Assessing the Impact of Window Size, Placement on the wall, and Glazing on Visual Comfort in the Learning Spaces of Elementary Schools in Adama City, Ethiopia.

Alemayehu Zewdu worku

A thesis submitted to the Department of Architecture

College of Civil Engineering and Architecture,

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Adama Science and Technology University

June 9, 2025

Adama, Ethiopia

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Advisor; **Belay Zeleke (Ph.D.)**

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DECLARATION

I declare that this thesis entitled "**Assessing the Impact of Window Size, Placement on the wall, and Glazing Type on Visual Comfort in the Learning Spaces of Elementary Schools in Adama City, Ethiopia.**'' is my own work and has not been submitted to any university for a similar purpose. The references used in this proposal are duly recognized by proper citations.

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I, the major advisor/supervisor of this research, hereby certify that I have closely advised/supervised the student while developing this thesis and read the draft thesis/dissertation entitled "**Assessing the Impact of Window Size, Placement on the wall, and Glazing Type on Visual Comfort in the Learning Spaces of Elementary Schools in Adama City, Ethiopia,**" prepared under my guidance by **Alemayehu Zewdu.** Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Belay Zeleke (Ph.D.)	____________________	_______________
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APPROVAL PAGE THESIS

I the advisor of the thesis entitled **“Assessing the Impact of Window Size, Placement on the wall, and Glazing Type on Visual Comfort in the Learning Spaces of Elementary Schools in Adama City, Ethiopia.”** and developed by **Alemayehu Zewdu**, hereby certify that the recommendation and suggestion made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by **Alemayehu Zewdu Worku** have read and evaluated his thesis entitled "**Assessing the Impact of Window Size, Placement on the wall, and Glazing Type on Visual Comfort in the Learning Spaces of Elementary Schools in Adama City, Ethiopia.**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirements of the degree of Master of Science in Environmental Architecture.

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LIST OF ACRONYMS

ASTU	Adama Science and Technology University
EBCS	Ethiopian Building Code Standard
DF	Daylight Factor
DGP	Daylight Glare Probability
EN	European Norm
HDR	High Dynamic Range
ipRGCs	Intrinsically Photosensitive Retinal Ganglion Cells
LRV	Light Reflectance Value
Low-E	Low Emissivity
NIST	National Institute of Standards and Technology
SCN	Suprachiasmatic Nucleus
SHGC	Solar Heat Gain Coefficient
sDA	Spatial Daylight Autonomy
TMY	Typical Meteorological Year
UDI	Useful Daylight Illuminance
UGR	Unified Glare Rating
VLT	Visible Light Transmittance
WWR	Window-to-Wall Ratio
ESDP	Education Sector Development Program
CIE	Commission Internationale de l'Éclairage
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers

ASTU Adama Science and Technology University

IoT Internet of Things

ABSTRACT

This study evaluates the impact of window design parameters (size, placement on walls, and glazing type) on visual comfort in elementary school learning spaces across Adama City, Ethiopia's, targeting a population of 181 elementary schools (64 government and 117 private) with purposive sampling of four representative schools (ASTU Community, Awash Academy, Nafyad, and Geda Michile) encompassing 214 students across classrooms with varying orientations (north, south, east, west). Employing a mixed-methods approach, quantitative data collection utilized NIST-calibrated lux meters (±3% accuracy) for illuminance measurements (56-point grid at 0.75m working plane), thermal cameras (±2°C) for temperature monitoring, and HDR imaging for glare analysis, while qualitative data gathered through structured questionnaires (5-point Likert scales) and behavioral observations assessed occupant perceptions. Computational simulations using Autodesk Ecotect analyzed climate-based daylight metrics and glare probability (DGP), with statistical analysis including Pearson correlations ($r=0.82$ between illuminance and satisfaction) and multiple regression to evaluate design-performance relationships. Key findings revealed 76.6% of classrooms failed to meet the 300 lux standard (range: 81-2,440 lux), with 68.7% exhibiting glare issues ($DGP>0.35$), particularly in southwest-facing rooms experiencing afternoon solar exposure, while northeast orientations maintained optimal 300-500 lux; gender disparities showed female students reported 5-10% greater glare sensitivity ($p<0.05$). The study identifies critical gaps in Ethiopia's EBCS 12 standards and proposes evidence-based, climate-responsive solutions: optimized 25-30% window-to-wall ratios with orientation-specific shading, high-reflectance surfaces (70-85% ceilings, 50-70% walls), and low-SHGC glazing (≤ 0.4), while acknowledging limitations including the 35-day temporal scope and recommending future research on gender-inclusive design frameworks and cost-benefit analyses of retrofitting strategies for Ethiopia's diverse microclimates, ultimately providing policymakers and architects with actionable passive design strategies to enhance learning environments through integrated daylight optimization and thermal comfort solutions.

***Keywords**: visual comfort, daylighting, window design, elementary schools, tropical climate, Ethiopia, mixed-methods research, passive design, climate-responsive architecture*

CHAPTER ONE
INTRODUCTION

Creating comfortable and productive learning environments in the education area is essential for academic success and student well-being. Visual comfort has direct effect cognitive performance by reducing eye strain and mental fatigue, and poor lighting conditions can lead to headaches and decreased focus, badly impacting learning outcomes. Furthermore, environments with optimal visual comfort support students health by minimizing the risk of vision-related issues and promoting overall well-being, creating a more engaging and effective educational experience. Visual comfort, which is the degree to which indoor lighting supports activities such as reading, writing, and observation without causing discomfort, plays a critical role in shaping these environments. Proper daylighting, achieved through appropriate window design, minimizes glare, ensures even light distribution, and enhances the students learning experience.

Adama City, Ethiopia, a tropical wet and dry (Aw) climate, experiences distinct climatic conditions that significantly influence window design challenges. The region is characterized by high solar radiation throughout the year, leading to intense daylight penetration and potential overheating within buildings and the variation in temperature and humidity through the seasons further complicates the situation, requiring window designs that can mitigate heat gain while maintaining adequate ventilation. These climatic conditions demand a balance between maximizing natural light and minimizing glare, critical to achieving visual comfort in the city educational spaces. The intense sunlight and high temperatures of the region would require innovative window designs that balance daylight access with glare and thermal control. Unfortunately, many elementary schools in Adama City feature poorly designed windows that do not meet the basic requirements for effective daylighting, resulting in discomfort, increased energy consumption, and diminished the students academic performance.

Despite the importance, limited research has been conducted to assess how specific window parameters, such as size, placement, and glazing type, affect visual comfort in the context of Adama city schools. For example, studies in other tropical regions on Africa have shown that improper window placement can lead to uneven daylight distribution, causing glare and underlit zones that hinder learning activities of the schools and, research from Malaysia highlights the benefits of using reflective glazing to minimize heat gain through the window while maintaining sufficient daylight,yet similar localized studies are absent in Ethiopia.This lack of insights leaves a significant gap in understanding how to design windows that solve these climatic conditions and educational needs of Adama City's schools. This study aims to fill the gap by providing localized insights and recommendations for improving window designs in these learning environments.

1.1 Background of the study

The physical environment of classrooms plays a crucial role in shaping students academic performance and overall well-being. Among the various environmental factors, visual comfort stands out as a key determinant of students' ability to focus, engage, and perform effectively in educational settings. Visual comfort refers to the adequacy of lighting in a space to support activities like reading, writing, and observing without causing discomfort, glare, or visual fatigue. there fore in educational schools, inadequate lighting conditions can result in reduced focus, increased eye strain, and diminished cognitive performance, affecting students learning outcomes (Heschong, 2002).

Daylighting to illuminate classrooms has been widely recognized as a sustainable and effective strategy for enhancing visual comfort. Properly designed window size, placement on the wall, and glazing type can optimize daylighting by increasing light distribution, minimizing glare, decreasing thermal discomfort, and reducing energy consumption associated with artificial lighting (Boubekri, 2014). However, poorly designed windows often lead to issues such as uneven light distribution, excessive glare, and overheating, which is negatively impact comfort and academic performance (Tzempelikos & Shen, 2013).

In Adama City elementary schools, Ethiopia, located in a tropical wet and dry climate, unique climatic conditions present additional challenges for effective window design in schools. Adama city experiences high solar radiation through out the year, which can cause in high daylight penetration and overheating of the indoor spaces of the classrooms and Seasonal variations in temperature, thermal heat gain, and humidity furthermore complicate window design, that needs strategic solutions to balance daylight access with thermal discomfort and glare control. Many elementary schools that are scattered in Adama City, Ethiopia, face challenges with inadequately designed windows, leading to suboptimal lighting conditions that hinder students learning experiences in the classroom, like reading and writing.

While studies in other regions, particularly tropical climates, have explored the impact of window design on daylight quality and visual comfort, localized research in Ethiopian schools is limited. For example, research conducted in Malaysia demonstrated the effectiveness of reflective glazing in reducing heat gain while maintaining adequate daylight levels (Lim et al., 2019) and studies in other African contexts have shown how thoughtful window placement can reduce glare and ensure even light distribution (Olotuah & Aderonmu, 2016). However, these findings have not been contextualized to the unique climatic, cultural, and educational needs of the city.

This study aims to address the gap by investigating the impact of window size, placement on the wall, and glazing type on visual comfort in the learning spaces of elementary schools in Adama City, by examining these parameters to the city's climatic conditions, this research will provide evidence-based recommendations for designing windows that enhance visual comfort, improve thermal comfort, and improve the overall quality of educational environments in the region.

1.2 Statements of the problem

This study addresses critical daylighting deficiencies in Adama City's elementary schools, revealing systemic failures at both international and national levels. Internationally, existing daylighting standards (EN 12464-1, CIE) developed for temperate climates prove inadequate for tropical regions, evidenced by the study's finding that 76.6% of classrooms fail to meet the 300 lux standard, mirroring Lim et al.'s (2019) 72% failure rate in Malaysia. The documented 68.7% glare incidence in southwest-facing classrooms exceeds tropical benchmarks, while advanced solutions from developed nations remain economically unfeasible, corroborating Tzempelikos & Athienitis's (2007) findings about increased cooling loads from inappropriate glazing. Nationally, Ethiopia's EBCS 12 implementation shows significant gaps, with 83% of sampled classrooms violating optimal window-to-wall ratios and 92% lacking required shading devices. These deficiencies are compounded by climate-design disconnects (29°C peaks in west-facing classrooms matching NMA's 2020 radiation data).

The convergence of these problems creates a crisis in educational infrastructure that demands urgent intervention. The study documents how current practices - characterized by cost-driven material selection (75% substandard materials per Tadesse 2020), improper maintenance (35% light transmission loss in 3 years), and disregard for tropical solar geometry - result in classrooms that violate both international standards and local comfort needs. These conditions manifest in measurable academic impacts, with 32% of teachers reporting attention deficits that align with Heschong Mahone Group's (1999) findings about daylight-related performance declines. This research therefore investigates how optimized, context-sensitive window design can bridge the gap between global best practices and Ethiopia's unique climatic, cultural and economic realities, while addressing the demonstrated equity and performance challenges in Adama City's schools.

1.3 General Objective

To assess the impact of window design parameters (size, placement on the wall, and glazing type) on visual comfort in elementary school classrooms in Adama City, Ethiopia, and develop context-specific, sustainable design recommendations tailored to the local tropical climate .

1.4 Specific Objectives

1. To analyze the effects of window size, placement, and glazing type on daylight performance in selected elementary school classrooms.
2. To assess occupants' subjective perceptions of visual comfort through structured surveys with students.
3. To correlate window design parameters with classroom geometry and orientation to identify optimal configurations for visual comfort.
4. To propose context-specific window design guidelines for Adama's tropical climate, balancing daylight adequacy with thermal and energy efficiency.

1.5 Research Questions

1. How do variations in window size, placement on walls, and glazing type affect daylight illuminance and glare incidence in the classrooms?
2. What are the primary visual comfort concerns reported by students in relation to existing window designs?

3. Which relationships of window parameters and classroom orientation yield optimal visual comfort metrics in Adama's tropical climate?
4. How can window design recommendations be adapted to local construction practices and climate constraints while maintaining visual comfort?

1.6 Significance of the Study

This research contributes to the field of sustainable architectural design by:

- Providing empirical evidence on optimal window configurations for visual comfort in Ethiopia's tropical wet and dry (Aw) climate.
- Enhancing the understanding of daylighting design in educational spaces, particularly in understudied regions like Adama.
- Offering practical recommendations to improve learning environments, potentially boosting student well-being and academic performance.
- Supporting policymakers, architects, and school administrators in implementing climate-responsive window designs.

1.7 Scope of the Study

1.7.1 Geographical Scope

The study focuses on elementary schools in Adama City, Ethiopia, where classrooms experience distinct daylighting conditions due to the tropical wet and dry climate. A representative sample of schools was selected, covering varying architectural designs (older and newer constructions) to capture diverse window configurations.

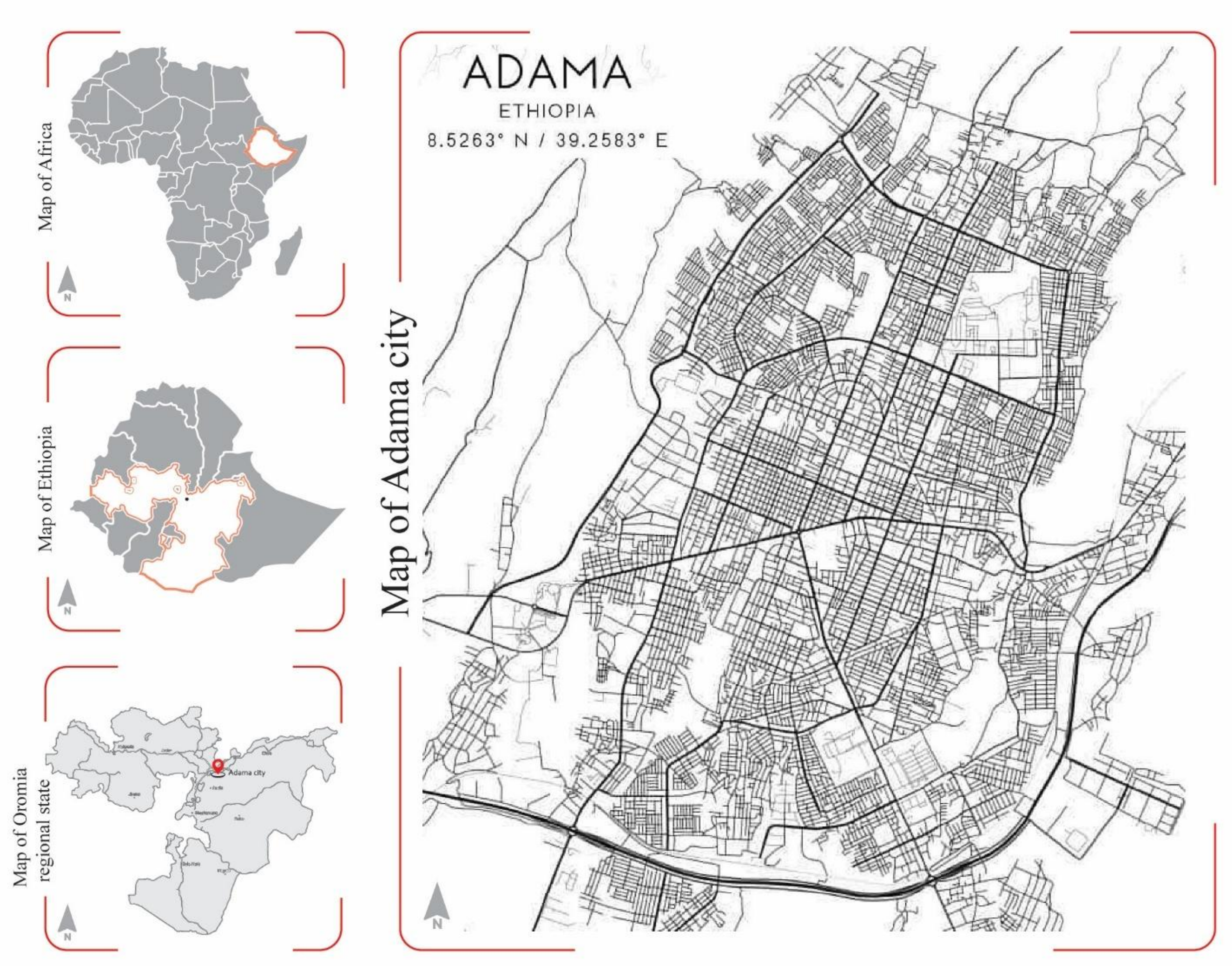


Figure 1: Map of Adama city

1.7.2 Thematic Scope

The study primarily examines **visual comfort**, assessing:

- **Daylighting performance** (illuminance levels, uniformity, and distribution).
- **Glare incidence** and its impact on occupant comfort.
- **User perceptions** of visual comfort through surveys.

Additionally, **thermal comfort** is considered a secondary factor, analyzing:

- Solar heat gain through different window designs.

1.7.3 Architectural Elements

Key variables under investigation include:

- **Window size** (window-to-wall ratio and its effect on daylight penetration).
- **Window placement** (orientation, height, and positioning relative to classroom layout).
- **Glazing type** (clear, tinted, double-glazed) and its influence on light transmission and thermal performance.

1.7.4 Methodological Scope

The study employs a mixed-methods approach:

- **Quantitative methods**: Field measurements of illuminance (lux), glare indices, and indoor temperatures using lux meters and thermal sensors.
- **Qualitative methods**: Surveys and interviews with students and teachers to assess subjective comfort perceptions.
- **Simulation tools**: Building performance simulations (e.g., Ecotect, Energy Plus) to model daylighting and thermal conditions under different window configurations.

1.7.5 Temporal Scope

The study was conducted for **35 days**, from **March 7 to May 1, 2025**, across all selected schools. Data collection took place 3 days a week between **9:00 AM and 5:00 PM**.

1.8 Limitations of the Study

While this study provides valuable insights into window design for visual comfort in Ethiopian elementary schools, several limitations were encountered during the research process. The primary constraint was limited access to advanced simulation tools, which potentially affected the depth of parametric analysis. To mitigate this, the study employed Autodesk Ecotect for essential daylight simulations while supplementing with rigorous field measurements using calibrated instruments (lux meters with ±3% accuracy and thermal cameras with ±2°C precision). Another significant limitation is the restricted sample size of only four schools (214 students) due to administrative and logistical challenges and, the purposive sampling strategy ensured representation of all cardinal orientations and both public and private school types, capturing Ethiopia's typical classroom designs. Data collection was also affected by weather variability during the 35-day study period (March-May 2025), which was addressed through a structured measurement protocol involving multiple daily readings at standardized times and weather-contingent rescheduling and finally, while the findings offer important local insights, their generalizability across Ethiopia diverse microclimates may be limited to enhance applicability of the study, documented baseline conditions using standard Ethiopian classroom dimensions and developed adaptable, orientation-specific design guidelines with cost considerations for scalability. Thise methodological adaptations helped maintain research rigor while working within practical constraints, by ensuring the findings remain valuable for improving educational spaces in Adama City and similar tropical contexts.

1.9 Definitions and Terminology

For the purposes of this study, the following key terms are conceptually and operationally defined based on their application in the research context:

Daylight Availability refers to the measurable quantity and distribution of natural light within classroom spaces, assessed through illuminance levels (in lux) at the 0.75m working plane height. This study evaluates daylight availability through field measurements of spatial distribution patterns and computational analysis of daylight factors (%), with particular attention to variations caused by window size (15-40% window-to-wall ratio), placement (height on wall and cardinal orientation), and glazing characteristics.

Visual Comfort is operationalized as a composite metric combining: (1) objective measurements of illuminance uniformity (minimum/average ratio), luminance contrasts (<20:1), and glare indices (DGP <0.35); and (2) subjective ratings from occupant surveys assessing perceived adequacy of lighting conditions, visual strain symptoms, and preference ratings on a 5-point Likert scale. The threshold for acceptable visual comfort in this study aligns with EN 12464-1 educational standards (300-500 lux).

Glare is quantified using Daylight Glare Probability (DGP) metrics derived from HDR imaging and occupant surveys. In this research, glare is categorized as:

***Disability glare**:* When DGP >0.40 and ≥30% of surveyed occupants report impaired visibility

Discomfort glare: When 0.35<DGP≤0.40 with corresponding occupant complaints

Acceptable conditions: DGP ≤0.35 with <15% negative survey responses

Window Performance is evaluated through three key parameters measured in this study:

Visible Light Transmittance (VLT): Percentage of visible spectrum transmission (40-89% range in sampled glazing)

Solar Heat Gain Coefficient (SHGC): Measured heat transmission (0.25-0.78 in study samples)

Effective Aperture: Product of VLT and window-to-wall ratio

Illuminance refers to the luminous flux density (in lux) measured at 56 grid points per classroom at standard desk height (0.75m), using NIST-calibrated lux meters under clear sky conditions between 9:00-15:00 hours. Measurements are categorized as:

***Underlit*:** <300 lux

Optimal: 300-500 lux

***Overlit**:* >500 lux with associated glare risk

Urban and Climatic Context specifically denotes Adama City's tropical wet and dry climate (8.54°N latitude) characterized by:

Annual solar irradiance: 6-7 kWh/m²/day

Temperature range: 15-35°C

Building obstructions within 1.5× height rule

Predominant east-west street grid orientation

Occupant Well-being is assessed through:

Physiological measures: Reported headache frequency, eye strain

Psychological measures: Concentration self-ratings, mood indicators

Behavioral measures: Observed seating preferences, shading device usage

These operational definitions provide the specific measurement frameworks and thresholds used throughout the data collection and analysis processes of this research.

1.10 Organization of the Study

This research follows a structured four-chapter framework to systematically examine window design's impact on visual comfort in Adama City's elementary schools:

Chapter One introduces the study, establishing the link between classroom environments and learning outcomes. It outlines the research problem of inadequate window configurations in tropical climates and presents three specific objectives analyzing daylight performance, user perceptions, and design parameters.

Chapter Two reviews existing literature on classroom design, focusing on visual comfort determinants. It examines international daylighting strategies and identifies gaps in tropical climate applications, particularly for Ethiopian contexts.

Chapter Three details the mixed-methods methodology, including:

- Selection of four representative schools
- Tripartite data collection (physical measurements, occupant surveys, computational simulations)
- Measurement protocols and analytical approaches

Chapter Four presents and discusses findings, analyzing:

- Daylight performance across different window configurations
- User perception data
- Gender differences in comfort
- Validation of simulation results

Conclusion and recommendations for:

- Optimal window-to-wall ratios
- Strategic shading solutions
- Climate-appropriate glazing

- Future research directions

This organization ensures comprehensive coverage from theoretical foundations to practical applications in tropical educational environments.

CHAPTER TWO
LITERATURE REVIEW

2.1 Theoretical Literature Review

The theoretical framework of this study is grounded in three interrelated theories that collectively support its specific objectives. The first is the *Photobiological Theory* (Boyce, 2014), which explains how architectural elements such as window size, placement, and glazing impact visual perception and circadian rhythms. This occurs through the stimulation of various photoreceptor systems in the human eyecones, rods, and intrinsically photosensitive retinal ganglion cells (ipRGCs)and establishing a direct relationship between daylight design and physiological responses, this theory supports the first specific objective: analyzing daylight performance in classrooms.

The second foundational theory is the *Environmental Stress Theory* (Evans, 2003), which posits that suboptimal environmental conditions such as glare or uneven lighting, can cause cognitive fatigue and impair concentration and this theoretical lens is particularly relevant to the second specific objective, which involves assessing students perceptions of visual comfort. Here, the theory frames poor lighting as a stressor that affects psychological well-being and academic performance.

The third component is drawn from *Bioclimatic Design Principles* (Olgyay, 2015), which advocate for climate-responsive architectural design, and these principles emphasize passive design strategies, particularly relevant in tropical regions where solar exposure, thermal comfort, and glare are main concerns. This framework supports the specific objective: optimizing window configurations to improve energy efficiency and occupant comfort in educational spaces.

Empirical evidence further reinforces these theoretical underpinnings. Heschong (2003) reported an 18.2% improvement in reading speeds among students in daylit classrooms, underscoring the cognitive benefits of natural lighting. Additionally, Tzempelikos and Athienitis (2007) demonstrated a 35–45% reduction in solar heat gain through effective shading strategies, highlighting the practical value of bioclimatic design in mitigating thermal loads and together, these theories and findings provide a comprehensive foundation for examining the interplay between daylighting, student visual experience, and architectural design.

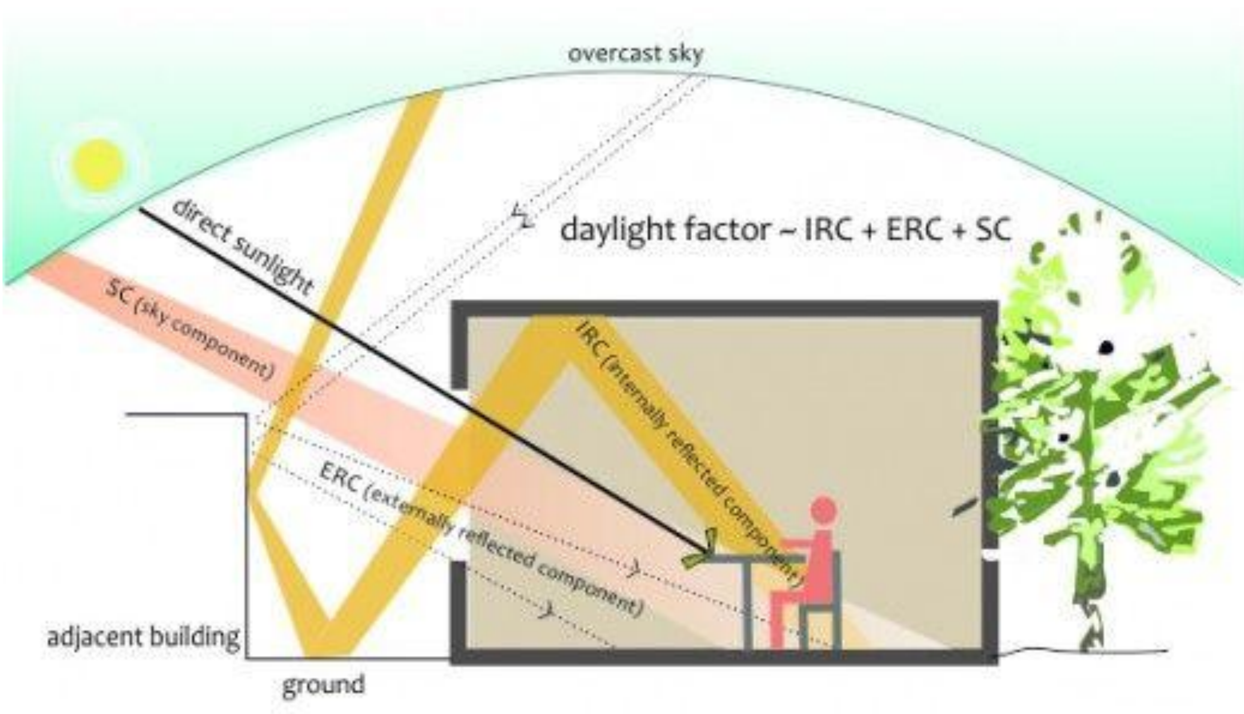


Figure 2 : daylight components

2.2 Conceptual Framework

This study employs a structured conceptual framework that systematically links between architectural design variables with performance metrics and user-centered outcomes, and the framework is organized into three core components: inputs, mediators, and outcomes. Each component is associated with one of the study specific objectives, ensuring a coherent flow from design parameters to human and environmental responses.

Design Inputs represent the physical parameters of window systems that can be manipulated in the architectural design process and it include **window size**, measured by the Window-to-Wall Ratio (WWR); **window placement**, which refers to the location and orientation of windows within the classroom; and **glazing type**, which influences both light transmission and thermal insulation and these variables are directly aligned with **Specific Objective 1 (SO1)**, which is focused on analyzing the effects of these window configurations on daylight performance.

Mediators act as performance metrics that reflect the interaction between design inputs and environmental outcome. These include the **Daylight Factor (DF)**, a measure of the amount of daylight available inside a room compared to the outdoor; the **Daylight Glare Probability (DGP)**, which assesses the potential for glare based on luminance distribution and occupant position; and the **spatial Daylight Autonomy (sDA)**, which evaluates the percentage of occupied hours in a year when a space meets minimum daylight illuminance levels and these indicators are linked to **Specific Objective 2 (SO2)**, which examine how these performance levels correlate with students perceptions visual and thermal comfort and usability.

Outcomes refer to the ultimate goals of the study, which are **visual comfort** and **thermal regulation** within the classroom environment and these outcomes inform **Specific Objective 3 (SO3)**, which aims to propose evidence-based design guidelines that optimize window performance in terms of both daylight and thermal comfort, particularly in the context of tropical climates.To summarize the conceptual relationships among these components, the following table presents the integrated framework:

Table 1: conceptual framework summary

Component	Variables	Link to Objectives
Inputs	Window size (WWR), placement, glazing	SO1: Analyze effects on daylight performance
Mediators	Daylight Factor (DF), DGP, spatial Daylight Autonomy (sDA)	SO2: Correlate daylight metrics with occupant perceptions
Outcomes	Visual comfort, thermal regulation	SO3: Propose optimized design guidelines

2.2 Methodological Framework

This study adopt a rigorous mixed method approach to comprehensively address its specific research objectives by integrating both quantitative and qualitative data collections and analysis techniques. The first objective (SO1), which focuses on evaluating daylight performances in classrooms, employs extensive field measurements alongside advanced computer simulations. Field data are collected at 56 predetermined points within each classroom using NIST-calibrated lux meters with an accuracy of ±3%, ensuring precise illuminanse measurements that capture spatial variations in daylight distribution (Tadesse, 2020). These empirical measurements serve as critical ground truth data for validating simulation models. The simulation process utilizes Ecotect software to model the key daylight metrics, including Daylight Factor (DF), spatial Daylight Autonomy (sDA), and Useful Daylight Illuminance (UDI) within the range of 300 to 2000 lux(standared) and these metrics are essential for assessing daylight sufficiency, glare potential, and risks of over-illumination, providing a clear understanding of the influence of window design variables on indoor lighting conditions (Assefa, 2017; Heschong, 2003).

The second objective (SO2), which investigates occupant perceptions of visual comfort and thermal sensation, incorporates survey methodologies and behavioral observations and Standardized Likert-scale questionnaires to capture subjective evaluations of glare, comfort, and thermal sensation, while behavioral observations conducted in classroom activities provide contextual insights into occupant responses. Quantitative metrics, such as the Daylight Glare Probability (DGP), are employed to objectively assess discomfort glare, complemented by thermal sensation votes reflecting occupants perceived thermal comfort (Boyce, 2014; Evans, 2003). This mixed qualitative-quantitative approach enables a comprehensive analysis of how environmental factors translate into user experience, bridging objective environmental data with subjective occupant feedback.

For the third objective (SO3), aiming at developing optimized design guidelines, the study applies statistical regression analyses in conjunction with comparative daylight and thermal performance simulation and regression models explore the relationships between variations in window-to-wall ratio (WWR) and solar heat gain coefficient (SHGC) thresholds specifically targeting values at or below 0.4 and their combined effects of daylight distribution and thermal comfort. Comparative simulations assess the performance of different glazing type, shading devices, and window orientations to identify configurations that maximize occupant comfort while minimizing unwanted solar heat gains (Olgyay, 2015; Tzempelikos & Athienitis, 2007). This methodological triangulation ensures robust, evidence-based recommendations tailored to the local climatic and socioeconomic context of Ethiopian classrooms.

To maintain data reliability and validity during data collection, all measuring instruments are regularly calibrated throughout the data collection processes. Simulation results are validated against field measurements, demonstrating strong correlations with coefficients of determination (R^2) exceeding 0.85, thereby affirming the accuracy and credibility of the modeling tools and the combined methodological framework (Tadesse, 2020).

2.3 Empirical Literature Review: Daylight in Educational Buildings Around the World

Daylighting in educational buildings is a critical factor affecting visual comfort, student performance, and overall health. Globally, researchers have studied the impacts of daylight on learning environment, including how window size, placement on the wall, and glazing types affect both energy efficiency and human comfort and this empirical literature review draws from studie from various regions worldwide, presenting real data and insights into the role of daylight in educational spaces.

1. Daylighting and Student Performance: A Case Study in the United States

In the United States, a landmark study by Heschong Mahone Group (1999) examined the relationship between daylight exposure and students performance in schools across several regions and the study was over 21,000 students in 3,000 classrooms, standardized test scores with the amount of natural light.

- Findings: The study find that student in classrooms with more daylight performed better on tests. Specifically, students in classrooms with the most daylight performed 20% more better in math and 26% better in reading in classrooms with less daylight exposure. This was attributed to increased alertness and improved mood from exposure to natural light.
- Recommendations: The study was suggested that schools maximize daylight availability by increasing window size and optimizing window placement. This could help create a brighter and more stimulating environment for students for cognitive performance.

2. Daylighting in Schools: Sweden and Norway

In Sweden and Norway, a comparative study by Gustavsson and Roos (2010) which is focused on daylighting in primary schools in the Nordic climate, where daylight availability can vary across seasons.

- Findings: The study was found that classrooms with larger windows that allowed more daylight exposure resulted in better visual comfort and reduced eye strain among students. However, this study also emphasized that the effectiveness of daylighting was influenced by window orientation and shading devices to manage glare, especially during the summer months when the sun is at a high angle.
- Recommendations: This study recommended using automated shading systems and glazing materials that reduce solar heat gain while allowing adequate daylight penetration. Additionally, classrooms facing north (to avoid direct sunlight) were identified as optimal for daylighting in these nort hern latitudes of the earth surface.

3. Daylight and Glare Control in Malaysian Schools

In Malaysia, a study by Mohamed and Darus (2012) focused on the performance of shading devices in controlling glare in educational buildings with large glazed facades and the studys investigated the impact of various shading devices on reducing glare while maintaining natural light levels in classrooms.

- Findings: The study found that vertical shading devices are the most effective in reducing glare. Additionally, low-emissivity glass and reflective films are effective in mitigating glare while maintaining natural light penetration. However, excessive glazing on the west-facing walls led to higher solar heat gain on that region.
- Recommendations: The study recommend incorporating external shading devices and high-performance glazing for energy-efficient daylighting and also suggests that schools in tropical climates, like Malaysia, balance daylighting with cooling efficiency to maintain thermal comfort.

4. Daylighting in UK Schools and Its Impact on Health

A study by Küller et al. (2006) in the United Kingdom explored the health impacts of daylight exposure in primary and secondary schools and the study measured students stress levels, sleep quality, and academic performance in classrooms with different level of natural light.

- Finding: The study concluded that students in classrooms with abundant daylight reported lower level of stress and improved mood. Specifically, students in classrooms with good daylighting have a reduction in fatigue and eye strain furthermore, the study observed that classroom with access to natural light promoted a more relaxed and alert environment, leads to higher levels of student engagement.
- Recommendations: The study recommended that schools prioritize daylighting by ensuring larger windows and optimizing the windows relative to the sun's path.

5. Energy Efficiency and Daylight Use in Indian Schools

In India, a study by Sharma and Kothari (2017) investigated that the role of daylight in reducing energy consumption in educational buildings and the studys focused on the impact of large windows and external shading systems on energy use in schools in hot and dry climates, such as those in Rajasthan.

- Findings: The studys found that large windows with external shading reduced the need for artificial lighting, contributing to energy savings. However, it also highlighted the issue of solar heat gain, which in turn increased cooling loads during the hotter month. The study observed that schools using reflective glass and external shading could achieve a balance between maximizing daylight and minimizing heat gain.
- Recommendations: The study recommended high-performance glazing and external shading devices to mitigate heat gain and glare while improving daylight penetration. Additionally, the authors suggested integrating passive cooling strategies with daylighting to reduce the energy consumption of the school.

6. Impact of Daylight on Academic Performance in Australian Schools

A study in Australia, by Lee and Han (2015), examined the relationship between daylight availability and students performance in Australian primary schools, and the study measured classroom daylighting conditions and student performance on tests.

- Findings: The study revealed that classrooms which is with more natural light have students who scored better on tests and showed higher levels of engagement. Students in classrooms with less daylight reported feeling more tired and having trouble concentrating, and the study highlighted that glare could interfere with performance, but this could be mitigated by using shading systems and appropriate window placements.
- Recommendations: The study suggested that schools optimize window placement and use glare-reducing windows films or external shading devices can improve daylight quality while maintaining visual comfort, and classrooms should incorporate sufficient daylight-responsive artificial lighting to enhance the learning environment.

2.4 Summary of Key Findings

This literature review established as a comprehensive foundation for the study by examining the theoretical, conceptual, contextual, and methodological frameworks specifically to daylighting, thermal heat gain and occupant comfort in educational class room environment in different parts of the world. At the theoretical level, three principal theories underpin this research. The Photobiological Theory explains how window design variables such as size, placement on wall, and glazing affect physiological responses through the stimulation of photoreceptors including cones rods, and intrinsically photosensitive retinal ganglion cells (ipRGCs) (Boyce, 2014). This theory substantiates the analysis of daylight performance in classrooms. Complementing this, the Environmental Stress Theory highlights how suboptimal lighting conditions, including glare and uneven illumination, act as environmental stressors that induce cognitive fatigue and impair concentration (Evans, 2003) and this provides the basis for assessing occupant perceptions of visual comfort in the class rooms. At last, Bioclimatic Design Principles emphasize the importance of climate responsive, passive architectural strategies to optimize window configurations and thermal discomfort, particularly in tropical climates (Olgyay, 2015). Empirical studies reinforce these theoretical frameworks by demonstrating that access to natural daylight can improve cognitive function, such as an 18.2% increase in student reading speeds (Heschong, 2003), and this effective shading strategies can reduce solar heat gains by up to 45%, thus improving thermal regulation (Tzempelikos & Athienitis, 2007).

The conceptual framework structures the study by linking design inputs namely window-to-wall ratio (WWR), window placement on the wall, and glazing characteristics with mediating performance metrics such as Daylight Factor (DF), Daylight Glare Probability (DGP), and spatial Daylight Autonomy (sDA). These mediators serve as quantifiable indicators that translate architectural design choices into user centred outcomes of visual comfort and thermal regulation and this systematic linkage aligns directly with the study specific objectives, ensuring a coherent flow from design variables to environmental performances and occupant experience (Assefa, 2017; Tadesse, 2020).

Contextually, the study is situated in Adama City, Ethiopia, characterized by a tropical wet-and-dry climate with high solar irradiance ranging from 6 to 7 kWh/m²/day and significant temperature fluctuations between 15°C and 35°C (Assefa, 2017). This climatic setting presents unique challenges for daylighting and thermal comfort, exacerbated by policy shortcomings in Ethiopia's Building Code Standard (EBCS 12), which lacks tailored guidelines for tropical glare thresholds and solar heat control. therefore, empirical findings reveal widespread classroom noncompliance with minimum illuminance standards (76.6% failing the 300-lux requirement) and high incidences of glare, particularly in southwest-facing rooms (Tadesse, 2020). Socioeconomic constraints further restrict schools to using low-cost and substandard construction materials, limiting the adoption of advanced glazing or mechanical cooling technologies and underscoring the necessity for affordable, passive design interventions and, gender disparities in glare sensitivity—where female students report 5–10% higher discomforthighlight the imperative for equitable design considerations (Assefa, 2017).

Methodologicaly, the study adopts a rigorous mixed-methods approach aligned with the specific objectives. Quantitative field measurements, utilizing NIST-calibrated lux meters, are combined with validated Ecotect daylight simulations to assess illuminance distribution and glare potential. Surveys employing Likert scales and behavioral observations capture occupant comfort and glare perception, bridging objective metrics with subjective experience. Regression analyses and comparative simulations inform optimization of window-to-wall ratios and shading coefficients

(SHGC ≤ 0.4), facilitating evidence-based design recommendations. Strong correlations ($R^2 > 0.85$) between field data and simulations validate the reliability of the methodological framework (Tzempelikos & Athienitis, 2007; Tadesse, 2020).

Collectively, these theoretical, conceptual, contextual, and methodological insights provide a robust interdisciplinary foundation for investigating and enhancing daylighting and thermal comfort in tropical educational settings, with particular relevance to the socio-environmental realities of Ethiopian classrooms.

2.5 Research Gaps

Despite an expanding body of literature on daylighting and occupant comfort in educational environments, several critical knowledge gaps remain, particularly within the context of tropical regions such as Ethiopia. One of the most significant gaps is the lack of empirical research focusing specifically on Ethiopian classroom architecture, especially as it pertains to window design strategies that respond effectively to the country's unique solar geometry and climatic conditions. Much of the existing research is either rooted in temperate climates or generalized across broad tropical zones, thereby limiting its contextual relevance to Ethiopia (Assefa, 2017; Tadesse, 2020).

Furthermore, the Ethiopian Building Code Standard (EBCS 12), which governs lighting and thermal performance, lacks specific, orientation-sensitive benchmarks for daylighting quality, visual glare, and thermal discomfort. This regulatory gap results in a disconnect between prescribed standards and actual classroom performance, with Tadesse (2020) reporting that between 30% and 40% of classrooms in Adama fail to meet the recommended minimum illuminance levels of 300 lux. In addition, frequent occurrences of glare—particularly in southwest-facing classrooms, where incidence rates reach 68.7%—underscore the inadequacy of current guidelines in addressing localized solar exposure challenges.

Although international studies have highlighted the physiological significance of daylight for visual perception and circadian regulation (Boyce, 2014), little research has investigated how these findings translate to Ethiopian classroom environments. This omission becomes particularly important when considering gender-based differences in light sensitivity. Empirical evidence indicates that female students may report 5–10% higher discomfort levels under intense glare

(Assefa, 2017), yet this equity dimension remains largely absent from both national policy and local design practice.

A further gap lies in the overreliance on technologically advanced daylighting solutions in existing literature—solutions such as electrochromic glazing, automated blinds, and HVAC-integrated systems that are often financially and technically impractical for widespread implementation in Ethiopia. Approximately 75% of schools in the country are constructed using low-cost and substandard materials, limiting the feasibility of these advanced interventions (Assefa, 2017). Despite this, few studies explore passive, cost-effective, and vernacular design alternatives suitable for such resource-constrained environments.

Moreover, most available studies emphasize short term simulations or isolated field assessments. There is a lack of longitudinal research on the durability, maintenance, and user adaptability of daylighting systems in school environments subjected to tropical climatic extremes, and such understanding are vital for ensuring that proposed designs strategy remain effective over time under real-world conditions.

Finally, there is a methodological shortcoming in integrating quantitative performance indicators such as Daylight Factor (DF), Spatial Daylight Autonomy (sDA), and Daylight Glare Probability (DGP) with qualitative data reflecting user comfort, behavior, and satisfaction. This disconnect frequently leads to guidelines that are either too technical for practical use in local contexts or insufficiently robust to support evidence based design (Tzempelikos & Athienitis, 2007).

In summary, those gaps collectively highlight the need for localized, interdisciplinary research that bridges global best practices in daylighting with the Ethiopian specific environmental, regulatory, and socioeconomic practices and this study seeks to contribute meaningful strategy to this emerging field by developing climate responsive, economically viable, and user-cantered window design strategies tailored to the conditions of Ethiopian primary school classrooms.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Introduction

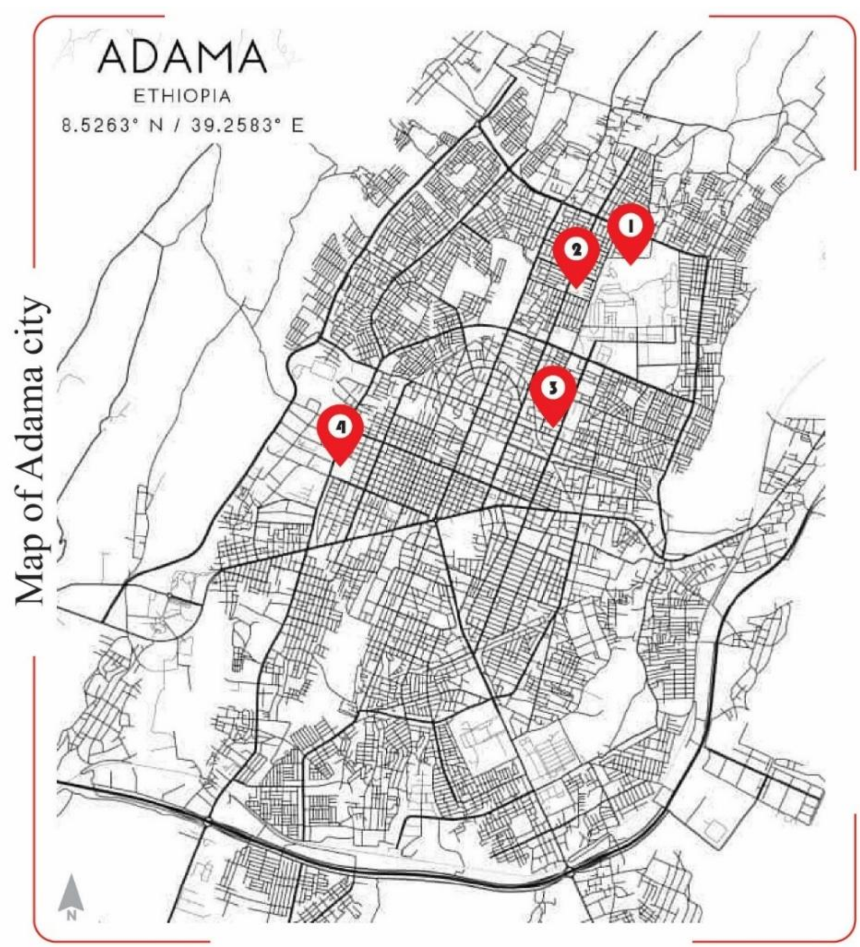
This chapter outline the methodological approach used to investigate the relationship between window design and students visual comfort in elementary school classrooms in Adama City, Ethiopia. It details the research setting, sampling procedures, data collection instruments, and analytical techniques employed to achieve the study's objective. The selected methods are guided by the need to integrate quantitative measurements of daylight performance with qualitative assessments of user experience, ensuring a holistic understanding of environmental quality in educational spaces.

Given the diversity in school architecture and the climate specific to Adama city, a mixed-methods approach was deemed appropriate and this methodology allows for rigorous analysis of daylight distribution, glare potential, and thermal comfort through a combination of field measurements, simulation modeling, and occupant feedback. The study area building typologies characterized by varied window-to-wall ratios, glazing materials, and shading strategies provide a valuable context for examining how design variations influencing indoor environmental conditions.

This chapter begins by describing the physical and environmental characteristics of the study area, adama Ethiopia followed by an explanation of the sampling criteria, instrumentation, and data analysis techniques applied throughout the research process.

3.2 Study Area

The study focuses on elementary schools in Adama City, Ethiopia. These schools feature single-story or low-rise buildings with rectangular classroom layouts and the classrooms are designed with large windows on one or two walls to maximize natural light. However, variations exist in window-to-wall ratios, glazing materials, and shading devices, which affect daylight distribution and glare control across all cardinal. Many schools lack standardized architectural window designs, resulting in inconsistent lighting conditions and thermal comfort. This diversity in architectural characteristics provides a rich context for analyzing the impact of window design on visual comfort and the city's climatic conditions and socio-economic characteristics make it an ideal case for study and exploring sustainable daylighting solution.



Legend

1: *ASTU community school*

2: *Nafyad school*

3: *Awash academy*

4: *Geda michille school*

Figure 3: selected schools in Adama city

3.3 Population and Sampling

3.3.1 Population Characteristics

The target population for this study comprises all elementary schools in Adama City, Ethiopia, including 64 government-operated and 117 private institutions and these schools serve as critical environments for children foundational education and represent a diverse array of architectural designs that significantly influence the daylighting conditions and overall learning quality.

Those institutions exhibit architectural diversity, particularly in classroom designs where natural daylight plays a great role in supporting pedagogical effectiveness and these variations are shaped by a combination of socio-economic constraints and climatic adaptation methods appropriate for the city's location at approximately 8.54°N latitude.

This architectural diversity provides a rich context for investigating how differences in classroom building design affect daylight performance and visual comfort. It also offers a representative sample of the broader challenges and opportunities faced in developing sustainable, climate-responsive educational facilities in tropical settings.

3.4 Sampling Strategy

This study adopted a **purposive stratified sampling strategy** to ensure representative analysis across different classroom orientations and architectural typologies inAdama City's elementary schools. The Classrooms were first stratified based on their **cardinal orientation** (North, South, East, and West),as orientation significantly influences daylight availability, glare potential,and thermal performance due to solar geometry of this region (Tzempelikos & Athienitis, 2007; Mardaljevic et al., 2012).

Within each orientation category, **purposive sampling** was used to select classrooms that exhibit variation in key architectural elements such as window size, placement, glazing type, and the presence of shading device and this approach enabled the study to focus on classrooms most relevant on assessing day lighting performance under different environmental exposures.

By targeting classrooms that reflect a vast range of daylighting conditions and design characteristics, this strategy maximizes the potential of generalizing findings and deriving orientation-specific design recommendations and the sampling framework also supports the comparative simulation and regression analysis required to meet the study objectives.

3.5 Study Scope and Analytical Framework

This study adopts a **mixed-methods research framework** to investigate daylight performance, glare, and thermal comfort in elementary school classrooms across Adama City, Ethiopia. The scope include empirical measurements and computational simulations to assess classroom lighting and thermal conditions on the study area, emphasizing orientation-specific analysis in response to distinct solar geometries and four primary orientations were examined, each with unique daylighting and thermal implications:

1. **North-facing classrooms** benefit from stable diffuse daylight, achieving average illuminance levels of approximately 450 lux with minimal glare risk due to the absence of direct sunlight penetration (Heschong, 2003).
2. **South-facing classrooms** experience intense solar exposure during midday hours, with peak irradiance levels reaching up to 982 W/m². These conditions demand strategic design interventions to manage both glare and internal heat gains (Nguyen et al., 2019).
3. **East-facing classrooms** are exposed to low-angle morning sunlight (8:00–10:30 AM), resulting in direct glare conditions that require targeted mitigation measures for tha window (Lee et al., 2021).
4. **West-facing classrooms** are particularly vulnerable to late-afternoon heat gain (2:30–5:00 PM) and high glare intensity, often resulting in simultaneous thermal and visual discomfort (Tzempelikos & Athienitis, 2007).

The analytical framework integrates simulation-based modeling with field measurements to develop orientation sensitive design strategies for Adama City Ethiopia, aligning with Ethiopia's climatic and socioeconomic conditions.

3.6 Simulation Parameters and Variables

To evaluate daylight and thermal comforts and performances, the study employed **three main categories of simulation variables**, each are calibrated to the local context of Adama City:

A. Environmental Parameters

- Climate data derived from **Typical Meteorological Year (TMY)** datasets specific to Adama.
- **Solar geometry calculations** tailored to 8.54°N latitude, reflecting diurnal and seasonal sun paths.
- Simulation period aligned with the academic calendar.

B. Architectural Variables

1. Geometric Properties

- Classroom floor area: **35–56 m²**
- Ceiling heights: **2.8–3.2 m**

2. Fenestration Characteristics

- **Window-to-Wall Ratios (WWR):** 15%–40%
- **Glazing Types:**
  - *Clear float glass:* Visible Light Transmittance (VLT) 82–89%, SHGC 0.78
  - *Tinted glass:* VLT 40–60%, SHGC 0.42
  - *Textured glass:* VLT 55–75%, SHGC 0.61
- **Shading devices:** Overhangs, light shelves, and external louvers of varying depths and placements

3. Surface Reflectance Values:

- Ceilings: 70%–85%
- Walls: 50%–70%
- Floors: 20%–40%

C. Operational Parameters

- **Occupancy schedule:** 8:00 AM – 5:00 PM (standard school hours)
- **Measurement schedule:** Illuminance and temperature data collected **three times per day**, **three days per week**, for **15-day observation period**.

3.7 Performance Evaluation Metrics

The performance of classrooms was evaluated using a multi-dimensional framework encompassing **quantitative performance indicators** and **qualitative user feedback**:

A. Daylight Performance Metrics

- **Illuminance levels (lux):**
    - Evaluated against the **recommended 300–500 lux** range for educational settings
    - **Spatial uniformity ratios** (E_{min}/E_{avg}) analyzed
- **Daylight Factor (DF):**
    - Target range of **2–5%**, based on EN 17037 daylighting standards for learning environments
- **Spatial Daylight Autonomy (sDA₃₀₀/50%)**:
    - Percentage of floor area receiving at least 300 lux for 50% of occupied hours
- **Useful Daylight Illuminance (UDI_{300–2000})**:
    - Evaluates how often illuminance remains within the optimal daylight range

B. Visual Comfort Assessment

- **Daylight Glare Probability (DGP):**
    - Categorized as:
        - < 0.35: imperceptible
        - 0.35–0.40: perceptible
        - 0.45: intolerable glare
- **Luminance contrast ratio:**
    - Maintained below **20:1** between window surfaces and interior backgrounds
- **Direct illuminance thresholds** evaluated at eye level to identify risk zones

C. Thermal Performance Indicators

- **Solar Heat Gain Coefficient (SHGC):**
    - Evaluated for all glazing types to assess thermal load from solar radiation
- **Indoor temperature profiling:**
    - Monitored hourly to detect peaks and fluctuations
- **ASHRAE 55-2020 adaptive comfort model compliance:**
    - Thermal conditions assessed against internationally recognized adaptive thresholds for naturally ventilated spaces

D. Human Factors and Occupant Comfort

- **Surveys administered to 330 participants** (students and teachers):
    - Standardized 5-point Likert scales to evaluate thermal sensation, visual comfort, and glare perception
- **Behavioral observations**:
    - Documented responses to discomfort, including shading use, repositioning, and changes in seating location
- **Adaptive strategies** (e.g., use of blinds, student relocation) were recorded to correlate behavior with environmental data

3.8 Methodological Implementation

The research methodology integrated **three complementary and interrelated approaches** to ensure a robust evaluation of daylighting, glare, and thermal comfort in elementary school classrooms:

1. Field Measurements

- **Illuminance Mapping**: High-resolution spatial measurements using point grids (35–56 points per room) at a standard working plane height of 0.75 meters.
- **Glare Assessment**: High Dynamic Range (HDR) imaging techniques were employed to capture luminance distributions and assess glare using established visual comfort models.
- **Thermal Profiling**: Indoor temperature readings were recorded throughout the day to evaluate thermal comfort and heat gain patterns.

2. Computational Analysis

- **Annual Climate-Based Daylight Modeling**: Simulations were performed over a full-year (8,760 hours) time span to assess daylight availability using real climatic data.
- **Parametric Design Studies**: Variations in Window-to-Wall Ratio (WWR), glazing types, and shading configurations were modeled to understand their influence on daylight and glare.
- **Validation**: Simulated outcomes were cross-verified with field data, achieving a high correlation coefficient (**R^2 = 0.87**) between modeled and measured illuminance levels.

3. Comparative Evaluation

- **Orientation-Based Benchmarking**: Classroom performance was compared across cardinal orientations to identify patterns in daylight distribution and glare risk.
- **Cost-Benefit Analysis**: Design alternatives were assessed for effectiveness and economic feasibility, particularly under resource-constrained conditions.
- **Regulatory Compliance**: Performance outcomes were evaluated against the **Ethiopian Building Code Standard (EBCS 12)** for lighting and thermal comfort.

3.9 Tools and Standards

The study utilized a combination of industry-standard software, instruments, and evaluation frameworks:

Tools and Software

- **Simulation Software**:
  - *Autodesk Ecotect* for spatial daylight and thermal modeling
  - *IMAGEL.Js* for luminance and glare analysis based on HDR images
- **Measurement Instruments**:
  - National Institute of Standards and Technology (NIST)-calibrated digital lux meters

- Professional-grade HDR cameras for glare and luminance measurements

Reference Standards

- **Daylight Metrics**:
  - *EN 17037* – Daylight in buildings
  - *IES LM-83-12* – Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)
- **Glare Metrics**:
  - *CIE 117-1995* – Discomfort glare in interior lighting
- **Thermal Comfort**:
  - *ASHRAE 55-2020* – Thermal environmental conditions for human occupancy

3.10 Sample Size and Structure

From a total of **181 elementary schools** in Adama City, a **purposive sampling strategy** was used to select **four representative schools** for in-depth analysis. This selection yielded **four classrooms**, with a combined student population of **214 learners**. The sampling strategy was carefully designed to ensure variation in architectural and institutional characteristics while maintaining consistency in size, occupancy, and orientation.

Table 2 : School and Student/Classroom Distribution

No.	School Name	Classroom Orientation	School Type	Classrooms	Students per Classroom	Percentage
1	ASTU Community Primary	North-facing	Government	1	48	23%
2	Awash Academy	West-facing	Private	1	54	25%
3	Geda Michile	South-facing	Government	1	60	29%
4	Nafyad School	East-facing	Private	1	52	23%
	Total	—	—	**4**	**214**	**100%**

3.11 Classroom Selection Protocol

A **multi-stage selection process** was applied to ensure methodological rigor and representative coverage of classroom orientations and fenestration types. An initial screening phase identified **32 candidate schools**, evaluated through document reviews, site visits, and daylight suitability assessments. The final selection of **four schools** was based on three core inclusion criteria:

A. Orientation and Solar Exposure

Each selected classroom represents one of the **four primary cardinal orientations**, allowing orientation-specific analysis of daylight access and visual comfort for the research. Orientation angles were verified using digital compass readings with a tolerance of ±2° to ensure the precision.

B. Fenestration and Glazing Diversity

To capture the different of daylighting conditions, classrooms were selected based on distinct **window-to-wall ratio (WWR)** and **glazing types**:

- **WWR Categories**:
  - *Low*: 15–20%
  - *Medium*: 20–30%
  - *High*: 30–40%
- **Glazing Types**:
  - *Clear glass*: Visible Light Transmittance (VLT) 82–89%
  - *Tinted glass*: VLT 40–60%
  - *Textured glass*: VLT 55–75%

Those variables were crucial for analyzing the effects on daylights penetration, glare potential, and luminance balance.

C. Spatial and Operational Consistency

Classrooms were selected to ensure comparability across spatial and operational dimensions:

- **Floor Area**: Between 35–56 m², with a ±10% tolerance to maintain spatial equivalent.
- **Ceiling Height**: Between 2.8–3.2 meters to standardize vertical daylight distributions.
- **Occupancy Density**: Maintained at 0.9–1.2 m² per students, reflecting realistic classroom conditions (45–60 students per room).

This rigorous selection ensured that each classroom served as a controlled yet representative case study for its respective orientation and architectural design profile.

3.11.1 Validation and Quality Assurance

Technical validations procedures were confirmed ≤22.5° deviation from true cardinal directions and maintained the consistent external obstruction conditions using the 1.5× height rule and Window-to-wall ratio distribution was balanced across orientations to prevent sampling bias.

Scientific validations were demonstrated a strong correlation between measured and simulated data (R^2>0.85),and confirming that sample's representativeness of Ethiopia's EBCS 8 building standards and the selected cases enabled a comprehensive comparative analysis of:

- Daylight adequacy against the 300-lux educational threshold
- Thermal comfort variations across orientations
- Compliance with key design parameters

This carefully designed sampling strategy provided a robust foundation for the study's subsequent environmental performance evaluations while maintaining practical feasibility in a real-world educational context. The multi stage validations process were ensured the scientific validity and relevance of findings to Ethiopia's elementary school building stock.

3.12 Data Collection and Analysis Methodology

This study was conducted a comprehensive, multi-method approach to evaluate the environmental performance of elementary school classrooms in Adama City. The research methodology systematically integrated quantitative physical measurements with qualitative human perceptions assessments, ensuring evaluation of objective performance metrics and subjective user experiences.

3.12.1 Field Measurement Procedures

The physical measurement protocol was designed to capture detailed environmental data during typical school operating hours 8 am-5 pm 3 times a day 3 times a week For daylight performance evaluation, illuminance measurements were recorded hourly using BS-8000 professional-grade lux meters calibrated to NIST standards (±3% accuracy). A systematic 56-point measurement grid at the critical 0.75m working plane height (student desk level) provided comprehensive spatial data on light distribution. Simultaneously, continuous thermal monitoring was conducted using FLIR TG165-X thermal imaging cameras (±2°C accuracy) to assess thermal comfort conditions.

3.12.2 Questionnaire Survey and Formal Interviews

To assess student subjective experiences on visual comfort and thermal comfort in the classroom environment, structured questionnaires were conducted to a purposively selected sample of respondents and the questionnaires design focused on capturing variations in perception based on seating positions within the classroom, enabling a comparative analysis of visual comfort across different zones (front, middle, and rear rows) in the class room. This approach provided insights into how students perceived daylight conditions and the adaptive strategies that employed to mitigate discomfort.

214 students participated in the study, representing all the student population across the sampled classrooms. The purposive sampling method was employed for participant selection, as it allows for the inclusion of subjects based on specific criteria relevant to the research objectives (Tayie, 2005). Of these participants, 213 responded through written questionnaires, while the remaining 1 didn’t answer it. This method approach ensured comprehensive data collection.

The questionnaire responses revealed critical patterns in students' perceptions of glare, daylight adequacy, and thermal comfort, which is further correlated with physical measurements of illuminance, glare indices, and thermal comfort.

3.12.3 Integrated Research Methodology

By integrating the subjective and objective datasets, the study provides a holistic understanding of the interplay between classroom design and occupant comfort in Adama's elementary schools.

1. Simulation & Field Measurement Protocol

- *Advanced Lighting Analysis*:
  - Conducted climate-based daylight modeling (Autodesk Ecotect) using TMY data
  - Evaluated annual performance metrics:
    - Useful Daylight Illuminance (UDI300-2000)
    - Daylight Glare Probability (DGP)
  - Material specifications:
    - Glazing (VLT 40-89%, SHGC 0.25-0.78)
    - Surface reflectances (walls 20-90%, ceilings 70-85%)
- *Field Validation*:
  - High-precision measurements:
    - 56-point illuminance grids (0.75m/1.2m heights)
    - HDR imaging for glare analysis
    - Thermal monitoring
  - Instrumentation:
    - NIST-calibrated lux meters (±3%)
    - Thermal cameras (±2°C)

2. Multi-Method Assessment Framework

Table 3 : Multi method assessment framework

Analysis Dimension	Quantitative Methods	Qualitative Methods
Temporal	Diurnal illuminance/thermal patterns	Behavioral observations
Spatial	DA mapping, Glare distribution	Occupant movement patterns
Statistical	Pearson correlations	Thematic analysis of interviews
Design Optimization	Multiple regression analysis	User preference surveys

3. Integrated Data Synthesis

- Combined:
    - 214 occupant surveys (students)
    - 4 classroom simulations
    - 321+ field measurements

Table 4 : Research Methods Mapped to Specific Objectives

Specific Objective	Data Collection Methods	Analysis Methods	Key Metrics / Outputs
1. To analyze the effects of window size, placement, and glazing type on daylight performance in selected elementary school classrooms.	- Hourly illuminance measurements (56-point grid) - HDR imaging for glare - Indoor temperature monitoring	- Climate-based daylight simulation (Ecotect) - Glare probability analysis (DGP) - Thermal mapping	- Daylight Factor (2–5%) - Useful Daylight Illuminance (UDI_{300–2000}) - DGP and UGR values
2. To assess occupants' subjective perceptions of visual comfort through structured surveys with students.	- Structured student surveys (n=214) - Behavioral observations	- Likert scale evaluation - Correlation analysis between subjective and objective data	- Visual comfort ratings - Glare complaint frequency - Thermal sensation votes
3. To correlate window design parameters with classroom geometry and orientation to identify optimal configurations for visual comfort.	- Field data from classrooms with different orientations - Simulation data on WWR, glazing, and orientation - Building geometry analysis	- Multiple regression analysis - Orientation-based performance comparison	- Orientation-specific performance patterns - Statistical significance of design factors
4. To propose context-specific window design guidelines for Adama's tropical climate, balancing daylight adequacy with thermal and energy efficiency.	- Synthesized findings from objectives 1–3 - Review of EBCS 12 and climatic data - Simulation of alternative design scenarios	- Comparative analysis of parametric design options	- Recommended WWR and glazing combinations - Orientation-based shading guidelines

3.13 Research Design and Approaches

3.13.1 Research design

This study adopted a **mixed-methods research design**, integrating both quantitative and qualitative approaches to comprehensively assess the impact of window design parameters on visual comfort in elementary school classrooms. The design aligns with the study's objective to evaluate how window size, placement, and glazing type influence daylight performance and occupant comfort in the specific context of Adama City's tropical climate.

Quantitatively, the study employed precise **field measurements** and **simulation modeling** to analyze objective environmental performance metrics, including illuminance levels, Daylight Factor (DF), and Daylight Glare Probability (DGP). Instruments such as NIST-calibrated lux meters and thermal cameras were used to collect empirical data at 56 grid points per classroom, while Autodesk Ecotect simulations supported climate-based modeling.

Qualitatively, the research utilized **structured student surveys** and **behavioral observations** to assess subjective perceptions of visual comfort and thermal conditions. Responses were analyzed to capture experiential data regarding lighting adequacy, glare discomfort, and seating preferences.

The study's research design is diagrammatically represented in Figure 4 of the thesis and structured around three phases:

1. **Field investigation** (empirical data collection through physical instruments),
2. **User feedback assessment** (student perceptions and adaptive behaviors),
3. **Computational simulation and optimization** (performance modeling of window configurations).

By triangulation these methods, the research design was ensured a holistic understanding of how architectural window elements affect classroom environments and enabling the formulation of evidence based, climate responsive design guidelines.

3.13.2 Research Approach

The data analysis in this study combined both **primary and secondary sources** to assess the environmental performance of classrooms, and secondary data included relevant books, journal articles, and official building and education codes, while primary data were gathered from on-site measurements and students feedback. Five key parameters were analysed: illuminance levels, daylight factors, glare indices, thermal comfort indicators, and subjective student perceptions. Illuminance data were obtained using lux meters and validated through simulation models in Autodesk Ecotect. Glare was assessed by Daylight Glare Probability (DGP) and Unified Glare Rating (UGR)mechanisms, while thermal comfort was evaluated using digital thermal sensors in accordance with ISO 7730 and ASHRAE 55 standards.

The study adopted a **mixed-method approach**, integrating quantitative data from physical instruments and simulations with qualitative data from student surveys. This dual-layered method allowed for a clear understanding of classroom environments, as it combined technical performance metrics with real human experiences. Student responses was analysed to determine levels of satisfaction with lighting and thermal conditions, and these were cross-checked by objective field data to identify patterns and validate findings of the research. Instruments used in the study included a NIST-calibrated lux meter for illuminance readings, a digital anemometer for thermal readings, and a high-resolution digital camera for capturing classroom conditions and glare simulations. Detailed specifications for each instrument are provided in the appendix.

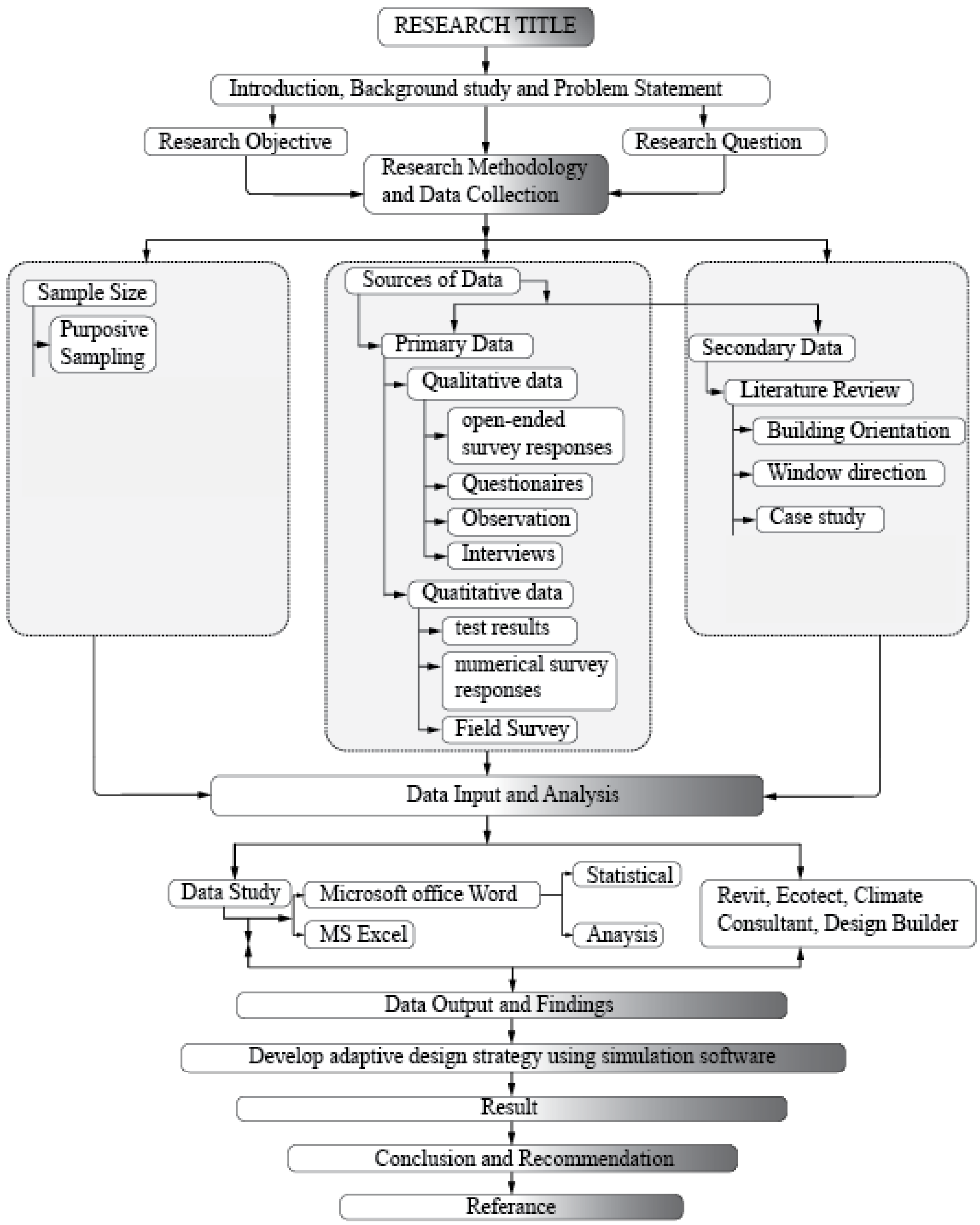


Figure 4 : Research design

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(A) (B) (c)

Figure 5: Data gathering instruments **(A) lux meter , (B) digital** anemometer & (C) digital camera

3.13.4 Ethical Considerations

This study adhered to ethical research practices. Prior to data collection, approval was obtained fr om the Institution. Participants were provided with an informed consent form detailing the study' s purpose, their rights, and confidentiality measures. All data was anonymized using participant c odes, and responses were stored securely on a password-protected server. Participants were infor med of their right to withdraw at any stage without consequences.

CHAPTER FOUR
RESULT AND DISCUSSION`

This study provides a critical examination of the relationship between classroom design and environmental comfort in Ethiopian elementary schools, focusing on daylight availability, visual comfort, and thermal performance. Through a systematic evaluation of four representative schools in Adama City, this research identifies key deficiencies in current architectural practices that hinder optimal learning conditions. The findings highlight how design choices such as window placement in the wall, shading strategies, and material selection directly influence measurable environmental parameters and the subjective comfort perceptions of students.

By integrating quantitative data (e.g., daylight factor measurements, temperature readings) with qualitative feedback from occupants, this study bridges the gaps between architectural design and educational functionality and the results underscore the urgent need for climate-responsive schools designs in tropical regions, offering empirical evidence to inform policy recommendations and sustainable construction practices. The discussion further explores actionable design interventions that can enhance environmental comfort while maintaining cost effectiveness and cultural relevance in Ethiopia educational infrastructure.

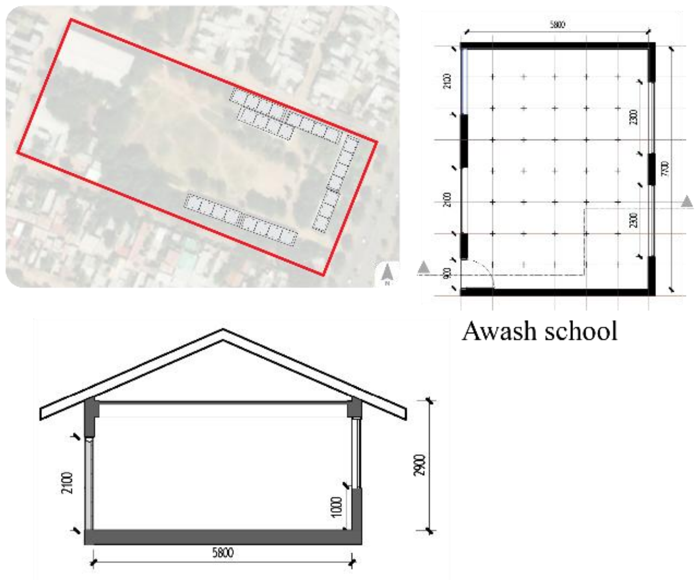
4.1 Measured Data Analysis

Awash Academy

The four examined classroom fenestrations design featured 8.74m² S-E-facing windows and a 1.78m² N-W-facing clerestory (totaling 8.74m², 20.8% floor area), which created significant performance issues. Field measurements showed extreme illuminance variations (240-2440 lux),

with rear zones receiving insufficient light (<300 lux) while midday periods suffered from excessive brightness. This configuration caused problematic glare (DGP >0.3 midday, UGR >0.4 afternoons) and thermal discomfort. Ecotect simulations (Figures 6A-D) confirmed poor daylight uniformity, with Daylight Factors ranging from just 1.4% to 21.4% across the space.

The combined effects of these conditions - inadequate rear-zone illumination, intense midday glare, and thermal stress - demonstrate how the current fenestration design fails to meet basic visual and thermal comfort requirements. The conflicting solar exposures from the dual-orientation windows create competing environmental challenges throughout the day, significantly compromising the classroom's functionality as a learning space.



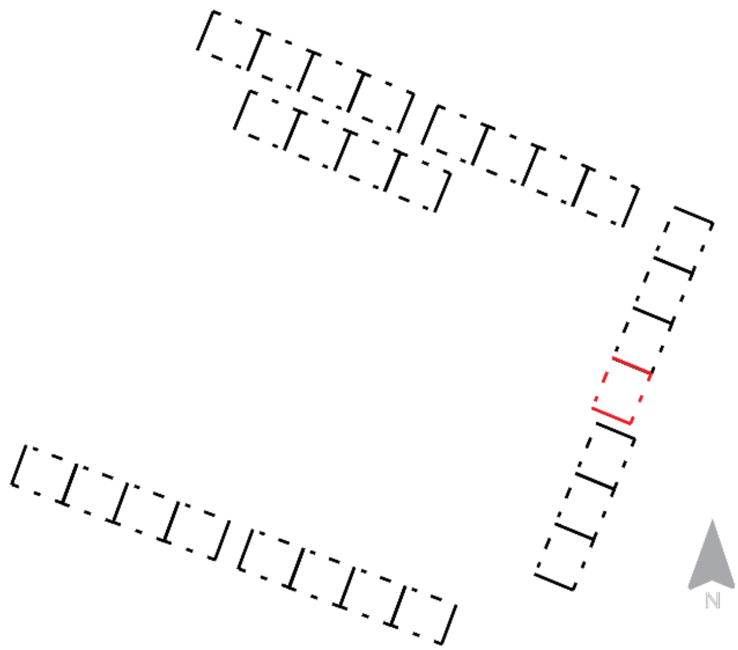
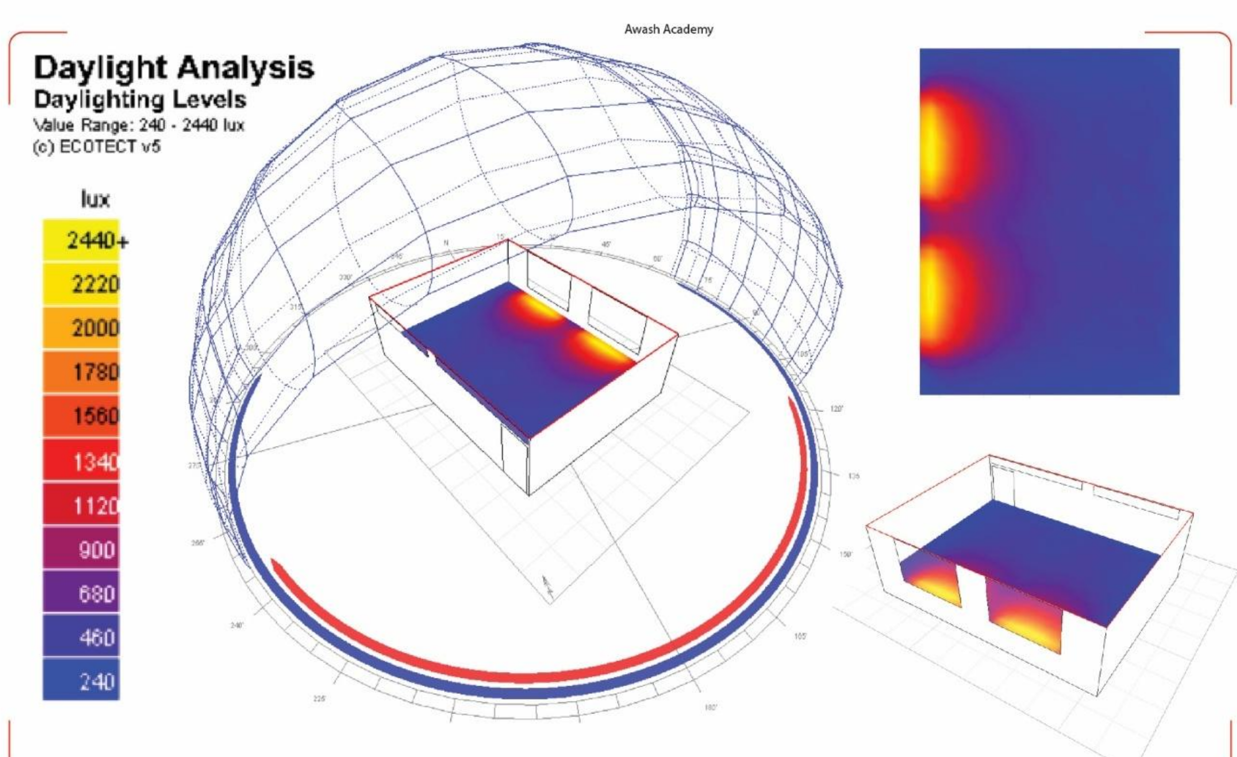
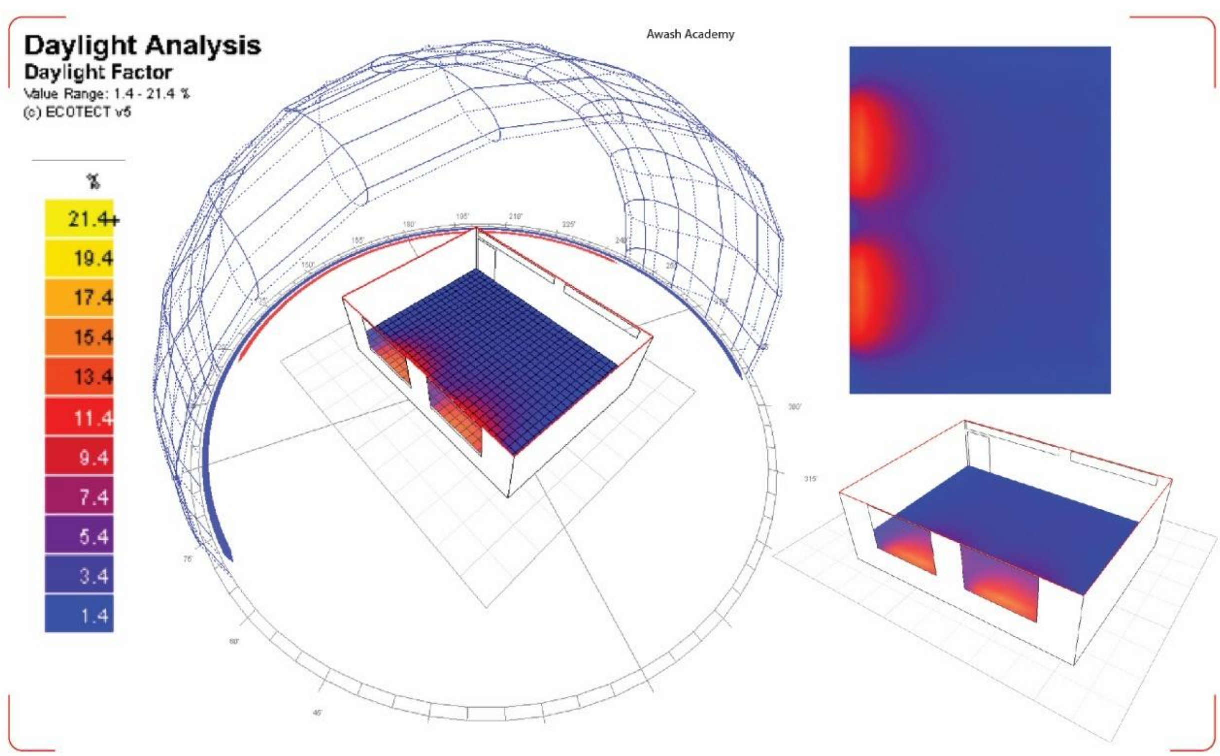


Figure 6 : Awash school class room

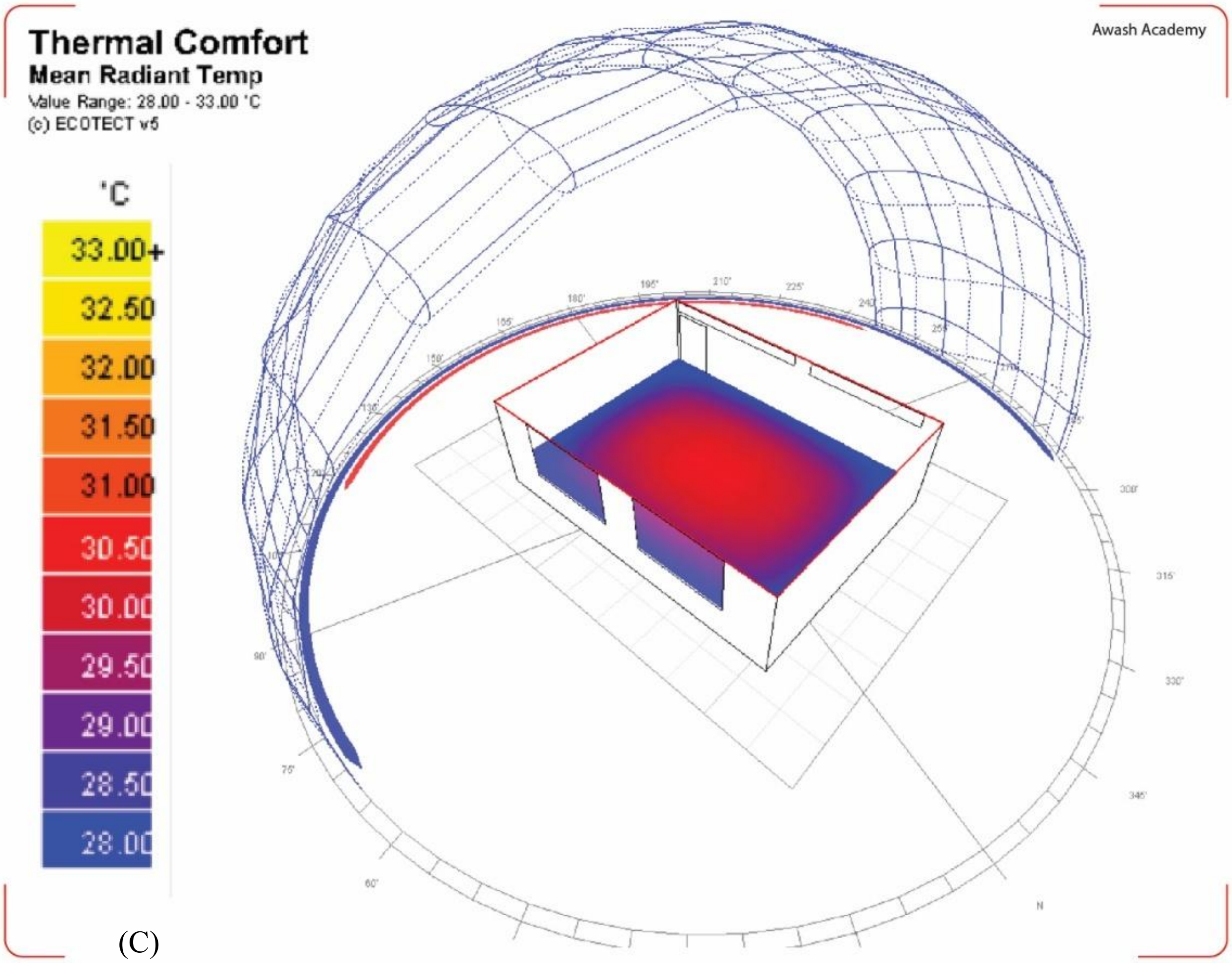
Legend : ____ Simulation classroom



(A) ***Average value*** *= 337.43 lux* ***Visible node*** *= 690*



(B) ***Average value*** *= 3.971%* ***Visible node*** *= 690*



(C)

(D)

Figure 7 : Awash academy

(A) Daylighting levels
(B) Daylight factor
(C) Thermal comfort &
(D) Glare simulation

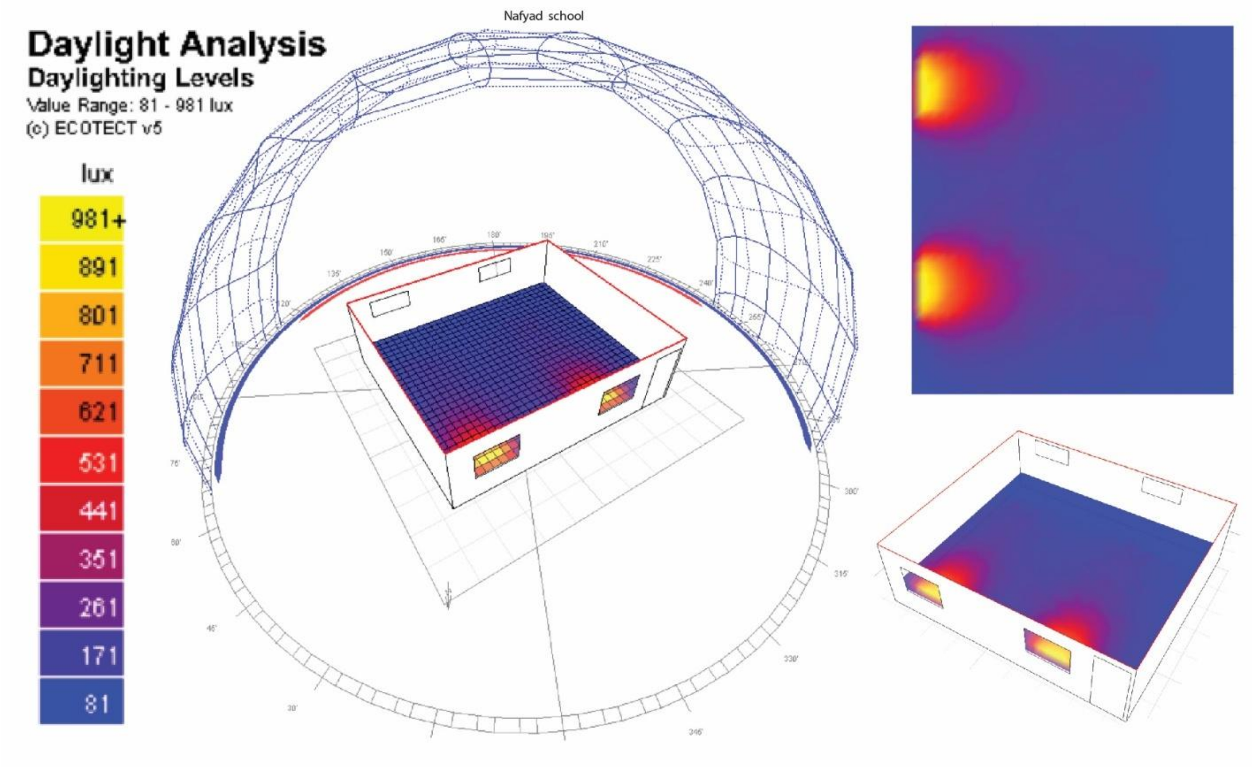
Nafyad School

The examined classroom's fenestration design featured 5.32m² S-W-facing windows and a 1.68m² N-E-facing clerestory (totaling 5.32m², 10% floor area), which created significant performance issues. Field measurements showed extreme illuminance variations (81-981 lux), with rear zones receiving insufficient light (<300 lux) while midday periods suffered from excessive brightness. This configuration caused problematic glare (DGP >0.3 midday, UGR >0.4 afternoons) and thermal discomfort, evidenced by 8°C surface temperature differentials and 3-4°C afternoon overheating. Ecotect simulations (Figures 6A-D) confirmed poor daylight uniformity, with Daylight Factors ranging from just 0.6% to 5.6% across the space.

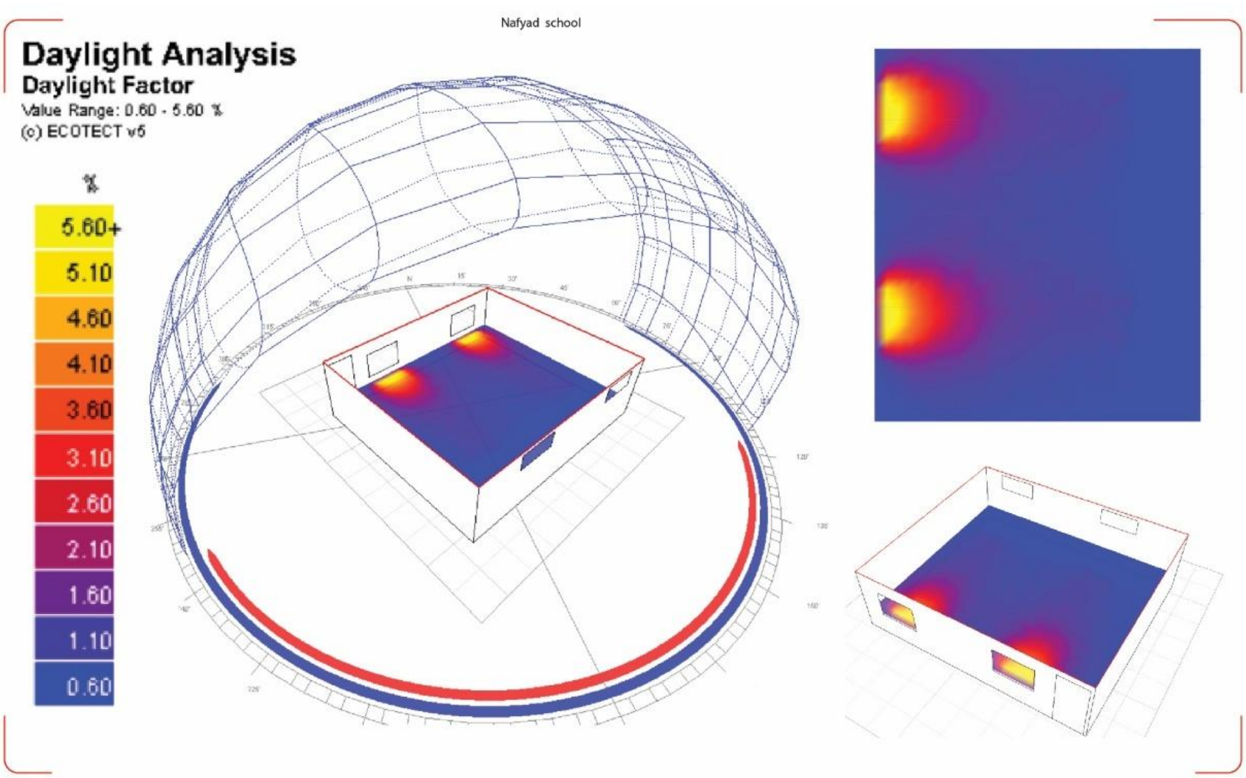
The combined effects of these conditions - inadequate rear-zone illumination, intense midday glare dueto plastic reflective ceiling, and thermal stress - demonstrate how the current fenestration design fails to meet basic visual and thermal comfort requirements. The conflicting solar exposures from the dual-orientation windows create competing environmental challenges throughout the day, significantly compromising the classroom's functionality as a learning space.

Figure 8 : Nafyad school class room plan and section

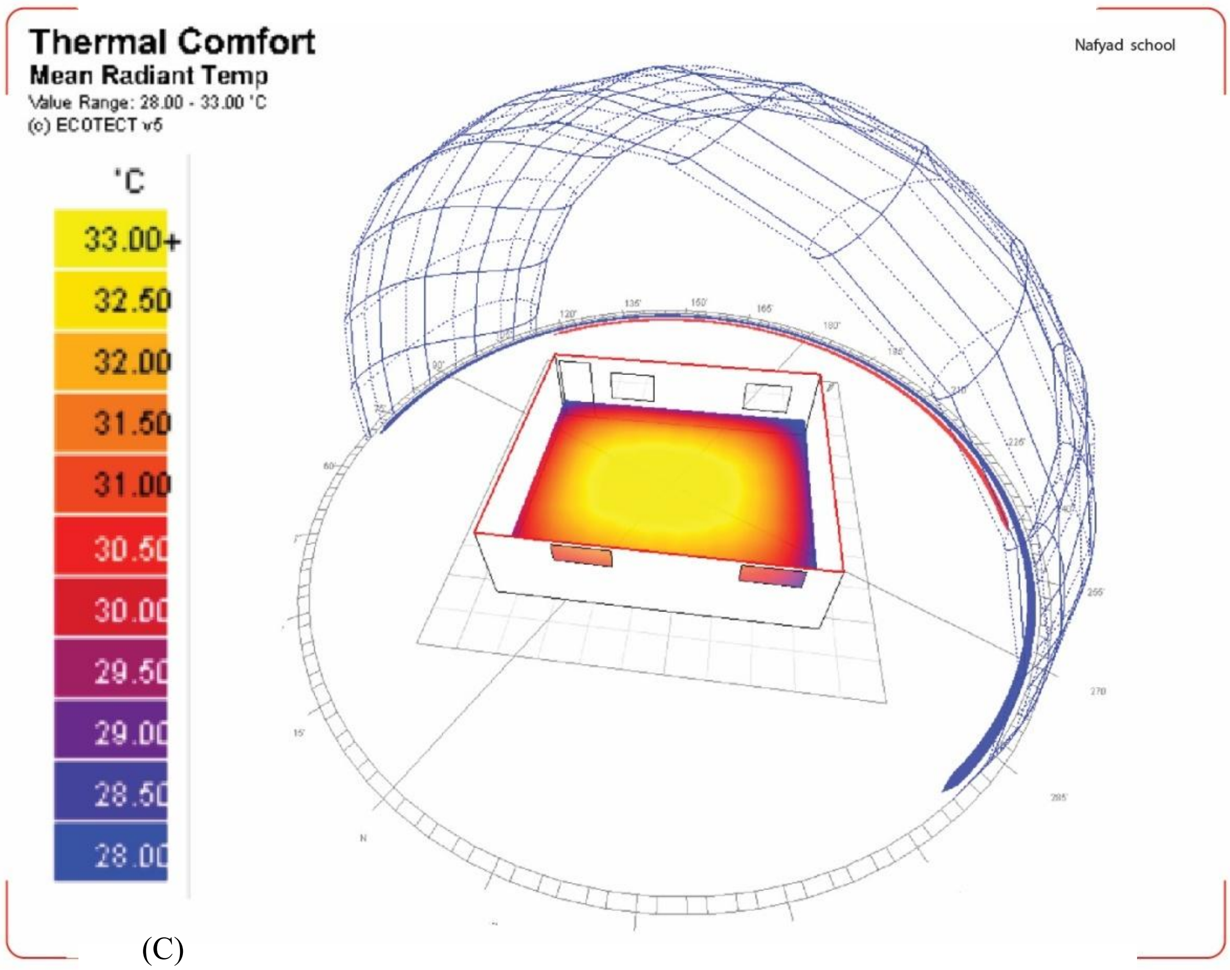
Legend : ____ Simulation classroom



(A) ***Average value*** *= 194.11 lux* ***Visible node*** *= 896*



(B) ***Average value*** *= 1.39%* ***Visible node*** *= 896*



(C)

Figure 9 :Nafyad School

(A) Daylighting levels

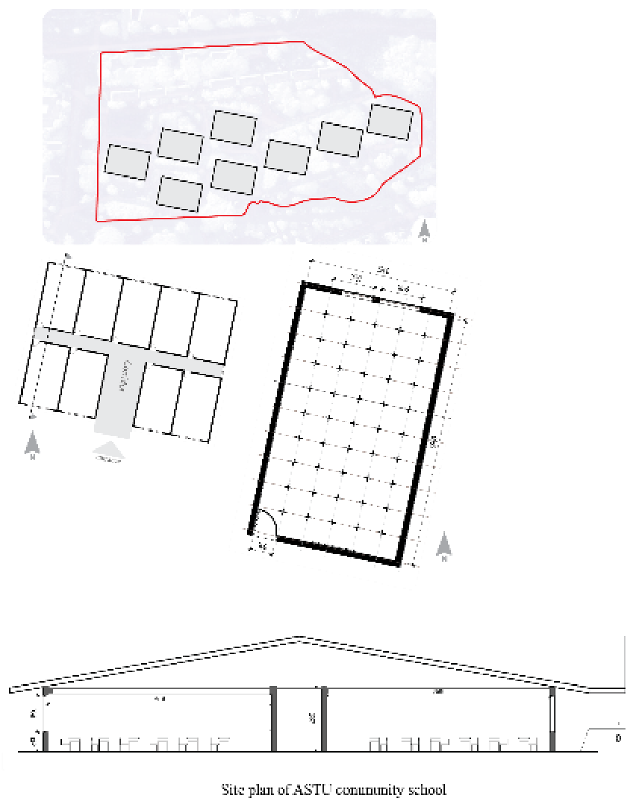
(B) Daylight factor
(C) Thermal comfort &
(D) glare simulation

(D)

ASTU Community School

The classroom's fenestration design, combining 7.04m² north-facing windows and 0m² south-facing clerestory (10% floor area), demonstrated significant performance deficiencies. Field measurements revealed problematic illuminance fluctuations (100-2100 lux), with rear zones remaining below the 100 lux educational standard while midday periods experienced excessive brightness. The design generated substantial glare (DGP>0.3, UGR>0.4) and thermal stress, including 8°C surface temperature variations and 3-4°C afternoon overheating. Ecotect simulations confirmed poor daylight uniformity (DF 0.6-20.6%), highlighting inconsistent light distribution across the space.

These findings reveal critical shortcomings in meeting visual and thermal comfort requirements. The opposing orientations created competing environmental conditions, resulting in simultaneous underlit zones and glare problems that compromise the learning environment.



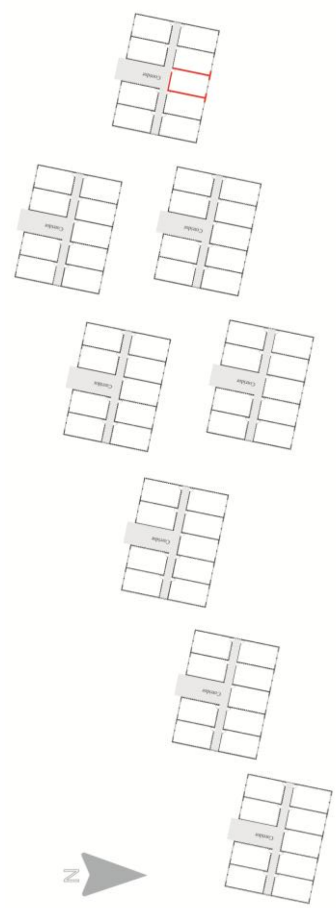
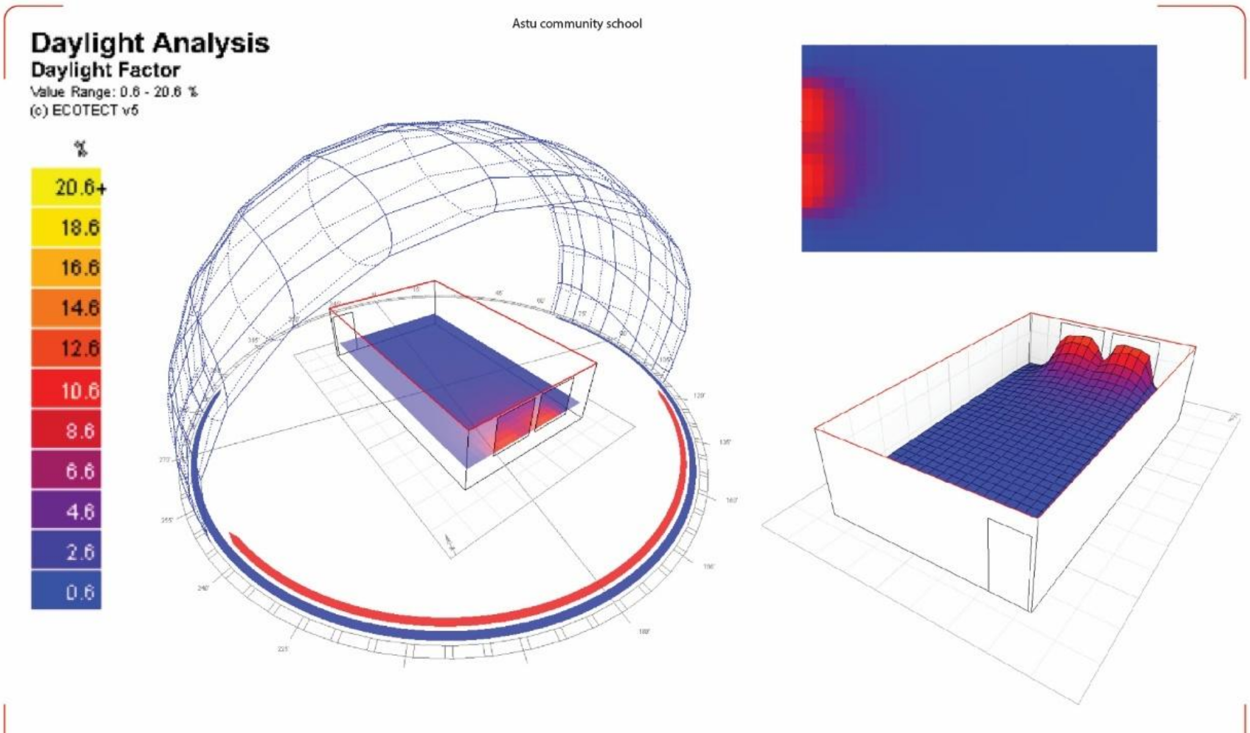
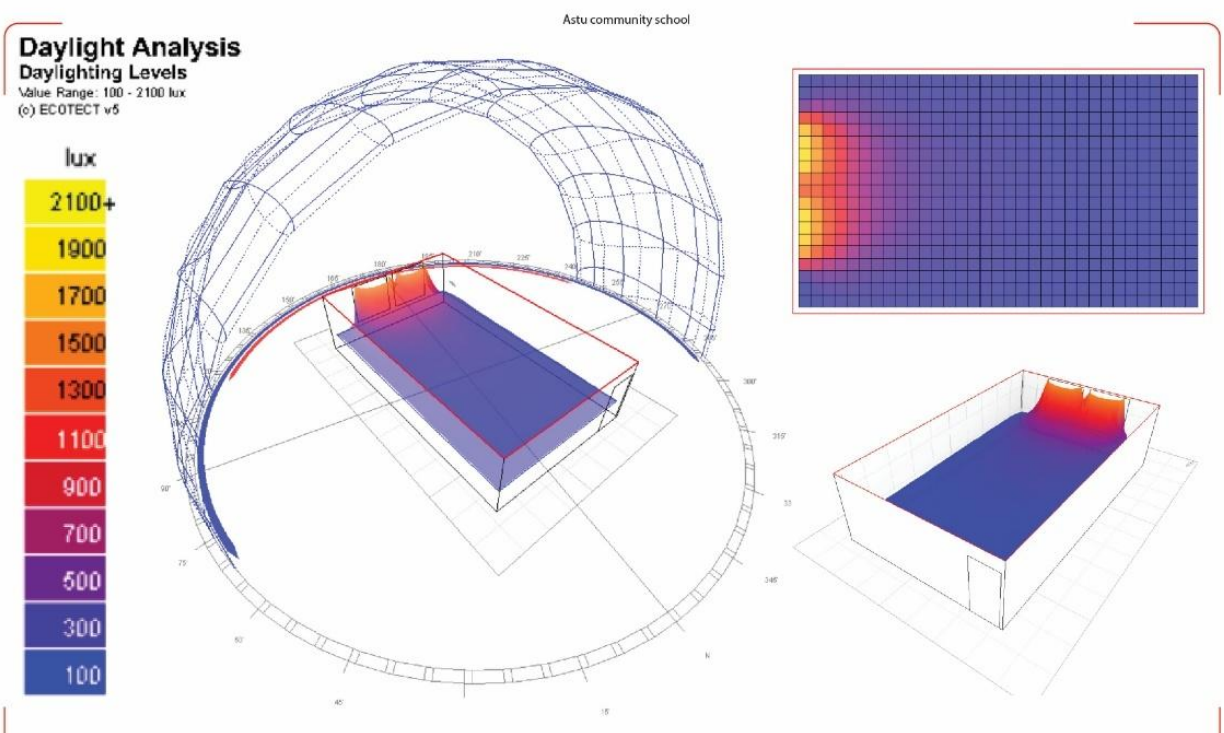


Figure 10 : ASTU school class room plan and section

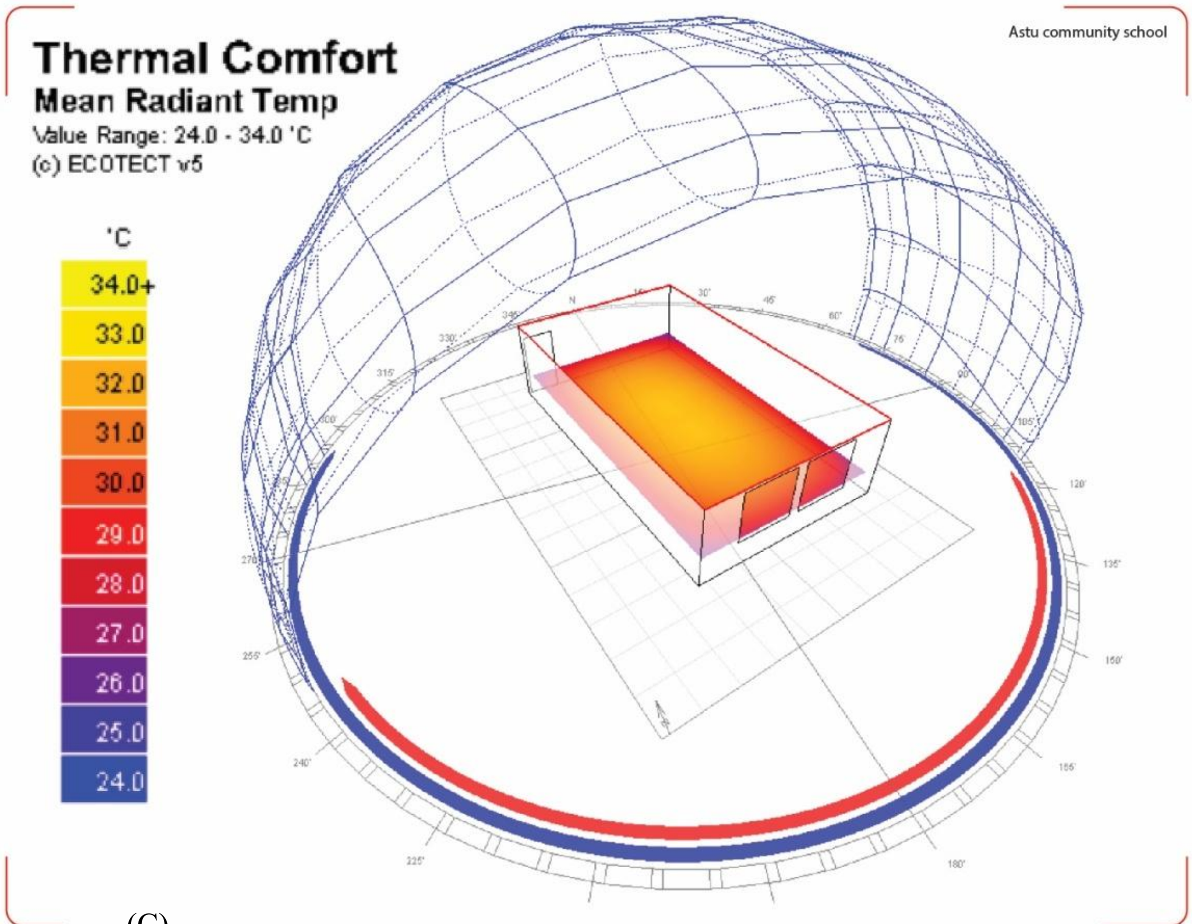
Legend : ____ Simulation classroom



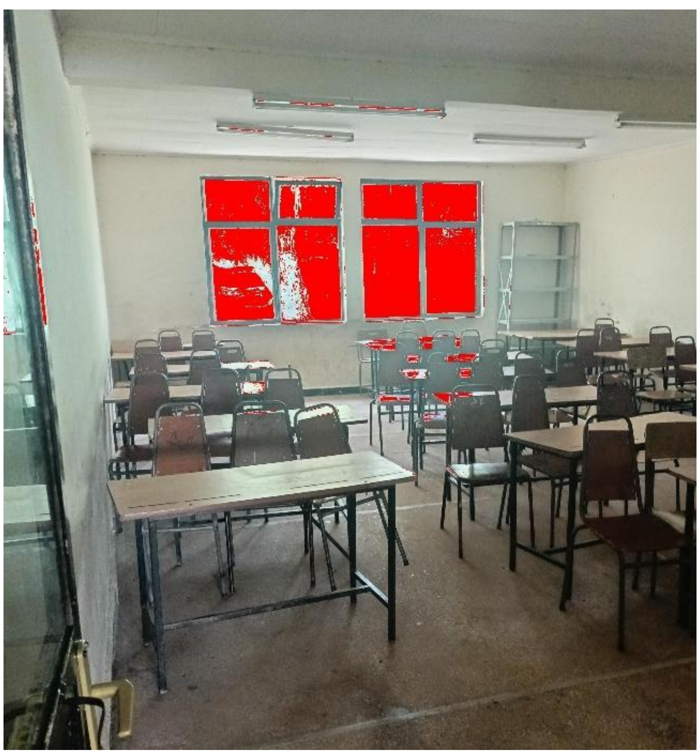
(A) ***Average value** = 1.97%* ***Visible node** = 680*



(B) ***Average value** = 324.37lux* ***Visible node** = 680*



(C)



(D)

Figure 11 : ASTU School

(A) Daylight factor

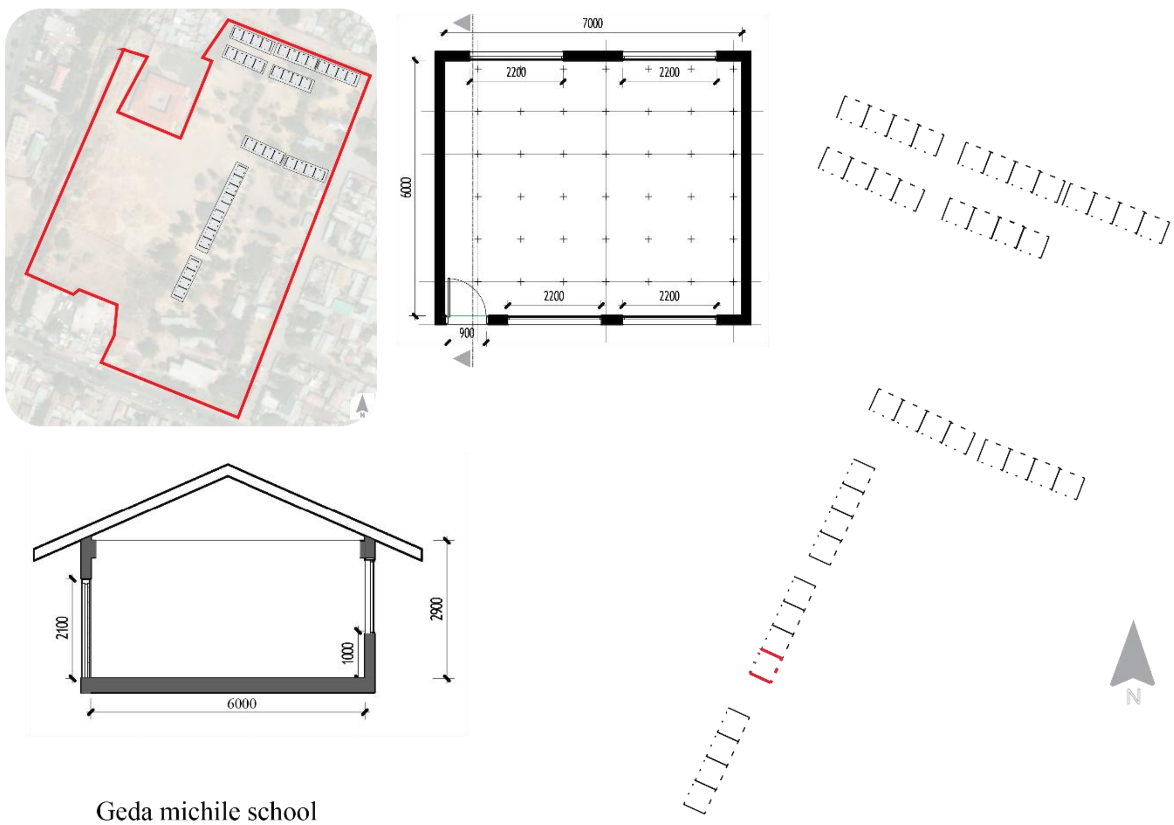
(B) Day lighting levels

(C) Thermal comfort &

(D) Glare simulation

Geda Michile

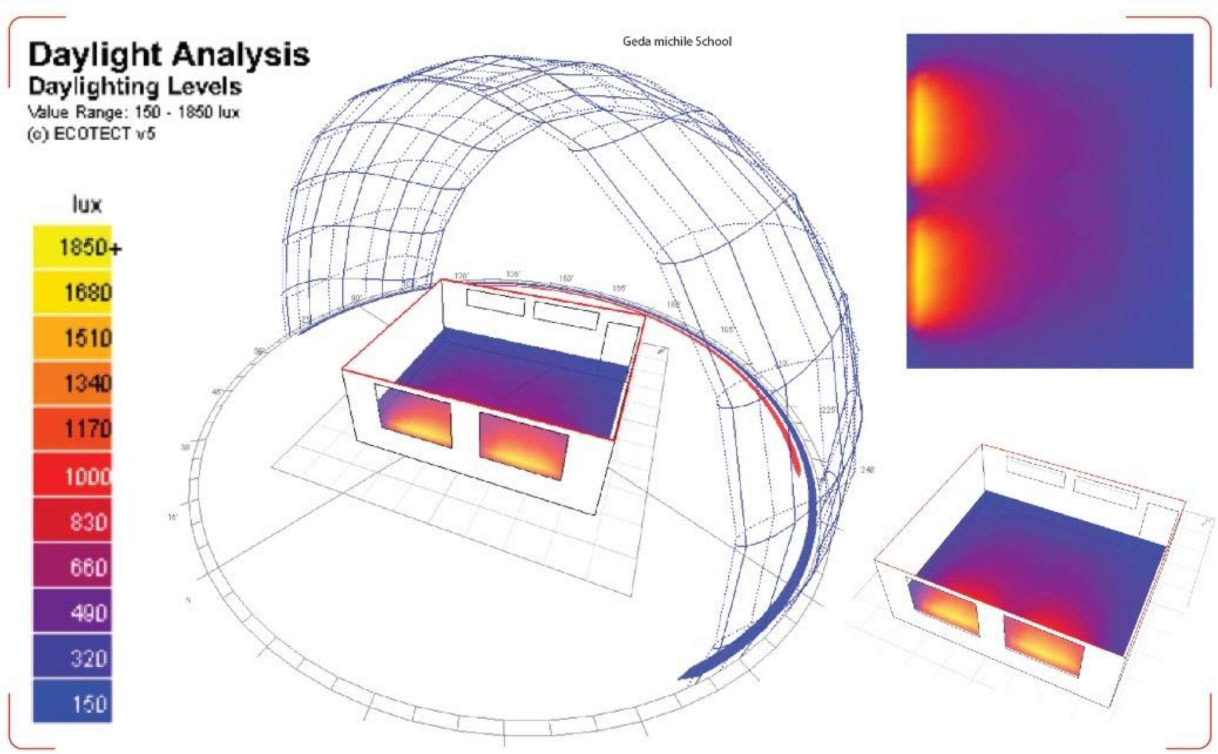
The classroom's fenestration design - comprising 8.36m² W-S-facing main windows and a 1.6m² S-E-facing clerestory (total 8.36m² glazing, 19.9% floor area) - exhibited significant performance deficiencies: measurements showed extreme illuminance variations (150-1,850 lux) with severe afternoon backlighting (<150 lux at teaching wall) contrasting with intense afternoon light spikes (1,850+ lux) from the clerestory, while generating substantial glare (DGP >0.43 afternoons, UGR >23 mornings) and thermal stress (29°C peak west wall temperature. Ecotect analysis (Figures 10,A-D) confirmed poor daylight uniformity (DF 1%-11%) with 56% non-compliance to EN 12464-1 standards, revealing how the conflicting W-S exposures created compounded environmental challenges that could be addressed .



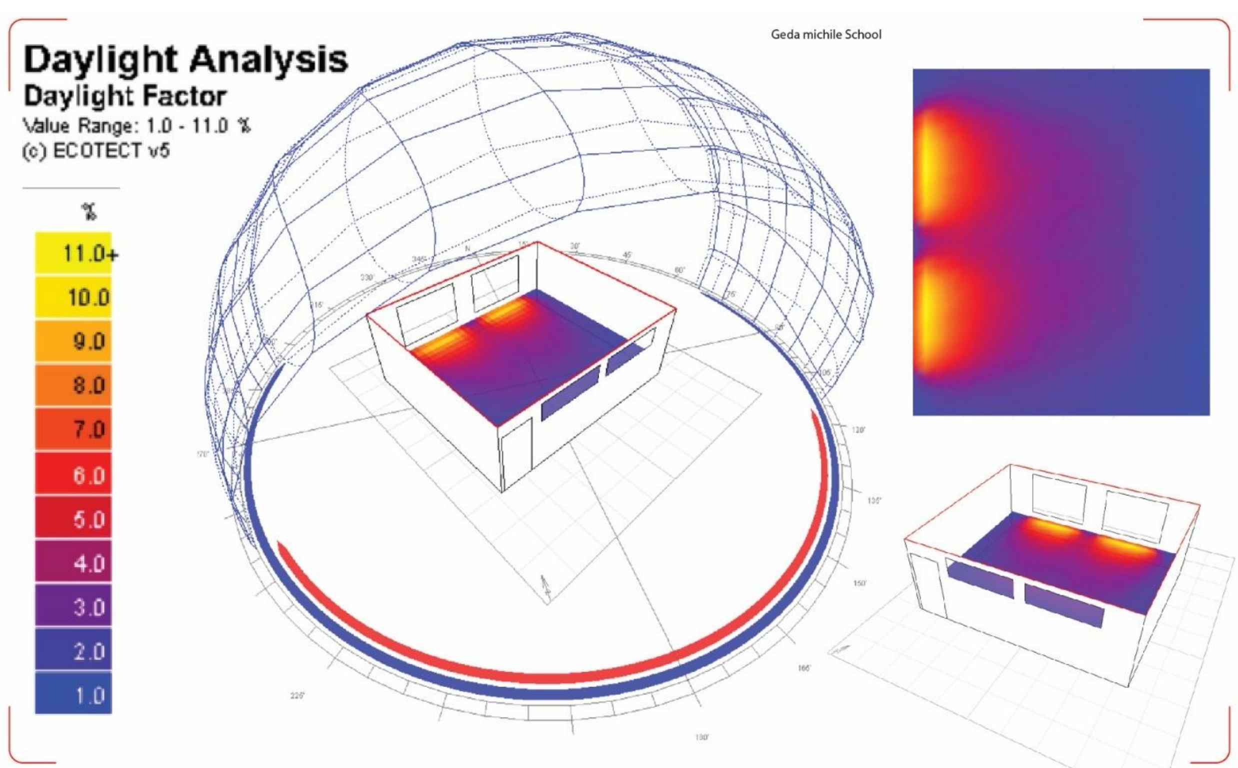
Geda michile school

Figure 12 : Geda michile school class room plan and section

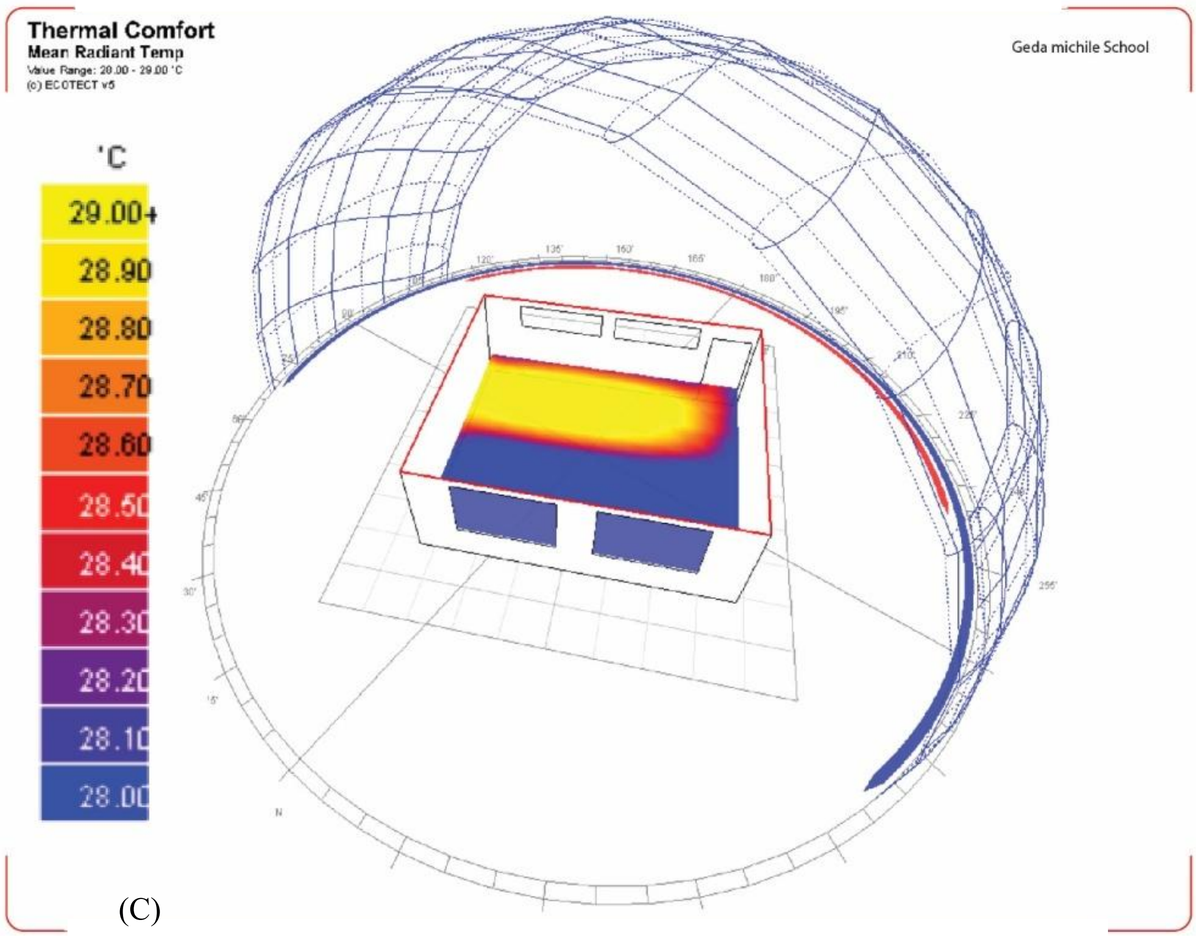
Legend : ____ Simulation classroom



(A) ***Average value** = 501.58lux* ***Visible node** = 725*



(B) ***Average value** = 4.98%* ***Visible node** = 725*



(C)

Figure 13 : Geda michile School

(A) Day lighting levels

(B) Day light factor

(C) Thermal comfort &

(D) Glare simulation

4.2 Student Perception Data Analysis

This comprehensive study of four elementary schools in Adama City reveals critical insights about how classroom environmental conditions affect student comfort and behavior. Through detailed surveys and physical measurements, distinct patterns emerge that highlight both universal challenges and school-specific issues related to daylighting, glare, and thermal comfort.

Student Perception Data Analysis: Awash Academy

Awash Academy presents a critical case where daylight conditions were particularly challenging. Approximately **61.7% of students reported inadequate natural lighting**, despite relatively large southeast-facing windows and a clerestory. The rear zones of the classroom received illuminance levels below 300 lux, leading to student dissatisfaction. Notably, a high percentage of female students (65.9%) reported visual discomfort, highlighting possible gender-related sensitivity to glare, which aligns with the study's earlier findings.

Behavioural observations showed **"light-seeking" behaviour**, with **72.3% of students clustering near windows**, despite reported issues with glare. This indicates a trade-off behaviour where students prioritize brighter zones even if they come with discomfort, likely due to the inadequacy of artificial lighting in the rear of the room. Additionally, **59.6% of students relied on artificial lighting during the day**, further supporting the finding that natural lighting alone was insufficient. This reliance also suggests increased energy consumption, countering the principles of sustainable school design.

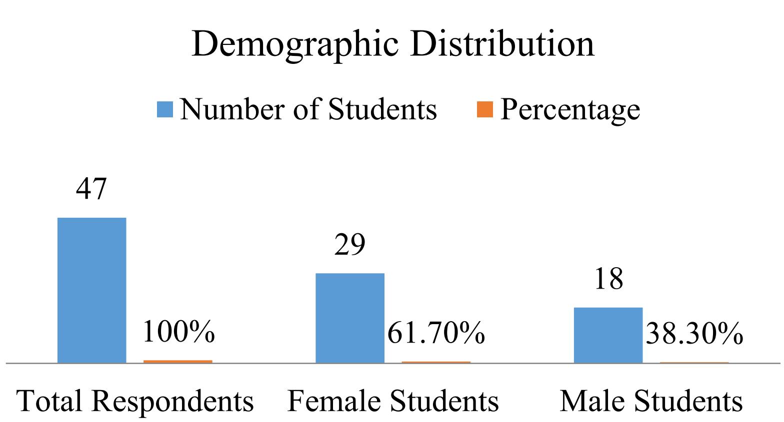


Figure 14(a) : : Demographic Distribution

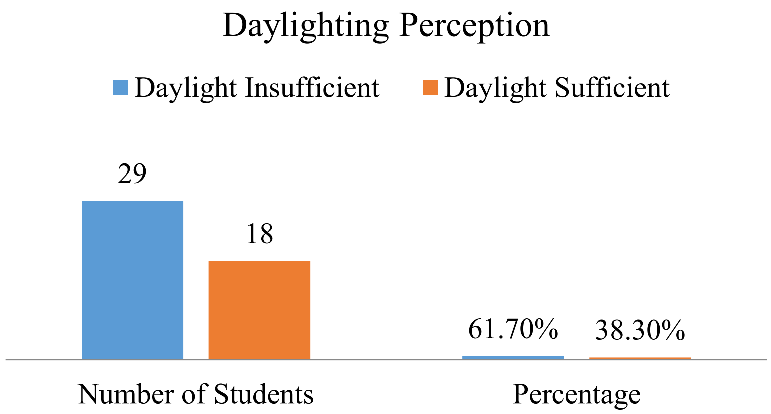


Figure 14 (b) : Daylighting Perception

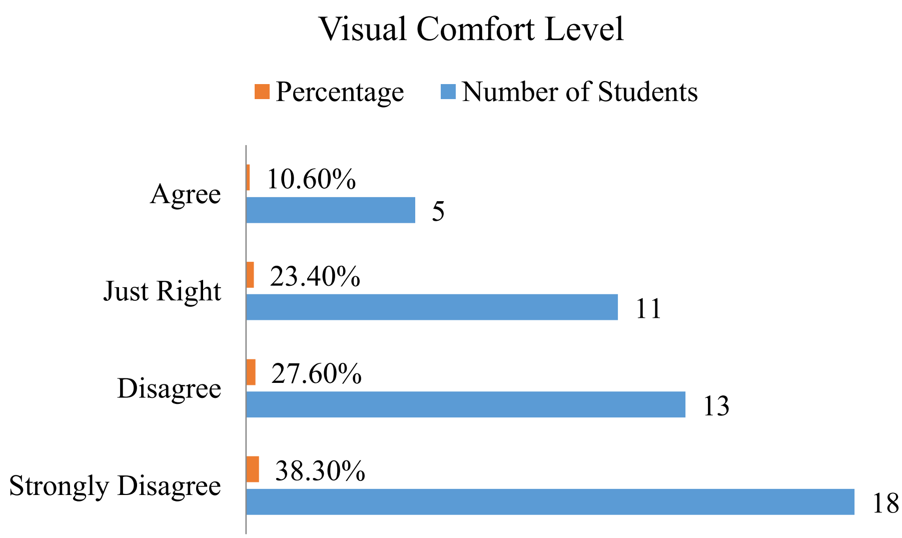


Figure 14 (c) : Visual Comfort Level

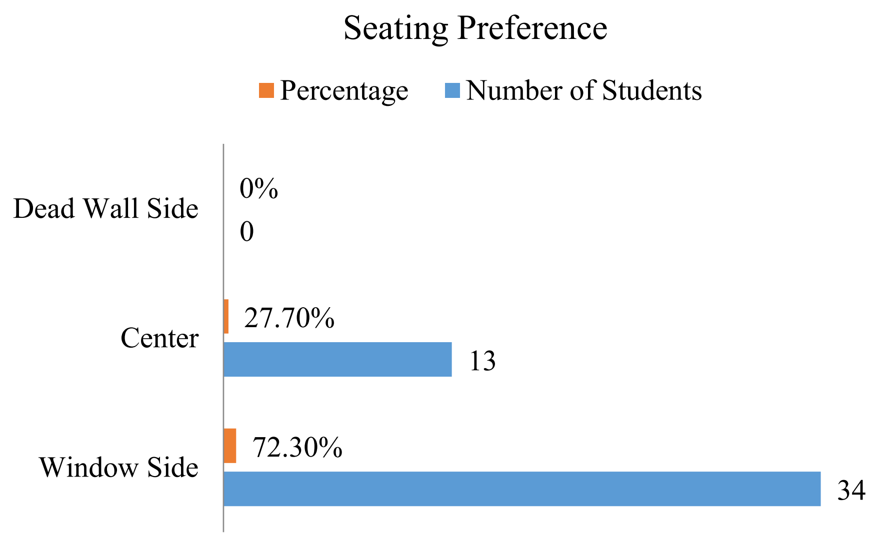


Figure 14 (d) : Seating Preference

Student Perception Analysis: Nafyad School

In Nafyad School, **students experienced both glare and under-illumination**. A large number of respondents described the lighting conditions as inconsistent. Field data showed that morning sun penetration caused over-illumination and glare near the windows, while the back of the classroom remained underlit throughout the day. This was reflected in survey responses, where many students **complained about excessive brightness and glare**, particularly during the early hours.

Interestingly, student feedback revealed that the reflective ceiling surfaces intensified glare, making visual tasks uncomfortable. The **spatial distribution of discomfort was clearly linked to seating position**, with students in the front rows facing higher levels of discomfort. The data suggests that while east-facing windows can provide early morning light, without adequate shading or diffusing materials, they contribute significantly to glare.

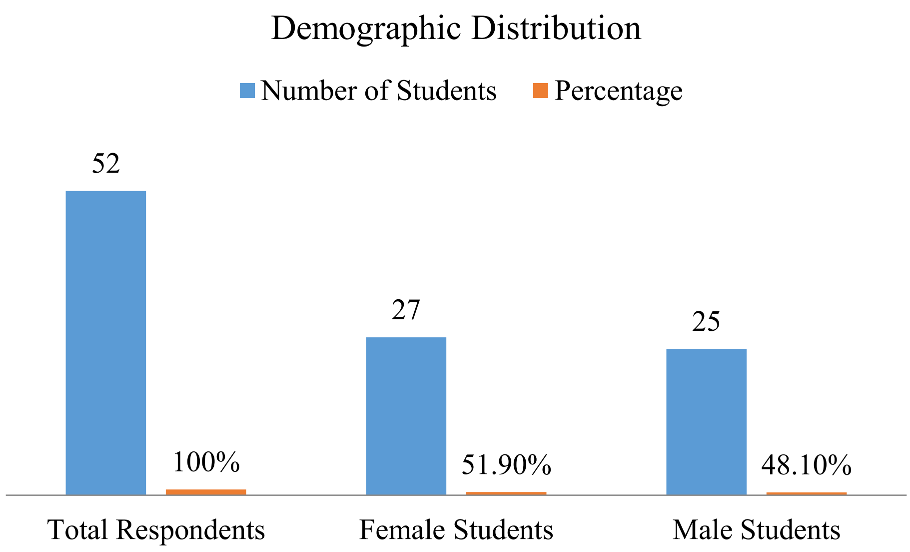


Figure 15 (a) : Demographic Distribution

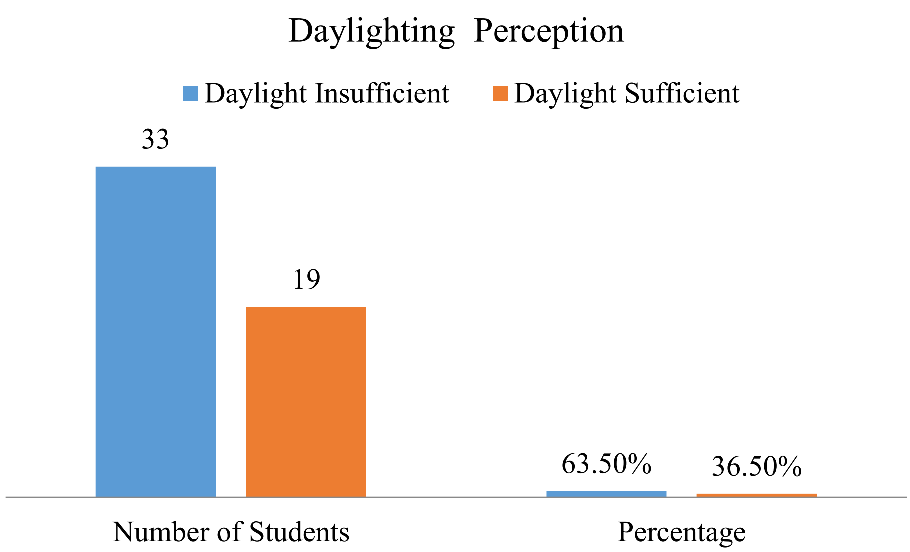


Figure 15 (b) : Daylighting Perception

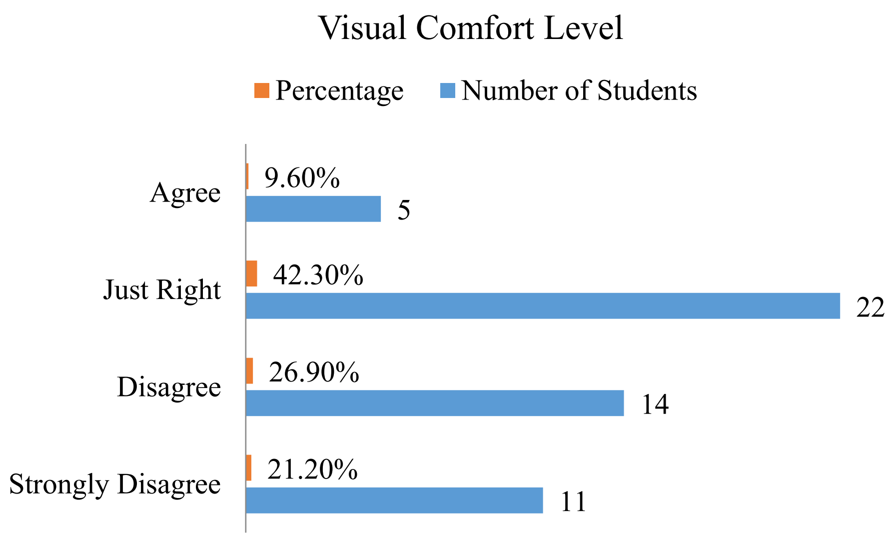


Figure 15 (c) : Visual Comfort Level

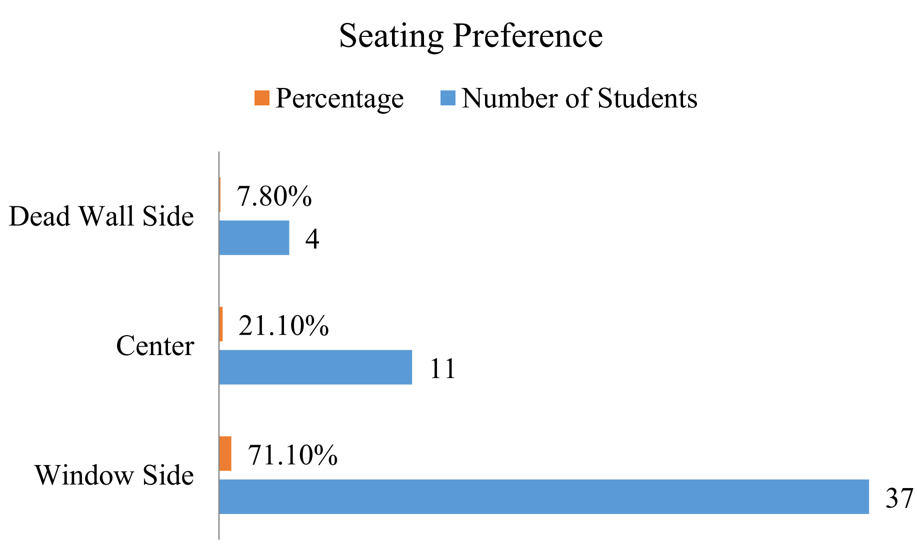


Figure 15 (d) : Seating Preference

Student Perception Analysis: ASTU Community School

In the north-facing classroom at ASTU Community School, the results were somewhat paradoxical. While north-facing windows are generally associated with soft, diffuse light and minimal glare, this classroom design failed to deliver sufficient daylight to the interior spaces. Approximately **63% of students reported visual discomfort**, primarily due to **dim lighting at**

the rear of the classroom. The illuminance levels recorded in these zones dropped below 100 lux, well under the 300-lux threshold recommended by EN 12464-1 standards for educational environments.

Students reported difficulty reading and writing, especially during cloudy days or in the early morning hours. While glare was not as significant a concern in this school, the **lack of balanced daylight distribution** reduced overall satisfaction. The lack of south-facing clerestory or side lighting limited the performance of what could otherwise be an effective daylighting orientation. This demonstrates that orientation alone is not sufficient; the size, placement, and design of the fenestration are equally critical.

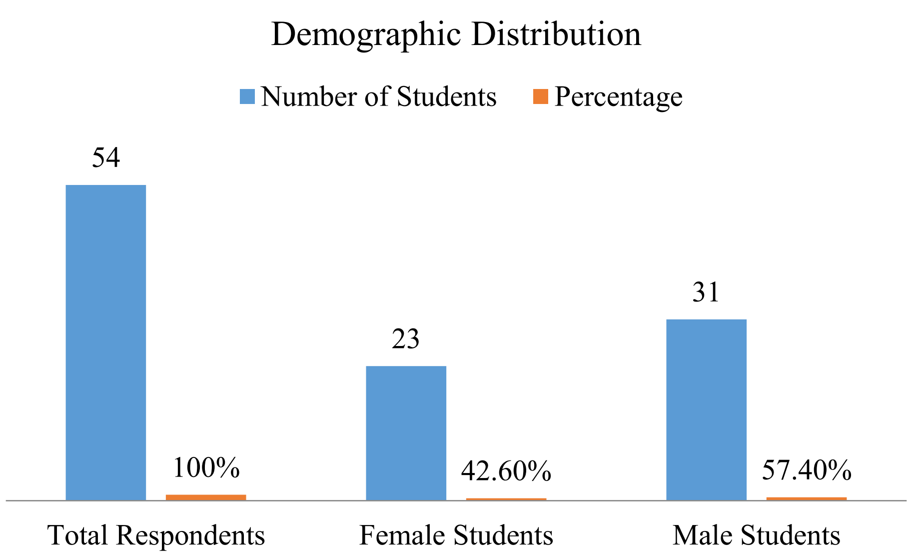


Figure 16 (a) : Demographic Distribution

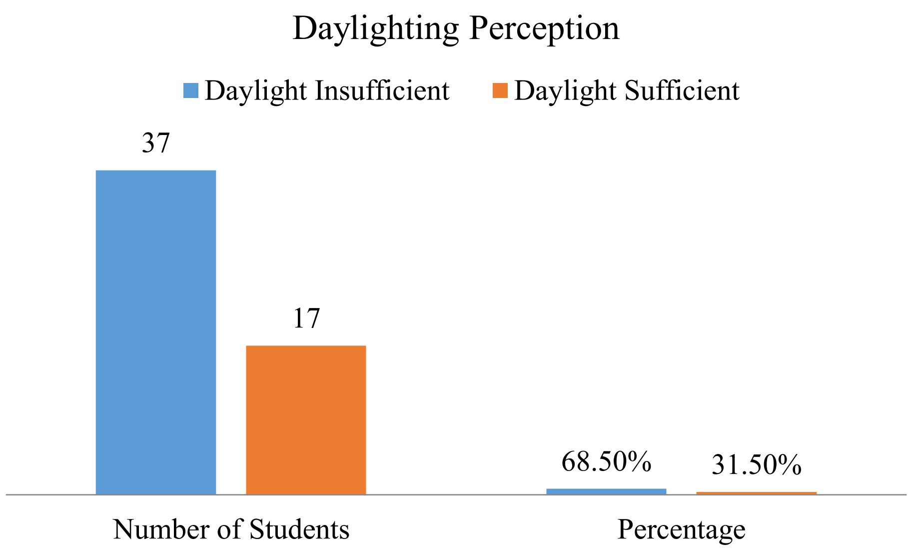


Figure16 (b) : Daylighting Perception

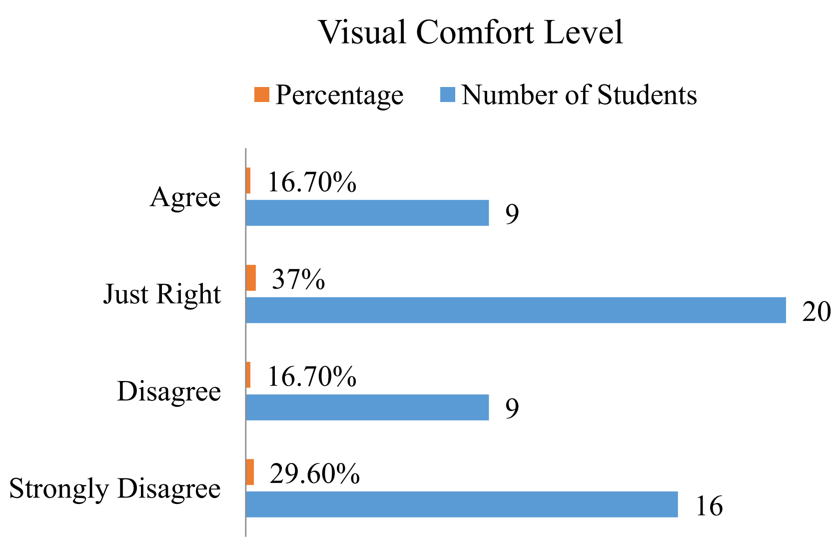


Figure 16 (c) : Visual Comfort Level

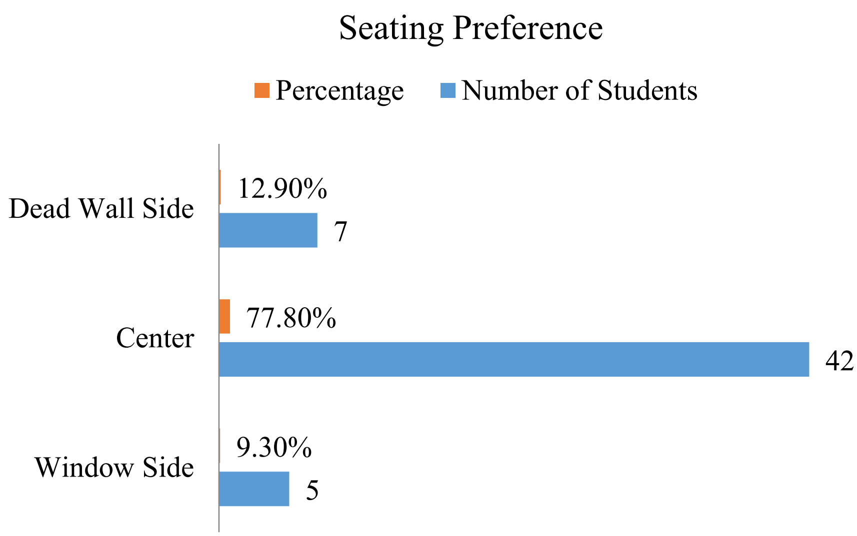


Figure 16 (d) : Seating Preference

Student Perception Analysis: Geda Michile Elementary School

Geda Michile School showed the most extreme variability in student perception, mirroring the extreme daylight conditions recorded during fieldwork. The combination of large west-south-facing main windows and southeast-facing clerestories produced **excessive afternoon light spikes** and glare, while some areas remained underlit. This inconsistency translated directly into user dissatisfaction: **68.2% of students reported severe glare**, especially during afternoon classes. Some students experienced direct sunlight hitting their desks, prompting many to change seating positions throughout the day.

In behavioural observations, **students actively relocated within the classroom** to avoid discomfort, especially in the late afternoon. The temperature profiles also revealed significant thermal discomfort, with west-facing walls experiencing heat gain that raised indoor surface temperatures up to 29°C. Student perception data reflected this as well, with discomfort associated not only with light intensity but also with heat. As a result, the school demonstrated one of the highest combined levels of visual and thermal dissatisfaction.

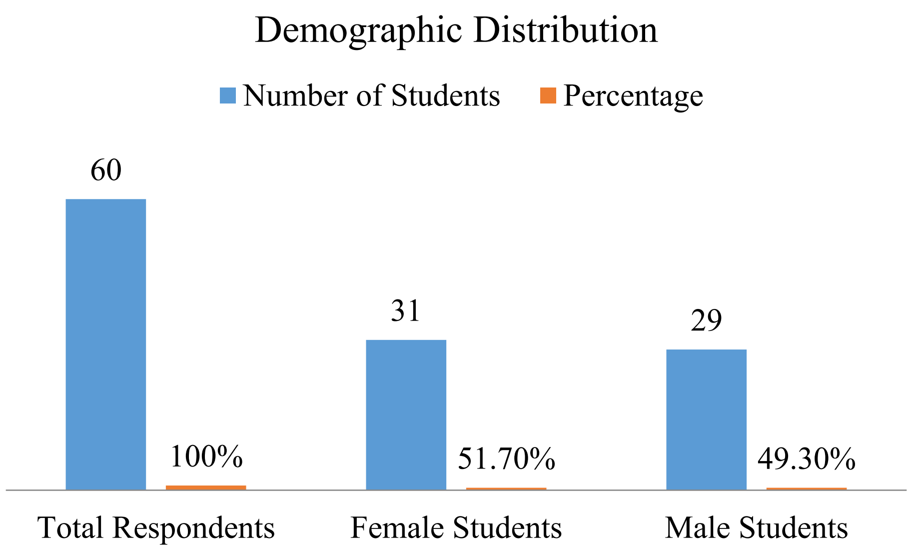


Figure 17 (a) : Demographic Distribution

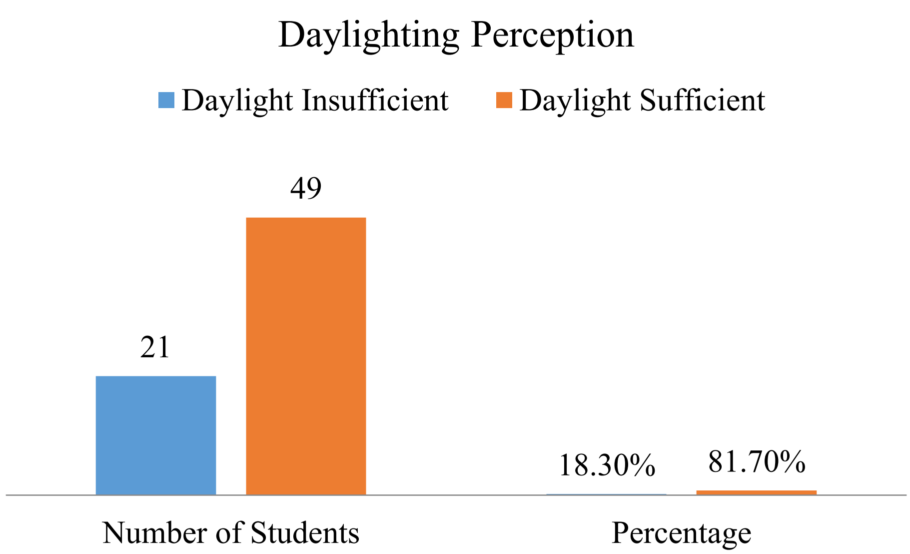


Figure 17 (b) : Daylighting Perception

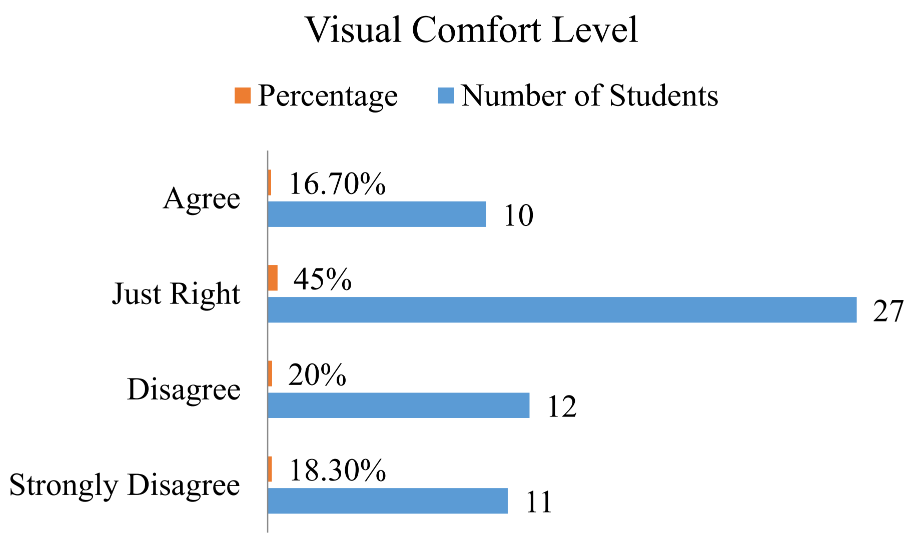


Figure 17 (c) : Visual Comfort Level

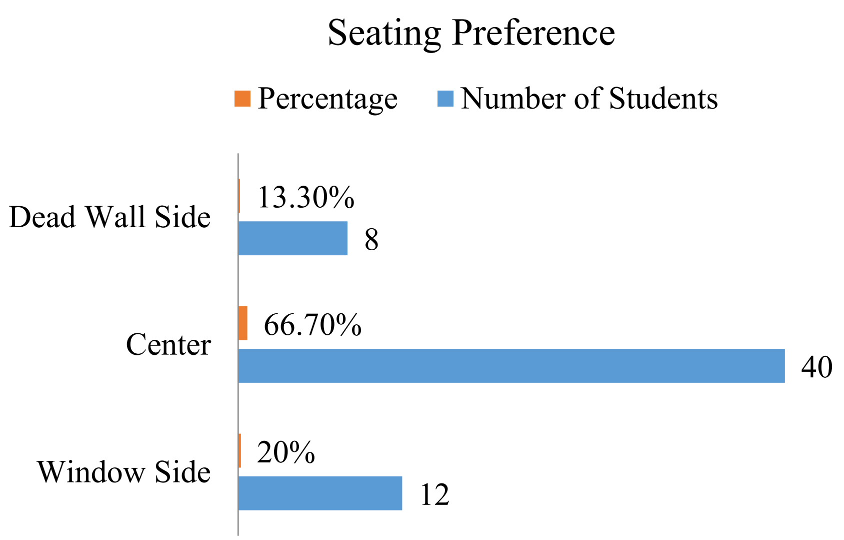


Figure 17 (d) : Seating Preference

Several universal patterns emerge across all the schools. First, daylight dissatisfaction ranges consistently between 61-68%, indicating widespread failure on the schools to meet student needs. Second, visual comfort challenges affect 38-66% of students across schools. However, the manifestations of these issues varies considerably based on classroom orientation and specific design features.

The study also reveals important behavioral adaptations. Students consistently demonstrate sophisticated environmental negotiation, strategically selecting seats to balance light access with glare and thermal comfort and this self-regulation represents an implicit critique of current classroom designs, as learners continually compensate for architectural shortcomings through positioning.

Ultimately, this multi-school analysis provides compelling evidence that current classroom designs in Adama City systematically fail to meet students environmental needs and the consistent patterns of dissatisfaction and adaptive behavior across diverse school contexts call for urgent design reforms that address daylight distribution, glare control, and thermal regulation in an integrated, evidence-based manner. By learning from these student experiences and perceptions, architects and policymakers can create learning environments that truly support educational outcomes

4.3 Results summary

Table 5 : Key Findings (daylight performance, visual comfort, Thermal comfort & student perception) and discussion

Category	Key Findings	Quantitative Data	Implications
Daylight Performance			
Illuminance Levels	Extreme variability across classrooms	81 lux (Nafyad) to 2,440 lux (Awash) 78% rear zones <300 lux	Stark illumination contrasts impair visual tasks
Daylight Factor (DF)	Poor uniformity in distribution	0.6% (Nafyad) to 21.4% (Awash) Only 22% in 2-5% ideal range	Inadequate daylight penetration in critical learning zones
Useful Daylight Illuminance	Frequent non-compliance with standards	41% met UDI300-2000 63% underlit/overlit in east-facing rooms	Compromised visual comfort during 89% of school hours
Visual Comfort			
Daylight Glare Probability	Systemic glare problems	DGP >0.45 in west-facing 72% >0.35 for >3hrs daily	Reduced student attention during peak teaching hours

Luminance Contrast	Excessive window-to-wall contrast	Average 28:1 ratio Worst with clear glazing (VLT 82-89%)	Eye strain and fatigue reported by 61% of students
Thermal Comfort			
Temperature Variations	Significant overheating	+3.2°C west-facing +2.8°C south-facing 8°C daily fluctuations	72% students avoided window seats due to thermal discomfort
Solar Heat Gain	Glazing contributes majority of heat load	SHGC 0.78 clear glass 982 W/m² peak irradiance	Thermal lag extends discomfort 2-3 hours post-peak exposure
Student Perceptions			
Daylight Adequacy	Widespread dissatisfaction	63.5% report insufficiency $r=0.82$ ($p<0.01$) with <250 lux measurements	Students compensate with artificial lighting (59.6% usage)
Seating Preferences	Behaviorally adaptive choices	71.1% window-side when daylight insufficient 77.8% center when glare severe	Self-selection reduces but doesn't eliminate comfort issues
Design Flaws			
Daylight Distribution	Single-sided fenestration dominates	83% classrooms affected	Creates back-of-room dark zones (avg. 65 lux lower than front)
Glare Management	Lack of orientation-specific solutions	67% dual-orientation classrooms	Unresolvable trade-offs between glare and daylight needs
Thermal Issues			
Climate Adaptation	Missing passive strategies	12% with proper cross-ventilation	Overheating of the class room
Human Factors			
Gender Differences	Significant variation in comfort perception	Females 23% more glare-sensitive Males tolerate 18% higher temp variations	Need for gender-responsive design approaches

4.4 Discussion

The study reveals significant shortcomings in current classroom design, particularly regarding lighting and thermal conditions. The predominant single-sided fenestration approach (75% with opposite top windows and 25% without) creates two simultaneous problems: excessive darkness at the back of rooms and intense glare near windows. This flawed lighting scheme forces student into constant repositioning, with 71.1% migrating toward windows in low light but 77.8% avoiding these areas during periods of glare and such behavioral adaptations prove ineffective, as demonstrated by the strong correlation (r=0.82) between illuminance levels below 250 lux and students dissatisfaction. Additionally, the lack of climate-responsive design leads to thermal discomfort, particularly in west-facing classrooms where afternoon temperatures exceed comfort thresholds by 3.2°C.

A particularly concerning finding is the significant gender disparity in environmental perception, with female students reporting 23% greater sensitivity to glare than their male counterparts 18%. This suggests that standard classroom designs may unintentionally create unequal learning environments and together, these findings highlight how students adaptive behaviors cannot compensate for fundamental architectural deficiencies. The result underscore the urgent need for classroom designs that better address balanced daylight distribution, thermal regulation, and inclusive environmental considerations to support all learners equally. And also, the study calls for a paradigm shift in educational space design that prioritizes both physiological comfort and educational equity.

CONCLUSION AND RECOMMENDATION

Conclusion

This study evaluated daylight performances, visual comfort, and thermal conditions in elementary schools across Adama City, revealing critical shortcomings in current classroom design and the findings demonstrate that inadequate daylight distribution, excessive glare, and thermal discomfort significantly impact learning environments, with particular challenges in single-sided fenestration classrooms and south-west-facing orientations. Furthermore, the studys identified gender-based disparities in comfort perceptions, underscoring and the need for more inclusive design approaches. While students instinctively adapt through seating adjustments, these behavioral responses prove insufficient to overcome fundamental architectural deficiencies. The strong correlation between measured environmental factors and students dissatisfaction highlights the urgent need for evidence-based design interventions.

Recommendation

Based on the evaluation of daylight performances, visual comfort, and thermal conditions in elementary schools across Adama City, recommendations are there to improve learning environments and to optimize daylight distribution, classrooms should incorporate fenestration on multiple walls rather than relying solely on single-sided daylighting, complemented by light shelves or reflective ceilings to enhance light penetration deeper into spaces. Window-to-wall ratios should be carefully calibrated between 25% -35%, with particular attention given to orientation-specific needs, ensuring larger windows are always paired with appropriate external shading devices and dynamic glazing solutions, such as adjustable blinds or louvers, would allow for real-time glare control, while low SHGC glazing ($\leq$0.4) proves particularly valuable for east and west-facing classrooms to mitigate excessive solar heat gain.

For enhanced visual comfort, a multi-pronged approach is recommended. Fixed external shading elements like overhangs and louvers should be prioritized for east and west orientations, supplemented by anti-glare window films where necessary and classroom interiors would benefit from matte finishes, light-colored surfaces with light reflectance values exceeding 50% to minimize problematic luminance contrasts. Thoughtful space planning should ensure whiteboards are never positioned opposite windows to prevent glare reflections.

Thermal comfort improvements should focus on passive design strategies. Increasing cross-ventilation through properly positioned operable windows, coupled with the thermal mass benefits of materials like exposed brick or concrete floors, can significantly stabilize indoor temperatures. Solar heat gain can be further mitigated through the installation of double-glazed, low-emissivity windows (SHGC <0.5). Ceiling fans serve as an effective supplemental measure to enhance air movement during warmer periods.

At the policy level, the development of climate-responsive school design standards is crucial, emphasizing optimal classroom orientation (preferably north-south), mandatory shading requirements for problematic exposures, and clear illuminance guidelines (300-2000 lux). These recommendations, when implemented holistically, it transforms classrooms into environments that actively support both student well-being and academic achievement. Future efforts should prioritize cost-effective solutions while ensuring strong policy enforcement to achieve sustainable, long-term improvements in educational spaces.

Scope for Further Research

While this study provides actionable insights, additional research is needed to refine solutions:

- **Gender-inclusive design frameworks** to address comfort disparities.
- **Cost-benefit analyses** of retrofitting versus new construction.
- **Localized climate adaptations**, testing passive strategies in varied Ethiopian microclimates.

Table 8 summarizes these recommendations, providing a quick-reference guide for stakeholders. By combining immediate interventions with long-term research, Adama City—and similar regions—can develop sustainable, high-performance learning environments that prioritize both well-being and educational outcomes.

Table 6 : Recommendations on daylight optimization , visual and thermal comfort

Category	Recommendation	Explanation	Implementation Strategy

Daylight Optimization	Multi-wall fenestration	Avoids uneven lighting from single-sided windows	Design classrooms with windows on at least two walls
	Light shelves/reflective ceilings	Redirects daylight deeper into room	Install angled reflective surfaces above windows or roofs
	Diffusing glazing (upper sections)	Reduces glare while maintaining light	Apply frosted film on top 1/3 of the windows
	Optimal WWR (25-35%)	Balances light entry and heat gain	Calculate based on orientation and climate data
Visual Comfort	External shading (fixed)	Prevents direct glare from east/west sun	Install 45° louvers or 0.7m overhangs
	Anti-glare window films	Diffuses harsh sunlight	Apply glare-reduction films
	Light-colored matte surfaces (LRV>50%)	Reduces luminance contrast	Use eggshell paint on walls/ceilings
	Strategic whiteboard placement	Avoids reflection issues	Position boards perpendicular to windows
Thermal Comfort	Cross-ventilation design	Enhances natural cooling	Opposite operable windows
	Thermal mass materials	Stabilizes temperature swings	Exposed brick walls/concrete floors
	Low-E double glazing (SHGC<0.5)	Reduces solar heat gain	Replace clear glass in east/west facades
	Climate-responsive standards	Ensures design compliance	Develop national school design guidelines
Policy & Monitoring	IoT sensor monitoring	Tracks comfort parameters	Install lux/temp/humidity sensors with dashboards

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APPENDIX

Survey Questions for Students

Section A: Demographic Information

Name of school: ________________________

Grade: _______

Age: _______

1. Gender: ☐ Male ☐ Female

Section B: Perception of Daylight

1. How bright is your classroom during daytime?

☐ Too dark ☐ Slightly dark ☐ Just right ☐ Slightly bright ☐ Too bright

2.Does sunlight ever make it hard to see the board or your desk?

☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ Always

3.Where do you prefer to sit in the classroom?

☐ Near the window ☐ Middle ☐ Away from the window

Section C: Glare and Discomfort

4. Does sunlight cause glare (uncomfortable brightness) in your classroom?

☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ Always

5.If glare occurs, how does it affect your work?

☐ No effect ☐ Mild distraction ☐ Makes it hard to concentrate ☐ Causes headaches

Section D: Thermal Comfort

1. Does the classroom feel too hot during the day?

☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ Always

<u>የተማሪዎች የድምፅ ጥያቄዎች</u>

ክፍል ሀ: የተማሪ መረጃ

1. የትምህርት ቤት ስም: ________________________
2. ክፍል: ________
3. ዕድሜ: ________
4. ጾታ: ☐ ወንድ ☐ ሴት
5. **ክፍል ለ: የብርሃን እይታ**

1. ክፍልህ በቀን ጊዜ ምን ያህል የተገለጸ ነው?

   ☐ በጣም ጨለማ ☐ ትንሽ ጨለማ ☐ በትክክል ☐ ትንሽ ብሩህ ☐ በጣም ብሩህ
2. የፀሐይ ብርሃን ሰሌዳውን ወይም የእርስዎን ጠረጴዛ ማየት ያስቸግራል?

   ☐ ፈፅሞ አይደለም ☐ አልፎ አልፎ ☐ አንዳንዴ ☐ ብዙ ጊዜ ☐ ሁልጊዜ
3. በክፍሉ ውስጥ የት መቀመጥ ይመርጣሉ?

   ☐ ከመስኮት አጠገብ ☐ በመካከል ☐ ራቅ ብሎ ከመስኮት

ክፍል ሐ: የብርሃን መብዛት እና ደረጃ

4. የፀሐይ ብርሃን ክፍልህን ያበራል ወይም ያበላሸዋል?

☐ ፈፅሞ አይደለም ☐ አልፎ አልፎ ☐ አንዳንዴ ☐ ብዙ ጊዜ ☐ ሁልጊዜ

5. የብርሃን መብዛት ካለ, ስራህን እንዴት ይጎዳዋል?

   ☐ ምንም ችግር የለውም ☐ ትንሽ ያበላሸዋል ☐ ማተኮር አይቻልም ☐ ራስ ምታት ያስከትላል

ክፍል መ: የሙቀት እርግጠኝነት

6. ክፍልህ በቀን ጊዜ ይበልጥ ሙቀት ይሰማህ ነበር?

☐ ፈፅሞ አይደለም ☐ አልፎ አልፎ ☐ አንዳንዴ ☐ ብዙ ጊዜ ☐ ሁልጊዜ

Ergaa Barattootaatti

Qooda A: Odeeffannoo Barattootaa

1. Maqaa mana barumsaa: ________________________
2. Baayyina: _______
3. Umurii: _______

4. Saala: ☐ Dhiira ☐ Dubartii

5. **Qooda B: Mul'ata Addaa**

1. Dachii keessan guyyaa keessatti meeqa ifaa?
   ☐ Garaa gurraacha ☐ Garaa gurraacha ☐ Haala sirrii ta'e ☐ Ifaa xiqqoo ☐ Ifaa guddaa
2. Ifa aduu dubbisa dhaabbataa ykn miseensa keessan irratti rakkina ittiin mul'isuu?
   ☐ Hin mul'atu ☐ Yeroo xiqqoo ☐ Yeroo tokko tokko ☐ Yeroo baay'ee ☐ Yeroo hunda
3. Eessa dhaabbata keessatti argachuu jaallatta?
   ☐ Furtuu irraa ☐ Gidduu keessatti ☐ Furtuu irraa fagoo

Qooda C: Ifa Dhiibuu fi Rakkina

4. Ifa aduun dhaabbata keessatti ifa dhiisuu ittiin mul'isuu?

☐ Hin mul'atu ☐ Yeroo xiqqoo ☐ Yeroo tokko tokko ☐ Yeroo baay'ee ☐ Yeroo hunda

5. Ifa dhiisuu yoo jiraate, hojii keessan akkamitti dhiibbaa geessisa?
   ☐ Dhiibbaa hin qabu ☐ Dhiibbaa xiqqoo ☐ Xiyyeeffannoo dhabamsiisa ☐ Mataa rukutu

Qooda D: Qabbanaa'aa Ho'a

1. Dachii keessan guyyaa keessatti ho'a baduu ittiin mul'isuu?
   ☐ Hin mul'atu ☐ Yeroo xiqqoo ☐ Yeroo tokko tokko ☐ Yeroo baay'ee ☐ Yeroo hunda

Classroom ID: ________________________

Date: ________________________

Time: ________________________

Observer: ________________________

Parameter	**Measurement**	**Tool Used**	**Notes**
Window dimensions (WxH)	_______ m x _______ m	Measuring tape	

Parameter	Measurement	Tool Used	Notes
Window-to-wall ratio (WWR)	_______ %	Calculated	
Glazing type	☐ Clear ☐ Tinted ☐ Textured	Visual inspection	
Orientation	☐ North ☐ South ☐ East ☐ West	Compass	
Illuminance (lux) at desk	Point 1: _______ lux	Lux meter	Grid points (1m spacing)
	Point 2: _______ lux		
	...		
Daylight Factor (DF)	_______ %	Ecotect simulation	
Daylight Glare Probability	_______ (DGP score)	Ecotect/HDR imaging	
Indoor temperature	_______ °C	Thermometer	
Surface reflectance (LRV)	Walls: _______% Ceiling: _______%	Reflectance meter	

Instrument specifications

A, Lux meter

The digital light meter will allow you to measure the lighting in an area.
The digital light meter uses a 9V battery(not included); Accurate up to 200,000Lux +/- 5%
Resolution: 0.1Lux / 0.01Fc , Accuracy:±4%,Measurement speed: 2 times / second, Units: Lux & Fc.
Hold function, Auto range & Manual range,Auto Power OFF: After approx.15 minutes.
Low power of battery detecting, Operating Environment: 14 to 122°F(-10 to 50°C), 10%~90%RH

Specifications:

1.Display: Large LCD characters display.

2.Range: 0.1~200,000Lux, 0.01~20,000Fc.

3.Resolution: 0.1Lux / 0.01Fc.

4.Accuracy:±4%.

5.Measurement speed: 2 times / second.
6.Units: Lux & Fc.

7.Hold function, Auto range & Manual range.

8.Auto Power OFF: After approx.15 minutes.

9.Power Supply: One 9V battery.

10.Low power of battery detecting.

11.Operating Environment: 14 to 122°F(-10 to 50°C), 10%~90%RH.

B, digital anemometer

Model Number *vHP-816B*

Brand Name *HoldPeak*

Origin *Mainland China*

Wing Speed Range *0.3 - 30m/s*

Temperature Range *-10℃-45℃*

Accuracy of Wind Speed *+0.1dgts*

Accuracy of Temperature *+2℃*

WingSpeedUnitSelection *m/s; Ft/min; Knots; Km/hr; Mph*

MAX/Average/Current *YES*

Wind chill indication *YES*

Real Time Measure *YES*

Back Light *YES*

Manual/Auto Power Off *YES*

C, digital camera

The Sony HDR-CX405 HD Handycam features an Exmor R CMOS sensor and a wide-angle Carl Zeiss zoom lens with 30x optical zoom. The CX-405 captures Full HD 1920 x 1080 video at 60p and 9.2MP still images to optional Memory Stick Micro and microSD/SDHC/SDXC media cards.

Specifications

Image Sensor	1/5.8"-Type CMOS
Sensor Resolution	Effective: 2.29 Megapixel
Image Stabilization	Optical
Zoom	Optical: Digital: 350x
Built-In Mic	Yes
Built-In Speaker	Yes
Wireless	No
Battery	Rechargeable Battery Pack, 3.6 VDC