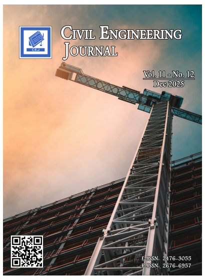
Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 12, December, 2025



Improving Thermal Comfort and Air Quality: PET and CO_2 Evaluation of School Courtyard's Orientation

Muna Salameh [1*], Basim Touqan [2]

[1] Department of Architecture, College of Architecture, Art and Design, Ajman University, Ajman 00971, United Arab Emirates.

[2] Department of Engineering, Faculty of Engineering and IT, British University in Dubai, Dubai 999041, United Arab Emirates.

Received 27 September 2025; Revised 24 November 2025; Accepted 28 November 2025; Published 01 December 2025

Abstract

This study aims to investigate the thermal conditions related to the variations in the school courtyard's orientation, focusing on mass temperature (Tm), outdoor air temperature, and Physiological Equivalent Temperature (PET). A qualitative methodology based on ENVI-met software was adopted. Simulations for the existing school building were performed in the four basic orientations on 21 March and 21 September to assess the thermal impact of the courtyard's orientations. Results showed that orientation produced slight but meaningful differences in Tm, with variations of 0.16°C in September and 0.20°C in March. Though modest, these differences become significant when scaled to the large mass of the school buildings, where even small reductions affect energy demand and comfort. For outdoor air temperature, the south orientation achieved reductions of 0.53–1.13°C in September and 1.1–1.9°C in March compared to ambient conditions. PET and wind maps supported these findings, with the south orientation allowing better airflow and better thermal comfort. Furthermore, analysis of CO_2 concentration confirmed that the south-facing courtyard provided the healthiest air quality. The study highlights that courtyard orientation should not be overlooked in large educational buildings, as even slight orientation-driven improvements become critical, reinforcing the importance of integrating orientation into holistic passive design strategies.

Keywords: Building Orientation; Thermal Comfort; PET; Courtyards; UAE Schools; Passive Design; ENVI-Met; CO_2 Concentration.

1. Introduction

Educational buildings in hot-arid regions face major challenges in maintaining thermal comfort while minimizing energy consumption. Schools, in particular, require special attention because of their large masses, high occupancy, and specific operational schedules. Even slight differences in building mass temperature or outdoor microclimate can scale into significant impacts when applied to such large institutional forms. Therefore, evaluating orientation and courtyard design is essential for developing sustainable strategies that improve comfort and reduce cooling loads [1].

1.1. Schools and Energy Consumption

Educational facilities, and schools in particular, use high amounts of energy to maintain comfortable thermal conditions essential for student learning. In the UAE's hot arid climate, schools typically consume over 100 kWh/m² annually, presenting a significant energy challenge largely driven by solar heat gain and cooling demands [2]. Despite their limited hours of operation, schools offer notable opportunities for energy savings—with some strategies achieving reductions of up to 25% [3]. Therefore, incorporating energy efficiency from the design phase is critical, as both school

* Corresponding author: m.salameh@ajman.ac.ae

http://dx.doi.org/10.28991/CEJ-2025-011-12-023

design and student behavior substantially influence energy use. Passive design features—such as solar orientation, courtyard design, and solar energy integration—can enhance thermal comfort and promote more sustainable learning environments [4-6].

In recent years, a growing body of research has explored sustainable strategies for improving energy performance and thermal comfort in school buildings. While orientation is a critical factor, many of these investigations prioritized other passive design elements or environmental concerns (Table 1). For instance, Al-Khatatbeh & Ma'bdeh (2017) [7] examined how modifying building materials could enhance lighting and thermal quality in UAE schools. Abanomi & Jones (2005) [8] studied passive cooling techniques in Saudi classrooms—such as shading devices, night ventilation, and occupancy control—to mitigate excessive heat gain. In Iran, Zomorodian & Nasrollahi (2013) [9] emphasized the importance of spatial layout, shading design, and window-to-wall ratios as part of holistic sustainable school planning. Similarly, Harputlugil et al. (2011) [10] in Turkey proposed cluster-based school designs tailored to different climatic regions. Gil-Báez et al. (2019) [11] investigated passive retrofitting strategies, including advanced glazing and insulation, for Mediterranean schools. Other scholars focused on region-specific needs: Hong et al. (2012) [12] developed a predictive model to manage seasonal energy loads in South Korea; Ramli et al. (2012) [13] assessed lighting and air quality under Malaysia's Green School Guidelines; Matsuoka & Kaplan (2008) [14] highlighted the role of landscaping for comfort and aesthetics in U.S. schools; and El-Nwsany et al. (2019) [15] explored sustainable water use strategies in Egyptian educational facilities. Heracleous et al. (2021) [16] evaluated solar shading in Cyprus, while Salameh et al. (2024) [17] showed how courtyard designs in the UAE can enhance learning environments. Despite the richness of this literature, limited attention has been given to examining building orientation as a primary variable in large-scale educational facilities. This gap highlights the need for targeted studies focusing on how orientation interacts with thermal, visual, and environmental comfort metrics in school design.

Table 1. Summary of some prior studies examining various strategies to improve energy efficiency in school buildings (excluding building orientation)

Main Focus for the research	Reference
Optimizing building materials for lighting and thermal comfort in schools (UAE)	[7]
Applying heat gain reduction strategies: shading, ventilation, and occupancy control (Saudi Arabia)	[8]
Architectural adjustments for sustainability: window ratios, shading, and orientation (Iran)	[9]
Cluster school design for climate adaptability and energy control (Turkey)	[10]
Passive refurbishment strategies in diverse Mediterranean school climates	[11]
Decision-support model for energy-efficient school design (South Korea)	[12]
Green School Guidelines impact on lighting and indoor air quality (Malaysia)	[13]
Role of landscaping for thermal comfort and aesthetics in schoolyards (USA)	[14]
Water management strategies for sustainable school environments (Egypt)	[15]
Solar shading systems to manage cooling loads in school buildings (Cyprus)	[16]
Courtyard-based school design to improve student satisfaction and performance (UAE)	[17]

1.2. Courtyard Orientation as a Passive Design Strategy

In architectural design, orientation refers to the intentional placement of buildings to leverage climatic factors—such as sun paths and prevailing winds—to improve energy performance and occupant comfort. In hot climates like the UAE, orientation plays a pivotal role in reducing solar gain and enabling natural ventilation [18, 19]. Research confirms that orientation significantly impacts microclimatic conditions by regulating solar exposure and heat reflection [20], for example, in Jeddah, orientation substantially affects ambient temperature and humidity [21].

Courtyards—rooted in cultural and environmental contexts—serve as effective passive design components that enhance thermal comfort while lowering energy consumption [22, 23]. They are especially important in hot regions [15], such as Dubai, where courtyards consistently prove cooler than outdoor spaces [24]. As passive buffers, they also shield against dust and wind; their performance depends on their proportional relationship to surrounding structures, aspect ratio, and internal activities. Numerous studies affirm their effectiveness as thermal strategies in warm climates [25, 26].

Few studies underscore the significance of courtyard orientation within educational environments, MODI, (2022) [27] emphasized the role of size, layout, and orientation in enhancing courtyard thermal efficiency in humid regions; Diz-Mellado et al. (2021) [28] showed that adaptive cooling strategies substantially lower courtyard temperatures during heat waves. Li, et al. (2022) [29] demonstrated that optimizing courtyard morphology improves operative temperatures and reduces energy consumption. While Markus, et al. (2017) [30] noted creative courtyard use in university buildings, its thermal performance often remains unquantified. Mundra & Kannamma (2019) [31] proposed design guidelines for courtyard optimization. In the UAE context, Salameh et al. (2024) [17] confirmed that courtyard orientation and configuration significantly enhance thermal comfort in semi-open school designs. Moreover, newly published research by Salameh & Touqan (2024) [32] investigates the microclimatic and energy performance of school courtyards in the UAE. North-facing courtyards consistently achieve lower mean temperatures (up to 1.9 °C cooler) and reduce cooling loads by 1–4%, particularly on equinox dates (21 September, 21 March).

Other studies have confirmed that buildings courtyards orientation – not schools- play a significant role in pollutant dispersion and air renewal. For instance, Sun et al. (2024) [33] demonstrated that courtyard buildings misaligned with prevailing wind directions may suffer from pollutant cross-transmission due to insufficient air exchange; in one scenario, CO_2 concentrations in adjacent rooms increased from baseline levels to as high as 3,211 ppm under a wind speed of 4.51 m/s. In a complementary direction, optimization studies of courtyard ventilation emphasize that aligning courtyard openings or axes with the prevailing wind significantly enhances pollutant flushing and cross-ventilation effectiveness (e.g., studies on courtyard geometry and windward opening optimization) [34]. These findings accord with earlier wind tunnel and experimental work on courtyard and atrium airflow, which show that the angle of incidence of wind relative to facades (e.g. perpendicular vs. oblique) affects pressure differentials and internal circulation patterns [35]. Moreover, the stack (or buoyancy) effect and courtyard aspect ratio further modulate the vertical and horizontal movement of warm air and entrained pollutants, strengthening natural vertical exchange when designed appropriately.

Finally, many research has extensively explored the role of orientation in shaping microclimatic conditions and thermal comfort within architectural spaces in general and not schools as in Table 2. Balah et al. (2024) [36] explored the thermal dynamics of glazed courtyard envelopes in educational buildings, revealing that certain configurations can significantly reduce heating duration (from 17 h to 2 h) and modulate cooling effects depending on courtyard aspect ratio and glazing. Martinelli & Matzarakis (2017) [37] demonstrated that courtyard orientation significantly affects solar exposure and shadow duration, largely mediated by the sky view factor (SVF), which in turn influences thermal comfort levels. Forouzandeh (2018) [38] highlighted that internal courtyard air temperatures tend to be lower than adjacent outdoor spaces, with this variation closely tied to orientation. In the context of arid climates, such as Jeddah, Saudi Arabia, Hegazy & Qurnfulah (2020) [39] found that both air temperature and humidity are sensitive to building orientation. Verma & Bano (2023) [40] observed that courtyard buildings oriented along the north-south axis and possessing considerable vertical height exhibited superior thermal comfort and daylight penetration into adjacent rooms. Similarly, Sun et al. (2023) [23] identified orientation and courtyard size as the most critical design parameters for achieving optimal thermal conditions. Dervishi & Baçi (2023) [41] stressed the importance of carefully considering orientation, aperture design, and exposure to climatic elements when aiming for enhanced environmental performance.

Table 2. Previous Studies Investigating the Impact of Building Orientation on Microclimate and Thermal Conditions in Non-Educational Buildings

Previous Studies Investigating the Impact of Building Orientation	Reference
Courtyard orientation shapes sun path exposure and shading duration, which directly influences thermal comfort.	[37]
Air temperature inside courtyards generally registers lower than outdoor levels depending on directional layout.	[38]
In hot arid zones, orientation plays a role in altering indoor thermal and humidity profiles.	[39]
North–south facing courtyard homes with taller volumes enhance indoor daylighting and thermal balance.	[40]
Design parameters like orientation and courtyard size are critical to outdoor thermal conditions.	[23]
Architectural planning must address directionality, exposure to wind, and natural elements for comfort.	[41]

1.3. Research Gap and Structure

While numerous studies have examined the energy performance of school buildings and explored various passive design strategies, limited attention has been directed toward understanding the influence of building orientation on the environmental behavior of large-scale educational facilities in hot arid regions like the UAE. Many investigations into courtyard performance have emphasized parameters such as proportions, sky view factor (SVF), shading configurations, or landscape integration, but not orientation itself. Furthermore, studies that have addressed orientation often focused on residential settings or smaller-scale public buildings, rather than expansive institutional typologies such as schools which typically possess expansive courtyards and accommodate high occupant loads. Thus, the intersection between courtyard orientation and its microclimatic and energy implications in school buildings—particularly under hot arid conditions like those in the UAE—remains underexplored deeply, mainly with current school design guidelines that tend to prioritize spatial standards for classrooms and playgrounds while placing limited emphasis on the role of orientation in environmental performance. This leaves a clear gap in the literature concerning how courtyard orientation specifically influences thermal comfort, air quality, and energy indicators at the scale of UAE school campuses which typically possess expansive courtyards and accommodate high occupant loads. To fill this gap, the current study evaluates four different courtyard orientations using high-resolution ENVI-met simulations, aiming to quantify their effects on microclimate variables including mass temperature (Tm), outdoor air temperature, PET, and CO_2 concentrations.

2. Materials and Method

The theoretical approach in this research was grounded in principles of bioclimatic and passive design theory, which emphasize the role of building orientation and architectural form in mediating microclimatic conditions and energy performance. In hot arid climates such as the UAE, thermal comfort is closely tied to solar exposure, air movement, and shading—factors influenced by courtyard orientation and design configuration. The study also draws on thermal comfort theory, particularly the use of the Physiological Equivalent Temperature (PET) index, which integrates multiple environmental variables to assess outdoor comfort levels. Additionally, the mass temperature (Tm) and CO_2 concentration are used as proxies for internal heat accumulation and air quality, aligning with established sustainable building performance metrics. By focusing on these indicators, the study builds upon existing literature while addressing a notable gap: the lack of systematic exploration of courtyard orientation in large school buildings under extreme climatic conditions.

Based the theoretical Approach**,** the methods in this research was carefully structured to investigate how variations in courtyard orientation influence the microclimate and building temperature of public schools in the UAE (Figure 1). Using a combination of field observations, advanced environmental simulations, and qualitative analyses, the study aimed to determine the extent to which courtyard design affects environmental conditions and energy demand in educational facilities.

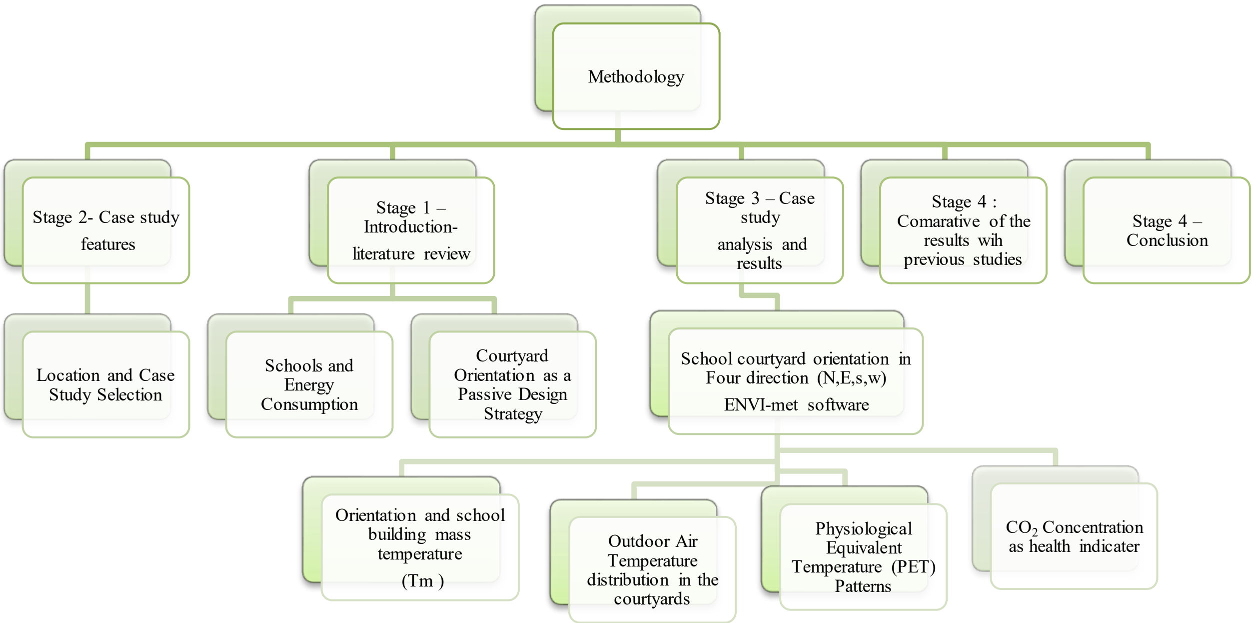


Figure 1. Methodology outline

2.1. Location and Case Study Selection

The study was carried out on an existing modern school building situated within the UAE's hot, humid climate zone in Ajman – Al Goaz district (Figure 2). Characterized by high summer temperatures—peaking at an average maximum of 41 °C in August—and influenced by prevailing north-westerly winds, the region presents unique climatic challenges for building design. The selected case study, referred to as the 586 School model as in Figure 3, represents one of the most widespread publicschool designs in the UAE, with over 70 schools constructed following the same architectural layout but oriented differently. This design approach, introduced by the Ministry of Public Works in 1989, has influenced numerous educational institutions, including examples such as Al Mualla Secondary Female School. The layout is organized around a large central closed courtyard, complemented by two smaller courtyards primarily intended for daylight provision. The schools are typically two-floors structures containing 18 or 24 classrooms, equipped with modern service facilities and a theatre. The design features a reflective symmetry in the arrangement of the courtyards, integrating a variety of educational and recreational spaces. The total courtyard area is 4,779 m², which represents approximately 49 % of the plot. This distribution highlights the design emphasis placed on outdoor spaces (Table 3).

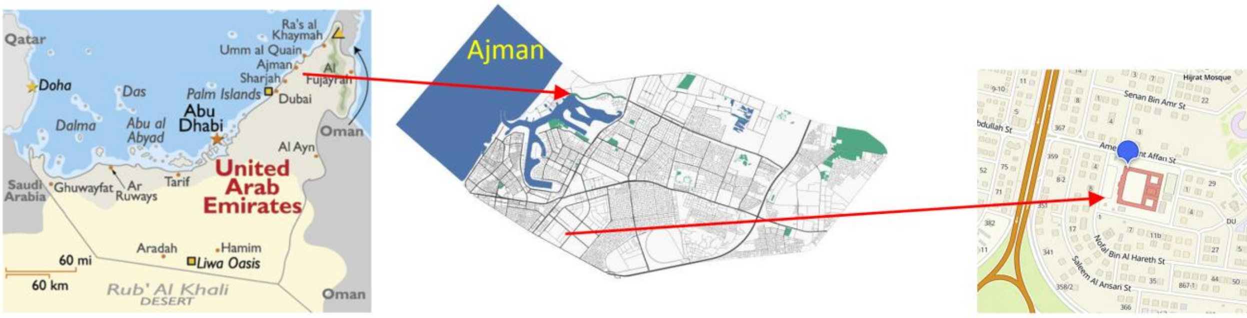


Figure 2. Location of the case study [42, 43]

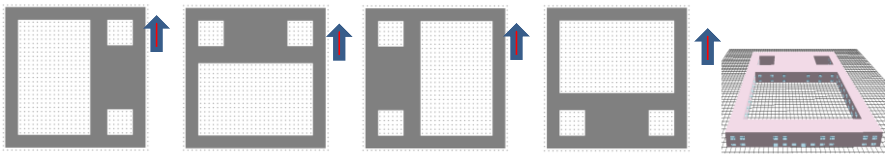
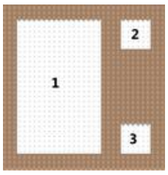


Figure 3. The existence case study school – in the four orientations

Table 3. The existence case study general design characteristics

School name	No. of outdoor spaces	Type of outdoor space	Area of outdoor space	Courtyards area	Built-up area	Courtyards / plot area
Plot Area: 9.801 m² 	Court 1	Closed	4,131 m²	4,779 m²	5,022 m²	0.49
	Court 2	Closed	324 m²			
	Court 3	Closed	324 m²			

Thermal simulations were focused on two key dates—21 September and 21 March—chosen because recorded conditions exceeded the 20–27 °C comfort threshold identified by Li et al. (2022) [29]), in line with Wah & Lot (2017) [30], and Salameh (2024) [1] who emphasized on enhancing school microclimates to achieve cooling benefits.

It was noticed that in reality this school model was built in different orientations – across UAE - with same materials and design as in Figure 4, which encourage the authors to investigate the effect of the orientation on the thermal conditions of the school.

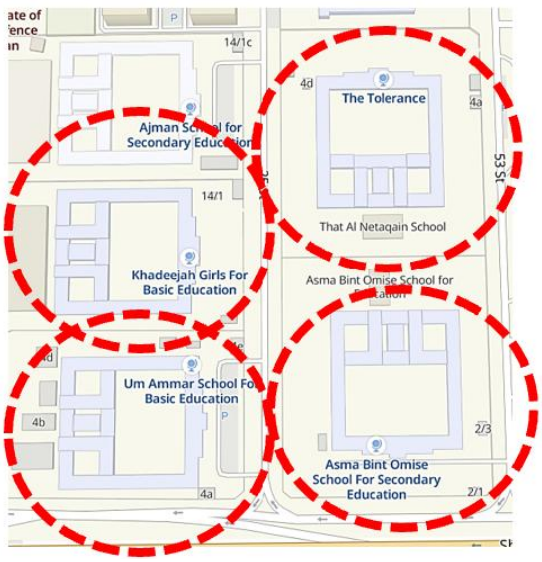


Figure 4. Examples of existing models of the case study buildings with different orientations [44]

2.2. Simulation Dates

In this study, the simulation dates were selected to align with solstice and equinox days that occur during the school year when ambient temperatures exceed the 27°C comfort threshold in schools. According to Khalfan & Sharples (2016) [45] as well as Salameh et al. (2024) [17], a temperature range of 20–27°C constitutes the comfort zone, based on Schnieders' thermal comfort chart. As courtyards are semi-enclosed spaces intended for various outdoor student activities, they should ideally provide comfortable conditions within this thermal range.

Thus, the dates chosen for analysis were those when outside temperatures rose above the comfort zone: specifically, September 21 (reaching a maximum of about 39°C) and March 21 (with a minimum of roughly 28°C), as shown in Figure 5. These two days represent the highest and lowest school-day temperatures above the comfort level, and the courtyards in the case study are evaluated under these extreme conditions. Focusing on these dates is crucial, as a major challenge in hot arid regions like Dubai is minimizing energy consumption for cooling [46]. Consequently, days on which temperatures remained at or below the comfort threshold were omitted from the evaluation.

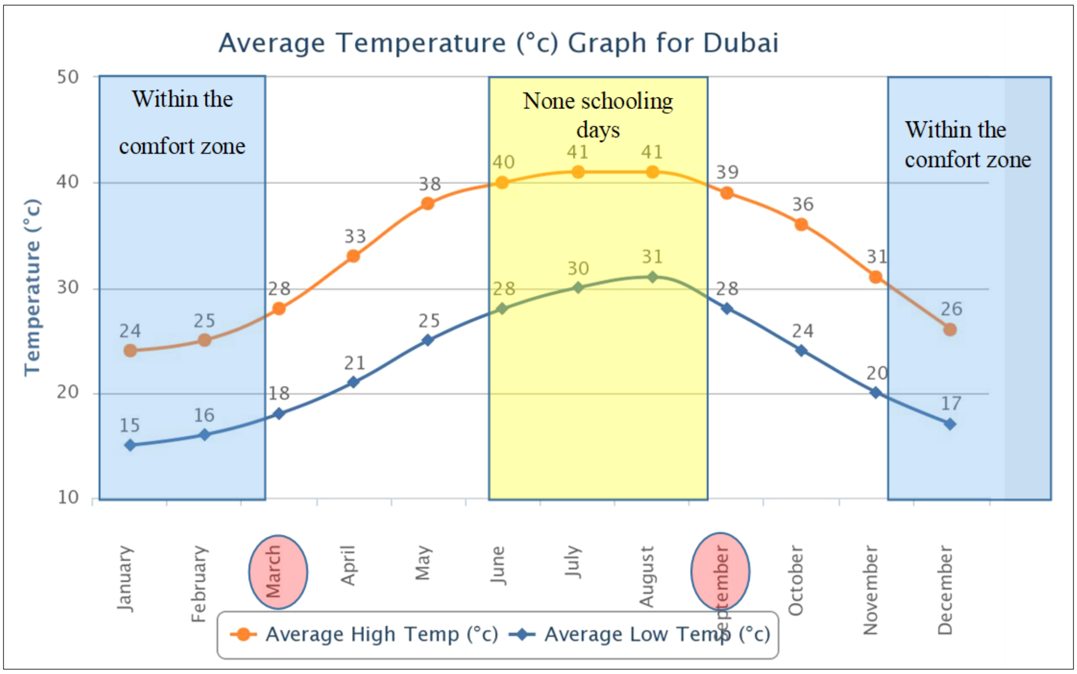


Figure 5. Simulation dates [17]

2.3. ENVI-met Software as a Simulation Tool

ENVI-met software was employed to assess the thermal impact of courtyard orientation. Recognized for its advanced capability in modelling complex interactions of solar radiation, wind patterns, and temperature distribution, ENVI-met has been widely applied in similar environmental studies. In their validation study, Salameh et al. (2024) [17] compared ENVI-met outputs with measured environmental data, producing a scatterplot analysis with an R^2 value of approximately 0.9. This strong correlation supports the software's reliability in predicting microclimatic conditions, despite some deviations due to limitations in simulating heat storage on building surfaces.

2.4. Simulation Criteria and Input Data

Simulations were designed to model the thermal behavior of the school building under different courtyard orientations on the two selected dates. The virtual model incorporated site-specific climatic inputs, including wind direction, wind speed, and humidity, to replicate realistic conditions. Climatic data were sourced from actual meteorological records to ensure accuracy.

The building model consists of two floors, each 4 m in height, with hollow block concrete construction for walls and slabs. Window-to-wall ratios were set at 20%, consistent with Al-Sallal (2010) [47] recommendations for optimal daylight and ventilation in schools.

To ensure simulation accuracy, the model domain was defined with a grid size of 3 × 3 × 2 m, covering a 60 × 60 × 20 grid. This resolution offered an effective balance between computational efficiency and capturing airflow and temperature variations within the courtyard, while maintaining adequate buffer zones to mitigate edge distortion. Meteorological boundary conditions were derived from the Dubai International Airport weather station and forced into the ENVI-met model, ensuring real-time relevance of air temperature, humidity, and wind direction inputs as in Table 4. The architectural and construction parameters—including material properties, glazing, and spatial layout—were held constant across scenarios to isolate the effect of courtyard orientation. To verify the model's reliability, simulated data were compared with field measurements taken on-site at selected courtyard points. The results demonstrated a strong correlation with observed data ($R^2 = 0.9$), affirming the robustness of the ENVI-met model and supporting the interpretation of microclimate outputs used in this study. Climatic conditions for each date included hourly variations in air temperature (°C) and relative humidity (%)—with September reaching up to 41.0 °C and March peaking at 29.0 °C during midday.

Table 4. Simulation data [17, 48]

The basic 3D model - data- established in ENVI-met	
Location and climate	Dubai-UAE – Hot arid climate
The main boundary model area:	x-Grids= 60, y-Grids=60, z-Grids=20
The cell size:	dx=3 m, dy =3 m, dz =2 m, this specific dimension was selected following multiple trials to optimize performance.
Wind Direction is	315 degrees from the North.
Wind speed is	3.5 m/s
Roughness Length z at Reference Point [m] is	0.01.
Specific Humidity is	7.0 g Water/kg air.
The simulation period	The simulation ran for a full day -24 hours-from midnight 20 September to midnight 21 September, repeated for 21 March.
Output interval main files The model produces a PET value, indicating the equivalent temperature felt under the specified conditions.	60 min • Body Parameters: - Age: 35 years - Weight: 75 kg - Height: 1.75 m - Gender: Male - Body Surface Area: 1.91 m² (using the DuBois formula) (A holistic microclimate model, 2024). • Clothing Parameters: - Outdoor static insulation: 0.90 clo - Indoor static insulation: 0.90 clo • Metabolism: - Total metabolic rate: 164.49 W (86.21 W/m²) - Metabolic rate (met): 1.48

Relative Humidity and Initial Temperature Atmosphere forced data					
Average air temperature (T) and relative humidity (RH) 21st Sep			**Average air temperature (T) and relative humidity (RH) 21st March**		
Time	**T °C**	**RH (%)**	**Time**	**T °C**	**RH (%)**
00:00	35.75	64.25	00:00	21.00	76.67
01:00	35.31	66.94	01:00	20.20	77.33
02:00	34.88	69.63	02:00	19.40	78.00
03:00	34.44	72.31	03:00	18.60	78.67
04:00	34.00	75.00	04:00	17.80	79.33
05:00	34.88	69.63	05:00	17.00	80.00
06:00	35.75	64.25	06:00	18.33	78.89
07:00	36.63	58.88	07:00	19.67	77.78
08:00	37.50	53.5	08:00	21.00	76.67
09:00	38.38	48.13	09:00	22.33	75.56
10:00	39.25	42.75	10:00	23.67	74.44
11:00	40.13	37.38	11:00	25.00	73.33
12:00	41.00	32.00	12:00	26.33	72.22
13:00	40.56	34.69	13:00	27.67	71.11
14:00	40.13	37.38	14:00	29.00	70.00
15:00	39.69	40.06	15:00	28.20	70.67
16:00	39.25	42.75	16:00	27.40	71.33
17:00	38.81	45.44	17:00	26.60	72.00
18:00	38.38	48.13	18:00	25.80	72.67
19:00	37.94	50.81	19:00	25.00	73.33
20:00	37.50	53.50	20:00	24.20	74.00
21:00	37.06	56.19	21:00	23.40	74.67
22:00	36.63	58.88	22:00	22.60	75.33
23:00	36.19	61.56	23:00	21.80	76.00

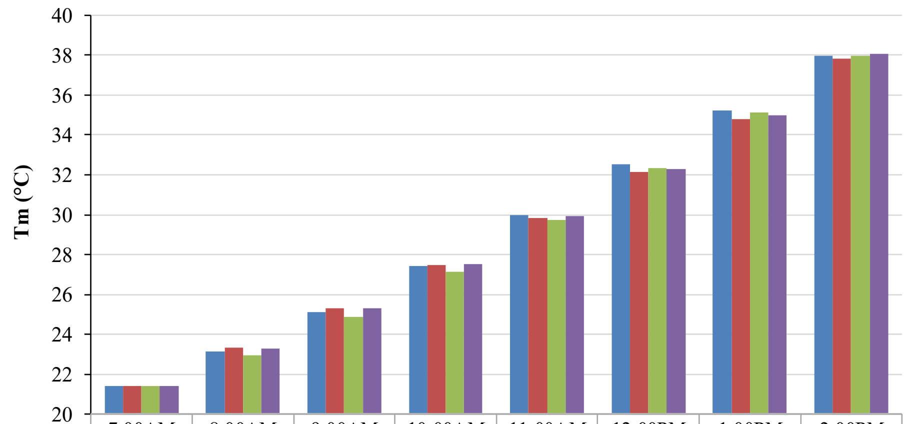
3. Results and Discussion

The school model was simulated in four different orientations while maintaining the original courtyard ratios and overall configuration of the base design. The findings indicated that the building's thermal performance varied with orientation, reflecting real-world conditions. Although in some cases the variations were minimal, even subtle differences could have tangible impacts. This was particularly evident in:

- The mass temperature of the school building (T_m)
- The distribution of outdoor air temperature in the courtyards
- The stands for Physiological Equivalent Temperature**.** **(**PET**)** patterns both around the school and within the courtyards, which were closely linked to variations in air temperature and wind flow distribution.
- The CO_2 concentration in the main courtyard at the break time for the students.

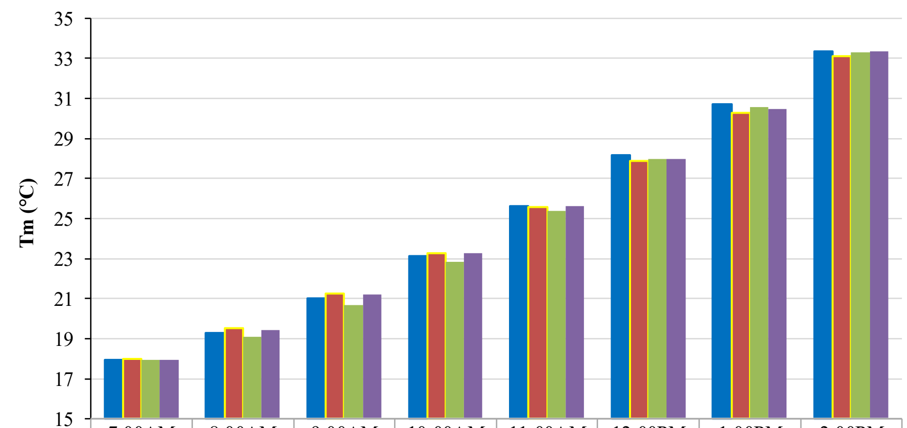
3.1. Orientation and School Building Mass Temperature (T_m)

The impact of building orientation on the mass temperature for the school structure was assessed through ENVI-met simulations conducted for two critical dates: 21st September and 21st March. As presented in Figures 6 and 7, the hourly variations of Tm during schooling hours (7:00 AM to 2:00 PM) reveal modest yet notable differences across the four orientations.



	7:00AM	8:00AM	9:00AM	10:00AM	11:00AM	12:00PM	1:00PM	2:00PM
ND (°C)	21.39	23.13	25.11	27.42	29.99	32.53	35.24	37.97
ED (°C)	21.4	23.31	25.29	27.47	29.83	32.14	34.79	37.81
SD (°C)	21.39	22.96	24.86	27.16	29.75	32.34	35.12	37.95
WD (°C)	21.39	23.26	25.3	27.52	29.93	32.3	35	38.05

Figure 6. Hourly T_m for School 21st September within schooling time in the four orientations



	7:00AM	8:00AM	9:00AM	10:00AM	11:00AM	12:00PM	1:00PM	2:00PM
ND (°C)	17.92	19.3	20.99	23.12	25.64	28.19	30.73	33.36
ED (°C)	17.98	19.53	21.25	23.26	25.57	27.87	30.27	33.12
SD (°C)	17.92	19.1	20.7	22.82	25.36	27.96	30.57	33.29
WD (°C)	17.92	19.41	21.19	23.25	25.62	27.99	30.45	33.35

Figure 7. Hourly T_{in} for School 21st March within schooling time in the four orientations

On 21st September, the school oriented to the south recorded the lowest average Tm (28.94°C) as in Figure 8, while the north-oriented configuration reached 29.10°C, marking the highest value among the cases. A similar trend is observed on 21st March (Figure 9), where the south orientation again exhibited the most favorable thermal performance (24.71°C), with the north-facing orientation registering the highest average T_m (24.91°C).

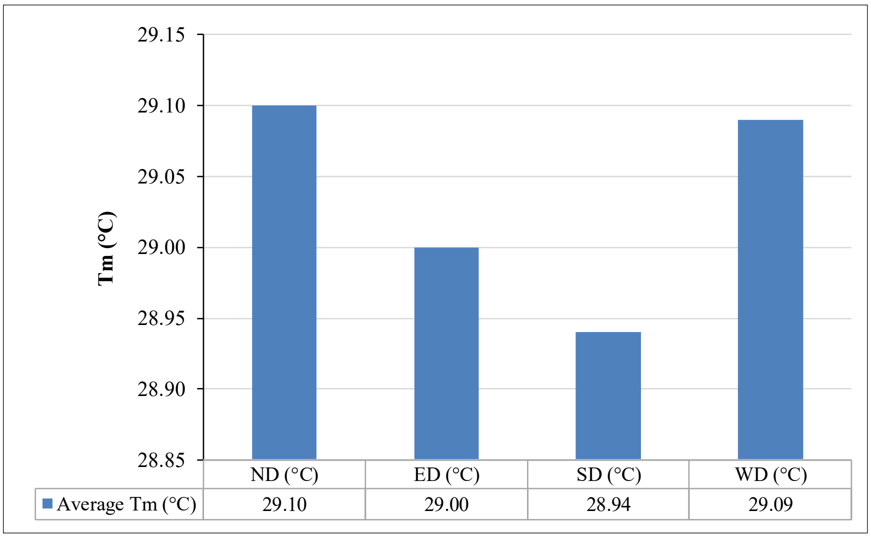


Figure 8. Average hourly T_m for the school on 21st September within schooling time in the four orientations

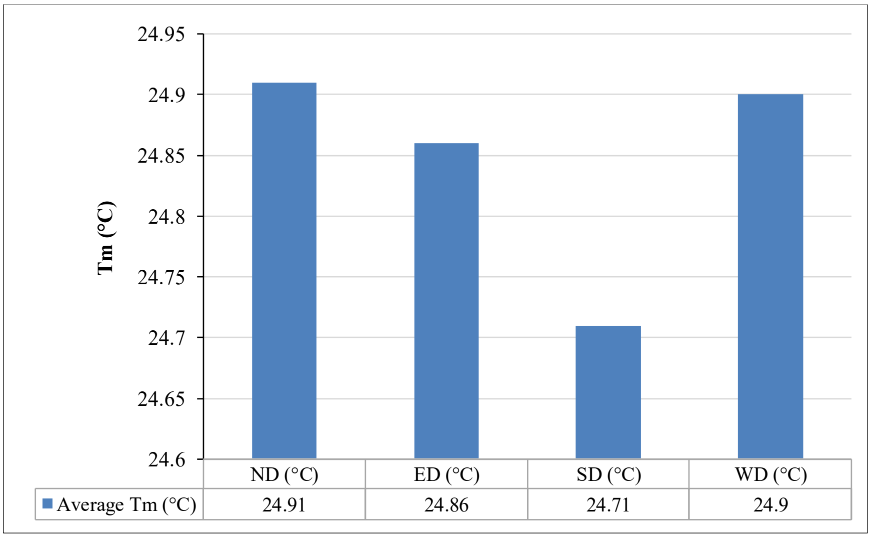


Figure 9. Average hourly T_m for the school on 21st March within schooling time in the four orientations

These temperature differences—approximately 0.16°C in September and 0.20°C in March—are relatively minor. This limited variation can be attributed to the symmetrical architectural configuration and the dominance of a large closed rectangular courtyard (81 m × 51 m, 4,131 m²), which represents approximately 85% of the total courtyard area. Surrounded by uniform 9 m thick masses on three sides and a thicker 39 m deep eastern block, the courtyard's spatial configuration produces consistent exposure to solar radiation across orientations.

The high Sky View Factor (SVF) of the main courtyard further contributes to these results. As high SVF reduces the shading potential and limits the courtyard's thermal buffering capacity. Furthermore, the limited building height (8 m) in relation to the expansive courtyard area compromises the stack effect and convective cooling, as courtyards enclosed by short walls are suboptimal in hot-humid climates. Consequently, orientation alone yields only modest influence on Tm due to the overriding role of courtyard geometry and enclosure ratios.

Contextualizing Small Temperature Differences

Average reduction level: For the average Energy savings per degree: Empirical rules of thumb support these results as raising the cooling setpoint by 1 °C or reduction in the air temperature typically cuts HVAC energy use by about 6–10% [49]. By scaling, a 0.2 °C reduction implies roughly a 1–2% savings. For a large building such as the school building in this research or across many cooling hours, a 1–2% reduction can translate into hundreds of kWh saved annually.

Moreover, the Building heat gain (and thus cooling load) is directly proportional to the temperature difference (ΔT) across the envelope. In fact, the basic heat-transfer equation is $Q = U{\cdot}A{\cdot}\Delta T$ *where* Q = Heat transfer rate, in watts (W) or energy (kWh) over time as in Equation 1 [50]. Based on that in this research, a 0.16–0.20 °C drop in average school day temperature yields a proportionally small drop in heat gain, with a typical concrete U≈0.5 W/m²·°C, an A = 1 m² and a ΔT =0.2 °C reduction saves ≈0.1 W/m² continuously, roughly 0.7 Wh/m² over 7 hours in one schooling day. Although the per-hour saving is small, it accumulates over a year and over large areas, making it non-negligible, as the 0.7 Wh/m² was for 1 m², thus it will be around 3500 Wh reduction for all the school building which area around 5000 m² - as mentioned in the previous Table 3.

$$Q = U{\cdot}A{\cdot}\Delta T \tag{1}$$

where, Q = Heat transfer rate, in watts (W) or energy (kWh) over time; U= *U value;* A= Area; and ΔT= Difference in temperature.

Hourly reduction level: Although the hourly temperature reductions observed—such as 0.2–0.4°C—may appear minor, their cumulative impact on building energy performance is considerable. Based on the established equation Q=U·A·ΔT, the energy savings for 1 m² of the school envelope were calculated as 0.695 W/m² on 21st March and 0.995 W/m² on 21st September as in Tables 5 and 6. When extrapolated to the full built-up area of the school—approximately 500 0m²—this equates to 3475 W and 4975 W of cooling energy saved respectively during the occupied hours simulated. These values underline the significance of orientation-driven design improvements, especially in hot arid climates where HVAC loads dominate energy consumption. Even fractional thermal gains achieved through optimal orientation can contribute meaningfully to long-term operational energy savings and improved indoor comfort, supporting broader sustainability goals.

Table 5. Hourly Saving energy when SD as the best orientation on 21st March

Time	ND-T_m (°C)	ED-T_m (°C)	SD-T_m (°C)	WD-T_m (°C)	Difference for Tm (°C) between the SD as best orientation and the worst orientation	Saving energy (W/m²) where $Q = U{\cdot}A{\cdot}\Delta T$
7:00AM	21.39	21.4	21.39	21.39	0.01	0.005
8:00AM	23.13	23.31	22.96	23.26	0.35	0.175
9:00AM	25.11	25.29	24.86	25.3	0.43	0.215
10:00AM	27.42	27.47	27.16	27.52	0.36	0.18
11:00AM	29.99	29.83	29.75	29.93	0.24	0.12
12:00PM	32.53	32.14	32.34	32.3	NA	-
1:00PM	35.24	34.79	35.12	35	NA	-
2:00PM	37.97	37.81	37.95	38.05	NA	-
General total Energy savings (W/m²)						**0.695**

Worst orientation Best Orientation

Table 6. Hourly Saving energy when SD as the best orientation on 21stSeptember

Time	ND-T_m (°C)	ED-T_m (°C)	SD-T_m (°C)	WD-T_m (°C)	Difference for Tm (°C) between the SD as best orientation and the worst orientation	Saving energy (W/m²) where $Q = U{\cdot}A{\cdot}\Delta T$
7:00AM	17.92	17.98	17.92	17.92	0.06	0.03
8:00AM	19.3	19.53	19.1	19.41	0.43	0.215
9:00AM	20.99	21.25	20.7	21.19	0.55	0.275
10:00AM	23.12	23.26	22.82	23.25	0.44	0.22
11:00AM	25.64	25.57	25.36	25.62	0.28	0.14
12:00PM	28.19	27.87	27.96	27.99	0.23	0.115
1:00PM	30.73	30.27	30.57	30.45	NA	-
2:00PM	33.36	33.12	33.29	33.35	NA	-
General total energy savings (W/m²)						**0.995**

Worst orientation Best Orientation

3.2. Outdoor Air Temperature Distribution in the Courtyards

Figure 10 presents outdoor air temperature distributions in the courtyards at the pedestrian height (1.4 m, K=3) at 10:00 AM—selected to represent typical student break time. While the differences are not extreme, spatial patterns clearly vary across orientations, reflecting microclimatic dynamics shaped by built form.

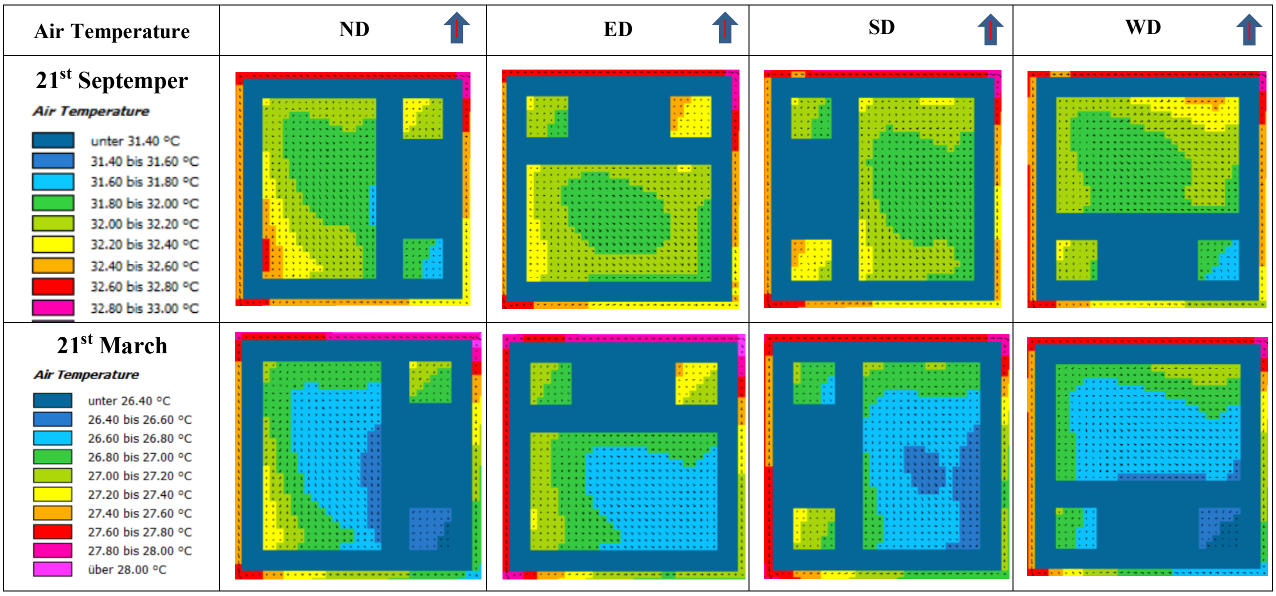


Figure 10. Outdoor air temperature distribution in the courtyards with different orientations on both dates of simulation

On 21st September, the south-oriented school demonstrated the most homogeneous and favorable air temperature distribution, with inner courtyard temperatures ranging from 31.8°C to 32.0°C. In contrast, the north- and west-oriented layouts exhibited higher localized temperatures, reaching 32.8°C and 32.6°C, respectively. The east orientation fell in between. Given that the ambient simulated outdoor air temperature at this hour was 32.93°C, the courtyard of the south-oriented case provided a reduction of 0.53–1.13°C.

Similarly, on 21st March, the south orientation again offered superior thermal moderation, with courtyard temperatures ranging between 26.4°C and 26.6°C, compared to an ambient outdoor temperature of 28.3°C. The reduction ranged from 1.1°C to 1.9°C, indicating improved thermal comfort and reduced heat gain potential.

The performance is closely linked to the large courtyard's scale relative to the surrounding massing. With three sides enclosed by thin 9 m deep structures and the eastern edge by a thicker 39 m block, the wind flow is restricted, limiting natural ventilation. While the northwest prevailing wind direction theoretically offers passive cooling potential, the courtyard's configuration inhibits effective airflow. Moreover, the high SVF in the main courtyard allows extensive solar penetration during peak hours, increasing surface and air temperatures. These results align with findings from Salameh (2024) [1] and Ghaffarianhoseini et al. (2015) [51] who emphasized that courtyards with high SVF and short perimeter walls tend to perform poorly in warm, humid climates due to inadequate shading and airflow.

Overall, the south-oriented courtyard consistently demonstrated better thermal performance in terms of outdoor air temperature moderation at pedestrian level. This orientation not only maintained temperatures closer to or slightly below ambient levels but also exhibited less spatial temperature variance, indicating a more thermally stable microclimate. Such stability is particularly beneficial during student break times, as it enhances outdoor usability and reduces exposure to heat stress. The observed reductions of up to 1.9°C—especially during midday peaks—are notable given that even small differences in outdoor temperature can significantly affect perceived comfort and radiant heat exposure. This highlights the potential of orientation-sensitive courtyard planning to passively mitigate thermal discomfort in educational settings located in hot climates

3.3. Physiological Equivalent Temperature (PET) Patterns

The Physiological Equivalent Temperature (PET) serves as a comprehensive index for outdoor thermal comfort, incorporating air temperature, mean radiant temperature, humidity, and wind speed. PET values were evaluated at 10:00 AM on both 21st March and 21st September. PET values were emphasized at 10:00 AM, aligning with students' primary courtyard break time, when outdoor comfort is most critical. After this period, the courtyard is largely unoccupied, making this time window the most relevant for evaluating real thermal experience and usability.

According to PET maps (Figure 11) and histograms (Figures 12 and 13), the south-oriented school demonstrated the most favorable PET conditions. On 21st March, 71.31% of the analyzed grid cells recorded PET values of 49°C**,** with fewer areas exceeding 52°C (only 10.91%), and only 2.07% of cells surpassing 55°C. Comparatively, the north-oriented school showed 79.16% of cells at 49°C, but with 11.97% reaching 52°C and 1.91% at 55°C. Similar patterns were observed on 21st September, where the south-facing orientation again held more cells in the 46–49°C range and fewer in the highest PET bands compared to other orientations.

PET maps visually confirm that the north-oriented case exhibited the largest and most intense heat zones**,** especially within the main courtyard and the surrounding wind-shadowed zones. Conversely, the south-oriented layout showed more dispersed and milder thermal zones, with the lowest PET intensity concentrated along the courtyard's eastern and southern edges, benefitting from shading cast by the thick eastern mass during the morning.

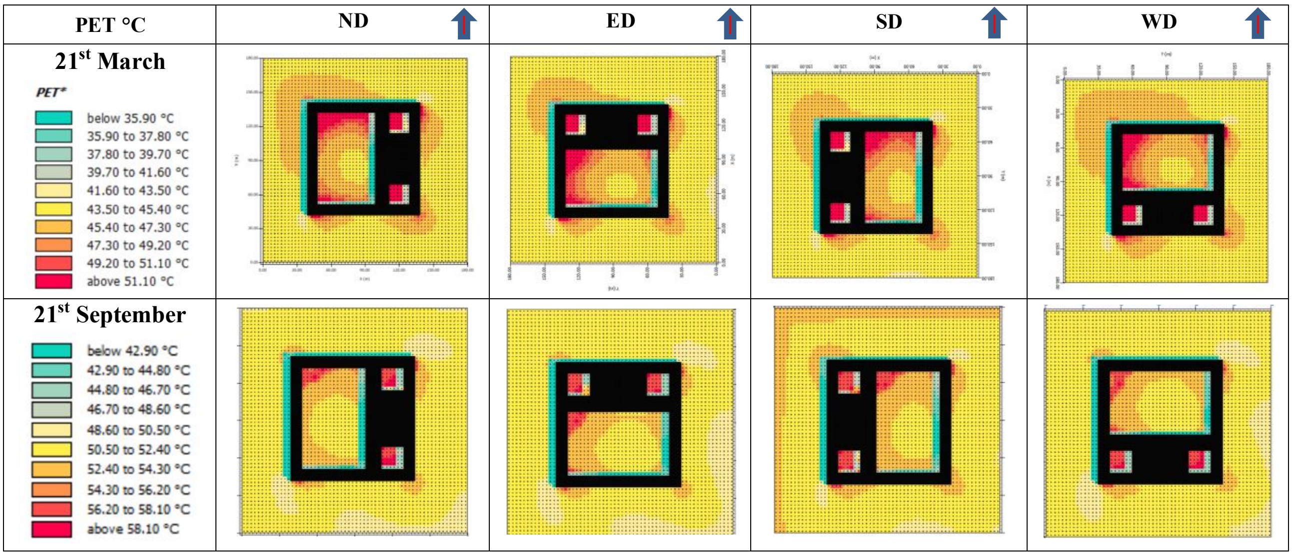
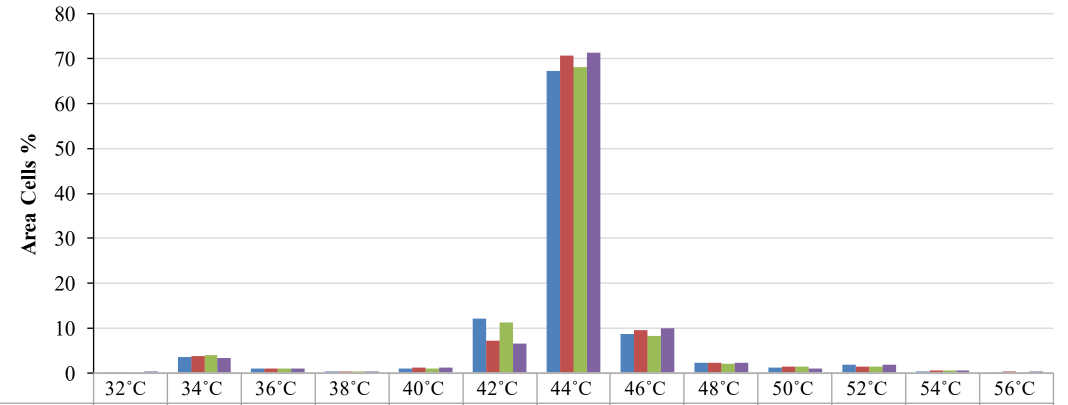
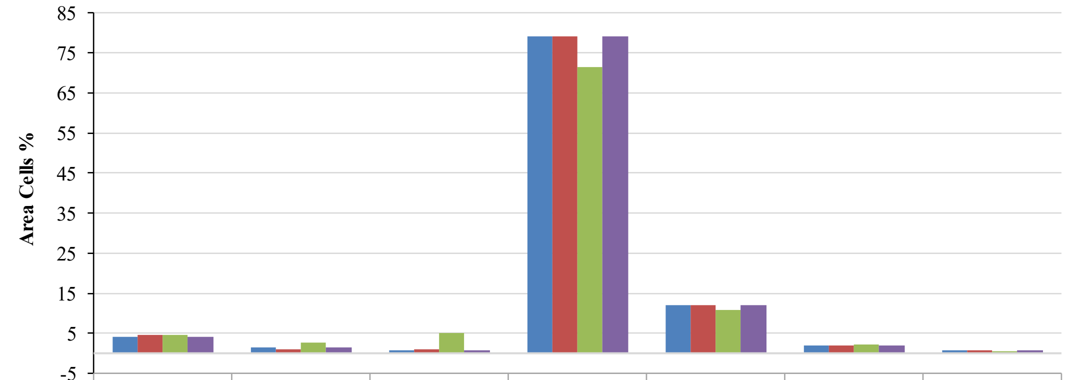


Figure 11. Outdoor PET distribution in the courtyards and around the school with different orientations at 10:00 am, on both dates of simulation



	32°C	34°C	36°C	38°C	40°C	42°C	44°C	46°C	48°C	50°C	52°C	54°C	56°C
ND -Cells %	0.2	3.7	0.9	0.3	1.1	12.0	67.3	8.6	2.2	1.2	1.9	0.4	0.2
ED -Cells %	0.2	3.8	1.0	0.4	1.2	7.2	70.6	9.5	2.2	1.4	1.4	0.7	0.4
SD -Cells %	0.2	3.9	0.9	0.4	1.1	11.2	68.2	8.3	2.2	1.4	1.5	0.6	0.1
WD-Cells %	0.3	3.3	1.1	0.5	1.2	6.5	71.4	9.9	2.3	1.1	1.8	0.5	0.3

Figure 12. Outdoor PET distribution around the school and within the courtyards on 21st of March at 10:00 am, with different orientations



	40 °C	43 °C	46 °C	49 °C	52 °C	55 °C	58 °C
ND -Cells %	4.11	1.38	0.82	79.16	11.97	1.91	0.66
ED -Cells %	4.50	1.08	0.99	78.99	11.90	1.84	0.69
SD -Cells %	4.62	2.58	5.05	71.31	10.91	2.07	0.46
WD-Cells %	4.11	1.38	0.82	79.16	11.97	1.91	0.66

Figure 13. Outdoor PET distribution around the school and within the courtyards on 21st of September at 10:00 am, with different orientations

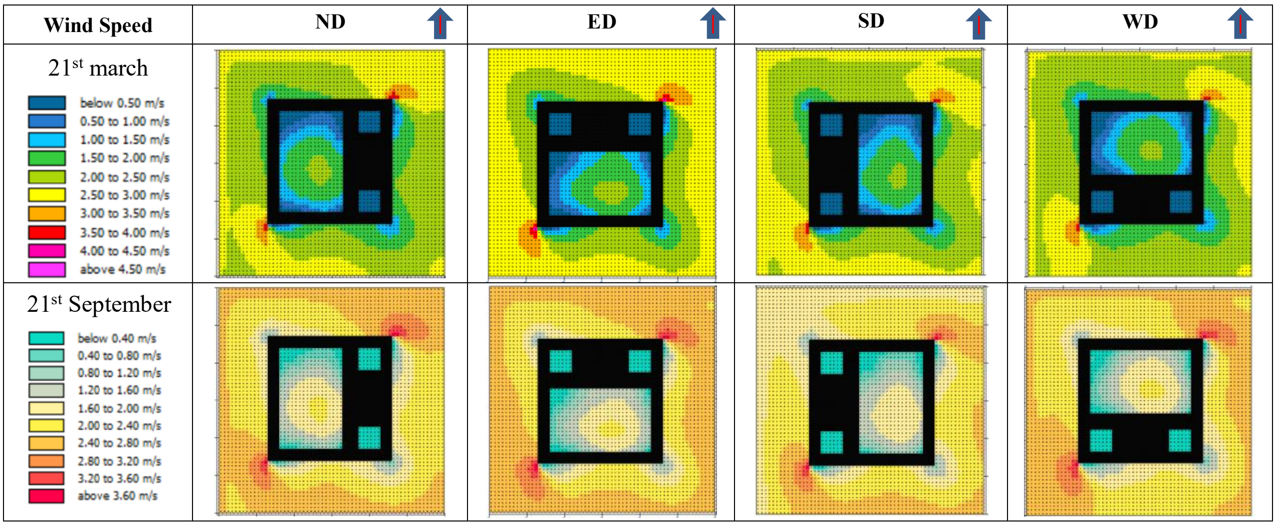
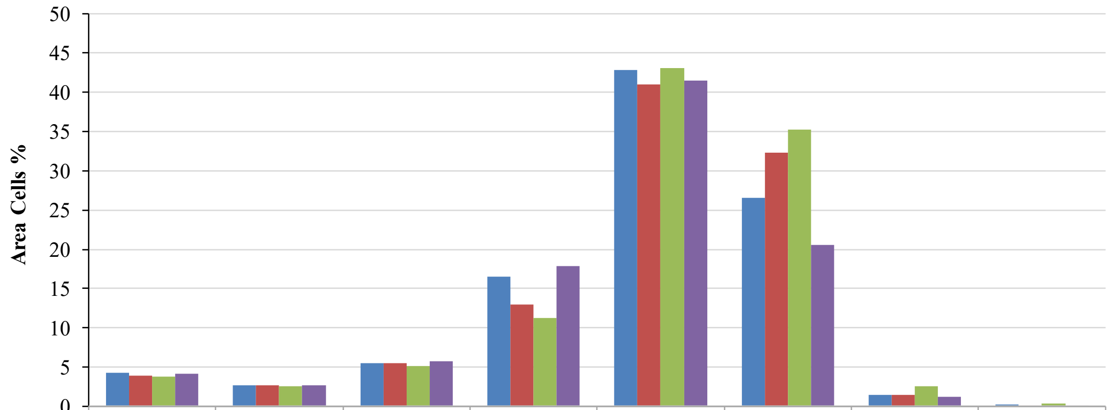
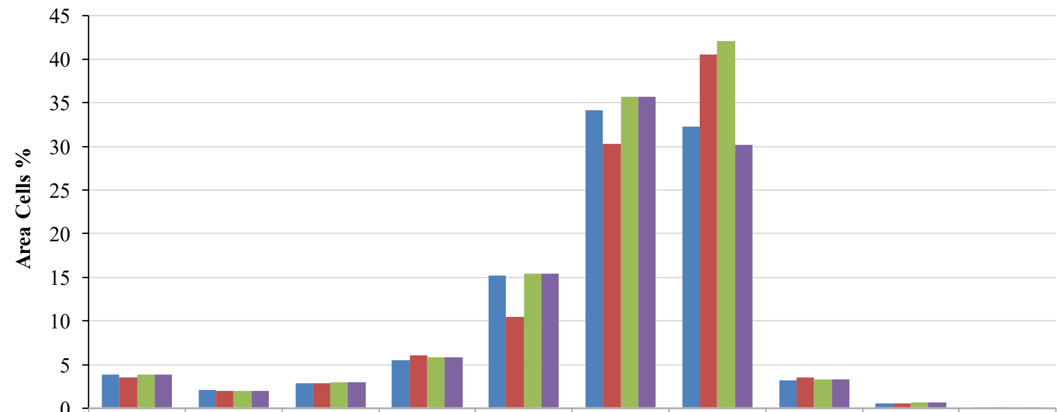


Figure 14. Wind speed distribution around the school and in the courtyards with different orientations at 10 am



	0.0 m/s	0.5 m/s	1.0 m/s	1.5 m/s	2.0 m/s	2.5 m/s	3.5 m/s	4.0 m/s
North	4.31	2.70	5.49	16.54	42.83	26.53	1.41	0.20
East	3.88	2.70	5.52	12.92	41.03	32.28	1.51	0.16
South	3.85	2.60	5.10	11.24	43.03	35.22	2.60	0.33
West	4.21	2.73	5.79	17.85	41.50	20.55	1.25	0.13

Figure 15. Wind speed histogram around the school and in the courtyards with different orientations at 10 am on 21st March



	0 m/s	0.4 m/s	0.8 m/s	1.2 m/s	1.6 m/s	2.0 m/s	2.4 m/s	2.8 m/s	3.2 m/s	3.6 m/s
ND -Cells %	3.88	2.14	2.86	5.49	15.22	34.19	32.31	3.22	0.59	0.10
ED -Cells %	3.55	1.94	2.89	6.05	10.42	30.31	40.53	3.58	0.59	0.13
SD -Cells %	3.88	2.01	2.99	5.85	15.48	35.67	42.14	3.29	0.62	0.07
WD-Cells %	3.88	2.01	2.99	5.85	15.48	35.67	30.14	3.29	0.62	0.07

Figure 16. Wind speed histogram around the school and in the courtyards with different orientations at 10 am on 21st September

Wind speed distribution directly influences PET patterns. As seen in the wind maps and histograms (Figure 14 to 16), the south orientation enabled relatively higher proportions of wind speeds within the 2.0–2.4 m/s range (35.67% in September and 41.03% in March), compared to the north and east orientations, which were predominantly confined to lower velocities (<2.0 m/s). This improved air movement enhanced convective heat loss and mitigated surface heating.

Notably, wind maps also indicated blocked airflow zones behind the eastern mass in all configurations, but the south orientation's openness to the northwest prevailing wind permitted better penetration and dispersion of airflow through the courtyard. In contrast, the north and east orientations displayed more stagnant air zones, particularly near courtyard edges and in leeward areas.

Sky View Factor (SVF) remained a constant parameter across all orientations due to fixed massing geometry; however, its effectiveness was modulated by solar angle and wind access**.** In orientations where airflow was obstructed, high SVF resulted in higher PET values due to increased direct solar radiation and reduced cooling capacity.

Overall, the south-oriented school demonstrated superior thermal comfort**,** with balanced PET values, favorable wind flow, and more effective use of shading and mass configuration. This reinforces the conclusion that geometry, wind access, and SVF have a more profound impact than orientation alone. For hot-humid climates, strategies such as enhancing wind corridors, optimizing SVF, and managing solar exposure are essential for achieving thermally comfortable outdoor learning environments.

Finally, it is very important to indicate that a small temperature drop can extend thermal comfort. For instance, one study reported that a 0.2 °C reduction in the "standard effective temperature" (SET) led to a measurable comfort improvement: the thermal damping coefficient rose from 0.81 to 0.84 [52, 53]. In other words, even 0.2 °C can meaningfully improve how long conditions stay within the comfort range. Thus, the small drop in PET emphasizes practical comfort benefits.

3.4. CO_2 Concentration as Health Indication

While previous sections of this study addressed mass temperature, air temperature, and PET distributions, a complementary environmental indicator relevant to student health and ventilation performance is CO_2 concentration. Courtyards, particularly in school buildings, serve not only as passive cooling elements but also as transitional breathing zones that can accumulate or disperse pollutants depending on design and environmental interactions.

In this study, CO_2 concentration was evaluated using ENVI-met simulations at 10:00 AM—representing student break time—on 21st March and 21st September (Figure 17). The orientation cases (ND, ED, SD, WD) were compared visually and quantitatively using color-based histograms derived from simulation outputs. Results indicated that although the ED orientation showed slightly lower average CO_2 in September, the SD (south-oriented) courtyard consistently maintained the lowest CO_2 accumulation across both seasons. This was evident in March, where over 60% of the courtyard area recorded concentrations below 359.5 ppm. September histograms showed a similar trend, with SD and ED outperforming other orientations (Figures 18 and 19).

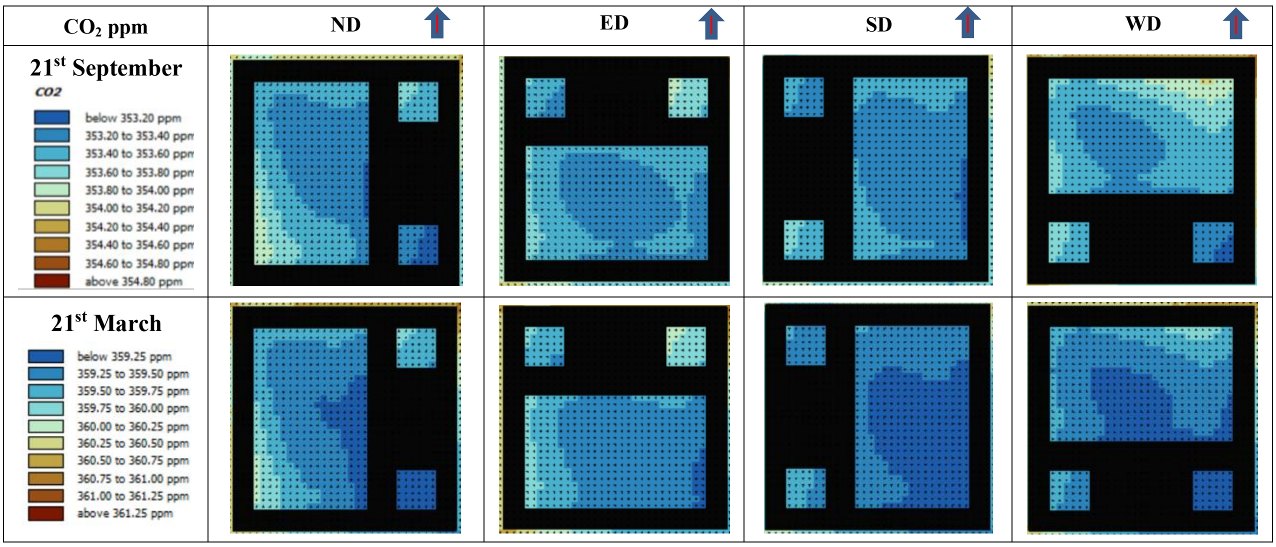
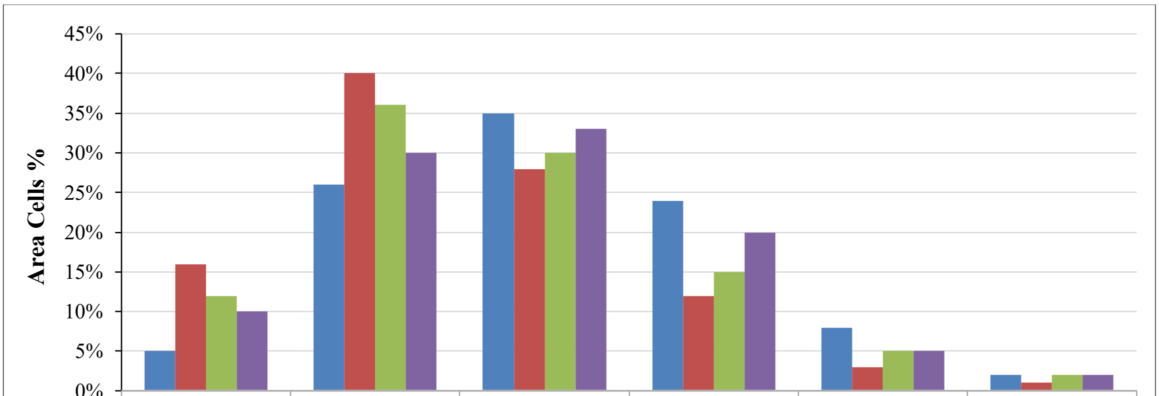
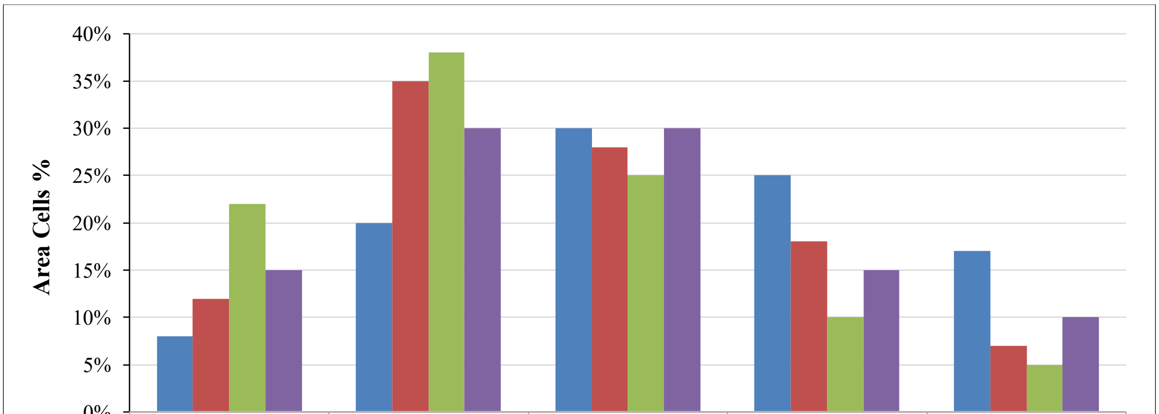


Figure 17. CO_2 Concentration distribution in the school courtyards with different orientations at 10 am



	<353.20 (Deep Blue)	353.20–353.40	353.40–353.60	353.60–353.80	353.80–354.00	>354.00
ND	5%	26%	35%	24%	8%	2%
ED	16%	40%	28%	12%	3%	1%
SD	12%	36%	30%	15%	5%	2%
WD	10%	30%	33%	20%	5%	2%

Figure 18. September 21st – Main Courtyard CO_2 Distribution



	<359.25 (Deep Blue)	359.25–359.50	359.50–359.75	359.75–360.00	>360.00
ND	8%	20%	30%	25%	17%
ED	12%	35%	28%	18%	7%
SD	22%	38%	25%	10%	5%
WD	15%	30%	30%	15%	10%

Figure 19. March 21st – Main Courtyard CO_2 Distribution

These findings suggest that the SD orientation benefits from partial alignment with the prevailing northwest wind direction (315°), enabling better diagonal air flushing. Moreover, the SD case also demonstrates improved convective removal through the stack effect, as solar-induced buoyancy aids vertical air movement in the morning hours. The courtyard's high Sky View Factor (SVF), while a limiting factor in thermal buffering, may enhance upward CO_2 dissipation under the SD orientation when combined with wind-assisted crossflow.

All courtyard configurations analyzed in this study recorded CO_2 concentrations well below 500 ppm during the peak occupancy hour, aligning with international thresholds for safe exposure in outdoor school environments. This confirms that despite orientation differences, natural respiration was the sole CO_2 source and ventilation remained adequate. According to Verma & Bano (2023) [40], outdoor concentrations up to 400 ppm are normal thus acceptable for children, provided that airflow is sufficient and pollutant sources are minimal.

The implication for design is clear: in hot-arid climates like Ajman, UAE, optimizing courtyard orientation to align partially with dominant wind and maximize stack-induced flow can significantly improve air quality during critical occupancy periods. Therefore, while PET and temperature metrics offer insight into thermal comfort, CO_2 distribution adds a vital layer of understanding regarding ventilation effectiveness and occupant health.

3.5. Comparison with Previous Studies

This section, compared the research findings on courtyard orientation in UAE school buildings with previous studies of passive thermal comfort strategies. Earlier research predominantly examined features like courtyards in housing or other small-scale structures, leaving a significant gap in understanding their benefits for large educational facilities. By focusing on a hot arid climate and a school context, our study fills this gap and underscores courtyard orientation as a vital passive design strategy to improve thermal comfort in such institutions.

Habibi (2024) [54] - *Global energy efficiency focus*- examined how building orientation affects energy use across different climates and building scales. Using simulation-based optimization, that study evaluated orientation's impact on overall energy performance (energy use intensity, EUI) and heating vs. cooling loads. It found that orientation alone has a minimal effect on total EUI, though it does alter the balance of heating and cooling demand depending on climate zone. In other words, while turning a building may slightly reduce cooling in one climate or season (and increase heating in another), the net annual energy savings from orientation were relatively small. Habibi's work was broadly energy-centric and not tied to a specific building type or occupant comfort criteria. In contrast, this study targets an educational building's *thermal comfort* and *air quality* outcomes rather than just energy use. As it focused on a hot-arid context (UAE) and analyze how courtyard orientation influences indoor operative temperature and outdoor PET (comfort metrics), as well as CO_2 levels – factors outside Habibi's energy efficiency scope.

Zheng et al. (2024) [55] - *Office energy and carbon optimization in China*- optimized exterior wall insulation for each cardinal orientation in a 6-story office building, spanning latitudes 20–40°N in China. Their methodology involved extensive simulations (41,160 TRNSYS runs) coupled with an ANN–GA algorithm to find the most economical U-value for walls facing north, east, south, and west. The key parameters were orientation-specific insulation levels, latitude (climate), window-to-wall ratio (WWR), and aspect ratio. They found that the optimal wall insulation varied with orientation and climate: for lower latitudes, south-facing walls could have the highest U-value (least insulation) while north-facing walls needed the most insulation, with intermediate needs for east/west. Optimal U-values tended to increase in warmer climates (and with higher WWR) and decrease in colder climates or more compact buildings. By tailoring insulation to orientation, the office model achieved modest improvements – roughly a 3–7% reduction in life-cycle cost, annual energy use, and carbon emissions compared to a uniform-code design. Zheng et al.'s study, however, focused purely on energy and carbon performance in offices, without examining thermal comfort or indoor air quality. In comparison, this research goes beyond energy optimization: as it investigated a *school courtyard* orientation's effect on occupant comfort (via T_m and PET indices) and ventilation efficacy (CO_2 levels). This means this research addresses not only how orientation impacts cooling loads, but also how it affects the thermal experience of students and the air quality in classrooms – an area not covered by Zheng et al.'s energy-focused research.

Mangkuto et al. (2024) [56] - *Tropical PV and daylight in a prototype building*- explored the optimum facade orientation for building-integrated photovoltaics (BIPV) on a tropical building, considering both solar energy yield and indoor daylight performance. Their study took place in Bandung, Indonesia (tropical climate) and combined physical experiment with simulation. They tested a scale-model building with a PV panel on one facade, rotating it to face each cardinal direction, and evaluated annual PV output alongside five daylight metrics. The results showed a trade-off: a south-facing façade provided the best overall daylight conditions (e.g. minimal glare and high useful daylight, with virtually zero hours of over-illumination) and was deemed the optimal orientation when balancing multiple objectives. The north-facing orientation produced the greatest PV electricity yield annually, but at the cost of more variable performance and less favorable daylight inside. Based on their multi-criteria analysis, the authors concluded that the south orientation was the most favorable for that tropical context, as it achieved a well-rounded performance on both daylight and solar energy fronts. This study underscores how orientation can simultaneously affect renewable energy generation and indoor environmental quality (visual comfort). Still, its scope was limited to a small prototype and did not address thermal or air quality parameters. By contrast, this research deals with a full-scale school building and concentrates on *thermal comfort* (not lighting) and *air quality* (CO_2) in a hot climate. Where Mangkuto et al. looked at sun angles for PV and daylight, this research examined sun and wind effects on courtyard microclimate. This study's novelty lies in extending orientation analysis to the thermal realm and occupant health (ventilation) for a large educational building – a different performance aspect than Mangkuto's PV/daylight evaluation.

Dai et al. (2023) [57] – *Courtyard house orientation and comfort in Kashgar* - investigated how building layout ("enclosure type") and orientation impact indoor thermal comfort in traditional courtyard residences of Kashgar. Kashgar's climate is extreme (hot summers, very cold winters), and the authors simulated 20 scenarios combining five courtyard geometries (denoted T, I, L, C, and O shapes) with different orientations. Their focus was on residential buildings with central or attached courtyards, examining metrics like indoor air temperature and predicted comfort (likely via PMV or similar). They found that each courtyard configuration has an optimal orientation for comfort. For example, a fully enclosed courtyard house ("O" type) performed best when oriented south (maximizing winter sun), whereas an L-shaped or linear ("I" type) house stayed most comfortable when oriented north, minimizing direct summer sun exposure on large. Similarly, a "T" shaped layout was optimal facing east in that climate (benefiting from morning sun and avoiding harsh west sun). These results highlight that both building form and orientation jointly influence indoor comfort – aligning a courtyard to the appropriate cardinal direction significantly improved occupants' thermal conditions. Dai et al. (2023) [57] work is directly relevant in that it also deals with courtyard orientations; however, it was confined to residential scale and focused only on thermal comfort (temperature/PMV). This research builds on this idea of courtyard orientation affecting comfort, but it applies it to a large school building in a hot-arid climate and we include additional dimensions like CO_2. Moreover, unlike the Kashgar study which addressed a dual-season (summer/winter) comfort optimization in houses, this research emphasizes the prolonged hot conditions of the UAE and how orientation can be leveraged to improve natural ventilation (not just temperature) in classrooms. This expands the discussion from "orientation vs. indoor temperature" to a more holistic view including ventilation and CO_2, which were beyond the scope of Dai et al. (2023) [57] case study.

Muhy Al-Din et al. (2023) [58] – *Thermal comfort orientation in Iraqi homes (objective vs. subjective)*- studied the impact of house orientation on thermal comfort in a semi-arid region (Garmian, in Kurdistan, Iraq) using a hybrid approach. They surveyed occupants (capturing Thermal Sensation Votes, TSV) and simultaneously calculated comfort indices (Predicted Mean Vote, PMV) in actual homes to compare how orientation influences both measured and perceived comfort. Geographically, this context has very hot, dry summers and cool winters. The study revealed that objective metrics and occupants' perceptions can differ on the best building orientation. According to the PMV-based analysis, north-facing houses had the coolest indoor conditions in summer (best comfort objectively), and west-facing houses were the most uncomfortable due to intense afternoon sun. In winter, the PMV model found west-oriented homes warmest (best) and north-oriented the coldest (worst) for comfort. However, the residents' subjective feedback told a slightly different story: people reported feeling hottest in *south*-oriented houses during summer, and in winter they actually felt most comfortable in south-facing homes (preferring the winter sun), with north orientation consistently perceived as worst. Notably, the study found east-facing houses offered a good compromise – they were always the second-best orientation in both summer and winter by both objective and subjective criteria. As a result, the authors recommended an east orientation for new homes in that region and suggested design interventions (like buffer zones on the most sun-exposed sides) to enhance thermal comfort. This work is significant for incorporating human comfort perception into orientation studies. Still, it centers on small-scale residential buildings and purely thermal comfort outcomes. In comparison, this study in a UAE school targets a different scale and scope: it did not conduct subjective surveys, but it integrated multiple objective measures (thermal indices and air quality). Moreover, by focusing on CO_2 along with thermal metrics, this research addresses comfort in a broader sense – thermal *and* respiratory comfort – which is critical in classrooms. While Muhy Al-Din et al. (2023) [58] highlighted the human element in thermal comfort, this study's unique contribution is linking orientation to thermal comfort comfort and air quality, thereby extending the dialogue to include health and learning environment quality in hot-climate schools.

Unique Contributions of Our Study: Across these five studies, orientation has been examined in contexts of energy use envelope optimization, PV generation and daylight, or thermal comfort in homes. However, none of them addresses educational buildings in an extreme hot climate with a comprehensive multi-variable lens. This study fills this gap by focusing on a large school with a courtyard, typical of the UAE, and evaluating orientation impacts on a suite of performance indicators: indoor thermal conditions (T_m), outdoor microclimate comfort (PET), and courtyard air quality (CO_2 levels). This combined analysis goes beyond previous works that tended to isolate one domain (be it energy, thermal comfort, or daylight). For instance, whereas prior researchers looked at orientation largely in terms of energy or temperature effects, this study showed how rotating the courtyard can alter wind flow and ventilation rates, directly affecting CO_2 build-up in classrooms – a crucial factor for student health and cognitive performance that was not considered in earlier studies. Furthermore, by concentrating on a school, this study emphasizes a building type where comfort and air quality are especially vital (young occupants, high densities, scheduled use), under climatic conditions (prolonged heat and high solar exposure) that push passive design strategies to their limits. In summary, the findings of this research extend the knowledge from past orientation studies by demonstrating that in hot-arid educational settings, courtyard orientation is not just about thermal performance; it also has meaningful implications for air quality and occupant well-being.

4. Conclusion

This study investigated the thermal and environmental performance of a school building under four different orientations, focusing on mass temperature, outdoor air temperature, and Physiological Equivalent Temperature (PET). The analysis was conducted using ENVI-met simulations on two representative dates—21st March and 21st September—corresponding to critical points in the school calendar for hot climates.

The findings confirm that building orientation alone yields only slight differences in mass temperature; however, these differences—0.16°C in September and 0.20°C in March—become significant when considered in the context of the school's large built mass and enclosed courtyard. The south-oriented configuration consistently recorded the lowest Tm (28.94°C in September and 24.71°C in March), demonstrating its potential to slightly but meaningfully improve indoor thermal performance. While the quantitative hourly temperature differences observed between orientations may appear small (0.2–0.4 °C on average during school hours), they were systematically analyzed in terms of energy implications using the steady-state heat transfer equation $Q = U \cdot A \cdot \Delta T$. Thus, even small reductions in Tm led to measurable cooling energy savings of approximately 0.7 W/m² on 21st March and around 1.0 W/m² on 21st September. For a typical school footprint of 5000 m², this results in hourly savings of 3500–5000 W, highlighting the cumulative impact of passive orientation strategies.

In terms of outdoor air temperature and PET, orientation exerted a more noticeable influence. The south-facing layout had more favorable PET values, particularly with 71.31% of cells at 49°C in March, and lower critical exposure to PET values above 52°C. This was supported by higher wind speeds in the courtyard (41.03% of cells within the 2.0–2.4 m/s range in March), enhancing evaporative and convective cooling.

The results also revealed that the best PET conditions were directly associated with the lowest building mass temperatures and the most balanced outdoor temperature distributions, both of which were achieved in the south-oriented configuration. This orientation combined reduced Tm, more homogeneous courtyard air temperatures, and enhanced wind penetration, thereby producing the most favorable comfort outcomes for users. This synergy between lower structural heat storage and improved outdoor microclimate highlights why orientation, even with seemingly slight differences, plays a critical role when applied to large institutional buildings.

Finally, analysis of CO_2 concentration patterns confirmed that the courtyard orientation significantly affects air quality. Simulations using ENVI-met at 10:00 AM—representing peak student activity—demonstrated that the south-oriented courtyard consistently achieved the lowest CO_2 concentrations across both 21st March and 21st September. In March, over 60% of the main courtyard area recorded CO_2 values below 359.50 ppm, while September results showed similarly favorable distributions. These findings are critical from a health and comfort standpoint, as improved air quality reduces fatigue, supports cognitive function, and lowers the risk of pollutant exposure. Therefore, the south direction represents the best and healthiest courtyard orientation for student use, ensuring both thermal and respiratory comfort during school hours.

5. Declarations

5.1. Author Contributions

Conceptualization, M.S. methodology, M.S. and B.T.; software, M.S.; validation, M.S. and B.T.; formal analysis, M.S.; investigation, B.T.; resources, B.T.; data curation, B.T.; writing—original draft preparation, M.S.; writing—review and editing, B.T.; visualization, M.S.; supervision, B.T.; project administration, M.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

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

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgments

Special thanks to Ajman University and the research Centre for their assistance in paying the APC for publishing.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Salameh, M. (2024). Modifying School Courtyard Design to Optimize Thermal Conditions and Energy Consumption in a Hot Arid Climate. Journal of Architectural Engineering, 30(4), 4024033. doi:10.1061/jaeied.aeeng-1813.

[2] Dias Pereira, L., Raimondo, D., Corgnati, S. P., & Gameiro Da Silva, M. (2014). Energy consumption in schools - A review paper. Renewable and Sustainable Energy Reviews, 40, 911–922. doi:10.1016/j.rser.2014.08.010.

[3] Zhang, A., Bokel, R., van den Dobbelsteen, A., Sun, Y., Huang, Q., & Zhang, Q. (2017). The effect of geometry parameters on energy and thermal performance of school buildings in cold climates of China. Sustainability (Switzerland), 9(10), 1708. doi:10.3390/su9101708.

[4] Mahyuddin, N., Samzadeh, M., Zaid, S. M., & Ab Ghafar, N. (2021). Towards nearly zero energy building concept – visual comfort and energy efficiency assessments in a classroom. Open House International, 47(1), 167-187. doi:10.1108/ohi-05-2021-0099.

[5] Emirates Green Building. (2019). Energy and Water Performance of DUBAI SCHOOLS. Bea Fact Sheets School Final, Emirates Green Building Council, Dubai, United Arab Emirates. Available online: https://emiratesgbc.org/wp-content/uploads/2020/06/BEA-Fact-Sheets-School-Final.pdf (accessed on November 2025).

[6] Edarabia. (2023) UAE School Holidays (2026), Edarabia, Dubai, United Arab Emirates. Available online: https://www.edarabia.com/school-holidays-uae/#:~:text=UAE%20School%20Holidays%20(2024)&text=The%20United%20Arab%20Emirates%20(UAE,793%2C295%20students%20(private%20schools) (accessed on November 2025).

[7] Al-Khatatbeh, B. J., & Ma'Bdeh, S. N. (2017). Improving visual comfort and energy efficiency in existing classrooms using passive daylighting techniques. Energy Procedia, 136, 102–108. doi:10.1016/j.egypro.2017.10.294.

[8] Abanomi, W., & Jones, P. (2005). Passive cooling and energy conservation design strategies of school buildings in hot, arid region: Riyadh, Saudi Arabia. Proceedings of the international conference passive and low energy cooling for the built environment, 19-21 May, 2005, Santorini, Greece.

[9] Zomorodian, Z. S., & Nasrollahi, F. (2013). Architectural design optimization of school buildings for reduction of energy demand in hot and dry climates of Iran. International Journal of Architectural Engineering & Urban Planning, 23(1), 41–50.

[10] Harputlugil, G. U., Hensen, J., & Celebi, G. (2011). A prospect to develop thermally robust outline design and to explore its applicability to the different climate necessities of Turkey. International Journal of Low-Carbon Technologies, 6(1), 76–85. doi:10.1093/ijlct/ctq050.

[11] Gil-Baez, M., Padura, Á. B., & Huelva, M. M. (2019). Passive actions in the building envelope to enhance sustainability of schools in a Mediterranean climate. Energy, 167(C), 144–158. doi:10.1016/j.energy.2018.10.094.

[12] Hong, T., Koo, C., & Jeong, K. (2012). A decision support model for reducing electric energy consumption in elementary school facilities. Applied Energy, 95, 253–266. doi:10.1016/j.apenergy.2012.02.052.

[13] Ramli, N. H., Masri, M. H., Zafrullah, M., Taib, H. M., & Hamid, N. A. (2012). A Comparative Study of Green School Guidelines. Procedia - Social and Behavioral Sciences, 50, 462–471. doi:10.1016/j.sbspro.2012.08.050.

[14] Matsuoka, R. H., & Kaplan, R. (2008). People needs in the urban landscape: Analysis of Landscape and Urban Planning contributions. Landscape and Urban Planning, 84(1), 7–19. doi:10.1016/j.landurbplan.2007.09.009.

[15] EL-Nwsany, R. I., Maarouf, I., & Abd el-Aal, W. (2019). Water management as a vital factor for a sustainable school. Alexandria Engineering Journal, 58(1), 303–313. doi:10.1016/j.aej.2018.12.012.

[16] Heracleous, C., Michael, A., Savvides, A., & Hayles, C. (2021). Climate change resilience of school premises in Cyprus: An examination of retrofit approaches and their implications on thermal and energy performance. Journal of Building Engineering, 44, 103358. doi:10.1016/j.jobe.2021.103358.

[17] Salameh, M., Abu-Hijleh, B., & Touqan, B. (2024). Impact of courtyard orientation on thermal performance of school buildings' temperature. Urban Climate, 54, 101853. doi:10.1016/j.uclim.2024.101853.

[18] McGee, C., Reardon, C., & Clarke, D. (2017). Orientation. Your Home, Australian Government, Canberra, Australia. Available online: http://www.yourhome.gov.au/passive-design/orientation (accessed on November 2025).

[19] Shrestha, M., & Rijal, H. B. (2023). Investigation on Summer Thermal Comfort and Passive Thermal Improvements in Naturally Ventilated Nepalese School Buildings. Energies, 16(3), 1251. doi:10.3390/en16031251.

[20] Karimimoshaver, M., & Shahrak, M. S. (2022). The effect of height and orientation of buildings on thermal comfort. Sustainable Cities and Society, 79, 103720. doi:10.1016/j.scs.2022.103720.

[21] Abdallah, A. S. H., Mahmoud, R. M. A., & Aloshan, M. A. (2025). Optimizing Urban Spaces: A Parametric Approach to Enhancing Outdoor Recreation Between Residential Areas in Riyadh, Saudi Arabia. Buildings, 15(9), 1527. doi:10.3390/buildings15091527.

[22] Abuhussain, M. A., Al-Tamimi, N., Alotaibi, B. S., Singh, M. K., Kumar, S., & Elnaklah, R. (2022). Impact of Courtyard Concept on Energy Efficiency and Home Privacy in Saudi Arabia. Energies, 15(15), 5637. doi:10.3390/en15155637.

[23] Sun, Q., Luo, Z., & Bai, L. (2023). The Impact of Internal Courtyard Configuration on Thermal Performance of Long Strip Houses. Buildings, 13(2), 371. doi:10.3390/buildings13020371.

[24] Liedl, P., Hausladen, G., & de Saldanha, M. (2011). Building to Suit the Climate. De Gruyter Brill, Berlin, Germany. doi:10.1515/9783034608787.

[25] Sadafi, N., Salleh, E., Haw, L. C., & Jaafar, Z. (2011). Evaluating thermal effects of internal courtyard in a tropical terrace house by computational simulation. Energy and Buildings, 43(4), 887–893. doi:10.1016/j.enbuild.2010.12.009.

[26] Jara, E. ángel R., de la Flor, F. J. S., Domínguez, S. Á., Lissén, J. M. S., & Casado, A. R. (2017). Characterizing the air temperature drop in Mediterranean courtyards from monitoring campaigns. Sustainability (Switzerland), 9(8), 1401. doi:10.3390/su9081401.

[27] Modi, S., IIiyasu Sanke Isyaku, Timothy Marcus Kogi, Amos Danladi, Bilkisu Priscilla Sambo, & Emmanuel Adamu Gado. (2022). Orientation as a panacea for improving the Thermal Performance of a fully enclosed courtyard in a typical tropical climate. Journal of Environmental Science and Economics, 1(3), 51–59. doi:10.56556/jescae.v1i3.240.

[28] Diz-Mellado, E., López-Cabeza, V. P., Rivera-Gómez, C., Galán-Marín, C., Rojas-Fernández, J., & Nikolopoulou, M. (2021). Extending the adaptive thermal comfort models for courtyards. Building and Environment, 203, 108094. doi:10.1016/j.buildenv.2021.108094.

[29] Li, M., Jin, Y., & Guo, J. (2022). Dynamic characteristics and adaptive design methods of enclosed courtyard: A case study of a single-story courtyard dwelling in China. Building and Environment, 223, 109445. doi:10.1016/j.buildenv.2022.109445.

[30] Wah, Y., & Lot, B. (2017). Examination of Courtyard Dimensions and Proportions in Universiti Teknologi Malaysia Buildings. International Journal of Real Estate Studies, 11(2).

[31] Mundra, S., & Kannamma, D. (2019). Effect of Courtyard on Comfort-Study of thermal performance characteristics of courtyards in hot and humid climate. Proceedings of the Architectural Science Association (ANZAScA), 26-28 November, 2020, Roorkee, India.

[32] Salameh, M., & Touqan, B. (2024). Optimizing educational environments: microclimate analysis and energy efficiency through courtyard orientation in UAE schools. Frontiers in Built Environment, 10, 1448743. doi:10.3389/fbuil.2024.1448743.

[33] Sun, H., Owen, J. S., Almazmumi, S., Liu, C., Mohammadi, M., Dik, A., Jimenez-Bescos, C., & Calautit, J. K. (2024). Pollutant cross-transmission in courtyard buildings: Wind tunnel experiments and computational fluid dynamics (CFD) evaluation. Building and Environment, 264, 111919. doi:10.1016/j.buildenv.2024.111919.

[34] Ferrari, S., & Tendas, L. (2024). Ventilation and pollutant dispersion in a group of courtyard buildings with a diagonal wind. EPJ Web of Conferences, 299, 1011. doi:10.1051/epjconf/202429901011.

[35] Sharples, S., & Bensalem, R. (2001). Airflow in courtyard and atrium buildings in the urban environment: A win tunnel study. Solar Energy, 70(3), 237–244. doi:10.1016/S0038-092X(00)00092-X.

[36] Balah, E. M., Shokry, H., Hagishima, A., & Mahmoud, H. (2024). Reversed cooling and heating performance of modernized courtyard envelope in hot-arid climates: a case study at an educational campus. Clean Technologies and Environmental Policy, 26(12), 4521–4542. doi:10.1007/s10098-024-02833-y.

[37] Martinelli, L., & Matzarakis, A. (2017). Influence of height/width proportions on the thermal comfort of courtyard typology for Italian climate zones. Sustainable Cities and Society, 29, 97–106. doi:10.1016/j.scs.2016.12.004.

[38] Forouzandeh, A. (2018). Numerical modeling validation for the microclimate thermal condition of semi-closed courtyard spaces between buildings. Sustainable Cities and Society, 36, 327–345. doi:10.1016/j.scs.2017.07.025.

[39] Hegazy, I. R., & Qurnfulah, E. M. (2020). Thermal comfort of urban spaces using simulation tools exploring street orientation influence of on the outdoor thermal comfort: A case study of Jeddah, Saudi Arabia. International Journal of Low-Carbon Technologies, 15(4), 594–606. doi:10.1093/ijlct/ctaa028.

[40] Verma, L. A., & Bano, F. (2023). Socio-Environmental Sustainability of Traditional Courtyard Houses of Lucknow and Varanasi. U.Porto Journal of Engineering, 9(1), 72–103. doi:10.24840/2183-6493_009-001_001438.

[41] Dervishi, S., & Baçi, N. (2023). Early design evaluation of low-rise school building morphology on energy performance: Climatic contexts of Southeast Europe. Energy, 269, 126790. doi:10.1016/j.energy.2023.126790.

[42] UAE maps 2025, UAE Travel Guide, Dubai, United Arab Emirates. Available online: http://emiratesvoyage.com/uae-maps/ (accessed on November 2025).

[43] 2GIS, Novosibirsk, Russia. Available online: https://2gis.ae/sharjah/geo/13933750081633894?m=55.441692%2C25.352723%2F16.4%2Fp%2F1.09%2Fr%2F-15.85 (accessed on November 2025).

[44] Google maps, Mountain View, United States. Available online: https://www.google.com/maps/place/6029:+That+Al+Netaqain+Girls+Schools/@25.3940745,55.4876186,629a,35y,39.28t/data=!3m1!1e3!4m6!3m5!1s0x3e5f5874b268149f:0xfb998da900a1825b!8m2!3d25.3978378!4d55.4867104!16s%2Fg%2F1yg56gvtf?entry=ttu (accessed on November 2025).

[45] Khalfan, M., & Sharples, S. (2016). Thermal comfort analysis for the first Passivhaus project in QATAR. Proceedings of the SBE16 Dubai, Dubai, United Arab Emirates, 17-19 January, 2016, Dubai, United Arab Emirates.

[46] Feroz, S. M. (2014). Achieving thermal comfort by applying passive cooling strategies to courtyard houses in Dubai (UAE) Master Thesis, The British University in Dubai, Dubai, United Arab Emirates.

[47] Al-Sallal, K. A. (2010). Daylighting and visual performance: Evaluation of classroom design issues in the UAE. International Journal of Low-Carbon Technologies, 5(4), 201–209. doi:10.1093/ijlct/ctq025.

[48] A holistic microclimate model. (2024). PET and PET* (PET Reviewed). Available online: https://envi-met.info/doku.php?id=apps%3Abiomet_pet (accessed on November 2025).

[49] Kin, E., Forsch, S., & Glickmans, L. (2021). Cooler buildings in a warming South Asia. World Bank Blogs, Washington, United States. Available online: https://blogs.worldbank.org/en/endpovertyinsouthasia/cooler-buildings-warming-south-asia (accessed on November 2025).

[50] Bhatia, A. (2020). HVAC Cooling Load Calculations and Principles. Course M318 (5 PDH), PDH online, Fairfax, United States.

[51] Ghaffarianhoseini, A., Berardi, U., & Ghaffarianhoseini, A. (2015). Thermal performance characteristics of unshaded courtyards in hot and humid climates. Building and Environment, 87, 154–168. doi:10.1016/j.buildenv.2015.02.001.

[52] Alvarez, E. G., Mueller, C. T., & Norford, L. K. (2022). Dynamic thermal performance of structurally optimized concrete floor slabs. In Building Simulation Conference Proceedings (Vol. 17, pp. 989–996). IBPSA. doi:10.26868/25222708.2021.31052.

[53] CO2METER. (2025). Carbon Dioxide Levels Chart, Ormond Beach, United States. Available online: https://www.co2meter.com/blogs/news/carbon-dioxide-indoor-levels-chart?srsltid=AfmBOorFUfKfiElUUcWhyKcgL712oJvwvyeyrzllc1V5YIhIjUJe4PXB (accessed on November 2025).

[54] Habibi, S. (2024). The effect of building orientation on energy efficiency. Clean Technologies and Environmental Policy, 26(4), 1315–1330. doi:10.1007/s10098-023-02695-w.

[55] Zheng, Z., Xiao, J., Yang, Y., Xu, F., Zhou, J., & Liu, H. (2024). Optimization of exterior wall insulation in office buildings based on wall orientation: Economic, energy and carbon saving potential in China. Energy, 290, 130300. doi:10.1016/j.energy.2024.130300.

[56] Mangkuto, R. A., Tresna, D. N. A. T., Hermawan, I. M., Pradipta, J., Jamala, N., Paramita, B., & Atthaillah. (2024). Experiment and simulation to determine the optimum orientation of building-integrated photovoltaic on tropical building façades considering annual daylight performance and energy yield. Energy and Built Environment, 5(3), 414–425. doi:10.1016/j.enbenv.2023.01.002.

[57] Dai, J., Wang, J., Bart, D., & Gao, W. (2023). The impact of building enclosure type and building orientation on indoor thermal comfort -A case study of Kashgar in China. Case Studies in Thermal Engineering, 49, 103291. doi:10.1016/j.csite.2023.103291.

[58] Muhy Al-Din, S. S., Ahmad Nia, H., & Rahbarianyazd, R. (2023). Enhancing Sustainability in Building Design: Hybrid Approaches for Evaluating the Impact of Building Orientation on Thermal Comfort in Semi-Arid Climates. Sustainability (Switzerland), 15(20), 15180. doi:10.3390/su152015180.