

Integrating Qibla-Oriented Design with Energy Efficiency: A Comparative Simulation Study of Building Shape and Orientation Across Diverse Egyptian Climatic Regions

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Integrating Qibla-Oriented Design with Energy Efficiency: A Comparative Simulation Study of Building Shape and Orientation Across Diverse Egyptian Climatic Regions

Abstract:

This study investigates the impact of building shape and orientation, including Qibla alignment, on energy consumption and CO₂ emissions across three distinct climatic regions in Egypt: Cairo, Alexandria, and Aswan. A simulation-based methodology was employed to evaluate four building geometrical shapes: square, rectangular, triangular, and circular—under multiple orientation angles. The analysis was conducted under controlled conditions, where building dimensions, material properties, and operational parameters were kept constant to isolate the effects of geometry and orientation.

The results demonstrate that building geometry is the dominant factor influencing energy performance, while the orientation plays a secondary level, but a climate-dependent role. Compact geometries consistently exhibited lower energy consumption and emissions, whereas irregular shapes showed higher sensitivity to solar exposure. The impact of orientation increased with climatic severity, reaching its highest levels in hot desert conditions.

The Qibla orientation demonstrated stable and acceptable performance across all cases, with only minor increases in energy consumption relative to optimal orientations. The energy penalty remained within approximately 3–7% in Cairo, 3–6% in Alexandria, and below 3% in Aswan.

These findings confirm that aligning buildings with the Qibla direction does not significantly compromise energy efficiency when appropriate design strategies are applied. The study highlights the potential for integrating cultural and functional requirements with energy-efficient building design, providing a validated methodological framework for climate-responsive architecture.

Keywords

Building shape, Orientation, Qibla Direction, Energy Consumption, CO₂ Emissions, Thermal Performance.

1. Introduction

The architectural building orientation is considered one of the essential factors affecting environmental design. In Islamic countries, building orientation may be influenced by religious requirements, such as alignment toward the Qibla. This orientation is due to the cultural and religious identity, which affects the solar radiation, ventilation, thermal comfort, and energy consumption [1]. The Qibla, defined as the direction toward the Kaaba in Makkah, serves as a fundamental orientation for Muslims all over the world in performing prayer and constitutes a significant factor influencing building orientation in predominantly Muslim contexts. Within Islamic architecture, orienting buildings towards the Qibla holds profound spiritual and symbolic value, extending beyond ritual practice to shape the organization of interior spaces [2]. For the mentioned reasons, it is necessary to arrange the Prayer rooms or spaces for individual worship directly to face the Qibla, while service spaces such as kitchens and bathrooms are positioned on the opposite side, in harmony with both religious regulations and functional considerations. Consequently, the Qibla is regarded not only as a determinant of spiritual orientation but also as a structuring element in spatial organization within Islamic architecture [3]. As prescribed by the Qur'ān, Islamic architecture aims to provide a suitable

and comfortable environment in which Muslims can carry out their duties. The Qur'ān, for example, declares that houses should be made resting places: “It is Allah Who made your habitations homes of rest and quiet for you “(16:80). Houses, therefore, should provide comfort, calmness, and healthy living, and should fulfill the needs of occupants. This also requires good ventilation, lighting, and spaciousness. In a verse of the Qur'ān, Muslims are instructed to orient their homes toward the *Qiblah* (Ka'bah in Mecca) “Settle your people in Egypt in houses and make your houses [facing the] qiblah... “(10:87). Regarding hygiene, Muslims are directed to position toilets away from the direction of the *Qiblah*, according to a ḥadīth (saying) of Prophet Muḥammad (pbuh) [4].

The Arab Republic of Egypt, a predominantly Muslim country, has a Qibla direction of approximately 136° from north (towards the southeast). This research paper examines the orientation toward the Qibla in three Egyptian cities (Cairo, Alexandria, and Aswan) representing the country's major climatic zones. The Qibla direction is 138.2° in Cairo, 137.6° in Alexandria, and 100.29° in Aswan [5]. When the primary façades of the building are oriented southeast ($\sim 136^\circ$ from north, as in Cairo), they are exposed to strong morning solar radiation from the east and additional solar gains from the south, which provide beneficial winter heating. This contrasts with west-facing façades, which experience the most severe afternoon heat gains during summer.

Selecting the appropriate building orientation contributes to optimizing the use of natural energy sources such as solar radiation and wind flow, thereby supporting the creation of comfortable and energy-efficient living environments. Thermal conditions are a decisive factor in this regard, as building orientation directly affects its capacity to utilize solar heat and air currents for regulating indoor temperatures [6–8]. A study conducted in (Rumoh Aceh, Indonesia) [9] indicates that orienting a building at 292.19° (aligned with the Qibla) provides the best thermal quality in terms of temperature and humidity, while also embodying cultural significance and reflecting local wisdom. Conversely, an orientation of 260° achieves improved thermal comfort when supported by favorable wind speed. The results further reveal variations in indoor thermal performance, including temperature, humidity levels, and air movement speed, depending on geographic location and seasonal cycles throughout the year (January to December). These findings highlight the necessity of considering geographic factors in building design to achieve optimal thermal performance.

Additionally, Azmi [10] demonstrated that optimizing the Qibla wall design in mosques can reduce the internal surface wall temperature by $4\text{--}6^\circ\text{C}$ during peak heat periods. Combining improved wall design with mechanical ventilation ensures substantial enhancement of thermal comfort levels, with improvements ranging from 40% to at least 80% across different times of the day (this study focuses on mosques; its findings are equally applicable to residential and other building types, particularly regarding Qibla-facing façades). Regarding Ashmawy [11], who discussed the impact of building orientation on energy consumption in Egypt, building orientation is considered a crucial factor in determining the amount of energy required to achieve thermal comfort for users. The study results indicated that the southern façade results in the lowest energy consumption due to reduced heating loads during the winter season. In contrast, the western façade records the highest annual energy consumption, approximately 26% higher than that of the southern façade. Similarly, in Egypt, Elshamy in his study [12] presented a study which conducted at the British University in Egypt – Cairo, which compared two identical rooms in terms of shape and equipment but with different façade orientations (north and south). The results showed that the south-facing room required significantly higher cooling energy than the north-facing one, with the north orientation saving about 44.5% of cooling energy consumption compared to the south. Furthermore, Mohammed [13] compared different Egyptian cities

to determine the optimal building orientation and insulation layer thickness. The study found that the best orientation in Cairo and Port Said is along the north–south axis, while in other cities, intermediate orientations (NE, NW, SE, SW) may be acceptable or even preferable depending on the location. In another site in Upper Egypt (New Assiut), study [14] examined how changing the orientation of rooms or buildings affects indoor temperature during hot and cold periods. The results showed that the southern orientation (tilted at an angle of 180°) is the most favorable, as it results in higher indoor temperatures during the cold season, while the least efficient orientation is the north-west orientation (tilted at an angle of 315°).

Table 1. The Impact of Building Orientation on Energy Consumption in Egypt

Region	Optimal Orientation	Energy Reduction (%)	Additional Notes	Authors and Year	Ref. No.
Cairo	South–North	20–26%	Reduces cooling demand and improves daylight quality.	Ashmawy, R. E., (2018).	[11]
New Cairo	North-facing façades	44.5%	North-facing rooms consumed significantly less cooling energy than south-facing.	Elshamy, A. I., & Safwat, H. (2025).	[12]
Alexandria	North-East–South-West (NE–SW)	15–20%	Aligns with sea breeze direction, reducing solar heat gain.	El-Sayad, A., & Ahmed, S. H. (2022).	[17]
Aswan	North–South	30–36%	Low surface-to-volume ratio ($S/V < 0.38$) enhances cooling efficiency.	Mahmoud, A. R. (2022).	[15]
New Aswan	Aligned with prevailing north winds	—	Improved outdoor thermal comfort by 2–3°C.	Mahmoud, H. (2019).	[16]
New Assiut City	North-East	—	Balanced daylight and ventilation with reduced internal heat gain.	Aly, A. A. E. M. M., & Abdel Magid, E. S. S. (2011).	[14]
Multiple cities (Cairo–Port Said–Aswan)	North–South (N–S)	20–30%	Optimal for most Egyptian cities, slight variations for coastal regions.	Mohammed Arandah, W. M. & Abdel-Hamid, M. (2025).	[13]

The impact of building form, is considered one of the most significant factors influencing energy efficiency and thermal comfort, particularly in the hot arid climate that characterizes most regions of Egypt. The variation in the geometric form of a building leads to changes in the surface area-to-volume ratio, which directly affects the rates of heat loss and gain from the surrounding environment. Moreover, the building form is associated with the distribution of natural ventilation and indoor lighting conditions, which consequently influence the level of thermal comfort and the occupants' sense of climatic stability within indoor spaces.

Recent studies, such as study [18], compared four building forms (rectangular, square, circular, and elliptical) across multiple Egyptian cities (Alexandria, Cairo, Minya, Assiut, Hurghada, El Kharga and Aswan). The findings revealed that, in most cities, the forms that achieved the lowest annual energy consumption were the circular or elliptical ones, often followed by the square form, while the rectangular form performed the worst. In Cairo and Minya, the circular form was slightly better than

the square and elliptical ones in terms of energy consumption and thermal comfort. However, in Assiut, the elliptical form outperformed the circular one in both energy efficiency and user comfort. Hanafy, in his work [19] did not compare many forms but focused on two main shapes: (rectangular and square), within different window-to-wall ratios (WWR) ranging from 10% to 90% across several Egyptian cities. The results indicated that the rectangular form with a width-to-length (W/L) ratio of approximately 1:3 and a WWR of around 20% provided the best annual energy performance across most regions. Meanwhile, the square form required a WWR between 20% and 30% to achieve optimal performance in most cases. In study [20], a comparison was made among various shape families: circular/elliptical, letter-shaped forms (H, L, U, T), multi-angular shapes (polygon, pentagon, and decagon), and “pixel-complex cubic” or other complex cubic configurations. The results showed that the circular family achieved the best EUI (annual thermal energy consumption) compared to the basic square form. However, complex and letter-shaped forms can also yield good results if carefully designed, though they require longer simulation and optimization processes. Liang's work[21], which is a systematic review of research, investigated how building form affects heating and cooling energy consumption, found that the more compact the building form (i.e., lower external surface area relative to internal volume), the lower the cooling energy consumption—especially in hot climates. Circular or rounded forms generally produced the best efficiency results, although the difference tended to be minor when other design factors such as orientation, window openings, and shading were optimized.

Table 2. Comparison Between Building Forms and Their Impact on Energy Performance in Egypt’s Climate

Building Form	Energy Performance (EUI / Energy Consumption)	Thermal Comfort	Main Advantages	Main Disadvantages	Authors and Year	Ref. No.
Circular	The most efficient form in most studies consumes 5–15% less energy compared to square and rectangular forms	Highest thermal comfort; balanced distribution of heat and shading	Reduces surface-to-volume ratio → lower heat loss and better air distribution	Difficult to design and construct using traditional layouts	El-Agami, M., Hanafy, G., & Osman, M. (2021). Khalil, A., Lila, A. M. H., & Ashraf, N. (2023).	[18]• [20]
Elliptical	Very similar to circular, occasionally outperforming it in regions such as Assiut and Aswan	Provides comfortable indoor conditions with balanced solar exposure	Offers a good balance between performance and modern aesthetics	More complex construction and higher cost compared to square forms	El-Agami, M., Hanafy, G., & Osman, M. (2021).	[18]
Square	Performs well – comparable to circular when orientation and window openings are optimized	Acceptable – more sensitive to direction and ventilation	Simple to construct, flexible in layout and planning	Requires controlled window-to-wall ratios and shading to minimize solar gain	Hanafy, G., El-Agami, M., & Osman, M. (2022). Li, J., Liang, C., & Zhou, W. (2024).	[19]• [21]

Rectangular	Higher energy consumption (less efficient, especially in Cairo and Minya)	High thermal variation between façades	Easy to construct; performs better when oriented north–south	Large surface area → higher solar heat gain, especially on east and west façades	El-Agami, M., Hanafy, G., & Osman, M. (2021). Hanafy, G., El-Agami, M., & Osman, M. (2022).	[18], [19]
Alphabetic Forms (L, T, U, H)	Moderate to low performance depending on orientation and simulation results	Moderate	Allow good natural ventilation and daylight penetration into deeper spaces	High heat loss at corners and intersections	Khalil, A., Lila, A. M. H., & Ashraf, N. (2023).	[20]
Complex / Polygonal Forms (Pixel-like)	Generally, the highest energy consumption if not optimized	Lower thermal comfort if not properly designed	High architectural expressiveness and aesthetic value	Very large exposed surface → significant heat gain	Khalil, A., Lila, A. M. H., & Ashraf, N. (2023).	[20]

Finally, this paper examines the building orientation toward the *Qibla* (South–East) and its relation to other orientations, along with examining different building forms (circular, square, rectangular, and triangular) to investigate their impact on thermal comfort and energy efficiency in buildings in Egypt.

2. Materials and Methods

To achieve the objectives of the current work, a comprehensive methodology was adopted comprising three main components. The first component is the theoretical study, which relies on literature reviews aimed at identifying the most suitable building massing configurations for the Egyptian context to be adopted in this work, in addition to describing the selected case-study models. The second component is the analytical study, which involves determining the selected cities in which the case-study models are located and analyzing the climatic regions of these Egyptian cities to extract the optimal energy-efficiency levels for the most relevant parameters associated with the cases selected in the first component. The third component focuses on the computational study and the simulation tools used to assess the energy performance of the selected case-study models according to the climatic region in which they are located.

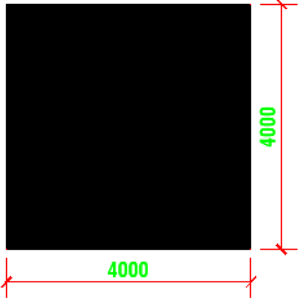
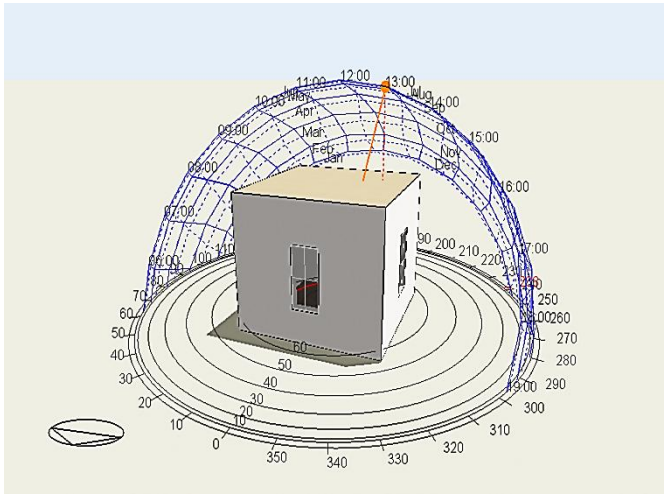
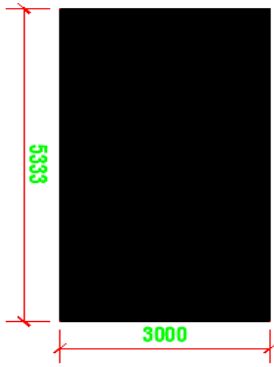
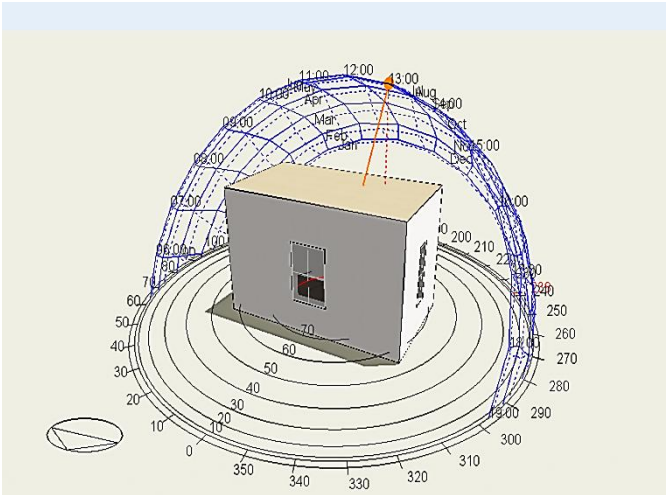
2.1. Theoretical Study and Case Study Description

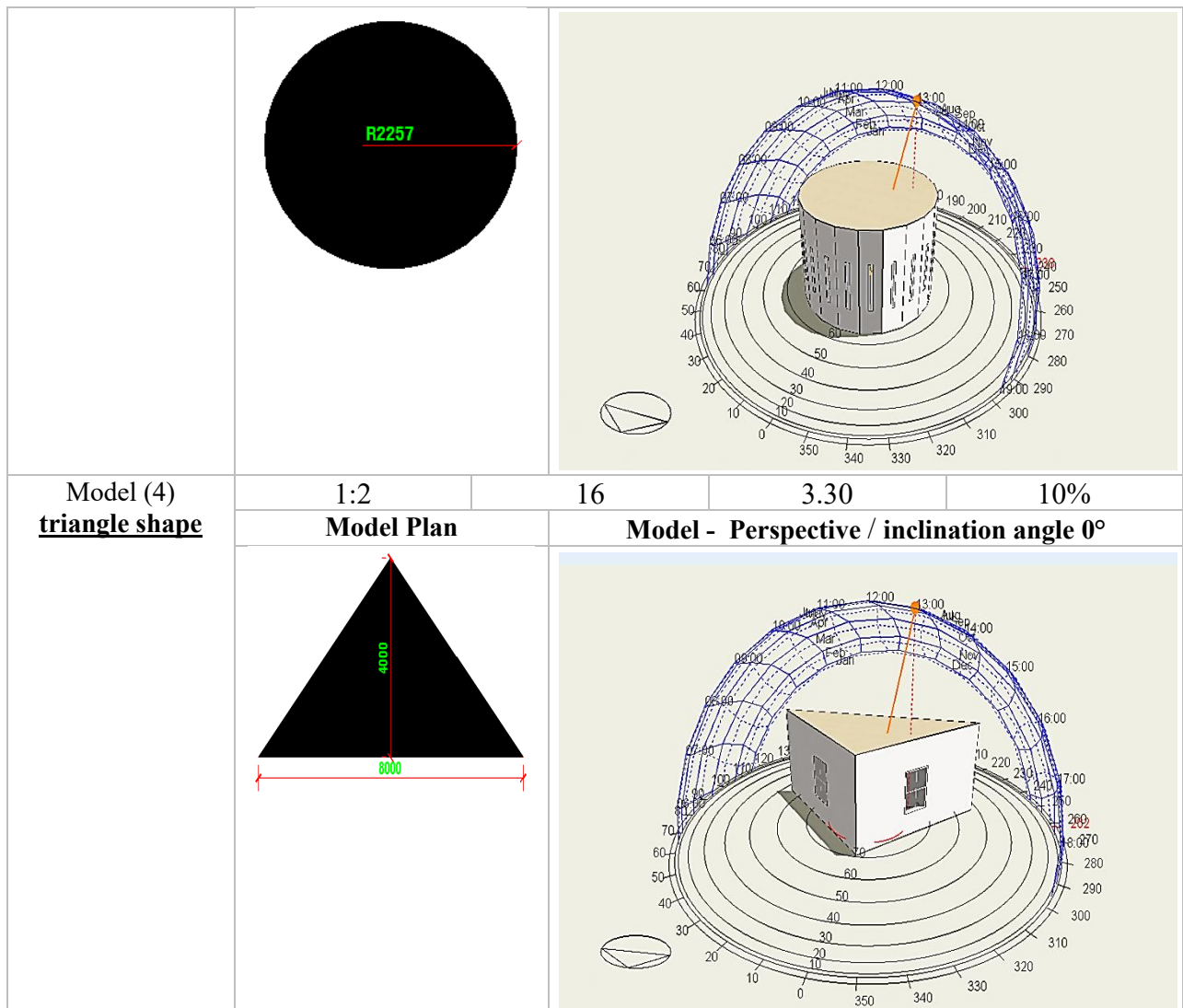
According to the previous work discussed in the introduction, Studies have consistently shown that primary geometric forms—such as the circle and the square—achieve the lowest levels of energy consumption across a wide range of climatic conditions [18–21]. Furthermore, the findings of Olgay [1, 22] and Yeang [23] demonstrate that width-to-length ratios (W/L) of 1:1 and 1:2 are among the most effective in minimizing heat gain in temperate and hot climates comparable to those of Egypt, thereby contributing to improved building energy performance. Drawing on these insights, the present study adopts four principal geometric configurations: square, rectangle, circle, and triangle. The optimal W/L ratios were applied to both the circular and square models to establish the geometric foundation of the proposed forms.

All tested models were standardized as single-story residential units (living rooms) with a height of 3.30 m and an approximately equal floor area of 16 m². The window-to-wall ratio (WWR) was set at 10%, following the recommendation of Hanafy [11], who examined rectangular and square

forms across multiple Egyptian cities to identify optimal energy-efficiency conditions. As a key study parameter, each tested model was rotated through the eight principal orientations (The cardinal directions) (from North at 0° to Northwest at 315°) and compared with the *Qibla* orientation for each selected studied city. Table 3 presents the geometric configurations of the case-study models in accordance with the methodological framework described above.

Table 3. Geometric shapes of study models

	W/L	Area (m ²)	H (m)	WWR
	1:1	16	3.30	10%
Model (1) <u>Square shape</u>	Model Plan	Model - Perspective/inclination angle 0°		
				
Model (2) <u>Rectangle shape</u>	≈ 1:2	16	3.30	10%
	Model Plan	Model - Perspective / inclination angle 0°		
				
Model (3) <u>Circle shape</u>	1:1	16	3.30	10%
	Model Plan	Model - Perspective / inclination angle 0°		



2.2. Analytical Study

The investigation was conducted across three Egyptian cities; Cairo, Alexandria and Aswan. Each of them represents a distinct climatic region. Cairo, the country's capital, is classified as a hot desert climate (BWh) according to the Köppen system [25, 26]. Alexandria, by contrast, falls within the temperate coastal climatic zone, while Aswan is situated in a hot arid desert region under the same classification framework. Table 4 provides a comparative overview of the three climatic zones and highlights the key environmental characteristics of each city. Figure 1 illustrates the monthly averages of temperature (°C) and precipitation (mm) for the selected cities based on the Köppen–Geiger climate classification.

Table 4. Comparing the climate of Cairo, Alexandria, and Aswan with the most important characteristics of each city.

City	Climate Zone (Köppen Classification)	Average Summer Temperature (°C)	Average Winter Temperature (°C)	Average Annual Precipitation (mm)	Key Climatic Notes
Cairo	Hot Desert / Semi-Arid (BWh/BSH)	34–36	10–15	25–50	Hot and dry summers, mild

					winters, mostly sunny days
Alexandria	Mediterranean, Semi-Humid (Csa/Csb)	30–32	12–18	200–250	Relatively mild summers, high humidity, scattered winter rainfall
Aswan	Hot Desert (BWh)	40–42	10–15	<50	Very long and hot summers, mild winters, very low humidity

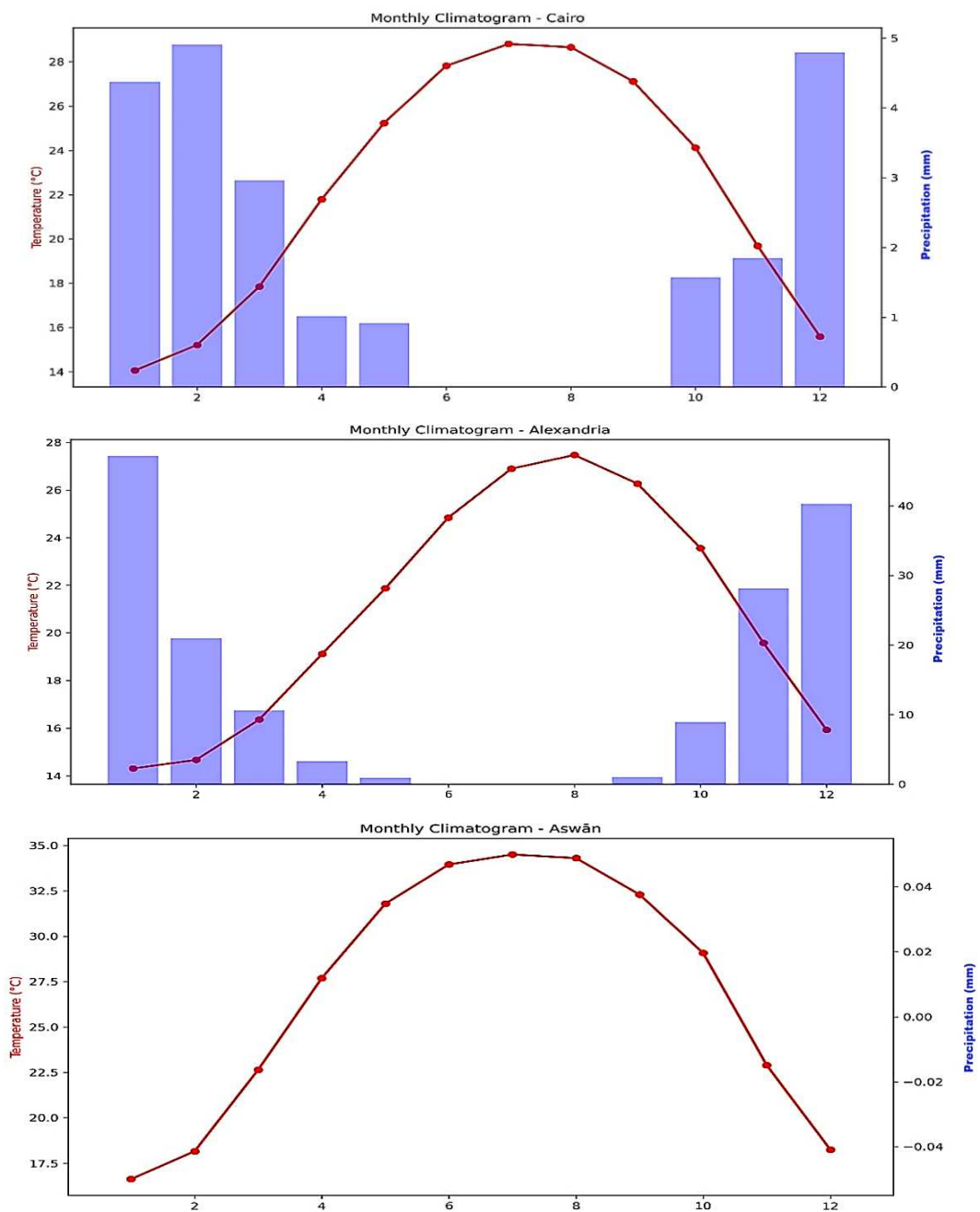


Fig. 1. Combined temperature (°C) and precipitation (mm) monthly averages for the three cities (Cairo, Alexandria, Aswan) according to the Köppen–Geiger classification system [25].

2.2.1. Analysis of climate data for the three regions:

The relationship between outdoor dry-bulb temperature and direct normal solar radiation throughout the entire year (365 days) for the three studied cities is presented in Figures 2, 3, and 4. Two curves are displayed in each figure:

- **Red line:** outdoor air temperature (°C).
- **Gray line:** direct normal solar radiation (kWh/m²).
- **Horizontal axis (X-axis):** Represents the days of the year (approximately 0 to 360).
- **Right vertical axis (Y-axis):** Represents temperature (°C) ranging from 10 to 40.
- **Left vertical axis (Y-axis):** Represents solar radiation (kWh/m²) ranging from 0 to 10.

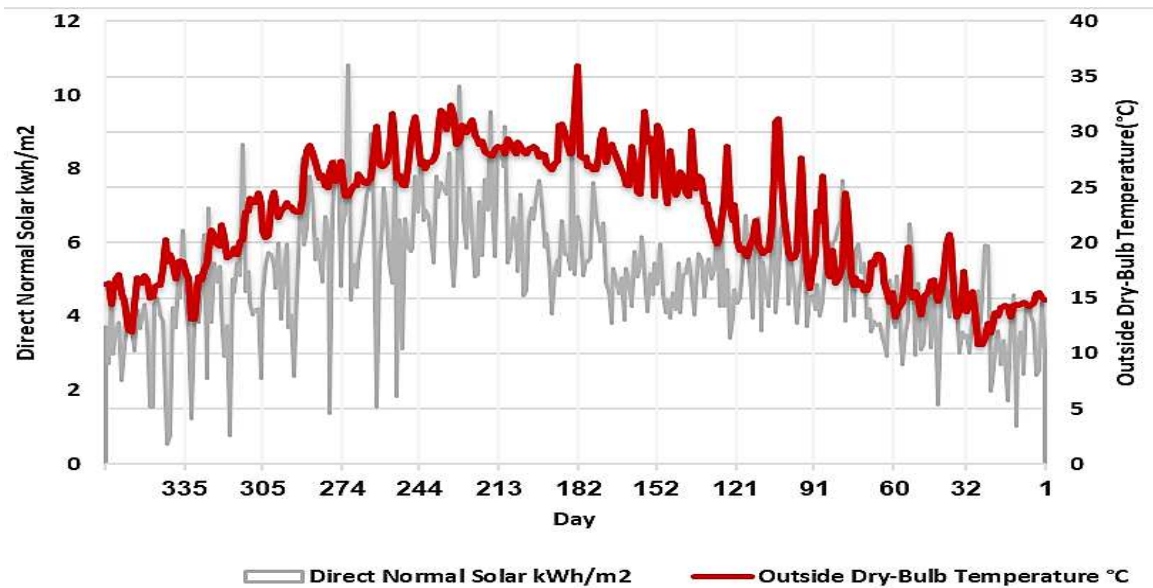


Fig. 2. The daily average temperatures (red) and global horizontal radiation levels (grey) in **Cairo** for the typical meteorological year.

In Figure 2, Cairo Climate Region, the outdoor temperature curve exhibits a gradual increase starting from the beginning of the year, reaching its peak approximately around mid-year, before gradually declining toward the end of the year. Maximum temperatures range roughly between 32 and 36 °C, while minimum values fall between 12 and 16 °C. The direct normal solar radiation follows a similar pattern, showing a clear increase during the mid-year period, with peak values reaching approximately 8–9 kWh/m². This behavior reflects a warm to hot summer and a mild winter, accompanied by relatively high solar radiation levels during the warmer months of the year.

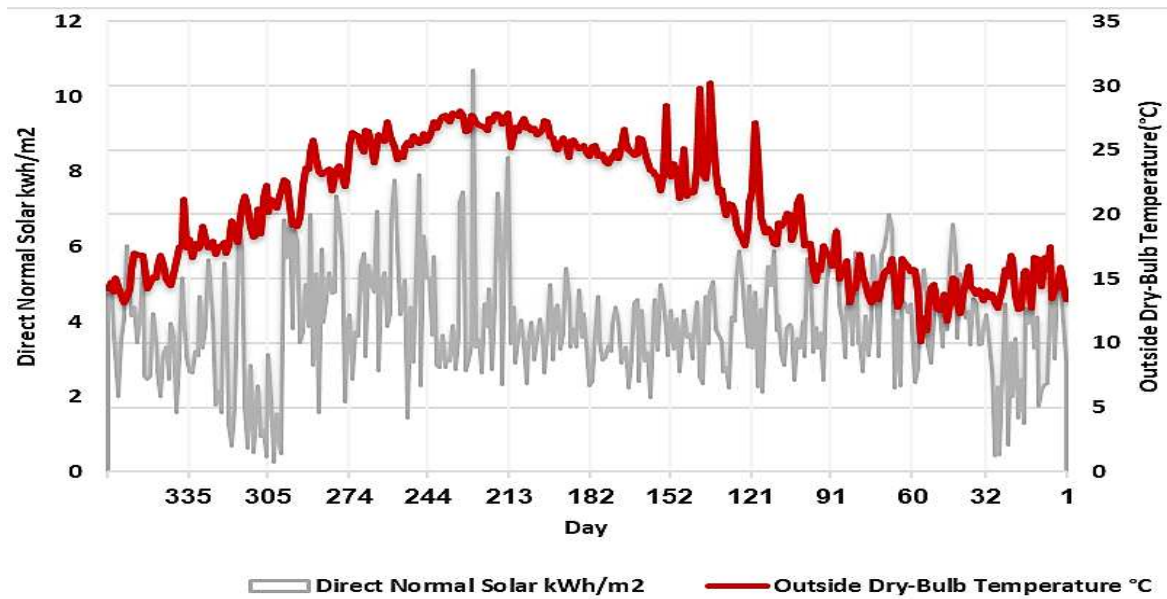


Fig. 3. The daily average temperatures (red) and global horizontal radiation levels (grey) in Alexandria for the typical meteorological year.

Regarding the Alexandria climatic region, Figure 3 shows relatively lower temperatures compared to the Cairo region. Maximum temperatures range between 29 and 31 °C, while minimum values fall between 12 and 15 °C. Temperature fluctuations are also less pronounced than those observed in Cairo. The direct normal solar radiation in this location exhibits a milder increase, with peak values generally ranging from 6 to 7 kWh/m², indicating a relatively lower solar intensity and a more moderate thermal profile throughout the year.

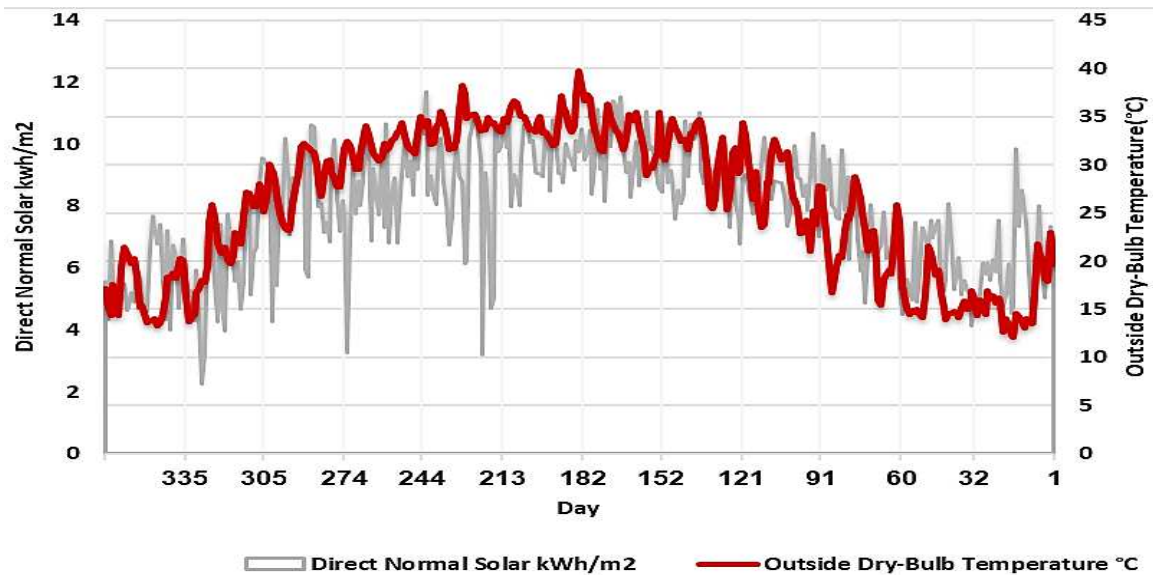


Fig. 4. The daily average temperatures (red) and global horizontal radiation levels (grey) in Aswan for the typical meteorological year.

Figure 4 illustrates the climatic conditions of the Aswan region, which records the highest temperatures among the three studied regions. Temperatures exceed 38–42 °C around mid-year, with elevated values persisting over an extended period. Minimum temperatures generally range between 14 and 18 °C. Furthermore, direct normal solar radiation reaches the highest values among the three regions, with peak levels ranging from 10 to 11 kWh/m² during mid-year periods. This pattern reflects a prolonged, intensely hot summer accompanied by a high level of solar energy.

Based solely on the climatic charts provided for Cairo, Alexandria, and Aswan, the three locations exhibit distinct thermal and rainfall behaviors throughout the year. Cairo demonstrates a clear seasonal pattern, with high temperatures peaking around mid-year and moderate winter conditions, accompanied by very limited rainfall concentrated mainly in December and January. Alexandria, on the other hand, shows a more tempered thermal profile with lower summer temperatures and noticeably cooler winters, in addition to a pronounced increase in rainfall during the winter months. Aswan presents the most extreme pattern among the three, with consistently high temperatures that reach approximately 38–42°C during the peak period and an almost complete absence of rainfall throughout the year. These chart-based observations highlight the substantial climatic variability across the three cities, which plays a critical role in shaping the thermal loads and environmental performance of buildings within each region.

Table 5. Comparative climatic characteristics of Cairo, Alexandria, and Aswan based on TMY data.

City	Annual Temperature Pattern (from chart)	Approx. Maximum Temperature (°C)	Approx. Minimum Temperature (°C)	Annual Rainfall Pattern	Highest Rainfall (mm)	Lowest Rainfall (mm)	Key Climatic Characteristics (chart-based)
Cairo	Hot summer – mild winter	~34–36	~12–16	Very limited winter rainfall	~7–10 (Dec–Jan)	≈0 (Jun–Aug)	Hot and dry summer; mild winter with minimal rainfall
Alexandria	Mild summer – relatively cool winter	~29–31	~12–15	Noticeable winter rainfall	~60–70 (Dec–Jan)	≈0 (Jun–Aug)	Coastal pattern; wet winter and distinct seasonal rainfall
Aswan	Very hot for most of the year	~38–42	~14–18	Nearly no rainfall	≈0	≈0	Extremely hot and arid; persistent high temperatures

2.3. Computer-Based Study and Simulation Tools

Computational simulation has emerged as a highly effective approach for analyzing and forecasting the energy efficiency and thermal performance of buildings [27]. In this study, the EnergyPlus—V8.9 simulation engine was employed via DesignBuilder—V6.1, which was selected for its robust functionality, intuitive modeling capabilities, and advanced graphical interface. Moreover, this software allows for precise evaluation of energy consumption, thermal comfort, daylight availability, and associated costs [28,29]. The overall workflow implemented in DesignBuilder is presented in Figure 5 [30].

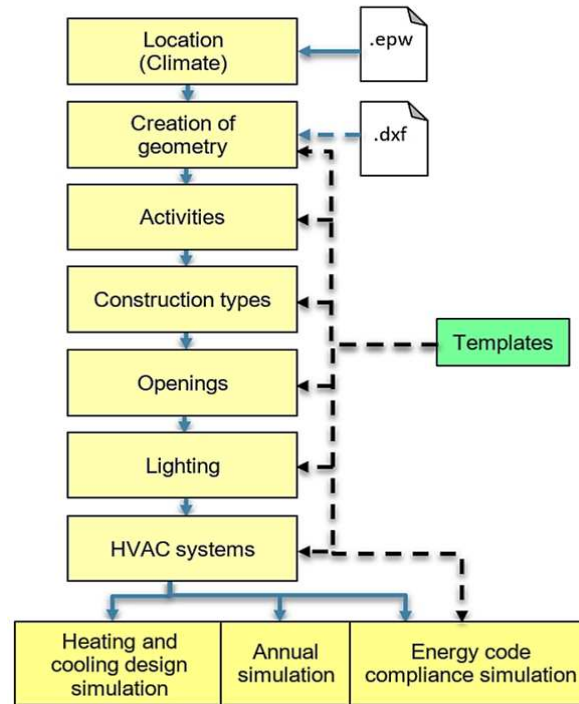


Fig. 5. DesignBuilder workflow [30].

A single-story residential building model (living room) was created for each case using DesignBuilder, with its characteristics, orientation, and floor area defined as described in Sections 2.1 and 2.2. TMY (Typical Meteorological Year) weather files corresponding to each representative city within the three studied climatic regions were assigned to the model. Occupant numbers and density were determined based on the following assumptions and calculations:

Assumptions:

- The occupancy schedule for the building rooms used in the simulation is based on survey results conducted by Attia [31, 32] in various Egyptian cities. These results reflect the average air-conditioning and lighting usage schedules across different spaces in multiple apartments, consistent with the present case study.
- Each occupant requires approximately 6 m² of living room space.

Calculations:

- Net living room area = 16 m²
- Total number of occupants = $16 \div 6 = 2.67 \approx 3$ person.

All input values for heating, cooling, humidity control, and ventilation rates were obtained from the Egyptian Code for Design and Execution of HVAC Works [33]. According to this code, the acceptable temperature range in residential living spaces is 24–26 °C for cooling and 21–23 °C for heating; therefore, this study adopted 24 °C as the upper limit and 21 °C as the lower limit. Lighting levels were adjusted to comply with the Egyptian standards for residential living rooms. Regarding the remaining model inputs, Table 6 presents only the parameters that were specifically modified by the authors, while all other settings within the software were maintained at their default values.

Table 6. DesignBuilder inputs assigned to study models.

Phases / Category	Name/ Parameter	Description/ Total area	Input / Values
Building Description	Type of Building	Residential (Living Room)	—

	Shape	Square (4 m × 4 m)	—
	Number of Floors	1 (Ground Floor)	—
	Total Area (Ground floor)	16 m ²	—
	Gross Wall Area	52.8 m ²	—
	Height	3.3 m	—
	External Walls Construction	(outside) 2 cm thick plaster + 25 cm solid clay brick + 2 cm thick plaster (inside)	U-value = 2.00 W/m ² ·K
	Window-to-Wall Ratio (WWR)	10%	—
	Window Glass Type	Sig Clr glass 6 mm	SHGC = 0.810 LT = 0.881 U-value = 6.121 W/m ² ·K
	Roof Construction	(outside) 2 cm thick Cemented tiles + 2 cm thick mortar + 6 cm thick sandstone + 7 cm slant concrete + 2 cm Bitumen + 15 cm concrete reinforced + 2 cm thick plaster (inside)	U-value = 2.07 W/m ² ·K
	Drawing	Using the DesignBuilder software for drawing the model	—
Program Inputs	Building Orientation		0°
	Weather Data File	(Alexandria/Nouzha, Cairo Airport, Aswan) Egypt	—
	HVAC System	Air-conditioner Type: Split no fresh air	Set the Air-conditioners at a temperature of 24°. Variant as shown in (Figure 6)
	Number of Occupants		3
	Artificial Lighting		2.5 W/m ³ (LED)

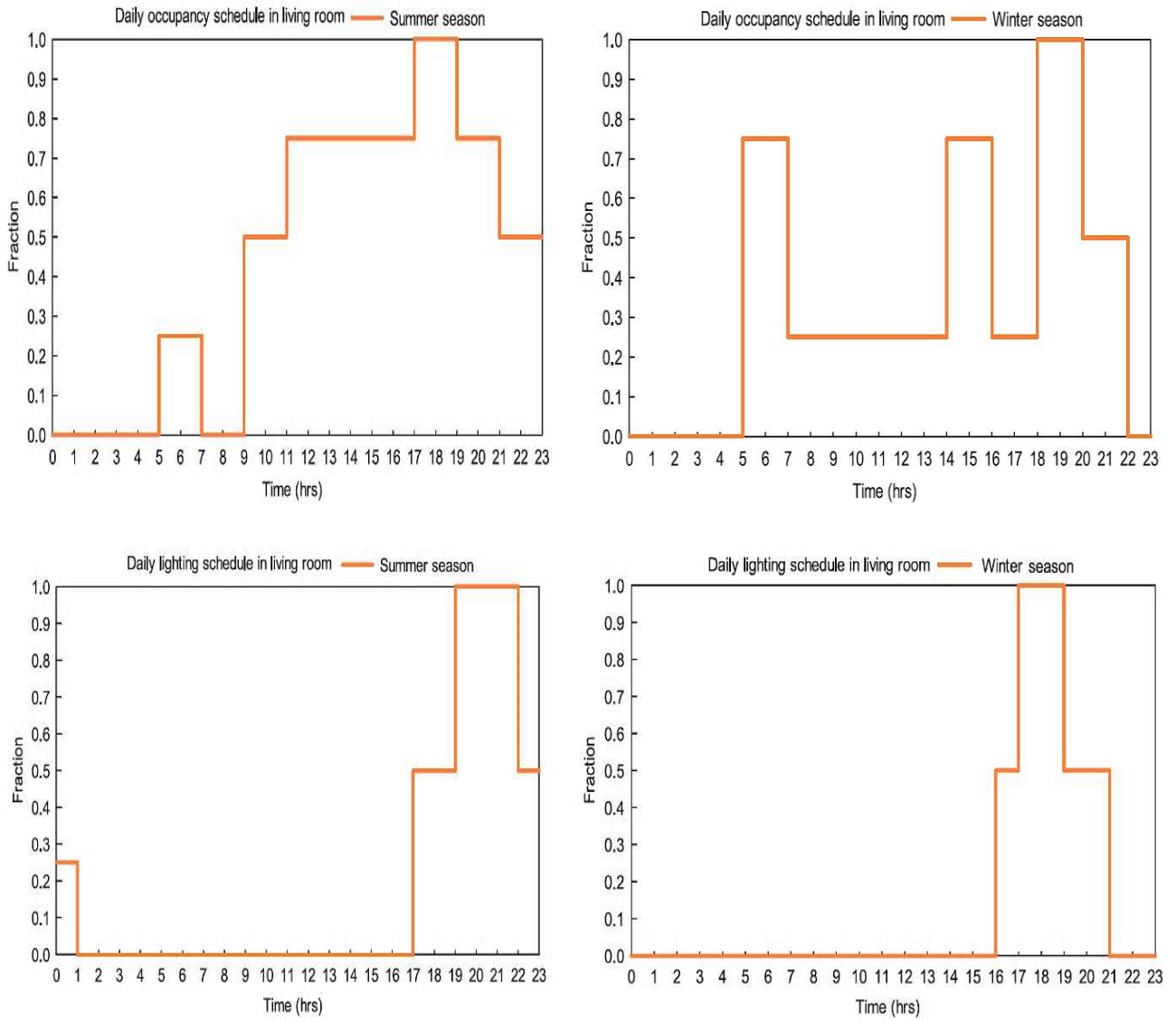


Fig. 6. Daily occupancy schedule for Living rooms.

3. Results

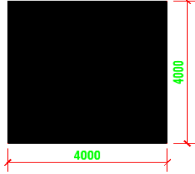
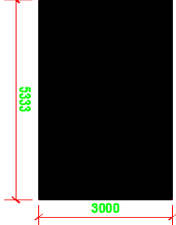
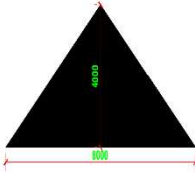
The study results, analyses, and discussions are presented using the simulation tools for both energy consumption and CO₂ emissions, considering various building orientation slope angles across the three distinct climatic regions of the selected Egyptian cities: Cairo, Alexandria, and Aswan. The analysis also accounts for different building shapes: square, rectangular, triangular, and circular. Also includes the evaluation of energy consumption when buildings are oriented toward the *Qibla*. Comparisons between general orientations and the *Qibla direction* are conducted to address the central research hypothesis: whether orienting buildings toward the *Qibla* contributes to the rationalization of energy consumption.

3.1. Cairo (Hot Arid Region)

The simulation results of building shapes in Cairo indicate a clear influence of both building geometry and orientation on annual energy consumption. According to the data presented in Table 7 and Figure 7, the *circular* form achieved the lowest energy consumption at 839 kWh/year, remaining unaffected by orientation (0% variation). In contrast, the *triangular* form recorded the highest values, ranging between 1211 and 1375 kWh/year, due to increased exposed surface areas and higher solar

heat gains. The *square* and *rectangular* forms exhibited moderate performance, with energy consumption values ranging between 1127–1159.87 kWh/year and 1107–1212 kWh/year, respectively. At the *Qibla* orientation (138.2°), the square, rectangular, and triangular forms recorded 1159.87, 1182, and 1277 kWh/year, respectively, representing slight increases compared to their optimal orientations of approximately 2.9%, 6.8%, and 5.5%. These findings indicate that adopting the *Qibla* orientation can achieve an acceptable level of energy efficiency, with only limited increases in energy consumption not exceeding 7%, particularly when compact and thermally efficient building forms are employed.

Table 7. Comparative Analysis of Annual Energy Consumption and CO₂ Emissions for Different Building Forms and Orientations, Including Qibla Direction, in Cairo.

Location	Shape	Slop/ inclination angle	Energy Consumption (kwh/year)	Co2 Emissions (kg Co2)
Cairo	Square (Dimensions 4 * 4 m) 	0.0°	1127	784
		90°	1127	784
		180°	1127	784
		270°	1127	784
		45°	1159.87	804.75
		135°	1159.87	804.75
		225°	1159.87	804.75
		315°	1159.87	804.75
		138.2° Qibla angle 	1159.87	804.75
	Rectangle (Dimensions 3 * 5.333 m) 	0.0°	1107	771
		90°	1212	835
		180°	1107	771
		270°	1212	835
		45°	1188	820
		135°	1199	827
		225°	1188	820
		315°	1199	827
		138.2° Qibla angle 	1182	816
	triangle (Dimensions (8 L * 4 h) m) 	0.0°	1211	829
		90°	1367	923
		180°	1220	834
		270°	1375	928
		45°	1284	873
		135°	1288	875
		225°	1272	865
		315°	1302	883
		138.2° Qibla angle 	1277	868
	Circle (Dimensions R= 2.257 m)	Any slope itself	839	612

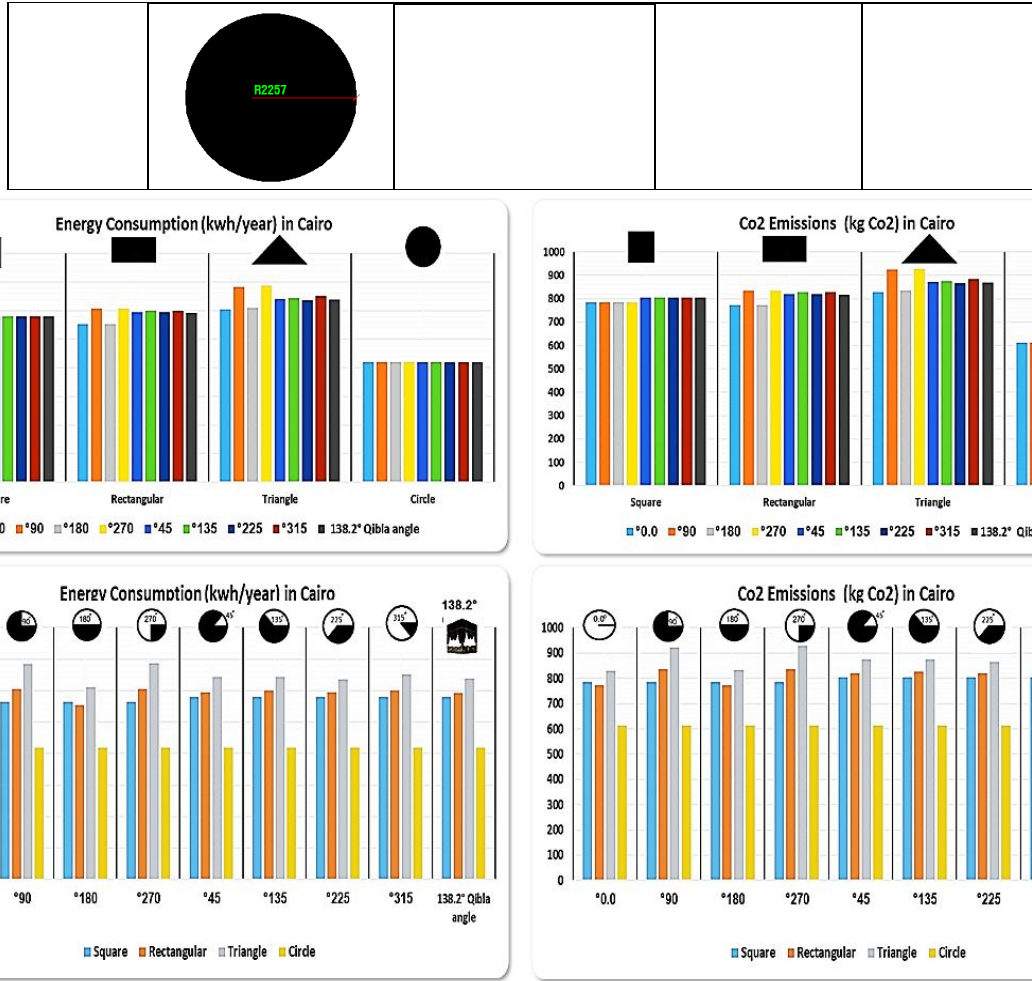


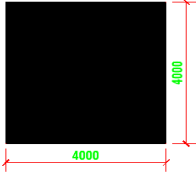
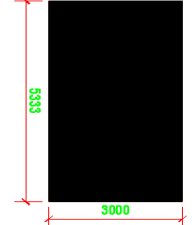
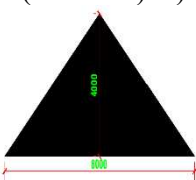
Fig. 7. Comparative Analysis of Energy Consumption and CO₂ Emissions Across Building Forms and Orientation Angles, Including Qibla Direction (138.2°), in Cairo.

3.2. Alexandria (Temperate Coastal Climate Region)

The simulation results for building forms in Alexandria, according to the data presented in Table 8 and Figure 8, demonstrate that both building geometry and orientation influence annual energy consumption under temperate coastal climatic conditions, with the magnitude of impact varying by building form. For the *square* form, energy consumption remained relatively stable, ranging between 727 and 745.65 kWh/year, with a maximum variation of approximately 2.6% across different orientations. At the *Qibla* orientation (137.6°), the energy consumption reached 745.85 kWh/year, representing an increase of approximately 2.6% compared to the optimal orientation. For the *rectangular* form, energy consumption ranged between 716 and 777 kWh/year, indicating a variation of approximately 8.5% across orientations. At the *Qibla* orientation, the recorded value was 764 kWh/year, corresponding to an increase of approximately 6.7% relative to the minimum consumption. The *triangular* form exhibited higher sensitivity to orientation, with energy consumption varying between 776 and 870 kWh/year, reflecting a variation of approximately 12%. At the *Qibla* orientation, energy consumption reached 820 kWh/year, representing an increase of approximately 5.6% compared to the optimal case. The circular form showed constant energy performance, with a fixed value of 526 kWh/year, remaining unaffected by orientation (0% variation).

Overall, the results indicate that the impact of orientation varies depending on building form, with relatively low sensitivity observed in compact geometries and higher sensitivity in irregular forms. The *Qibla* orientation consistently results in minor energy increases (generally below 7%), indicating that it can be adopted without significant compromise in energy efficiency.

Table 8. Comparative Analysis of Annual Energy Consumption and CO₂ Emissions for Different Building Forms and Orientations, Including Qibla Direction, in Alexandria.

Location	Shape	Slop/ inclination angle	Energy Consumption (kwh/year)	Co2 Emissions (kg Co2)
Alexandria	Square (Dimensions 4 * 4 m) 	0.0°	727	542
		90°	727	542
		180°	727	542
		270°	727	542
		45°	745.65	553.73
		135°	745.65	553.73
		225°	745.65	553.73
		315°	745.65	553.73
		137.6° Qibla angle 	745.85	553.85
	Rectangle (Dimensions 3 * 5.333 m) 	0.0°	716	534
		90°	777	571
		180°	716	534
		270°	777	571
		45°	767	565
		135°	763	563
		225°	767	565
		315°	763	563
		137.6° Qibla angle 	764	563
	triangle (Dimensions (8 L * 4 h) m) 	0.0°	776	565
		90°	870	622
		180°	779	567
		270°	870	622
		45°	825	595
		135°	812	587
		225°	819	591
		315°	820	592
		137.6° Qibla angle 	820	592
	Circle (Dimensions R= 2.257 m) 	Any slope itself	526	422

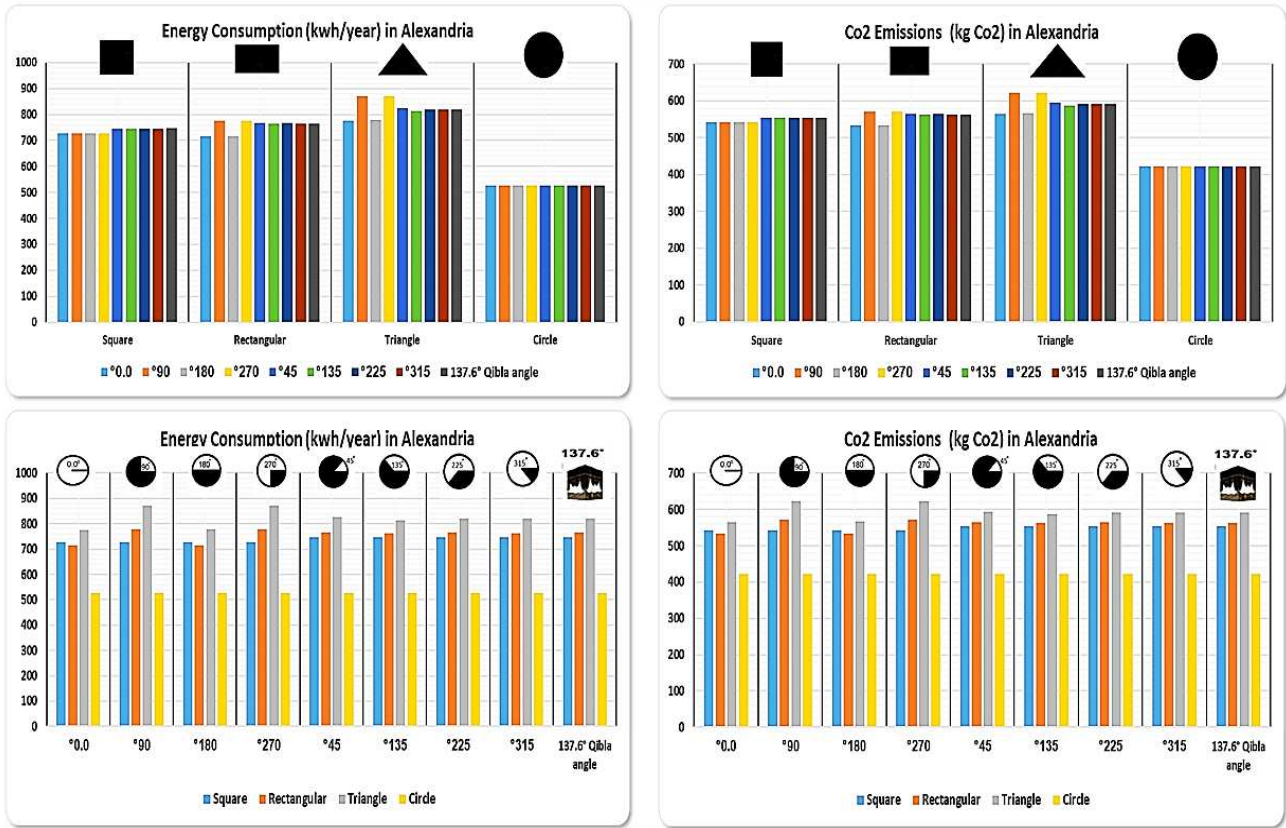


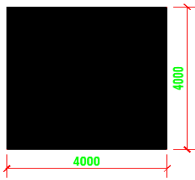
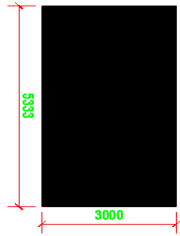
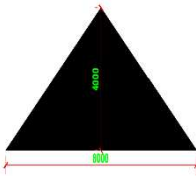
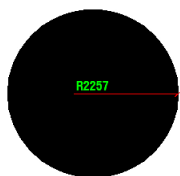
Fig. 8. Comparative Analysis of Energy Consumption and CO₂ Emissions Across Building Forms and Orientation Angles, Including Qibla Direction (137.6°), in Alexandria.

3.3. Aswan (Hot Arid Desert Climate Region)

The simulation results for building forms in Aswan, according to the data presented in Table 9 and Figure 9, demonstrate that both building geometry and orientation significantly influence annual energy consumption under hot arid desert climatic conditions, with the magnitude of impact varying depending on building form. For the *square* form, energy consumption ranged between 2150 and 2233 kWh/year, representing a variation of approximately 3.9% across different orientations. At the *Qibla* orientation (100.3°), the energy consumption was 2182 kWh/year, corresponding to an increase of approximately 1.5% compared to the optimal orientation. For the *rectangular* form, energy consumption varied between 2104 and 2333 kWh/year, indicating a variation of approximately 10.9%. At the *Qibla* orientation, the recorded value was 2156 kWh/year, reflecting a moderate increase of approximately 2.5% relative to the minimum consumption. The *triangular* form exhibited the highest sensitivity to orientation, with energy consumption ranging between 2339 and 2690 kWh/year, corresponding to a variation of approximately 15%. At the *Qibla* orientation, the energy consumption reached 2372 kWh/year, representing an increase of approximately 1.4% compared to the optimal case. The *circular* form showed constant energy performance, with a fixed value of 1670 kWh/year, remaining unaffected by orientation (0% variation).

Overall, the results indicate that orientation effects are more pronounced in irregular geometries under hot arid conditions, while compact forms demonstrate lower sensitivity. The *Qibla* orientation consistently results in minor energy increases (generally below 3%), indicating that it can be adopted with minimal impact on energy efficiency in desert climates.

Table 9. Comparative Analysis of Annual Energy Consumption and CO₂ Emissions for Different Building Forms and Orientations, Including Qibla Direction, in Aswan.

Location	Shape	Slop/ inclination angle		Energy Consumption (kwh/year)	Co2 Emissions (kg Co2)
Aswan	Square (Dimensions 4 * 4 m) 	0.0°		2150	1405
		90°		2150	1405
		180°		2150	1405
		270°		2150	1405
		45°		2233	1455
		135°		2233	1455
		225°		2233	1455
		315°		2233	1455
		100.3° Qibla angle	100.3° 	2182	1424
	Rectangle (Dimensions 3 * 5.333 m) 	0.0°		2104	1375
		90°		2333	1514
		180°		2104	1375
		270°		2333	1514
		45°		2297	1492
		135°		2310	1500
		225°		2297	1492
		315°		2310	1500
		100.3° Qibla angle	100.3° 	2156	1406
	triangle (Dimensions (8 L * 4 h) m) 	0.0°		2339	1512
		90°		2684	1721
		180°		2353	1520
		270°		2690	1725
		45°		2497	1608
		135°		2497	1608
		225°		2481	1598
		315°		2516	1620
		100.3° Qibla angle	100.3° 	2372	1532
	Circle (Dimensions R= 2.257 m) 	Any slope itself		1670	1115

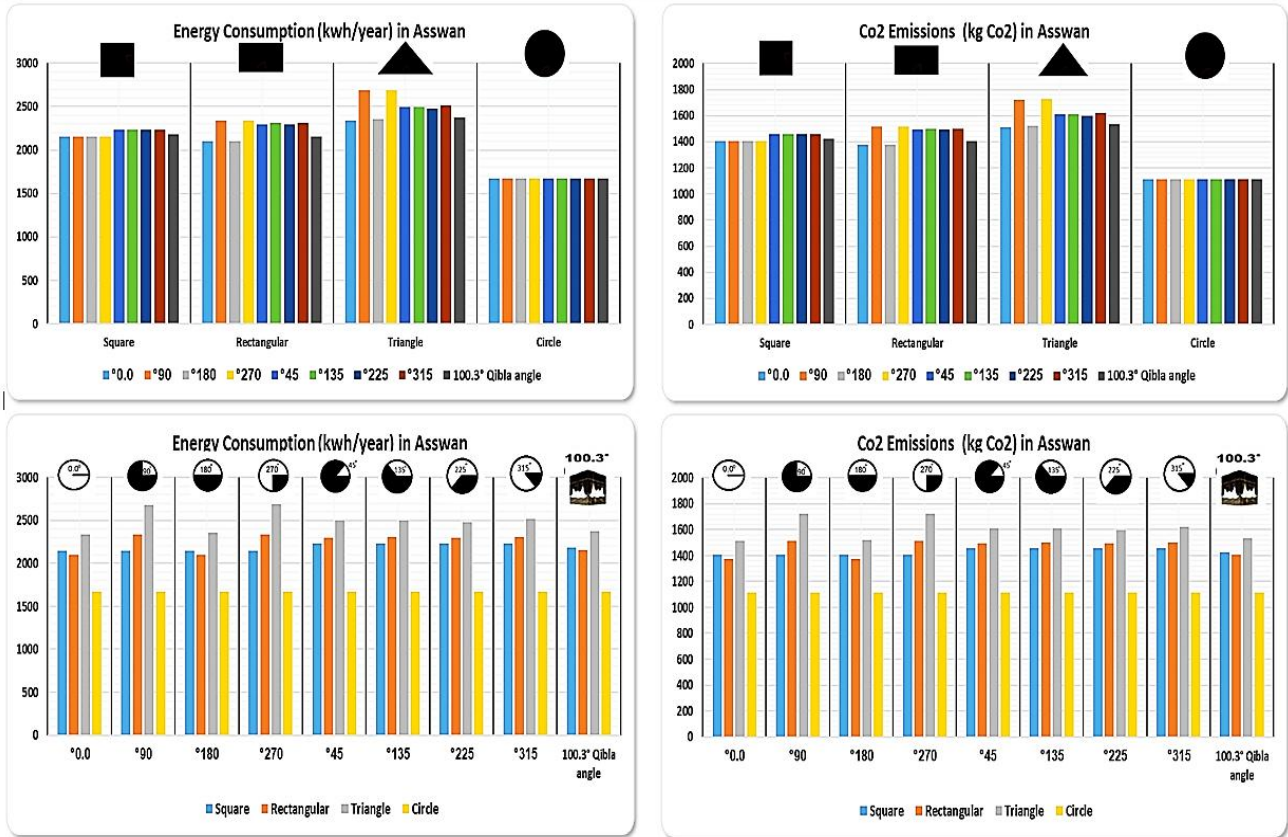


Fig. 9. Comparative Analysis of Energy Consumption and CO₂ Emissions Across Building Forms and Orientation Angles, Including Qibla Direction (100.3°), in Aswan.

4. Discussion

A comparative analysis of building forms and orientation effects across Cairo, Alexandria, and Aswan reveals consistent patterns alongside climate-specific variations in energy performance. Across all three climatic regions, building geometry emerges as the dominant factor influencing energy consumption. Compact forms, particularly those with lower surface-area-to-volume ratios, consistently demonstrate reduced energy demand, while irregular geometries exhibit higher sensitivity to solar exposure and thermal gains.

However, the impact of orientation varies significantly depending on climatic conditions. In the temperate coastal climate of Alexandria, orientation effects remain relatively moderate, with variations generally ranging between 2% and 12% depending on building form. In Cairo's hot arid climate, the influence of orientation becomes more pronounced, particularly for elongated and irregular geometries, with variations typically ranging between 3% and 10%. In contrast, under the extreme hot desert climate of Aswan, orientation sensitivity reaches its highest levels, especially for irregular forms such as the triangular configuration, where variations can reach up to 15%. Despite these variations, the *Qibla orientation* demonstrates a consistent pattern across all regions, with only minor increases in energy consumption relative to optimal orientations. The observed energy penalties remain within approximately 3–7% in *Cairo*, 3–6% in *Alexandria*, and below 3% in *Aswan*. Notably, the lowest relative impact of the *Qibla* orientation is observed in Aswan, indicating that its adoption becomes increasingly viable under more extreme climatic conditions.

These findings highlight that while climatic conditions influence the sensitivity of buildings to orientation, the *Qibla* direction maintains a stable and acceptable energy performance across different environments. This supports the integration of cultural and functional requirements into energy-efficient building design strategies without significant compromise in performance, particularly when appropriate building forms are employed.

5. Conclusions

This study employed a simulation-based methodology to evaluate the impact of building form and orientation, including Qibla alignment, on energy consumption and CO₂ emissions across three distinct climatic regions in Egypt: Cairo, Alexandria, and Aswan. The analysis was conducted under controlled conditions, where building dimensions, material properties, and operational parameters were maintained constant to isolate the effects of geometry and orientation.

The results confirm that building geometry is the primary determinant of energy performance, while orientation plays a secondary but climate-dependent role. The controlled simulation framework ensured that the observed variations are directly attributable to differences in form and orientation, eliminating potential confounding variables.

Across all climatic regions, compact geometries demonstrated lower energy demand and emissions, whereas irregular forms exhibited higher sensitivity to solar exposure. The influence of orientation increased with climatic severity, reaching its highest impact in the hot desert climate of Aswan.

Importantly, the Qibla orientation consistently demonstrated stable performance across all scenarios, with limited energy penalties ranging from **3–7% in Cairo**, **3–6% in Alexandria**, and **below 3% in Aswan**. These results, derived from a consistent simulation framework, indicate that aligning buildings with the Qibla direction does not significantly compromise energy efficiency when appropriate building forms are adopted.

This study highlights the effectiveness of integrating cultural orientation requirements within energy-efficient design strategies, providing a validated methodological approach for climate-responsive architectural design.

6. Research Limitations, Recommendations, and Future Work

This study was limited to investigating the effect of building form and orientation, including *Qibla* alignment, on energy consumption and CO₂ emissions under the Egyptian climatic context. To ensure a controlled comparison, key variables such as building dimensions, material properties, and operational conditions were kept constant, allowing the isolation of geometry and orientation effects. While this approach enhances the reliability of comparative results, it does not fully represent the complexity of real-world building performance.

In addition, several influential parameters were not considered in this study. Factors such as window-to-wall ratio (WWR), glazing properties, shading devices, natural ventilation strategies, and occupancy patterns may significantly affect energy consumption and should be further investigated. The interaction between these parameters and building orientation, particularly under *Qibla* alignment, could provide deeper insights into optimizing energy performance.

Based on the findings, it is recommended that designers prioritize compact building forms to enhance energy efficiency across different climatic regions. Moreover, adopting the *Qibla* orientation can be considered a viable design strategy, as it results in only minor energy penalties while fulfilling cultural and functional requirements. Integrating passive design strategies, such as improved envelope insulation, shading systems, and natural ventilation, in combination with renewable energy solutions, is also recommended to further reduce energy demand.

Furthermore, the study assumed simplified building configurations, including uniform zoning and consistent internal loads across all models. In practice, variations in space usage, occupancy density, and internal heat gains may significantly influence energy performance. Future research should consider multi-zone building models and dynamic occupancy scenarios to better reflect real conditions.

Finally, future work is encouraged to explore the combined effects of building form, orientation, and advanced energy-efficient technologies across a wider range of climatic regions. Expanding the analysis to include different building types and scales would also enhance the applicability of the findings and support the development of comprehensive climate-responsive design guidelines.

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“All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by [**Ahmed M. Seddik Hassan**] and [**Mohamed Ibrahim Abdelhady**]. The first draft of the manuscript was written by [**Ahmed Khamies Mohamed Ali**], and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.”

Data availability statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.