student demographics, as evidenced by de Vries et al. (2021) [12], where illuminance uniformity also played a role in their spatial assessment.

Data from scenarios S5 through S9 in Table 2 indicate that the illuminance uniformity tends to improve with the mounting height of the fixtures, reaching a saturation point between scenarios S8 and S9. While higher uniformity marginally reduces the luminance on the working surfaces, fixtures mounted below fan blades can lead to light reflection off glossy surfaces, which affects overall light quality by reflecting LED package light.

5.3. Optimized Classroom Lighting with 14 PAL and 3 BAL LEDs

An alternative lighting model in a typical classroom is explored, as illustrated in Figure 9a, where a 2 × 7 grid of PAL LED luminaires replaced the conventional 3 × 5 array. The PAL LEDs are aligned parallel to students' line of sight, optimizing viewing comfort and minimizing glare. The luminaire arrangement results in a working surface illuminance $\overline{E}_{work}$ of 683 lx, with a high uniformity U_{work} of 0.86, thereby surpassing the established classroom lighting standards. Furthermore, blackboard illumination is enhanced to $\overline{E}_{board}$ = 1034 lx with a uniformity U_{board} of 0.82, significantly above the EN 12464–1:2021 recommendation of 750 lx, ensuring clear visibility for all students and teachers.

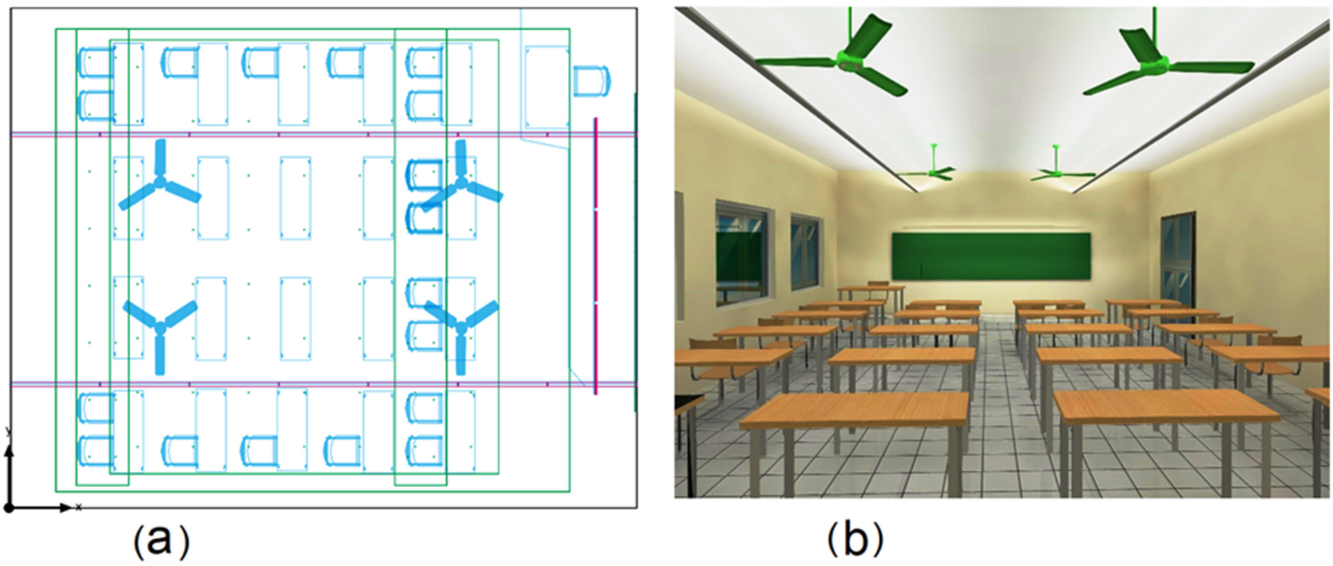

Figure 9. (**a**) Strategic arrangement of 14 PAL LED luminaires and 3 BAL LED luminaires designed for optimized classroom illumination, (**b**) ray tracing simulation depicting effective mitigation of shadows from classroom fixtures, achieving uniform lighting productive for learning.

The ray tracing visual in Figure 9b confirms the absence of shadows from ceiling fans and furniture, affirming the model's effectiveness in creating an optimal learning environment. Adjustments to the luminaire mounting height from 0.42 m in scenario S10 to 0.6 m in S11 yield an improvement in ceiling illuminance uniformity from below the desired level to 0.75, enhancing light spread without compromising the UGR, which remains comfortably below 10.

In essence, scenarios S3 to S11 demonstrate that various configurations of PAL and BAL LEDs can meet the illumination needs of contemporary classrooms by delivering high-quality, uniform lighting and establishing a glare- and shadow-free atmosphere productive for learning.

The practical implementation of scenarios S4 and S9 was met with positive feedback from both teachers and students. However, there is still a lack of quantitative assessments regarding the impact of these lighting solutions on students' visual acuity, alertness, and emotional well-being, indicating the need for further research.

5.4. Validation of PAL and BAL LEDs

An example of the patented ceiling-mounted PAL–LED luminaire described in Figure 4a includes four main components: the lamp fixture, LED strips, ALs, and power supply. The lamp fixture, which also functions as a heat sink and housing for the power supply, is made of aluminum and coated with electrostatic paint. Its dimensions are 1200 mm × 82 mm × 32 mm. Two white LED strips are soldered onto two printed circuit boards measuring 1175 mm × 13 mm × 1 mm each. In a preferred embodiment, each LED strip uses 100 LED chips, operating at 55 mA, with a total power consumption of 16.5 W for the LEDs. The chosen CCT is 6500 K, with a color rendering index of 85 and a luminous efficacy of 100 lm/W. Twenty-five LED chips were connected in series, forming four series chains suitable for a power supply rated at 220 mA, resulting in a voltage drop of approximately 75 V across the LED circuit. The fabrication of ALs was realized by using the extrusion of optical plastics such as polycarbonate or polymethyl methacrylate. Power supply consumption is less than 10% of total power, which is 36 W, giving a luminous flux of 3400 lm.

Similarly, the patented ceiling-mounted BAL–LED luminaire described in Figure 5a uses the same LED strip and ALs. The lamp fixture configuration is slightly different for a single LED strip with a total power consumption of 18 W and 1700 lm output.

5.5. Validation of Cost-Effective Classroom Lighting

The alternative scenario S4, portrayed in Figure 10, introduce a cost-effective classroom lighting design incorporating 12 PAL LED luminaires arranged in a 3 × 4 grid on the ceiling. These luminaires are mounted at height 0.6 m below the ceiling.

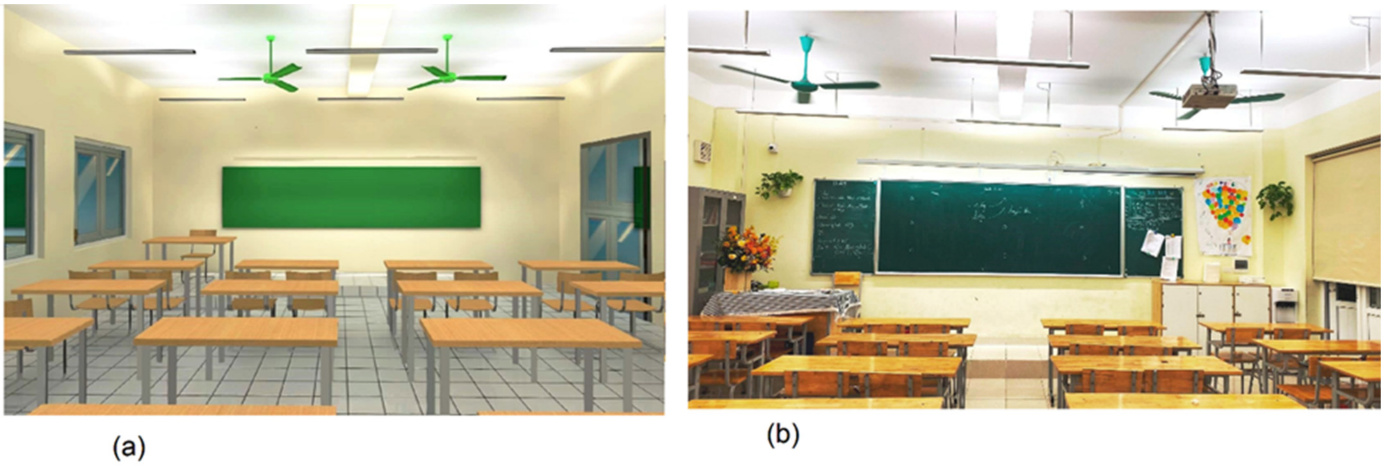

Figure 10. (**a**) A simulated ray tracing of the economic S4 lighting setup, illustrating the ceiling brightness from 12 PAL LEDs; (**b**) a photograph of a classroom employing the S4 lighting setup, with the actual installation of PAL and BAL LEDs reflecting the simulated outcome.

Figure 10a presents a ray tracing visualization for S4—the "economic scenario"—which represents an efficient lighting alternative that leverages PAL LEDs instead of traditional lighting solutions. Figure 10b displays a real-world implementation of this model, with 12 PAL LEDs and 3 BAL LEDs effectively emulating the simulated luminous intensity distribution. A detailed comparison between computed illuminance ($\overline{E}_{work}^{simul}$ = 667 lx) and measured illuminance ($\overline{E}_{work}^{meas}$ = 690 lx) on the table surfaces is shown in Figure 11a. The simulated uniformity U_{work}^{simul} = 0.87 and measured U_{work}^{meas} = 0.89 are high and closely aligned.

Similarly, small discrepancies in backboard illuminance between the simulated and measured results in Figure 11b indicate that the luminaire design and lighting model are valid for practical use.

The result is a classroom environment that meets EN-12464-1:2021 lighting standards for uniformity and visual comfort, free from the shadows and glare that can impede learning.

The new lighting arrangement successfully addresses the challenge of shadows cast by fans and furniture, achieving a uniform and glare-free illumination that simulates the diffused light of an overcast sky. This setup not only adheres to the simulated and measured results summarized in Table 2 but also maintains UGR values below 10 from all viewing perspectives, providing a visually comfortable and non-disruptive learning environment.

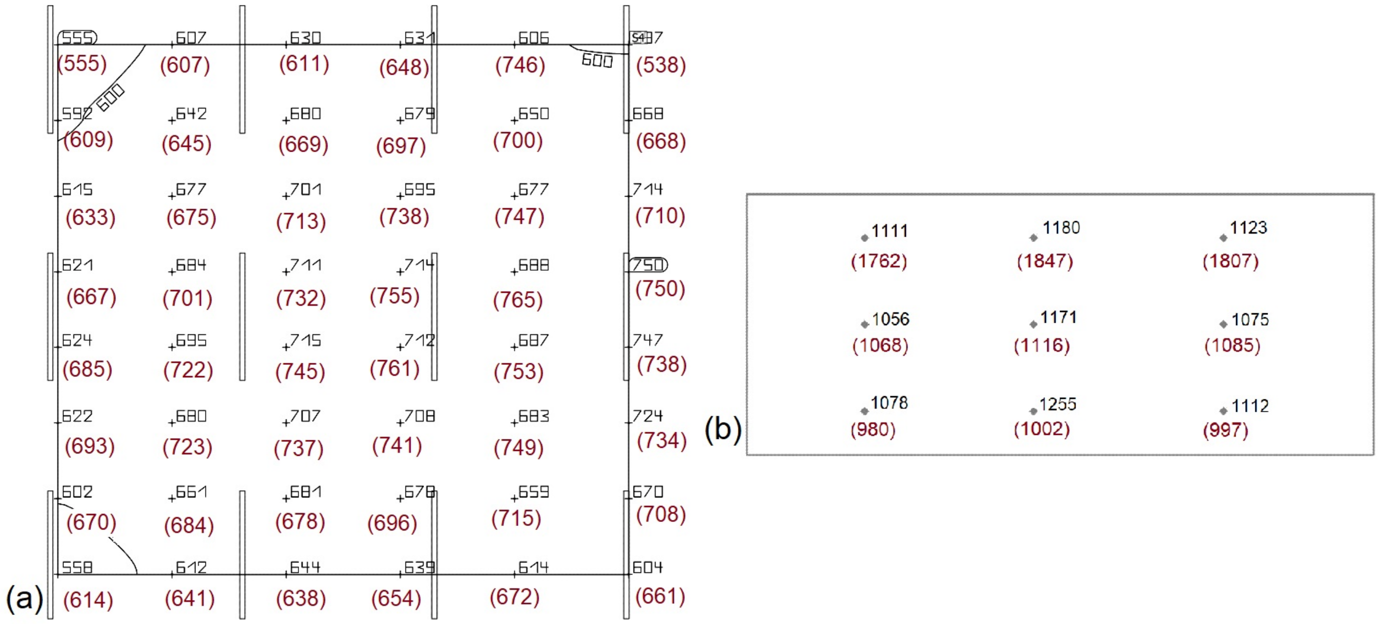

Figure 11. Validation of cost-effective classroom lighting: (**a**) comparison of computed and measured illuminance on table surfaces, with simulated values represented in black and real-world measured values shown in red (in parentheses), illustrating close alignment between the two; (**b**) comparison of computed and measured illuminance on blackboard, where simulated values are denoted in black, and real-world measured values are in red (in parentheses), confirming accuracy and practical validity of luminaire design and lighting model.

6. Conclusions

This study introduces the PAL LED luminaire as an innovative solution to address common lighting challenges in tropical classrooms, such as shadows from ceiling fans and uneven lighting distribution. The BAL LED luminaire complements this by enhancing visibility on educational boards, ensuring visual clarity and legibility, thereby contributing to an improved learning environment.

Both PAL and BAL luminaires significantly improve classroom lighting by providing soft, even illumination, achieving average illuminance levels of 935–1000 lx on the ceiling and 660–720 lx on working surfaces, with uniformity values exceeding 0.8 and a UGR below 10. This improved lighting quality enhances students' focus, reduces visual fatigue, and improves the overall aesthetic of the learning space. Additionally, the their compatibility with existing infrastructures and energy-efficient performance make them both practical and ideal for widespread implementation.

This research provides practical insights into the design, simulation, and implementation of the PAL and BAL systems, offering valuable guidance for educational stakeholders and lighting professionals. Future studies will focus on conducting psychophysical quantitative evaluations to determine the precise effects of these innovations on students' visual acuity, alertness, and emotional well-being.

Author Contributions: D.T.G.: writing—original draft preparation and project administration; P.H.D.: supervision, conceptualization, and methodology; N.V.Q.: formal analysis and investigation; T.N.T.T.: data curation; T.Q.K.: supervision and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ministry of Science and Technology of Vietnam under the project ĐTĐLCN.17/23.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

AL	asymmetric lens
BAL	blackboard asymmetric lens
CCT	correlated color temperature
FL	fluorescent lamp
TLED	tubular LED
PAL	pendant asymmetric lens
$\overline{E}$	average illuminance
$\overline{E}_{work}$	average illuminance on working surface
$\overline{E}_{ceiling}$	average illuminance on ceiling
$\overline{E}_{board}$	average illuminance on blackboard
$\overline{E}_{ceiling}^{direct}$	average direct illuminance on ceiling
U_o	illuminance uniformity
UGR	unified glare rating

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