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Impact of building envelope design modification on indoor temperature in classrooms in typical Omani schools

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ABSTRACT

In Oman's hot-arid climate, school buildings often experience elevated indoor temperatures due to inefficient building envelope designs, resulting in a heavy reliance on air conditioning systems and high energy consumption. To address this issue, this study aims to evaluate indoor air temperature in typical Omani school buildings and determine how modifications to key envelope components, such as walls, roofs, and glazing, can improve indoor temperature conditions and enhance thermal comfort. A mixed-method approach was adopted, combining field measurements with computer simulation. Indoor temperature and relative humidity were monitored in selected classrooms, while DesignBuilder software was used to model existing conditions and test alternative envelope configurations. This integrated method is appropriate for quantifying the thermal performance of building envelopes under realistic climatic and operational settings. Results showed that baseline classrooms reached average indoor temperatures of 33 °C in summer and 24.5 °C in winter, exceeding recommended comfort limits during hot periods. The most effective design alternative reduced indoor temperature by up to 2.3 °C and increased the number of hours within the comfort range by 29%. The study concludes that optimizing wall insulation, roof composition, and glazing selection can significantly improve indoor thermal comfort and energy efficiency in Omani schools, providing practical design guidance for future educational buildings in hot-arid climates.

1. Introduction

Oman has undergone rapid development over the past five decades, driven largely by the growth of its oil sector [1]. This expansion has led to significant increases in energy demand, with total national consumption rising by more than 150% between 2010 and 2017 [2, 3]. Within this context, the education sector represents one of the major consumers of electricity (Al-Badi et al., 2009). Most school buildings in Oman rely on air-conditioning to maintain comfortable indoor environments, especially during the long, hot summers typical of the country's arid climate [4]. The thermal design of these buildings has historically prioritised rapid construction and cost efficiency rather than climatic suitability [1]. Consequently, many classrooms experience indoor overheating, leading to excessive cooling loads and reduced energy efficiency. Environmental and energy-efficient design considerations were not a priority during Oman's initial construction boom following the 1970s oil era. As highlighted by Huovila [5] and CIBSE [6], early design decisions regarding building orientation, glazing, and shading have a significant impact on long-term thermal comfort and energy use. However, these principles were seldom applied in the early generations of Omani school buildings. Recent studies emphasise the importance of optimising the building envelope to enhance thermal comfort and reduce energy consumption [7–9]. However, most existing research in Oman has concentrated on residential or commercial buildings rather than educational facilities. There remains a limited empirical evaluation of how the thermal properties of school envelopes—specifically, walls, roofs, and glazing— affect indoor air temperature under local climatic conditions. Addressing this gap, this study aims to evaluate the indoor thermal performance of typical Omani school buildings and determine how modifications to key building envelope components—walls, roofs, and glazing—can improve indoor temperature conditions and enhance thermal comfort in Muscat's hot arid climate.

1.1 Typical School Buildings in Oman

According to Perkins (2002), "typical"refers to a building design approved in accordance with a district's current standards and specifications, which can be replicated in multiple locations. Since the 1980s, the Ministry of Education in Oman has developed several standardised school building models to meet the rapid growth in student enrolment [1]. These models vary in size and layout but share common features such as courtyards, double-storey blocks, and concrete construction materials. While standardisation helped accelerate construction and reduce costs, most designs were implemented with limited consideration of local climatic variations or passive thermal strategies. Earlier generations—such as the Simple Model, Eighties Model, and Nineties Model prioritised rapid expansion over climatic adaptation.

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Nomenclature

$ASHRAE$	American Society of Heating, Refrigerating and Air-Conditioning Engineers	RH	Relative Humidity (%)
CMU	Concrete Masonry Unit block	$R-value$	Thermal resistance of building materials $(m^2.^{\circ}C/W)$
$CVRMSE$	Coefficient of Variation of Root Mean Square Error	SC	Shading Coefficient
$HVAC$	Heating, Ventilation, and Air Conditioning	$SHGC$	Solar Heat Gain Coefficient
$Low-E$	Low-emissivity glazing	$U-value$	Overall heat transfer coefficient of $(W/m^2{\cdot}^{\circ}$C)
MBE	Mean Bias Error (model calibration indicator)	VT	Visible Transmittance of glazing (%)
PMV	Predicted Mean Vote (thermal comfort index)	WWR	Window-to-Wall Ratio (%)
PPD	Predicted Percentage Dissatisfied		

The current Millennium Model has improved functional spaces by adding computer labs and clinics, while retaining similar envelope characteristics, including concrete walls, reinforced-concrete roofs, and large glazed areas that permit significant solar heat gain. These typical schools are widespread across Oman, particularly in Muscat and other major governorates. However, because their envelopes were designed primarily for structural efficiency rather than thermal performance, classrooms often experience high indoor temperatures, especially during the summer. As noted by Al Hattali and Husin [10], most public schools have not yet incorporated green planning or energy-efficient design measures into their operations. Therefore, understanding how the thermal behaviour of these standard school models responds to Oman's hot-arid climate is crucial. Evaluating the performance of existing envelopes and identifying effective modifications can support future design improvements that enhance indoor comfort and reduce energy use in the education sector.

1.2 Building Envelope and Indoor Thermal Conditions

The construction components that separate the interior environment of the structure from the exterior environment are referred to as the building envelope. It considers several variables: environment, technology, functionality, and aesthetics. Therefore, the envelope design and indoor thermal comfort should be carefully inspected during the design phase; otherwise, it will negatively impact energy consumption and the occupants' performance [8]. Al-Saadi and Al-Jabri [7] optimised an energy-efficient envelope design, achieving 26.7% energy savings through simulation (Design-Builder). The emphasis on envelope design adds depth to understanding the architectural elements that contribute to energy efficiency in residential structures. Huovila [5] reported that passive solar considerations, such as building orientation, siting, window size and position, glazing area, ventilation, natural lighting, and shading device methods, must be considered when designing a building. Building envelope components can be divided into opaque and transparent elements; the first category includes roofs and walls, and glazed fenestrations encompass the latter category. Ideally, early design decisions should inform and guide the detailed and appropriate planning and execution of the approach to achieve the intended solution based on each element of the envelope [9]. During the rapid expansion of school construction following the 1970s oil boom, environmental performance and thermal design were generally overlooked. The focus was on delivering many buildings quickly rather than optimising their envelopes for climatic conditions. As a result, many typical schools were constructed without adequate consideration of insulation, glazing performance, or passive heat-reduction strategies. In public schools, Än Evaluation Study of Public Schools in Oman", Al Hattali and Husin [10] used survey questionnaires, emphasising green planning. This research contributes to a nuanced understanding of sustainability practices in public school infrastructure, particularly with a focus on green planning. To improve indoor temperature control and reduce cooling demand, school buildings should integrate climate-responsive envelope features—such as proper insulation, shading, and glazing selection—that minimise heat gain and stabilise indoor thermal conditions. A smaller air conditioning system may be used because of the significant reduction in cooling and heating loads that can be achieved through the ideal design of the building envelope. However, existing schools have fewer opportunities to alter or modify the elements of the envelope. Opportunities for energy conservation through the building envelope can be leveraged from the pre-design stage of new school buildings. Achieving this goal will preserve the environment for future generations while providing students with healthy and comfortable learning environments. This study aims to enhance the internal environments of typical schools while reducing energy consumption. Several studies have investigated the impact of the building envelope on indoor comfort for occupants in hot and arid climates. These studies explore various aspects, such as the thermal efficiency of the envelope, the influence of construction materials, and the role of the local outdoor environment, often in combination with passive strategies to enhance indoor thermal conditions. Khoukhi and Fezzioui [11] assessed the thermal comfort of modern Algerian homes using a comparative analytic method, analysing existing conventional dwellings to calculate the percentage of hours spent in thermal comfort. The study found that modern homes were unsuitable for hot, arid climates and that air conditioning was the only effective way to ensure thermal comfort during summer periods. Kokogiannakis et al. [12] examined the impact of material surface characteristics on thermal performance. They studied the energy implications of different outdoor-to-indoor surface finishes and found that roof coatings can significantly improve energy and thermal efficiency, particularly in buildings with low roof insulation levels. Ashrafian and Moazzen [8] investigated the effect of glazing size, window-to-wall ratio (WWR), and window configurations, based on critical orientations, on human thermal comfort in a prospective school building in Turkey's dry temperate climate using a simulation modelling approach. The study suggested that a WWR of 50% would offer comfortable indoor thermal conditions in the classroom. Similarly, Sharma et al. [13] evaluated thermal performance in naturally ventilated spaces, while Ma et al. [14] analysed parameters associated with thermal comfort and IAQ measurements. Kirankumar et al. [15] employed reflective double glazing to reduce heat gain through openings and lower indoor air temperatures. Muñoz-Viveros et al. [16] also explored passive improvements to building envelopes, such as incorporating overhangs and applying solar protection to glazed components. While many previous studies have contributed to understanding passive strategies for improving thermal conditions, most have focused on specific parameters rather than providing a holistic evaluation of thermal performance. In addition, research has largely concentrated on residential and commercial buildings, with limited attention given to educational settings. Unlike previous work, this study investigates a typical government school in Muscat's hot-arid climate, combining field measurements with calibrated simulations to assess the performance of multiple envelope components—walls, roofs, glazing types, and window-to-wall ratios—both individually and in combination. The analysis is tailored to local construction practices, material availability, and operational patterns, providing practical, context-specific strategies for improving classroom thermal comfort. Therefore, this study aims to evaluate the thermal characteristics of school building envelopes and identify effective strategies to mitigate indoor air temperature fluctuations in the hot and dry climate of Muscat, Oman. Recent research continues to validate the strong influence of building-envelope design on indoor thermal conditions, particularly in educational facilities. Studies conducted in hot-arid and tropical regions have demonstrated that upgrading wall and roof insulation, applying reflective surface coatings, and using low-emissivity glazing can reduce classroom air temperature by 1–3 °C and extend the comfort range by up to 30% [17–19]. These findings reinforce earlier evidence by Ashrafian and Moazzen [8] and Muñoz-Viveros et al. [16] regarding the benefits of optimised glazing and shading design in schools. However, empirical and simulation-based assessments focusing on Omani school buildings remain limited. Therefore, the present study addresses this gap by evaluating indoor temperature responses to envelope design modifications under Muscat's hot-arid climatic conditions. In this study, "building envelope design modifications"refer to changes applied to the main components that separate the indoor and outdoor environments—namely, the walls, roofs, and glazing systems—to enhance their thermal performance. These modifications include variations in insulation materials, layer thicknesses, surface properties, and glazing types, all of which influence heat transfer through the building envelope. Ïndoor temperature,ön the other hand, refers to the air temperature measured within classroom spaces and serves as a key indicator of thermal comfort and envelope performance. Evaluating the relationship between these two variables enables assessment of how envelope design improvements affect the thermal behaviour of classrooms under Oman's hot-arid climatic conditions. Previous studies consistently demonstrate a direct relationship between building-envelope design modifications and indoor air temperature. Changes to envelope parameters—such as wall insulation type and thickness, roof composition, glazing properties, and window-to-wall ratio—impact heat transfer rates and, consequently, influence the indoor thermal environment. For example, Al-Saadi and Al-Jabri [7] reported that optimising envelope insulation in Omani dwellings reduced cooling loads by over 25%, while Ashrafian and Moazzen [8] found that adjusting glazing size and configuration

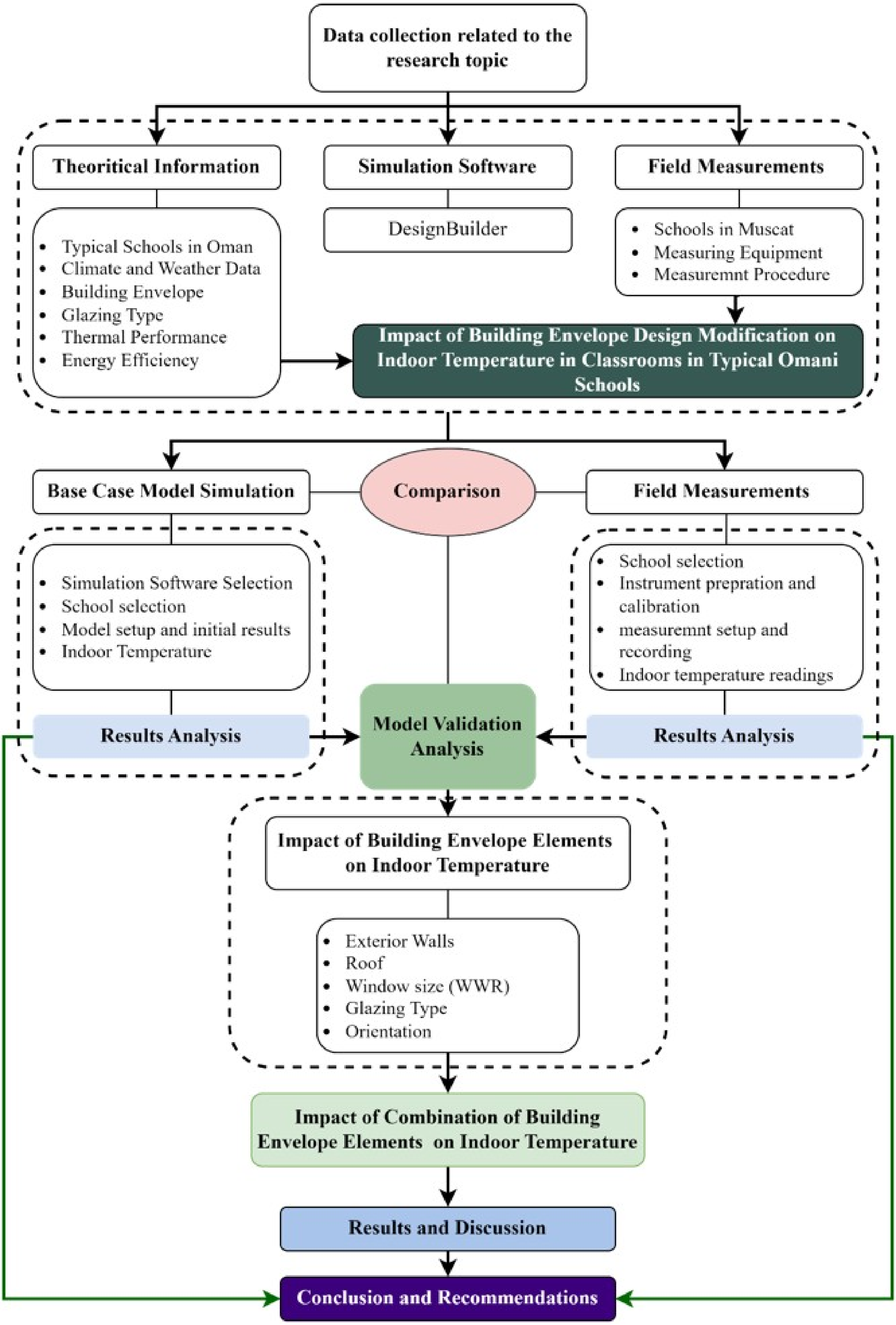


Figure 1. Research Design.

improved classroom thermal comfort in a dry climate. Kirankumar et al. [15] and Mohamed et al. [20] further highlighted that high-performance glazing systems lower indoor peak temperatures and energy use. Similarly, Elnabawi and Saber [21] demonstrated that improved roof materials and insulation reduce air temperature and increase the number of comfortable hours in hot-arid regions. Collectively, these findings confirm that modifications to the building envelope can effectively regulate indoor temperature, providing a scientific basis for the present study's evaluation of envelope design improvements in Omani school buildings.

2. Methodology

This study adopted a mixed-method research design that combines field measurements with computer-based simulation analysis. The mixed approach was selected to enable both empirical observation and predictive assessment of the indoor thermal environment in Omani school classrooms. Field measurements provided real data on indoor air temperature and humidity under actual operating conditions, while simulation modelling using Design-Builder software allowed controlled testing of different building-envelope configurations. This combination ensures a comprehensive evaluation of thermal performance and supports validation of the measured and simulated results. The chosen design is suitable for this topic because it combines quantitative precision from simulation with contextual realism from field data, allowing for replication and adaptation in similar studies of hot-arid climates. This study is implemented in two major phases to achieve and address the study objectives. The first phase involved field measurements in existing classroom buildings in the study area. This phase also included gathering fieldwork data by utilising suitable instruments for measuring different climate components, including relative humidity and indoor air temperature. The inferences from the fieldwork were analysed to develop the base case model. This phase also included the modelling and simulation of the base case and subsequent design alternatives using Design-Builder software. The simulation results were calibrated against actual data from the case studies in this study to ensure the reliability of the simulation results. The second phase involves studying the independent effects of external walls, roofs, windows, and glazing on indoor air temperature. Furthermore, these envelope elements are combined in a parametric approach to gain deeper insight and conduct a comprehensive analysis of their influence on indoor thermal comfort. The findings are interpreted to outline design recommendations for the building envelope suitable for the climate situation in the study area. Figure 1 illustrates the research phases and steps.

Figure 2. Site plan and different views of Fatima Bint Al-Waleed School.

2.1 Case study location and description

Muscat, located in Oman's central region, experiences a hot-arid climate characterised by long, extremely hot summers, mild winters, high humidity, and low annual rainfall of approximately 100 *mm* [4]. The summer season typically begins in mid-April and lasts until the end of October. The Muscat region was selected because it is the country's capital city and has many typical schools. Fatima Bint Al-Waleed School, located in Al-Seeb, Muscat (23°37′56.4″N, 58°12′08.5″E), was selected as the case study because it represents the typical Millennium Model of government school buildings constructed during the Ministry of Education's expansion programme in the early 2000s. This model is widely adopted across Oman and is therefore considered representative of the thermal and construction characteristics of public schools in the country's hot arid regions. The school, established in 2005, is rectangular in plan and oriented approximately 304° from true North. It has a total built-up area of 4,184 m^2 distributed over two suspended floors, each with a ceiling height of 3.3 *m*. The layout includes 30 classrooms, a central covered courtyard, laboratories, and administrative offices. The courtyard serves as a multifunctional space for student gatherings and provides partial shading during outdoor activities. The building envelope comprises 200 *mm* hollow concrete block walls finished with external cement plaster and either khaki or brown paint, a 150 *mm* reinforced concrete roof slab protected by a bituminous waterproofing layer, and single 12 *mm* clear glass windows with aluminium frames. The typical window-to-wall ratio (WWR) is approximately 25–30%, allowing daylight penetration and limited natural ventilation. The roof over the courtyard is framed in aluminium sheeting. The surrounding area consists mainly of low-rise residential buildings and paved open surfaces that contribute to high solar exposure during summer. For simulation analysis, the envelope components were modelled and subsequently modified to test alternative materials and configurations, including enhanced wall and roof insulation, reflective roof coatings, and double low-emissivity glazing. These options were selected to represent practical, climate-appropriate retrofit strategies commonly applied in hot-arid educational environments. Figure 2 presents the site plan and selected views of the school building.

2.2 Field Measurements

2.2.1 Instruments and materials

Indoor air temperature and relative humidity were measured using Testo 174H data loggers, Fig. 3, which record both parameters with an accuracy of ±0.4°C for temperature and ±3% for relative humidity. The devices were placed at the centre of selected classrooms at a height of 1.1 *m* above the floor, representing the typical breathing zone of seated occupants. Measurements were recorded at 10-minute intervals over a continuous period of seven days during both summer and winter conditions. Outdoor ambient conditions were obtained from the Oman Meteorology Department for the corresponding periods. Prior to deployment, all data loggers were tested and verified against a calibrated reference thermometer to ensure the accuracy and reliability of readings. The collected field data were later used for validation and calibration of the simulation model to ensure that the predicted indoor temperatures accurately represented the actual classroom conditions.

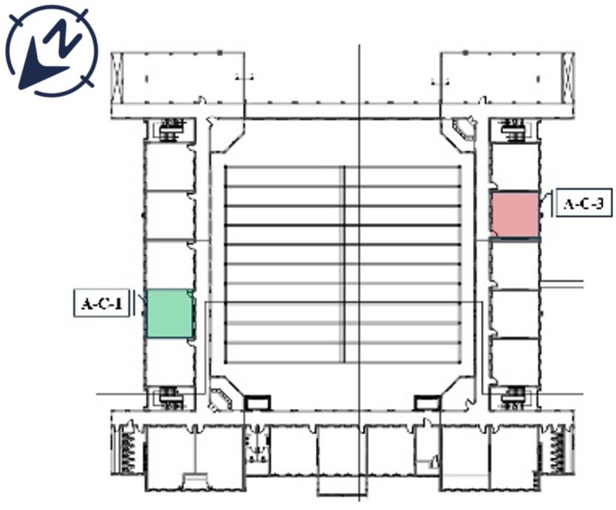
2.2.2 Measurement procedure

Data was collected from the school in two stages. In the first stage, information about the school's physical features and operational characteristics was gathered by examining the school's drawings and relevant documents from the school's management. This information included data on the roof and wall assembly, openings, air conditioning system, fenestration, school operation, and energy consumption, which helped develop a base case model similar to the actual school building. The second stage involved field measurements to record indoor air temperature and relative humidity in the classrooms. This stage was intended to evaluate the thermal performance of the classrooms in the selected school in Muscat (Fatima Bint Al-Waleed School) regarding indoor temperature and relative humidity. The fieldwork consisted of two main phases: preparing the classrooms for measurements and taking measurements inside the classrooms using appropriate equipment, in accordance with indoor thermal measurement standards. The layout of the classroom and measurement locations are shown in Figure 4.

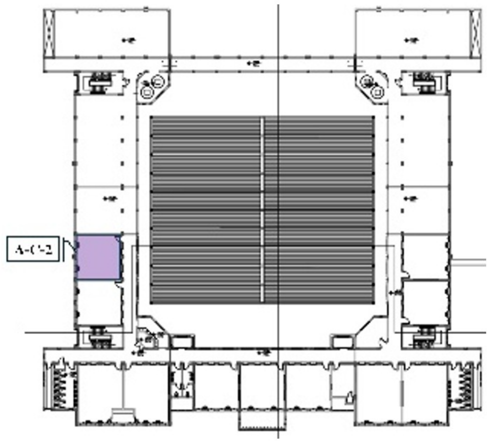
2.3 Modelling and simulation

The building's thermal performance was simulated using Design-Builder software, which operates on the EnergyPlus simulation engine. This program was selected because it allows detailed modelling of building envelope materials, occupancy schedules, internal gains, and climatic parameters. The school's geometry, construction materials, and window-to-wall ratios were modelled based on architectural drawings and site verification. Also, Design-Builder was selected for its validated accuracy and capability to simulate design features and perform energy-based calculations [22, 23]. Model calibration was carried out by comparing the simulated indoor temperature profiles with the field-measured data. Adjustments were made to infiltration rates and internal heat gains until the mean bias error (MBE) and coefficient of variation of the root mean square error (CVRMSE) values were within ASHRAE Guideline 14 acceptable limits (±10% for MBE and ≤30% for CVRMSE). This ensured that the model accurately represented the real thermal behaviour of the classrooms before testing the envelope modification scenarios. To accurately simulate thermal performance, a baseline energy model was developed using Design-Builder software based on the school's physical and operational characteristics. No air conditioning systems were modelled in the simulations. The analysis focused solely on the passive performance of the building envelope under natural ventilation conditions, isolating the impact of envelope modifications on indoor temperature. Table 1 summarises the key input variables and parameters used in the simulation.

Figure 3. Testo 174H data logger.



(a) Model 01

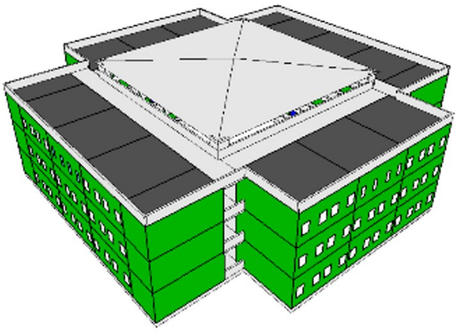


(b) Model 02

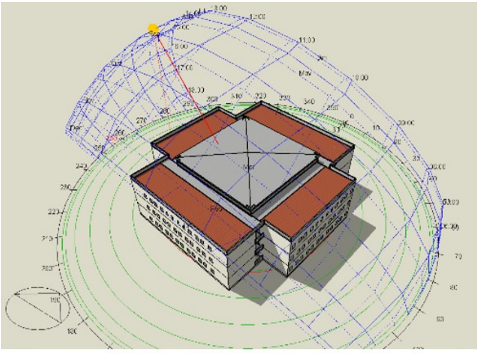
Figure 4. Measurement locations in the classroom.

2.4 Sampling method and sample size

A purposive sampling approach was adopted to select representative classrooms for measurement and simulation. Three classrooms were chosen based on their orientation (north, south, and west) and similar physical characteristics, Fig. 5. This selection ensured coverage of different solar exposures and provided a representative sample of typical classroom thermal conditions in the building.



(a) Model 01



(b) Model 02

Figure 5. 3D views of the school model.

2.5 Data Analysis Methods

The recorded data were processed using Microsoft Excel and SPSS software to calculate average, minimum, and maximum temperature and relative humidity values. A comparative analysis was performed between measured and simulated results to evaluate model accuracy and quantify the improvements resulting from envelope modification scenarios. Statistical indicators such as Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Square Error (CVRMSE) were used to validate the model's performance.

2.6 Ethical Considerations

This study did not involve human participants or personal data. Permission to access the school premises and collect environmental measurements was obtained from the Ministry of Education, Oman. All data collected were limited to physical environmental parameters and were used solely for research purposes.

Table 1. Summary of building simulation model parameters

Description	Value
Number of Floors	2
Floor-to-Ceiling Height	3.3 m
Total Floor Area	4,184 m^2
Orientation	304°from North
Glazing Type	Single-glazed, 12 mm
Window-to-Wall Ratio (WWR)	25%
Roof Construction	Reinforced Concrete
Exterior Wall construction	CMU Block
Exterior Wall U-Value	1.89 W/m^2 °C
Roof U-Value	2.31 W/m^2 °C

3. Results Analysis

3.1 Field Measurements

The fieldwork to record indoor temperature measurements in the selected school's classrooms was conducted in two periods. It was conducted in winter and summer, between 24 and 30 November and 21 and 27 April. One week was chosen during the summer, and the other was selected during the winter to reflect the warmest and coolest periods of the year, respectively, to assess the indoor temperature of the chosen schools and compare them with the thermal comfort range. Three classrooms were selected at different floor levels of the case study school building to record the indoor temperature. During the measurement period, the classrooms were in a passive mode without an air conditioning system. The outdoor temperature for the same period was obtained from the weather station in Muscat. A summary of the field measurements is presented in Table 2.

Table 2. Summary of the indoor temperature Summer and Winter.

Classroom	Value	Orientation	Summer			Winter		
			Max.	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**
A-C-1	1st Floor	North-East	34.7	31.9	33.6	28.5	22.3	23.5
A-C-2	2nd Floor	North-East	34.1	31.7	33.2	29.3	23.4	25.8
A-C-3	1st Floor	Southwest	34.0	30.1	33.8	28.4	23.4	24.6

3.1.1 Summer measurement results

From the analysis of the indoor air temperature in all the school's classrooms Fig. 6, it can be seen that from 10:00 am to 5:00 pm, the average indoor air temperature difference was approximately 2.3°C, ranging from 7°C to 0.1°C at 12:00 pm and 9:00 am, respectively. In comparison, from 5:00 pm to 9:30 am, the average indoor air temperature was higher than the outdoor air temperature, with an average difference of approximately 2.3°C. In contrast to the lowest outdoor air temperature recorded between 4 am and 6 am, which was 27.4°C, and the highest recorded between 12 pm and 2 pm, which was 39.2°C, the average indoor air temperature recorded at 6 am was 31.9°C, while the maximum recorded at 3 pm was 34.7°C. Despite a wide daily range of external air temperatures, there were only slight changes in the daily range of indoor air temperatures. These findings showed that the building's thermal mass stabilises the temperature inside. All air temperatures, both indoors and outdoors, fall within the range of discomfort, with most readings exceeding the highest threshold of thermal comfort. These results indicate that during summer, the existing building envelope fails to maintain acceptable indoor comfort levels, with temperatures consistently exceeding the 26°C upper limit suggested by ASHRAE Standard 55 [24]. The reduced daily temperature fluctuation confirms that the building's heavy concrete structure provides some thermal inertia, moderating diurnal swings but not preventing overheating. This pattern aligns with findings by Ashrafian and Moazzen [8] and Elnabawi et al. [18], who observed that uninsulated concrete walls and roofs in hot-arid school buildings lead to persistent indoor overheating despite thermal mass effects. The small temperature difference between floors suggests limited vertical stratification, while the consistently high indoor readings highlight inadequate insulation and glazing performance as key contributors to excessive heat retention.

3.1.2 Winter measurement results

Figure 7 shows the indoor temperature results for all classrooms in this school during the chosen winter week. It can be seen that from 10:00 am to 2:00 pm, the average indoor air temperature of all rooms was lower than the outdoor air temperature, with a range of 5.4°C to 0.1°C. However, during the unoccupied time, the indoor air temperature was higher than the outdoor air temperature, with an average difference of 1.3°C. In contrast to the lowest outside air temperature recorded between 4 *am* and 6 *am*, which was 17.7°C, and the highest recorded between 12 *pm* and 2 *pm*, which was 28.8°C, the average indoor air temperature recorded at 6 am was 22.3°C, while the highest recorded at 2 *pm* was 29.5°C. Despite a wide daily range of external air temperatures, there were only slight changes in the daily range of indoor air temperatures. These findings showed that the building's thermal mass stabilises the temperature inside. Most of the time, indoor air temperatures are comfortable, with the majority of readings below the highest thermal comfort threshold. The results of the field measurements show that the maximum average indoor temperature during the winter and summer periods was higher on the second floor than on the first; this may be because the classrooms on the second floor are exposed to direct sunlight through the roof. The field measurement results correlate with classroom orientation, significantly impacting heat gain or loss. The classrooms facing southwest have higher average temperatures than the classrooms facing northeast. The winter results confirm that the existing envelope provides adequate thermal stability under milder conditions, maintaining indoor temperatures within or slightly above the comfort range (20–26°C). The higher second-floor readings validate the influence of roof exposure on heat transfer, consistent with the conclusions of Al-Saadi and Al-Jabri [7], who noted that uninsulated roof surfaces contribute significantly to internal heat gain. The orientation effect—warmer southwest-facing classrooms—supports established evidence that solar exposure on west-facing façades drives elevated afternoon temperatures in hot climates [25]. Collectively, these results emphasise that both orientation and insufficient roof insulation are major determinants of thermal imbalance within the studied school building. Although this study used indoor air temperature as the primary indicator of indoor thermal conditions, it is acknowledged that comprehensive thermal comfort evaluation requires additional parameters such as relative humidity, air velocity, mean radiant temperature, and occupants' metabolic rates. Due to limitations in field instrumentation and the focus on building-envelope performance, air temperature was employed as a proxy indicator to reflect relative indoor comfort trends. This approach is consistent with prior building-envelope studies in hot-arid regions [21, 26], which used air temperature as a reliable measure of thermal behaviour when assessing passive design modifications. Future research will incorporate full comfort indices, such as PMV and PPD, to provide a more comprehensive assessment.

3.2 Comparison of field measurements with simulation results

The recorded indoor temperature is compared with the obtained results from the simulation process. The classroom in the first level of Fatima Bint Al-Waleed School is selected for this comparison. This classroom was chosen because it has the same typical classroom design used in the parametric analysis in the modelling and simulation phase. The simulated classroom model serves as the base case for the parametric analysis, which investigates the effect of building envelope design elements on indoor temperature. The comparison was made for one day in summer and one day in winter. A summary of measured and simulated mean indoor and outdoor temperatures for winter and summer is presented in Table 3. This table provides a quick comparison, while Table 4 contains the complete statistical analysis. The results show similar outdoor and indoor temperature profiles for simulated and recorded data, with a difference of less than 2°C in the average temperature. According to the result analysis, a significant correlation exists between the measured and simulated results, with a Pearson Correlation Coefficient ranging from 0.715 to 0.98, indicating a high degree of relationship between the simulated and measured results, as shown in Table 5. These results confirm that the simulation model developed using DesignBuilder accurately reproduces the real thermal behaviour of the classrooms. The slight differences (less than 1°C) between simulated and measured indoor temperatures fall well within acceptable calibration limits as recommended by ASHRAE Guideline 14 (MBE ±10%, CVRMSE $\leq 30\%$). This demonstrates that the input parameters—such as material properties, occupancy schedules, and infiltration rates—were appropriately defined. The strong correlation coefficient ($r = 0.715$–0.98) further validates the model's reliability for predictive analysis. Similar levels of model accuracy were achieved in comparable studies by Shamseldin [27] and Zhao et al. [28], who reported temperature deviations of less than 1°C when simulating classrooms in hot climates. Therefore, the calibrated model can be confidently used for the subsequent parametric simulations of envelope design modifications, ensuring that the predicted performance reflects realistic classroom conditions.

3.3 Effect of Building Envelope Modification on Indoor Air Temperature

This section presents the effect of modifying building envelope elements on indoor air temperature. This includes modifying the exterior wall, roof, glazing type, and window area. The impact of orientation on indoor temperature is also examined. One summer day was selected for this investigation, as it represents the worst indoor conditions based on the field measurements collected data.

Table 3. Comparison of Measured and Simulated Mean Temperatures.

Season	**Location**	**Measured °C**	**Simulated °C**	**Difference °C**
Winter	Indoor	24.33	24.65	0.32
Winter	Outdoor	23.13	23.77	0.64
Summer	Indoor	33.43	33.99	0.56
Summer	Outdoor	32.41	32.64	0.23

3.3.1 Exterior wall modification

The climatic conditions significantly impact schools because they are exterior load-dominated structures. As shown in Table 5, the interior temperature of typical school buildings in Muscat is assessed under different envelope designs utilising alternative wall designs that cover a wide range of thermal properties. The results of different exterior wall design alternatives for all orientations at both daytime and nighttime are illustrated in Figure 8. It is clear that wall design #4, with a U-Value of 0.27, provides the highest reduction in indoor temperature (2.1°C), followed by wall design #3, with a U-Value of 0.4 (about 1.0°C reduction in indoor temperature) and the most negligible decrease in

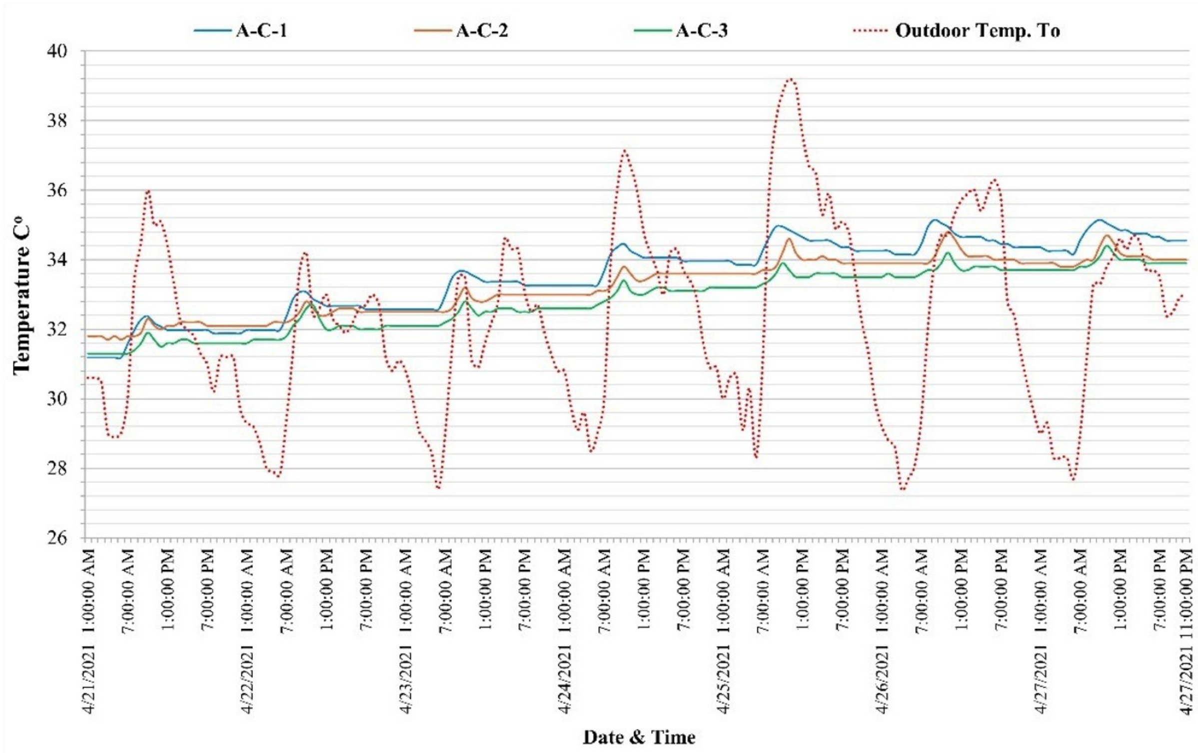


Figure 6. Indoor air temperature during the summer period (21 to 27 April).

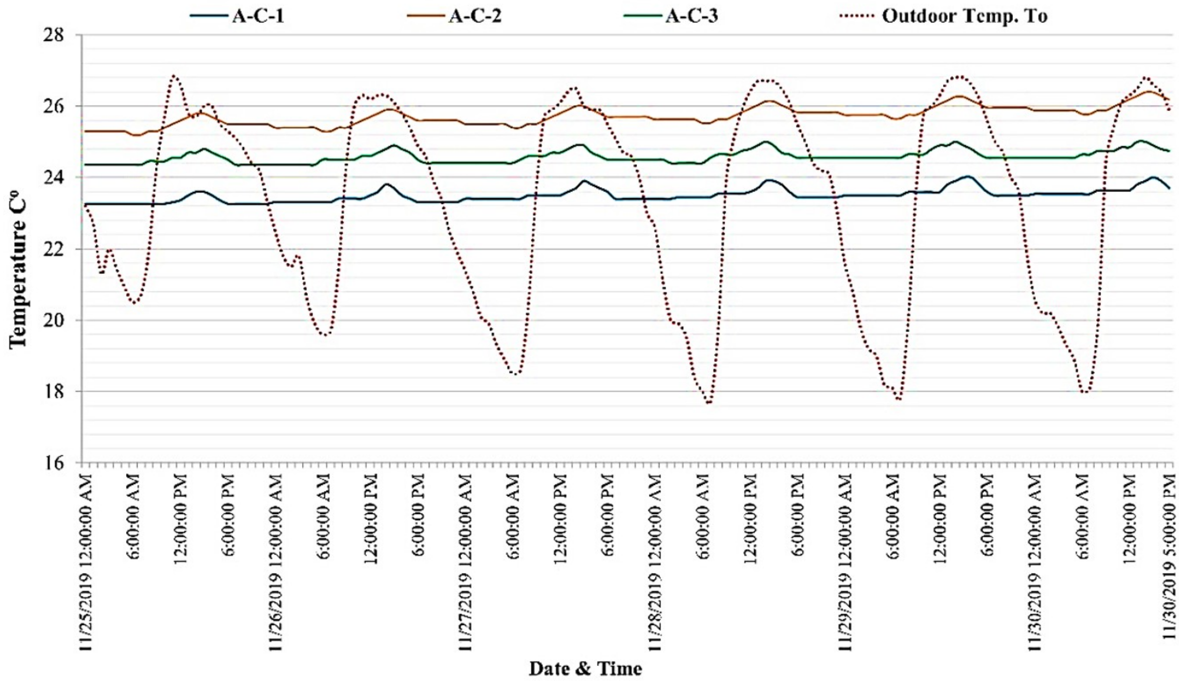


Figure 7. Indoor air temperature during the winter period (24 to 30 November).

indoor temperature was achieved when wall design #1 is implemented. However, it would be more economical to use wall design #3 instead of wall design #4 because wall design #3 uses 50 *mm* extruded polystyrene, which is cheaper and has significantly less thickness than wall design #4. The results demonstrated that the highest maximum indoor temperature was found with the east orientation, whereas the lowest indoor temperature was recorded with the north orientation. A possible justification for this is the sun's position for most of the day as it travels along the solar path during the simulation period. Wall design #3 is much more effective as the composition provides some form of insulation from the outdoor temperature increase throughout the day. Compared to other wall alternatives, the inexpensive nature of the material build-up makes it a more economical choice for developing educational buildings in Oman. The observed reduction in indoor temperature across various insulated wall types confirms the dominant role of conductive heat transfer through opaque elements in Muscat's hot, arid climate. The improved performance of Wall #3 and #4 is attributed to their lower U-values and higher thermal resistance, which reduce heat gain during daytime peaks and slow nighttime heat release. This trend aligns with previous work by Al-Saadi and Al-Jabri [7] and Sharma et al. [13], who found that adding 40–60 mm of high-density insulation to masonry walls in Gulf region schools decreased the peak indoor temperature by 1–3°C.

Table 4. Statistical analysis results between the recorded and simulated indoor temperature results.

Parameters	Field	Sim.	Field	Sim.	Field	Sim.	Field	Sim.
Mean Temperature	24.33	24.65	23.13	23.77	33.43	33.99	32.41	32.64
Variance	1.36	1.08	10.06	5.59	0.93	3.15	9.96	8.10
Observations	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00
Pooled Variance	1.22	—	7.83	—	2.04	—	9.03	—
Df	46.00	—	46.00	—	46.00	—	46.00	46.00
t Stat	-1.00	—	-0.80	—	-1.37	—	-0.27	-1.37
$P(T \leq t)$ one-tail	0.16	—	0.21	—	0.09	—	0.40	0.09
t Critical one-tailed	1.68	—	1.68	—	1.68	—	1.68	1.68
$P(T \leq t)$ two-tail	0.32*	—	0.42*	—	0.18*	—	0.79*	0.18*
t Critical two-tailed	2.01	—	2.01	—	2.01	—	2.01	2.01
*$P(T \leq t)$ two-tailed > Alpha Value (0.05). This means insignificant difference.								
Pearson Corr. Coeff.	0.72		0.99		0.77		0.79	

Table 5. Exterior wall alternatives for thermal simulation.

Alternatives	Wall composition	U-Value W/m^2.°C	R-Value m^2.°C/W	Heat Capacity KJ/m^2.°C
(Base Case)	200 *mm* CMU Block + No insulation + 15 *mm* Cement plaster on both sides	1.89	.53	300.69
Wall #1	200 *mm* Hollow CMU Block + 50 *mm* Expanded Polystyrene + 15 *mm* Cement plaster on both sides	0.6	1.69	380.31
Wall #2	200 *mm* Hollow CMU Block + 50 *mm* Extruded Polystyrene + 15 *mm* Cement plaster on both sides	0.5	2.00	380.92
Wall #3	200 *mm* Hollow CMU Block + 50 *mm* Polyurethane + 15 *mm* Cement plaster on both sides	0.4	2.50	380.1
Wall #4	200 *mm* Hollow CMU Block + 100 *mm* Extruded Polystyrene + 15 *mm* Cement plaster on both sides	0.27	3.70	383.6

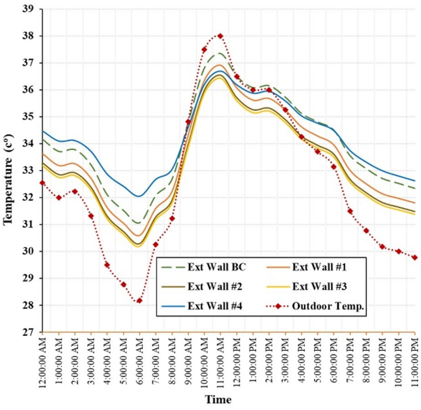
Table 6. Roof design alternatives for thermal simulation.

Alternatives	Wall composition	U-Value W/m^2.°C	R-Value m^2.°C/W	Heat Capacity KJ/m^2.°C
Base Case	15 *mm* Cement plaster + 200 *mm* Reinforced Concrete Slab + 100 *mm* Sloping Screed (Light Weight Concrete)	2.31	0.43	491.6
Roof #1	15 *mm* Cement plaster + 200 *mm* Reinforced Concrete Slab + 100 *mm* Sloping Screed + Level Screed 30 *mm* + Terrazzo Tiles $(300 \times 300 \times 30\ mm)$	2.07	0.48	582.5
Roof #2	15 *mm* Cement plaster + 200 *mm* Reinforced Concrete Slab + 100 *mm* Sloping Screed + 50 *mm* Expanded Polystyrene + Level Screed 30 *mm* + Terrazzo Tiles $(300 \times 300 \times 30\ mm)$	0.61	1.64	475
Roof #3	15 *mm* Cement plaster + 200 *mm* Reinforced Concrete Slab + 100 *mm* Sloping Screed + 50 *mm* Extruded Polystyrene + Level Screed 30 *mm* + Terrazzo Tiles $300 \times 300 \times 30\ mm$	0.5	2.00	471.5

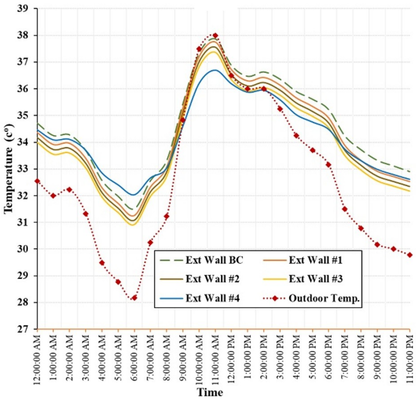
The orientation-dependent results further highlight solar radiation as the key external driver; similar orientation effects have been reported by Elnabawi and Saber [21] and Liu et al. [17] for classroom buildings in hot desert environments. Economically, Wall #3 offers an optimal balance between thermal performance and construction cost, suggesting that moderate insulation thickness, using polyurethane or extruded polystyrene, can achieve substantial thermal improvement without incurring excessive material expense. These outcomes offer practical guidance for envelope retrofits aimed at achieving energy savings and enhancing occupant comfort in existing Omani schools.

3.3.2 Roof modification

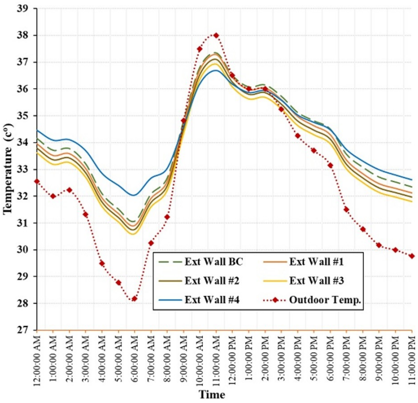
The indoor temperature of typical school buildings in Muscat is analysed under various envelope designs utilising several alternative roof designs Table 6 that cover a wide range of thermal properties representing the typical characteristics of Oman architecture. The roof composition (interior to exterior) includes materials appropriate for educational buildings with varying thermal and structural properties, but the same aesthetic (finish). Roofs for schools in Oman are not very open to flexibility in design and structure due to the prevailing climatic conditions; hence, the almost identical composition of materials is prevalent in this section. Figure 9 presents the results of indoor temperature when alternative roof designs were applied. It is evident from the findings that roof design #3, with a U-Value of 0.5, demonstrates the reduction in indoor temperature (1.5°C) represents 4.25% of the maximum indoor temperature (36°C), followed by roof design #2, with a U-Value of 0.6 and the slightest reduction in indoor temperature was achieved when roof design #1 is used. This is due to the lack of an insulation layer for the building cover, which fails to shield the indoor environment from the high outdoor temperature during the day, resulting in heat gain through the roof compared to other designs. This aligns with the comparison study conducted by Elnabawi and Saber [21] on the reduction of air temperature in roof designs in hot, arid climates. Nevertheless, there is little difference in the decrease in indoor temperature between roof design #3 and roof design #2. Therefore, it would be more economical to use wall design #2 instead of roof design #3 because wall design #2 utilises 50 mm extruded polystyrene, which is less expensive than the material used in roof design #3. Additionally, extruded polystyrene provides a superior solution in terms of structural stability and overall thermal performance in both construction and operation [29]. The results demonstrated that the highest maximum indoor temperature was similar across all orientations due to the homogeneous composition of the roof design alternatives and the negligible influence of the roof's thermal performance on orientation.



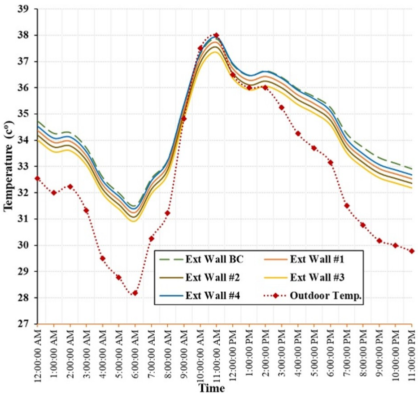
(a) North



(b) East

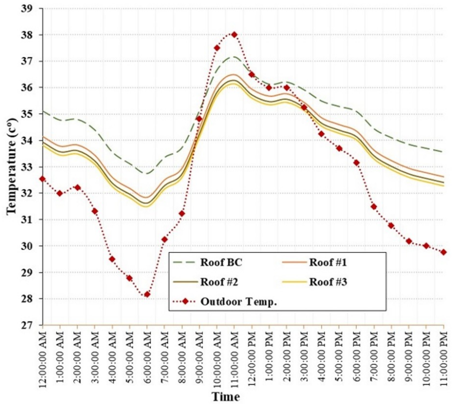


(c) South

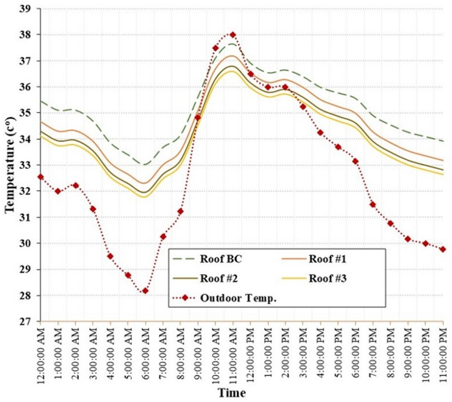


(d) West

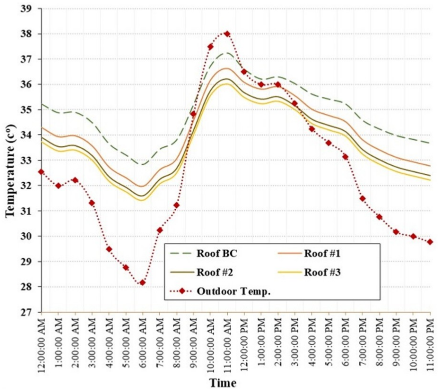
Figure 8. Effect of exterior wall modification on the indoor temperature in the North, East, South, and West classrooms.



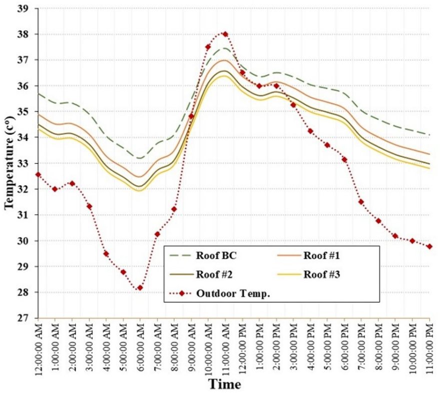
(a) North



(b) East



(c) South



(d) West

Figure 9. Effect of roof modification on the indoor temperature in the North, East, South, and West classrooms.

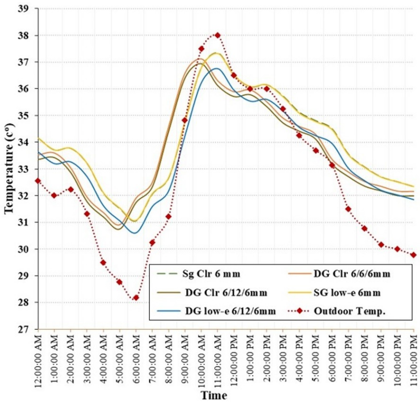
The simulation outcomes confirm that roof insulation plays a decisive role in mitigating solar heat gain, particularly in single- and double-storey educational buildings exposed to intense solar radiation. The 1.5°C reduction achieved with Roof #3, although seemingly minor, represents a significant improvement in thermal comfort and potential energy savings during school hours. Similar studies in the Gulf region or Saudi Arabia have shown that roof insulation yields measurable reductions in cooling loads and energy consumption [30], highlighting the practical relevance of these results. The minimal performance difference between Roof #2 and #3 demonstrates that moderate insulation thickness provides nearly the same thermal benefit at a lower cost, making Roof #2 a more viable solution for large-scale retrofits. The finding that orientation has a negligible impact confirms that, unlike wall exposure, horizontal surfaces receive nearly uniform solar radiation in Muscat's latitude. Consequently, improving roof insulation should be prioritised alongside wall enhancements to achieve optimal indoor comfort in Omani school buildings.

Table 7. Glazing types used in the thermal simulation (Clear glazed).

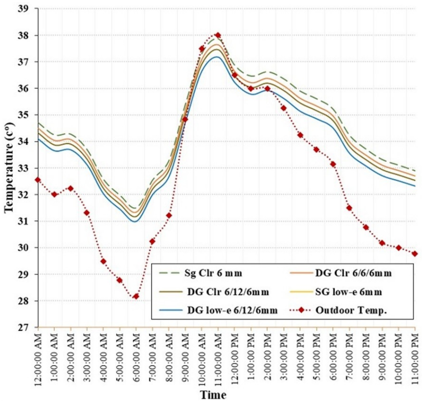
Alternative	Glazing type	VT	Shading coefficient	Solar heat gain coefficient	U-Value $W/m^2.K$
Base Case	Single glazed 6 *mm*	0.88	0.95	0.81	6.12
Glass 1	Double glazed 6/6/6 *mm*	0.78	0.60	0.70	3.16
Glass 2	Double glazed 6/12/6 *mm*	0.78	0.60	0.69	2.70
Glass 3 (low-E)	Double glazed 6/12/6 *mm*	0.74	0.47	0.56	1.7

3.3.3 Glazing type modification

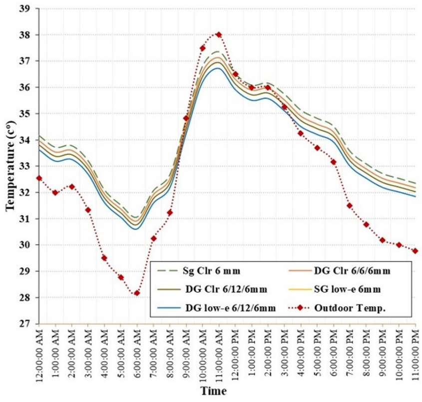
In this context, openings in buildings are also known as 'thermal holes', which significantly contribute to the comfort of the indoor environment. This is particularly important in schools, where air temperature and adequate natural lighting are crucial for daily tasks. Accordingly, the indoor temperature in the classrooms can be reduced by selecting the proper type of glazing for windows, which improves the thermal indoor environment and reduces direct solar heat gain through windows. The indoor temperature of typical school buildings in Muscat is evaluated under various envelope designs using different alternative glazing types based on the existing glasses available in the local market, which cover a broad range of thermal attributes, as shown in Table 7. The results of indoor temperature when alternative glazing types were used are shown in Fig. 10. The simulation results show that using Double Clear glass 6/6/6 *mm* resulted in the maximum reduction in indoor temperature in the north classroom, whereas the maximum reduction in indoor temperature in the west and east classrooms is obtained when clear double-glazed low-E 6/12/6 *mm* is used. This may be because east and west orientations are exposed to direct sun rays from the sun's path. It can be observed that there is only a slight variation between Double Clear 6/6/6 *mm* and Double-glazed Clear 6/12/6 *mm* in terms of the reduction in indoor temperature. Thus, the cavity dimension for double glazing might be negligible, and the double glass strategy is more important and influential enough to reduce solar radiation penetrating the indoor space in this instance. Thus, it is recommended to use Glass 1 rather than Glass 2, particularly in the north classroom, to reduce the glazing cost. On the other hand, it is recommended to use Double-glazed clear low-E glass with a thickness of 6/12/6 *mm* in the other orientation to minimise direct solar heat gain and consequently reduce indoor temperature, especially in hot, id climates [21,31]. The results highlight the substantial influence of glazing type on solar heat gain and indoor temperature distribution across orientations. The low-E double-glazed unit (Glass 3) achieved the highest temperature reduction because of its low SHGC (0.56), which minimises infrared transmission while maintaining adequate daylight. This finding aligns with previous studies in hot-arid climates [19,31], which demonstrated that using double glazing with low-emissivity coatings or aerogel infill can lower peak indoor temperatures by up to 2–3°C and enhance daylight performance compared to single glazing. The marginal difference between Glass 1 and Glass 2 confirms that, beyond a specific cavity thickness, additional air space has diminishing thermal benefit under natural ventilation conditions—an outcome also observed in studies such as Influence of Glazing Material Selection and Cavity Thickness of Double Skin Facade on the Thermal Performance of Hotel Guestrooms in Malaysia [32]. Therefore, the combination of orientation-specific glazing selection and low-E technology presents an efficient and cost-effective retrofit strategy for Omani schools, striking a balance between visual comfort, heat control, and construction feasibility.



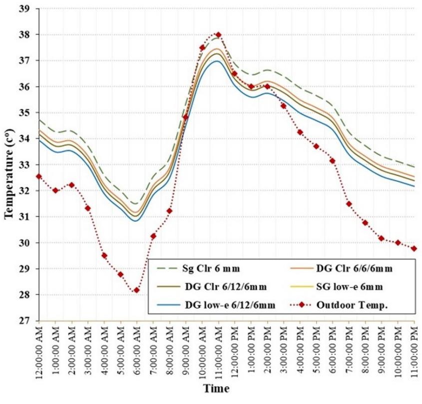
(a) North



(b) East

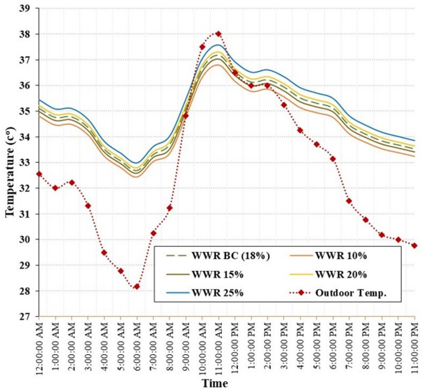


(c) South

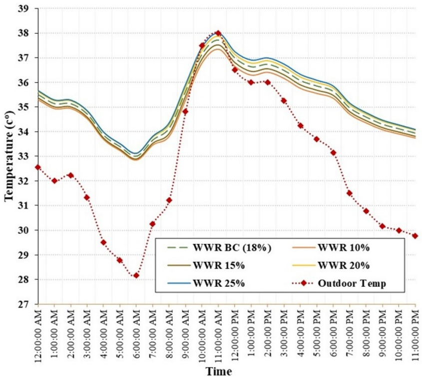


(d) West

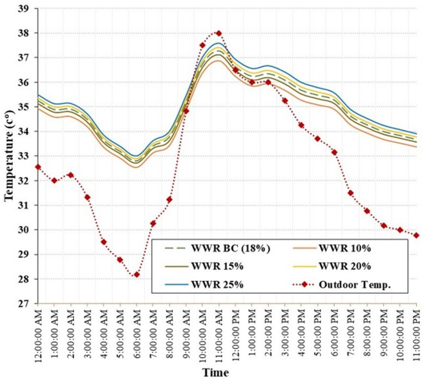
Figure 10. Effect of glazing type modification on the indoor temperature in the North, East, South, and West classrooms.



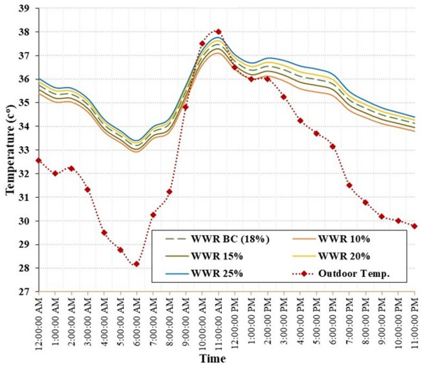
(a) North



(b) East



(c) South



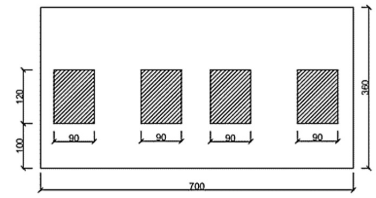
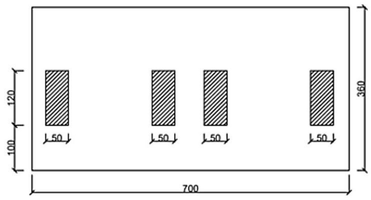
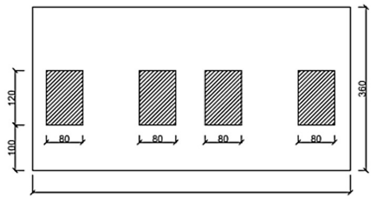
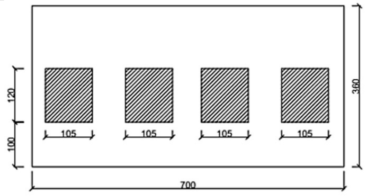
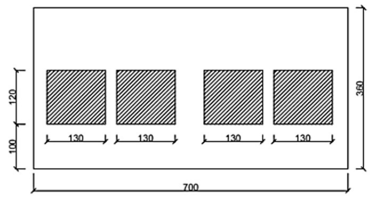
(d) West

Figure 11**.** Effect of WWR modification on the indoor temperature in the North, East, South, and West classrooms.

3.3.4 Window-to-wall ratio modification

Properly selecting window areas is crucial in classrooms to reduce heat gain through windows and, consequently, lower indoor temperatures. Window-to-wall ratio alternatives, ranging from 10% to 25% (four types), are illustrated in Table 6. According to the Advanced Energy Design Guide for K-12 School Buildings, WWR should not exceed 30% of the school's overall exterior gross wall area [33]. Table 8 shows the summary of the tested WWR results.

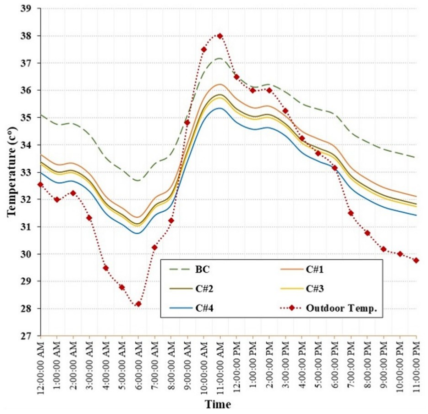
Table 8**.** Alternatives of window area (WWR).

WWR	Layout
18% (Base case)	
10%	
15%	
20%	
25%	

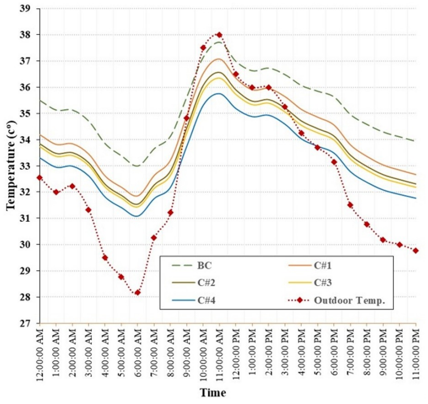
The results show no significant differences in modifying the WWR to reduce the indoor temperature. The charts indicate that a nearly consistent temperature was recorded on all orientations throughout the simulation period, even when there was a considerable change in outdoor temperature, especially at night, when lower temperatures are typically expected. This is due to the slow heat loss from the interior to the exterior after building operation hours when openings and fenestrations are shut; hence, the temperature profile remains the same or increases due to dense air movement and poor infiltration of fresh air, which cools the indoor space. The simulated indoor air temperature was above 32°C, averaging about 34°C. These values are higher than recommended for a conducive environment [33]. It can thus be inferred that WWR, or its modification, has a minimal effect on improving indoor air temperature through the building envelope. Figure 11 illustrates the simulation findings of the classroom with various orientations, revealing that for all orientations, the annual number of hours below the maximum thermal comfort temperature was recorded when the WWR was 15%, followed by 10% and 18%, while the annual number of hours within thermal comfort decreased as the WWR was increased to 25%. The analysis was conducted to observe the relationship between the WWR and room orientations. It was noted that the change in WWR does not provide a significant improvement related to the annual number of hours within thermal comfort. However, reducing the WWR to less than 18% will increase the annual number of hours within the thermal comfort zone. This will minimise the admitted daylight to the classroom and limit the outside view and connection with the outdoor environment, which is essential in classrooms. The negligible influence of WWR variation on indoor air temperature suggests that opaque and roof components predominate the thermal behaviour of the studied school buildings. The high internal heat storage and low ventilation rates in heavy concrete structures prevent rapid cooling at night, making glazing area adjustments less impactful than improvements to insulation or shading. This finding aligns with verified glazing studies in hot-dry climates [19, 31], which show that advanced double-glazing systems (including aerogel and low-E options) can noticeably reduce window heat gains and lower peak indoor temperatures by roughly 2–3°C while maintaining or improving daylight performance. The results suggest that optimal design requires balancing solar control with daylight quality rather than further minimising WWR. In the Omani context, maintaining a WWR between 15–20% coupled with high-performance glazing and shading devices can provide thermal comfort improvements without compromising natural light—a critical factor in learning environments.

3.4 Impact of the Combination of Envelope Design Parameters on Indoor Air Temperature

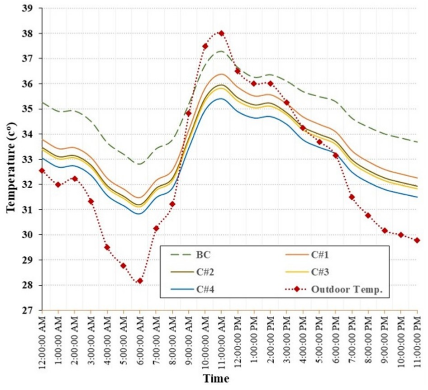
This section examines the effect of various envelope design options, including wall, roof, glazing type, and WWR modification, on indoor temperature. This section assesses the impact of combined envelope modification alternatives and passive methods on indoor temperature. According to a sensitivity analysis, the WWR has a negligible effect on indoor temperature. Consequently, a WWR of 0.2 is employed as the base case. The four envelope designs illustrated in Table 9 are used for comparison. The results of the performance on four orientations are presented in Fig. 12. A comparison was conducted during the summer period to examine the effect of various combination design alternatives on indoor air temperature. The internal air temperatures were reduced, but they did not reach the range of thermal comfort conditions during the summer. It is a result of the harsh summertime weather outside. These findings align with a study by Khoukhi and Fezzioui [11], who stated that cooling systems are the only way to guarantee thermal comfort in the summer. This suggests that relying solely on the building envelope characteristics and construction may not be sufficient to provide a thermally conducive indoor environment. Incorporating efficient active strategies to cool buildings could be necessary to achieve the desired comfort levels in these regions. The analysis reveals noticeable differences in the designs. The indoor air temperature of all designs was lower than that of the base case classroom, indicating that the current and conventional building envelopes designed are not thermally suitable for indoor comfort, as supported by the case study findings and analysis. The average difference during this period was approximately 1.9 °C to 2.3 °C. On the other hand, there were lower temperatures from 6:00 pm to 6:00 am and from 3:00 pm to 5:00 am, with an average difference of 1.3°C to 1.9°C. Figure 12 illustrates the impact of changes to the combination of envelope design elements on the indoor temperature in a typical classroom. The results show a significant reduction using the C#4 design alternative, with approximately 2°C, followed by C#3. This aligns with the results and findings of the earlier-discussed independent simulations of the building envelope components. This particular alternative (C#4) ensures a significant improvement in the thermal conditions of the indoor space, although it is not conducive to thermal comfort according to available metrics. Combining these envelope components with other cooling measures could be more effective in remarkably reducing the indoor air temperature in the classrooms. The combined-envelope simulations confirm that integrating multiple passive measures provides additive, though limited, thermal benefits under Muscat's extreme climate. The modest reduction of 1.9–2.3°C demonstrates that even optimised opaque and transparent assemblies cannot fully offset high solar gains and ambient temperatures exceeding 40°C. Similar results were reported by Elnabawi et al. [18] and Al-Tamimi et al. [25], who found that combining improved insulation, low-emissivity glazing, and reflective roof treatments effectively reduced indoor air temperatures by approximately 2–3°C and decreased cooling energy demand in buildings located in hot-arid regions. However, both studies highlighted that under extreme summer conditions, these passive measures alone were insufficient to achieve full thermal comfort, and hybrid strategies such as night ventilation or evaporative cooling remained necessary. The findings underscore the need for an integrated passive-active approach, where enhanced envelopes reduce peak cooling loads while mechanical systems maintain comfort efficiently. For Omani schools, adopting design C#4 or C#3 with supplemental low-energy cooling technologies could achieve sustainable thermal comfort and lower operational energy demand.



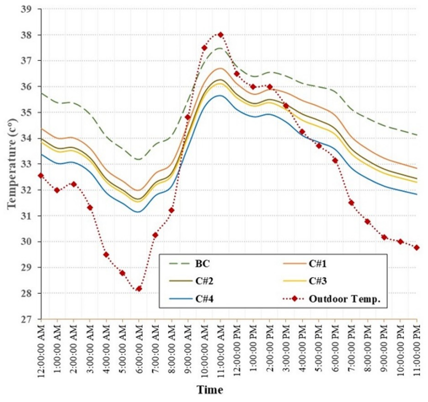
(a) North



(b) East



(c) South



(d) West

Figure 12**.** Effect of the combination of envelope design parameters on the indoor temperature in the North, East, South, and West classrooms.

Table 9. Alternatives of combined building envelope parameters for thermal simulation.

Combination	External Wall	Roof	Glazing Type	WWR
BC	200 *mm* CMU Block + No insulation + 15 *mm* Cement plaster on both sides	15 *mm* Cement plaster + 200 *mm* Reinforced Concrete Slab + Water proofing + 100 *mm* Sloping Screed+ Level Screed 30 *mm* + Terrazzo Tiles 300 × 300 × 30 *mm*	Single-glazed clear 6 *mm*	18%
C#1	200 *mm* Hollow CMU Block + 50 *mm* Expanded Polystyrene + 15 *mm* Cement plaster on both sides	15 *mm* Cement plaster + 200 *mm* Reinforced Concrete Slab + 44 Expanded Polystyrene + Waterproofing + 100 *mm* Sloping Screed + Level Screed 30 *mm* + Terrazzo Tiles 300 × 300 × 30 *mm*	Single clear Low-E 6 *mm*	25%
C#2	200 *mm* Hollow CMU Block + 50 *mm* Extruded Polystyrene + 15 *mm* Cement plaster on both sides	15 *mm* Cement plaster + 200 *mm* Reinforced Concrete Slab + 50 *mm* Extruded Polystyrene + Waterproofing + 100 *mm* Sloping Screed + Level Screed 30 *mm* + Terrazzo Tiles 300 × 300 × 30 *mm*	Double-glazed clear 6/6/6 *mm*	20%
C#3	200 *mm* Hollow CMU Block + 50 *mm* Polyurethane + 15 *mm* Cement plaster on both sides	15 *mm* Cement plaster + 200 *mm* Reinforced Concrete Slab + 50 *mm* Polyurethane Board + Waterproofing + 100 *mm* Sloping Screed+ Level Screed 30 *mm* + Terrazzo Tiles 300 × 300 × 30 *mm*	Double-glazed clear 6/12/6 *mm*	20%
C#4	200 *mm* Hollow CMU Block + 100 *mm* Extruded Polystyrene + 15 *mm* Cement plaster on both sides	15 *mm* Cement plaster + 200 *mm* Reinforced Concrete Slab + 100 *mm* Expanded Polystyrene + Waterproofing + 100 *mm* Sloping Screed+ Level Screed 30 *mm* + Terrazzo Tiles 300 × 300 × 30 *mm*	Double-glazed clear low-E 6/12/6 *mm*	20%

While the general influence of wall, roof, and glazing insulation on indoor temperature has been established in previous studies, this research provides new empirical evidence specific to typical Omani school buildings. The novelty of the findings lies in quantifying how each envelope component and its combinations perform under Muscat's extreme climatic conditions using field-calibrated simulations. This local validation is crucial, as the construction typologies, material availability, and school operation patterns in Oman differ from those examined in other hot-arid regions. Therefore, the results contribute practical, region-specific guidance for improving thermal performance in government educational buildings.

4. Discussion

This study examined the impact of various building envelope elements to identify optimal approaches for creating thermally conducive learning environments in Muscat's hot-arid climate. Instead of restating numerical results, this discussion focuses on interpreting the relationships between envelope design modifications and indoor temperature behaviour. In the context of this research, passive strategies refer to design-based, non-mechanical approaches that reduce indoor heat gain or enhance heat dissipation without relying on active cooling systems. These include optimising wall and roof insulation, glazing type, shading, and orientation—measures that passively regulate indoor temperature by controlling solar radiation and thermal transmission. The building-envelope modifications tested in this study, therefore, represent key passive techniques for improving thermal comfort and reducing cooling demand in Omani schools. The findings confirm that inadequate thermal resistance in conventional school envelopes significantly contributes to indoor overheating, particularly during the summer. High U-values in typical concrete block walls and roofs allow continuous solar heat gain, which passive insulation layers can effectively mitigate. The results indicate that integrating insulation in both walls and roofs can reduce indoor temperatures by up to 2°C, though this alone does not achieve full comfort under extreme outdoor conditions. These observations are consistent with findings by Elnabawi et al. [18] and Al-Tamimi et al. [25], who reported indoor temperature reductions of approximately 1.5–3°C through similar passive insulation and envelope-retrofitting measures in school buildings located in hot-arid Gulf climates. However, the current study extends this evidence to the Omani context by employing field-calibrated simulations, demonstrating that local construction typologies and material combinations significantly influence overall thermal performance. Furthermore, while glazing improvements produced additional benefits—particularly for east and west orientations—adjustments to the window-to-wall ratio (WWR) showed minimal effect, aligning with the findings of Alwetaishi and Benjeddou [34] who observed diminishing thermal returns and daylight losses when WWRs were reduced below 20% in arid-region school buildings. The inclusion of passive strategies in this study underlines their potential to reduce peak cooling loads even when complete thermal comfort cannot be achieved naturally. This balance between improved envelope performance and mechanical cooling efficiency aligns with hybrid comfort approaches discussed by Elnabawi et al. [18] and Xue et al. [35], which integrate passive envelope enhancements with low-energy or evaporative cooling systems to achieve optimal performance in hot-arid regions. Although air temperature was used as a proxy for indoor comfort, the relative changes observed across scenarios provide valuable insight into the thermal moderation potential of different envelope configurations. These results collectively highlight that passive envelope interventions—especially those combining high-performance roof and wall insulation with selective glazing—offer the most practical pathway to enhance indoor comfort and energy efficiency in Omani educational buildings. By comparing the results with earlier regional studies, this research contributes locally validated, quantitative evidence that can guide the refinement of national school design standards and passive retrofitting practices. The demonstrated reduction in indoor overheating using accessible materials confirms the practical applicability of passive design solutions in Oman's construction sector.

5. Conclusion

This study assessed the thermal characteristics of the school envelope and identified the most suitable approaches to designing envelope elements to reduce indoor air temperature in Muscat, Oman, ensuring a better environment for school users and minimising energy use. The findings confirmed that conventional school buildings in Muscat experience indoor temperatures of around 24.5°C in winter and 33°C in summer, indicating that adequate thermal protection is essential throughout the year to maintain comfort. Comparing the field measurements with DesignBuilder simulation results showed good agreement, with differences of less than 2°C between measured and simulated data, validating the reliability of the simulation model. The study demonstrated that improving thermal resistance through enhanced wall and roof insulation significantly reduces indoor temperature peaks, confirming the effectiveness of passive envelope design strategies in hot-arid climates. The use of extruded polystyrene insulation, in particular, proved to be one of the most efficient and locally feasible solutions. These findings provide new, locally validated evidence for the performance of passive envelope systems in Omani school buildings, a topic that has not been previously quantified using field-calibrated data. According to the outcomes obtained from field investigations and simulations combining alternative designs, it was inferred that design envelope C#4 achieved the best overall performance and should be prioritised in Omani schools to reduce indoor air temperature and improve thermal comfort. The recommended envelope design specifications are as follows:

- The exterior wall should consist of a 200 *mm* Hollow CMU block, 100 *mm* extruded polystyrene, and 15 *mm* Cement plaster on both sides.
- The roof should consist of a 15 *mm* Cement plaster, a 200 *mm* Reinforced Concrete Slab, 100 *mm* Expanded Polystyrene, Waterproofing, a 100 *mm* Sloping Screed, a 30 *mm* level screed, and Terrazzo Tiles measuring 300×300×30 *mm*.
- Use Double-glazed, clear low-E 6/12/6 *mm* glazing for windows.
- Consider a Window-to-Wall Ratio (WWR) of 20%.

The novelty of this study lies in its integration of real on-site temperature data with parametric simulation to generate evidence-based, region-specific guidance for school envelope design in Oman. This approach expands upon existing global research by demonstrating how local materials and construction typologies perform under extreme arid conditions, providing practical insights for passive retrofitting in similar contexts. Although the intended goals of this study have been achieved, various topics still require further investigation to advance the understanding of school envelope design in Oman's climate. The study is subject to certain limitations, including the use of air temperature as the primary comfort indicator and the short monitoring period (10 days) in a single unoccupied school building. While this approach enabled accurate evaluation of envelope thermal behaviour without internal heat gains, it may not fully capture the influence of occupancy, architectural variability, or long-term seasonal effects. Future research should therefore include multiple schools across diverse climatic zones in Oman, incorporate occupied conditions, and extend the monitoring period over a longer time frame. Additionally, integrating full thermal comfort indices (PMV/PPD), evaluating shading devices, and conducting cost–benefit analyses would enhance the understanding of passive–active design integration and its implications for national school building standards.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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