Alam Cipta Int. J. Sustain. Trop. Des. Res. Pract. 19 S1 (1): 45-67 (2026)

ALAM CIPTA

Sustainable Tropical Design Research and Practice

Journal Homepage: http://alamcipta.upm.edu.my/

Enhancing Indoor Thermal Comfort: Roof Design Strategies for Traditional Vernacular Mosques

Nur Athirah Khalit[1*]

[1]*Department of Architecture and Built Environment, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Malaysia*

ABSTRACT

In tropical climates, the roof functions as the main shield yet it receives the most solar exposure, where absorbed radiation turns into indoor heat. Traditional vernacular mosque in Malaysia portrays passive design in their roof design. Their pyramidal roof enhances the building's aesthetic with multiple volume expressions while utilizing high pitch for the stack effect, ventilated roof spaces, segmented roof openings to facilitate airflow for passive cooling. This research aims to investigate the effectiveness of tiered pyramidal roof design in providing indoor thermal comfort. Field measurements from five traditional vernacular mosques in Peninsular Malaysia were digitised and documented, focusing on roof design, structure, height, pitch ratio, and opening ratio. This study shows that roof's height, volume, opening size and placement crucially improve indoor thermal comfort. Taller buildings stay cooler through better stack effect ventilation, while smaller buildings trap heat near their roofs. Additionally, as demonstrated in Masjid Tinggi, optimizing opening proportions to a Window to Opening Ratio (WOR) of 0.20–0.30 and raising the Neutral Pressure Plane (NPP) enhances airflow via the stack effect. These insights guide future mosque designs to enhance thermal comfort, improve energy efficiency, and preserve architectural heritage of the Malay world.

Keywords: Natural ventilation, tiered pyramidal roof, thermal comfort, traditional vernacular mosque, roof ventilation

INTRODUCTION

Traditional vernacular mosque in Malaysia has been recognized as an exemplary model of low energy building that promote passive design approaches. It was designed in consideration of the local climate, environment and culture. It responds to local building materials and craftsmanship, incorporates advanced construction techniques, and maintains a strong connection to its surroundings, making it truly a unique building. Its physical attributes allows good natural ventilation to achieve a comfortable internal environment with minimal resources used.

Indoor thermal comfort greatly influences the activities of its occupants. Therefore, it is essential to assess and

ARTICLE INFO

Article history:
Received: 26 March 2025
Accepted: 11 January 2026
Published: July 2026

DOI: https://doi.org/10.47836/AC.19.S1.PAPER04

Email addresses:
athirah.khalit@ukm.edu.my (Nur Athirah Khalit)
* Corresponding author

improve the study of the current environmental performance of traditional vernacular mosque by focusing on parameters that directly address the present conditions (Wardah F.Y, 2020), particularly their building enclosure. Roof is the largest component in a building enclosure that is exposed to heat caused by high solar radiation and emissive levels which contributes to the total heat gain of the building. Therefore, more attention and consideration should be given to roof design, especially for naturally ventilated buildings to maintain the desired indoor comfort level.

According to MS1525 (2014), Green Building Index (GBI, 2010), and Malaysian Carbon Reduction and Environmental Sustainability Tools (MyCREST, 2020), the roof design is one of the significant factors that influences energy requirements. In hot and humid climate, a typical roof exposed to the greatest share of solar radiation. MyCREST suggests that roof space needs to have openings for ventilation to reduce the heat gain as the ventilated roof area is cooler than the unventilated roof spaces. Therefore, roof with the integration of natural ventilation strategies such as high pitch roofs, ventilated roof spaces, openings at roof segments and facades of the building can enhance natural ventilation through stack effect and facilitate the airflow.

Determining the ratio of the openings, the height of the roof and its volume is preliminary study to gain insights on the design that can enhance the natural ventilation in the mosque. The performance of tiered pyramidal roof components will affect the thermal comfort, day lighting and ventilation inside the mosques. This study provides a new platform for exploration, experimentation and discussion of roof ventilation strategies that commonly cover typology, configuration and theories.

This study aims to investigate the role of tiered pyramidal roof design in promoting indoor thermal comfort in traditional vernacular mosques. The objectives are to; (i) identify roof components of traditional vernacular mosque that affect natural ventilation performance, and (ii) analyze the ratios and configurations of ventilation strategies, including opening placement and roof-to-hall height proportions, in achieving optimal thermal comfort. Through this investigation, the research intends to generate design insights that contribute not only to improved thermal comfort and energy efficiency but also to the preservation of cultural authenticity and architectural heritage.

LITERATURE REVIEW

Passive Design Strategies for Mosque

Mosque is an essential place of worship for Muslims, where achieving a sense of tranquillity and physical comfort is fundamental to supporting spiritual practices. In Malaysia’s hot and humid climate, this expectation becomes more demanding as thermal discomfort can directly disrupt the quality of prayer and congregation. Najafi and Kamal (2011) highlight that congregations consistently emphasize the need for good ventilation in the mosque and the natural ventilation system is the most desired. Similarly, Yendo Afgani et al. (2015) also support the idea that mosques should be environmentally friendly, facilitating adequate airflow across the building to optimize natural ventilation and ensure acceptable thermal comfort during peak occupancy. However, existing mosque developments often contradict these principles. Despite widespread acknowledgment of natural ventilation as the preferred strategy, contemporary mosque designs increasingly rely on enclosed, monumental forms that restrict airflow.

According to MS1525:2014, the main strategies for effective passive design are to shade the building from intense solar radiation, insulate against solar heat gain, ventilate the indoor environment, and provide adequate daylight into the buildings. MS1525:2014 outlined seven (7) significant factors meanwhile, Carl Mahoney has listed nine (9) passive design recommendations for buildings in hot and humid climate (Table 1).

Table 1 *Passive design strategies: MS1525:2014 vs. Carl Mahoney*

	MS1525:2014	Carl Mahoney's
1	Site planning & orientation	Building layout
2	Daylighting	Building space
3	Façade design	Air movement
4	Natural ventilation	Opening size
5	Thermal insulation	Opening position
6	Strategic landscaping	Protection of openings
7	Renewable energy	Wall & floor materials
8	-	Roofs
9	-	External building features

Previous studies have extensively examined passive design strategies such as building layout, natural ventilation, façade treatment, openings, and roof design (Maarof, 2014; Abdullah et al., 2016; Khalit et al., 2017; Othman et al., 2019; Mohd Nawayai et al., 2020; Yusoff, 2020; Sanusi et al., 2021; Rasli et al., 2021; Rauzi et al., 2022; Azmi et al., 2023). However, limited attention has been given to vernacular buildings, despite their established use of sustainable and passive design approaches.

Given this gap, this study focuses on the building enclosure particularly roof design, as a key factor influencing indoor thermal comfort. Roofs are a major component in passive design, with MS1525:2014, GBI, and MyCREST emphasizing their influence on energy performance. Roofs are highlighted in MS1525:2014, GBI, and MyCREST because they absorb the most solar heat, between 50% to 85% in Malaysia's climate. Properly ventilated roofs can significantly reduce heat gain. Supporting this, Ibrahim et al. (2014) found that roof openings can lower indoor temperatures by up to 8°C compared to unventilated roofs, proving the effectiveness of simple passive techniques.

Natural Ventilation in Vernacular Traditional Mosque

Geographically, Malaysia is located on the Equator between latitude 1° - 7°N and longitude 100° - 119°E, exposing Malaysia to an average of 4000-5000Wh/m² in monthly solar radiation and an average of 4 to 8 hours of daily sunlight. Malaysia experiences high humidity, high temperature, and uniform diurnal pattern (Jamaludin et al., 2015) throughout the year. Buildings in tropical regions like Malaysia will typically endure a hot and humid climate all year round with uniform temperature and high humidity. According to the Malaysian Meteorological Department, the daytime minimum and maximum temperature ranges are 23°C to 27°C and 30°C to 34°C respectively. The relative humidity recorded was in the ranges of 52% to 91%. Meanwhile, according to MS1525:2007 and the Department of Standard Malaysia (DOSM), the recommended range for Malaysian indoor air temperature is 23°C to 26°C, and the relative humidity range is 55% to 70% respectively.

Although windows and openings are widely used as thermal control elements in tropical buildings, their effectiveness is not always straightforward. Natural ventilation through openings can improve thermal comfort by enhancing air movement, allowing occupants to tolerate higher temperatures and humidity. However, Daghigh (2015) notes that natural ventilation can also introduce more moisture into indoor spaces, potentially increasing discomfort if airflow is insufficient or poorly directed. This underscores a critical design tension: ventilation strategies must balance the need for cooling with the risk of elevating indoor humidity, especially in a climate where outdoor air is already moisture laden.

Previously, natural ventilation strategies have been applied for ages in providing thermal comfort, especially in our Malay traditional architecture. The traditional vernacular mosques have demonstrated the usage of natural ventilation approaches such as the high-pitch roof as stack effect function, ventilated roof space, opening at roof joint to allow ventilation, raised on stilt building to catch high-velocity of air movement and abundant of windows and openings to allow more natural ventilation as Figure 2. These strategies were applied in vernacular buildings to attain optimal climatic control which includes allowing adequate ventilation for cooling and reduction of humidity (Wahab & Ismail, 2016).

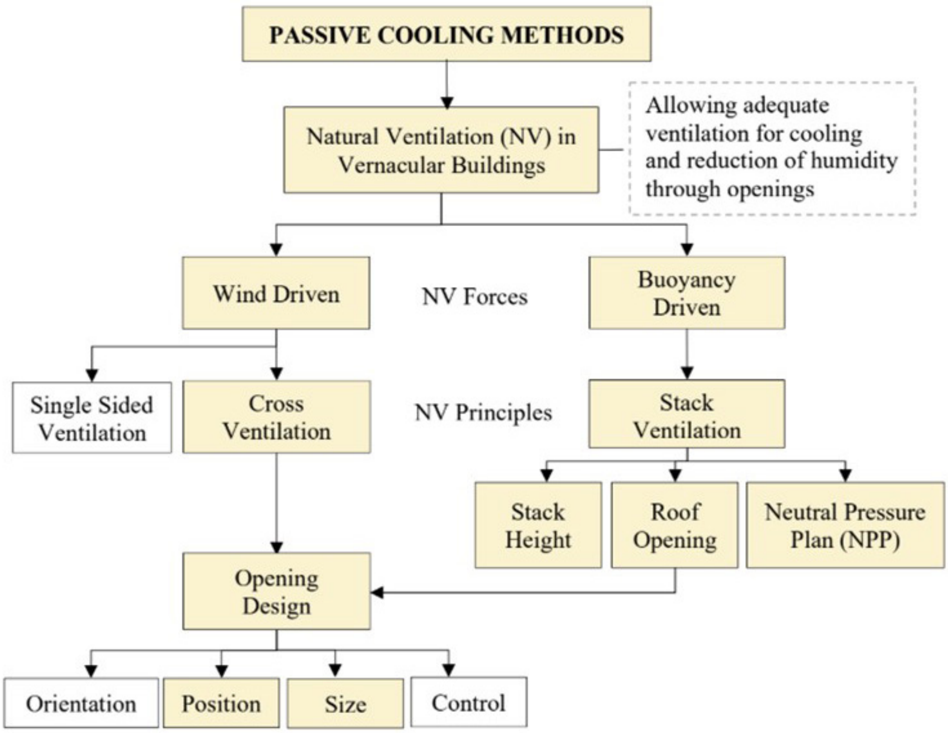


Figure 1. Natural ventilation (NV) strategies in vernacular buildings for passive cooling approaches. The highlighted boxes represent the selected lines of studies that will be discussed further.

Critically, the strong performance of vernacular buildings raises important questions about contemporary design practices. Despite centuries of proven effectiveness, many modern Malaysia's mosques neglect these passive strategies in favour of enclosed, air-conditioned spaces that are often thermally inefficient and environmentally unsustainable. This disconnect indicates that the passive design knowledge embedded in vernacular architecture has not been effectively incorporated into contemporary building standards or architectural decision making. Consequently, traditional strategies with clear potential to enhance thermal comfort, reduce energy consumption, and improve natural ventilation remain significantly underutilised.

Traditional Vernacular Mosque (T.V.M)

Vernacular mosques can be categorized into two types: traditional and regionally influenced. Vernacular mosques with regional influence are distinguished by their two or three-tiered roofs with decorative ridges, clay roof tiles, octagonal minarets, and a square layout. Examples include Masjid Tengkera, Masjid Kampung Keling, and Masjid Tanjung Keling, Melaka. Meanwhile, traditional vernacular mosques are featuring a raised floor with a square plan, a tiered pyramidal roof (tajug) or long gable roof, and the absence of a minaret (Hassan, 2011). Notable examples include Masjid Kampung Laut (Figure 2) and

Masjid Langgar in Kelantan (Figure 3), Masjid Paloh in Perak, and Masjid Kampung Raja in Negeri Sembilan. The traditional vernacular mosque is a key example of a building that uses passive design strategies, reflects a deep understanding of and respects for nature.

Figure 2. Masjid Kampung Laut

Figure 3. Masjid Langgar

Scholars summarized traditional vernacular mosque under five (5) categories of building parameter; (i) building plan and layout, (ii) roof design and construction, (iii) architectural style and language, (iv) building material and construction and (v) culture influences. However, the study has identified and listed seven (7) characters of traditional vernacular mosque in Malaysia that aligned with passive design approach which might influence the indoor thermal comfort (Figure 4); i) symmetrical layout with square or rectangle plan, ii) associated with two (2) or three (3) tiered pyramidal roof, iii) have *soko guru,* iv) raised on stilts, v) have many openings at wall, ceiling level and roof level, vi) prayer hall secured with wall as boundaries and vii) building material using timber for building structure, *attap nipah* or clay roof tiles for the roof.

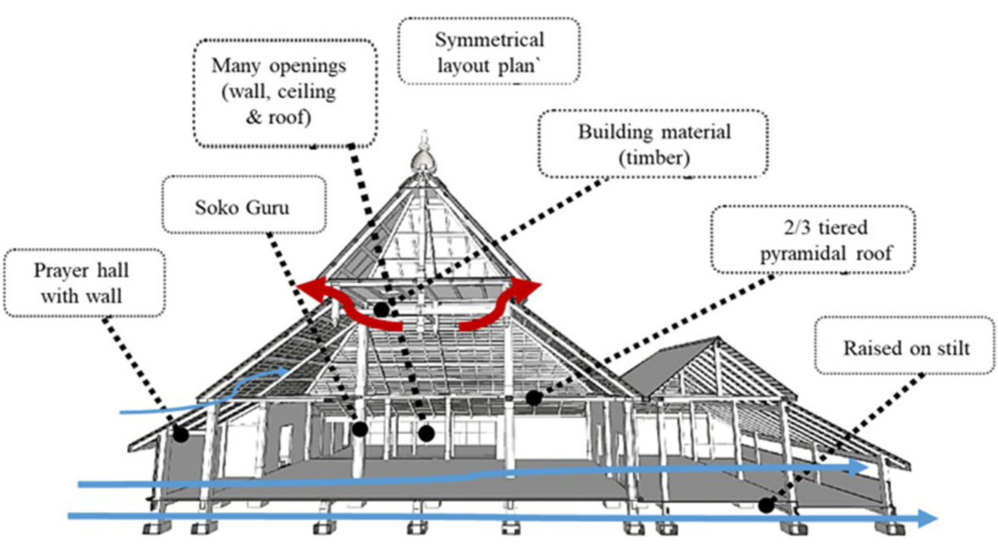


Figure 4. Characters of traditional vernacular mosques that promotes passive design strategies to enhance natural ventilation.

Tiered Pyramidal Roof - Roof Ventilation Strategies

The tiered pyramidal roof is the most defining characteristic of vernacular mosque architecture in Southeast Asia. Originating from the meru or mountain form known as tajug in Indonesia, this roof type first appeared in the oldest surviving wooden mosque in the region, Masjid Demak in Java. Its multi-tiered structure reflects strong Hindu-Balinese influences, showing the hybrid cultural and architectural evolution of early mosque construction. In Malaysia, Masjid Kg. Laut in Kelantan is regarded as the earliest example of this vernacular typology, featuring a three tiers pyramidal roof supported by the soko guru structural system. As noted by Shah et al. (2016), the roof's form, proportion, and construction reveal a highly pragmatic and climate-responsive approach to timber architecture. Critically, the sophistication of these historical roof systems highlights a gap in contemporary mosque design, where such climate responsive principles are rarely replicated. Hassan (2011) identifies key components of the vernacular roof which are; pyramidal roof form, tiered roof system, extended overhang, roof crown, ridges, tails, tiles, upper roof openings and structural system (Figure 5). These elements demonstrate an integrated environmental strategy that enhances ventilation, reduces heat gain, and moderates humidity. Their omission in many modern mosques suggests a missed opportunity to apply proven passive design principles. Accordingly, these traditional roof features form the foundation for this study's analytical framework and guide the selection of case study buildings.

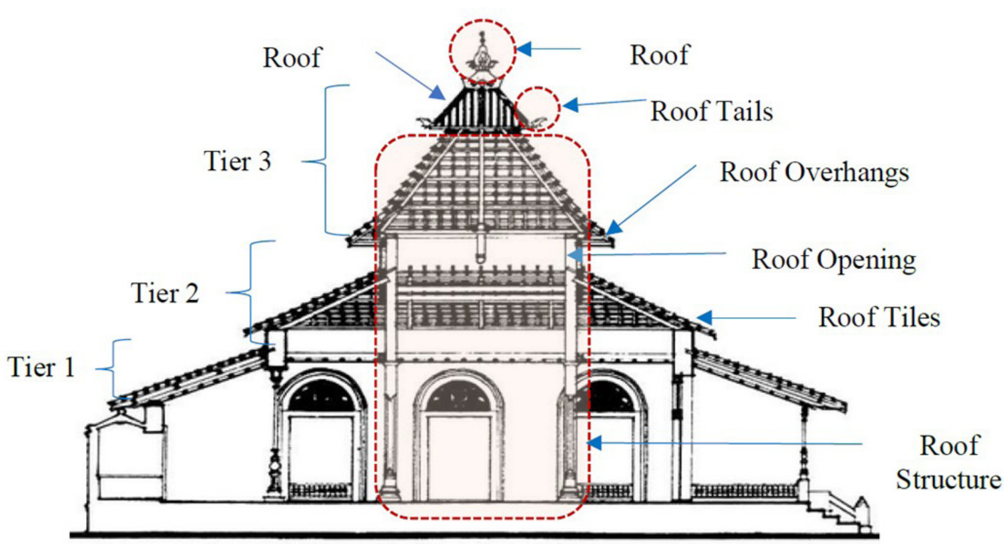


Figure 5. Roof components of traditional vernacular mosque.

According to Maarof (2014), roof design plays a crucial role in controlling the pattern of air movement, temperature and distribution. The multi-tiered pyramidal roof form mosques prevent temperature stratification, allowing air to circulate evenly and achieve thermal equilibrium. As a result of that, there is an active air circulation happens in the pitched roof of the mosque. The indoor air temperature distributed evenly in space and the air temperature can be controlled (Figure 6).

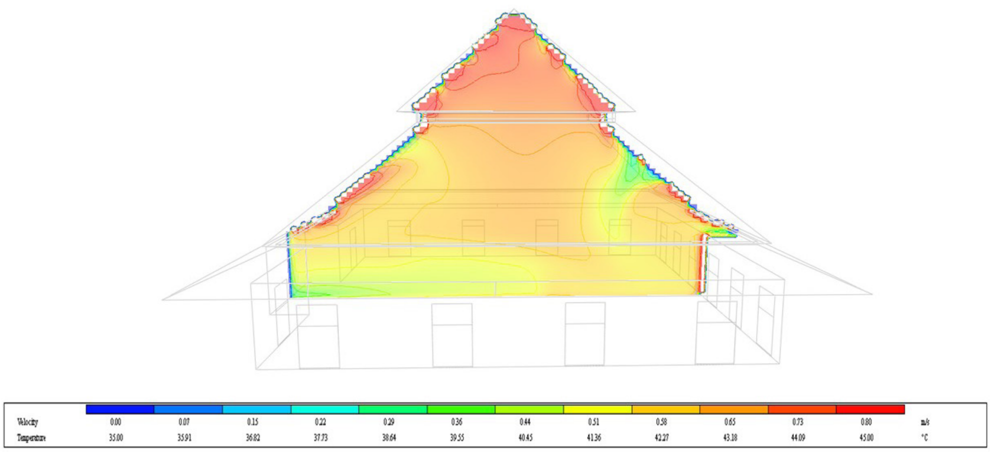


Figure 6. CFD simulation section showing air pressure and temperature distribution in Masjid Kg. Laut, illustrating absence of stratified air layers due to the pitched roof effect.

The air circulation created by the roof itself and activated due to the balancing act of the pressure and temperature influences on the air density assist by stack effect design. The narrowing of space toward the roof apex further concentrates airflow, improving ventilation efficiency. As air heats up, it becomes lighter and rises to the upper part of the building. In a pyramidal roof form, the pressure difference created between higher and lower levels enhances air movement, preventing stratification and promoting faster cooling through evaporation.

Critically, this demonstrates that the pyramidal roof is not merely an aesthetic element but an integral passive system that actively regulates indoor climate. Its effectiveness in hot and humid environments like Malaysia highlights a gap in contemporary mosque design, where such roof-driven passive strategies are often overlooked, despite their potential to enhance thermal comfort and reduce reliance on mechanical cooling.

Roof Angles (Pitches)

The high-pitched roofs have a great influence on creating the conditioning room. Space under the roof can be a buffer for hot air to be discharged out of the building. Furthermore, the high-pitched roofs with ventilation on the top exhaust the warm air by the stack effect. The traditional concept of the roof has prevailed without changes for a very long time. It is natural to expect that a steeper roof requires a larger area of roof material and forms a larger and higher attic space. Generally, in Malaysia, low slope roof trap more heat due to the absence of roof ventilation therefore, the heat takes a longer time to release (Ibrahim et al., 2014).

Wang and Shen (2012) studied the impact of roof pitch on airflow and cooling load in sealed and vented attics, finding that attic temperature decreases with roof pitches between 14° and 33.75°, but remains stable from 45° to 67.5°. While airflow rates seemed to reach a saturated state when above a 35° pitch, suggesting that increasing the pitch up to 33.75° enhances the cooling effects.

Tashoo et al. (2014) found that ventilation performance depends on external wind conditions and roof pitch, which helps reduce heat convection beneath the roof. When wind speeds are below 1.5 m/s, the inclined roof supports stack ventilation by reducing drag force. At roof angles of 30° and 42°, airflow along the roof slope was greater than at the building's centre. However, at a 15° pitch, the air wake expanded into the interior, causing internal air to escape through the roof openings. Under higher wind speeds (1.5–4.5 m/s), roof openings became less effective when the roof slope exceeded 30°. This underscores the importance of studying vernacular mosques with 30°–45° roof pitches, as this configuration is most capable of strengthening stack ventilation, promoting higher airflow, and achieving meaningful reductions in indoor air temperature.

Roof Opening

Scholars (Dwiyanto & Sari, 2015; Ibrahim et al., 2014; Kindangen & Rogi, 2020) have proved that the openings in the roof are effective to create airflow at the upper roof, moved by the buoyancy and indices the colder air to replace the hot air that comes out. Roof ventilation also can control humidity, save energy and increase the durability of building materials. Ibrahim et al. (2014) found that the size of openings plays an important role as a source of air movement. Air velocities improved and increased as the percentage of the opening increased. Specifically, when openings were increased to 50% or 100%, air movement was significantly enhanced, leading to a reduction in indoor air temperatures by 4°C-8°C.

Dwiyanto and Sari (2015) found that houses with higher roof openings have lower temperatures and better air movement, suggesting roof openings should be positioned away from inlet openings to optimize airflow. Kindangen and Rogi (2020) supported this by noting that roof insulation also impacts indoor air temperature, though further investigation is needed to determine the most effective solution.

The multi-tiered pyramidal roof creates segments in between the roof layer that allow the placement of openings such as *sisir angin* (clerestory windows) and louvers to facilitate air movement (Ahmad Sanusi, 2010). These upper openings enhance the stack effect by allowing warm air to rise and escape, drawing cooler air from below. Unlike standard windows, they are not intended for views or cross ventilation but specifically for vertical airflow. Case studies show that louvers, carved panels, and clerestory windows are commonly used in these roof segments. These openings are positioned between roof tiers and sheltered by roof overhangs to prevent rain penetration while diffusing sunlight into the prayer hall, with louvers being the most widely used type.

Wall to Opening Ratio (WOR)

Naturally ventilated buildings rely on air exchange between indoor and outdoor spaces, meaning outdoor temperatures directly affect indoor conditions. Therefore, façade openings play a crucial role in regulating indoor air temperature by allowing fresh air to enter and mix with indoor air (Maarof, 2014 & Rasli et al., 2021). The amount of solar radiation entering the interior spaces is determined by the wall-to-opening area ratio. ASHRAE 90.1-2007 recommends the ideal WOR is 0.24 for effective daylighting and natural ventilation, while other studies suggest an optimum range of 0.2-0.25 (Wang et al., 2012; Sukawi et al., 2013; Kindangen et al., 2020).

However, a higher WOR does not necessarily result in better performance. Larger window areas allow more heat and sunlight to enter, which can cause overheating and glare. Ratios above 0.30 often lead to excessive heat gain. Therefore, recording the WOR in the main prayer hall helps predict and assess the effectiveness of the design (Abdul Majid & Denan 2015). According to the Mahoney Table bioclimatic guidelines, the WOR should be between 20% to 35% of the total wall area on the north and south façades, and openings should be positioned at body height.

Stack Height and Neutral Pressure Plan (NPP)

The stack effect relies on thermal buoyancy to drive air movement, which is influenced by the height of the ventilation shaft and the temperature difference between indoor and outdoor air. Given that thermal differences are unpredictable and difficult to control, effective stack ventilation relies primarily on the careful design of the building's ventilation shaft and openings.

When temperature differences create variations in air density, a pressure difference forms, establishing a neutral plane at the height where indoor and outdoor pressures are equal (Izudinshah et al., 2016). At this neutral pressure plane (NPP), no horizontal airflow occurs. Identifying the NPP is essential for assessing stack-driven airflow (Figure 7). A higher NPP allows more fresh air to enter the space, but in hot tropical daytime conditions, a lower NPP is preferable to promote better indoor air movement (Izudinshah, 2016).

Determination of the NPP location is critical to evaluate the air flow pattern due to the stack effect. Based on the formula below, it can be said that the main contributor to a neutral plane (NP) is the size of the openings. However, the height difference between inlet and outlet does play a role in influencing the stack effect. Therefore, the NPP level for all the case studies were determined based on the following equation (Izudinshah, 2016a; Luo et al., 2007).

$h1 = (HF2^2)/(F1^2 + F2^2)$

$h2 = (HF1^2)/(F1^2 + F2^2)$

Where: -

h1 is the height of inlet to the neutral plane (m)

h2 is the height of neutral plane to outlet (m)

H is the total height between inlet and outlet (m)

F1 is the area of inlet (m2)

F2 is the area of outlet (m2)

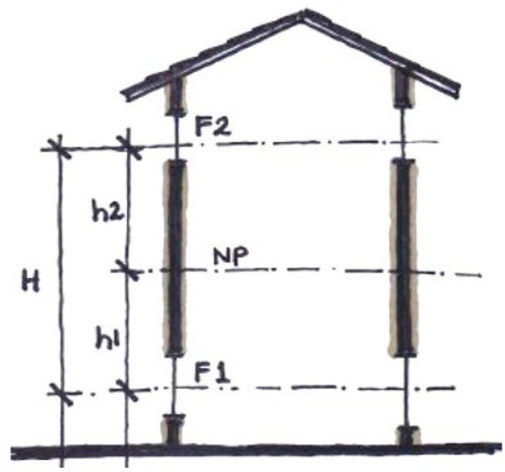


Figure 7. Placement of Neutral Pressure Plan (NPP)

Contemporary mosque designs in Malaysia often ignore vernacular passive strategies, favoring enclosed, air-conditioned spaces that reduce thermal comfort and sustainability. Although standards like MS1525:2014 provide general passive design guidance, they do not fully capture the climate responsive solutions of vernacular mosques, such as tiered pyramidal roofs, roof openings, and optimal wall-to-opening ratios. Roofs, façades, and stack effect ventilation are frequently overlooked, and limited empirical evaluation in modern construction further hinders their use. Reintegrating these proven vernacular strategies is crucial for improving indoor comfort, reducing energy consumption, and supporting sustainable mosque architecture in tropical climates.

METHODOLOGY

This research focused on distinguished traditional vernacular mosques in Peninsular Malaysia that remain standing, characterized by tiered pyramidal roofs and consistent vernacular features. Selected case studies of comparable scale were documented and analyzed to identify roof components that enhance natural ventilation. Selection criteria included heritage significance, architectural integrity, and representativeness of passive design principles. Data collection began with field measurement, combining primary data from site visits and secondary sources, covering samples from all states in Peninsular Malaysia.

Traditional vernacular mosques were identified using listings from the Centre for the Study of Built Environment (KALAM) UTM, State Islamic Councils, and State Museums (Rosniza, 2013; Azizul et al., 2013). From an initial shortlist of 30 mosques, five mosques; Masjid Kg. Laut, Masjid Kg. Parit, Masjid Kg. Tuan, Masjid Kg. Papan, and Masjid Tinggi were selected for detailed digitization and analysis of their roof design, components, height, pitch ratio, and opening ratio.

Table 2 *List of selected case studies*

No.	**Mosque**	No.	**Mosque**
1.	Masjid Kg. Laut, Kelantan (1730's) 	4	Masjid Kg. Papan, Perak (1888) 
2	Masjid Kg. Parit, Negeri Sembilan (1796) 	5	Masjid Tinggi, Perak (1890's) 
3	Masjid Kg. Tuan, Terengganu (1830) 		

The selection of these mosques is justified by their embodiment of key passive design strategies that directly contribute to thermal regulation and indoor environmental quality. The mosques' on-stilt design enables subfloor airflow for heat dissipation and temperature moderation, while full-length windows at occupant level facilitate effective cross ventilation by harnessing increased wind velocity with elevation. These architectural features demonstrate an inherent alignment with vernacular strategies for natural ventilation, substantiating their relevance as case studies in the evaluation of roof design and its role in enhancing thermal comfort.

RESULTS

Based on the selected case studies, the study identified four (4) building components that influence the roof ventilation strategies for traditional vernacular mosque which are; i) roof pitch, ii) roof height and ratio, iii) wall to opening ratio and iv) roof opening height and neutral plane pressure.

Tiered Pyramidal Roof Components

Previous scholars (Ahmad Sanusi, 2010, 2011; Ahmad Sanusi et al., 2014; Rosniza et al., 2015) identified ten components of the tiered pyramidal roof in Malay architecture, from which this study highlights three; roof tier, roof pitch, and roof opening as the most influential for passive natural ventilation in vernacular mosques.

Roof Pitch

In Malaysia, roofs are exposed to solar radiation for over 10 hours a day, making roof angles and building orientation critical. Since mosques face the Qiblat at 292°, roof height and slope significantly affect indoor thermal conditions. Al-Obaidi et al. (2014) reported common roof slopes of 0°, 30°, 45°, and 60°, while A. B. Ramly (2012) and S. Wang & Shen (2012) showed that steeper pitches increase airflow in ventilated roofs but also raise heating loads. Studies by Siti Halipah I. et al. (2018) and Tashoo & Namprakai (2014) identified 30° as the optimal pitch, balancing effective thermal regulation through improved airflow with practical maintenance considerations.

Table 3 *The slope range for the case studies*

					Range													
Mosque	**Roof Tier (°)**				**1**					**2**			**3**				**4**
	1	2	3	4	40-45	46-50	51-55	56-60	> 61	<35	36-40	41-45	21-25	26-30	31-35	36-40	26-30
Masjid Kg. Laut	47	42	23			√						√	√				
Masjid Kg. Parit	55	40					√				√						
Masjid Kg. Tuan	44	37	38	26	√						√					√	√
Masjid Kg. Papan	40	36			√						√						
Masjid Tinggi	74	18	21						√	√			√				
	Frequency				2	1	1	0	1	1	3	1	2	0	0	1	1

This study identified that the average roof slope across all case studies ranges between 21° and 45°. Accordingly, it may be concluded that the appropriate range for pitched roofs in the Malaysian context lies between 30° and 45°. As illustrated in Table 3, the slope distribution varies by tier, with Tier 1 roofs exhibiting gradients between 40° and 45°, Tier 2 roofs ranging from 36° to 40°, and Tier 3 roofs showing lower gradients of 21° to 25°.

Roof Tier, Height and Ratio

A tiered pyramidal roof, identifiable by its multiple layers, is classified in vernacular mosques by the number of tiers, typically 2, 3, or 4 in Peninsular Malaysia. The roof system creates multiple interior volumes, as height, scale, and proportion influence ventilation rates (Ahmad Sanusi, 2010). The multiple volume design allows indirect natural sunlight to enter and promote airflow from outside.

Roof slope or pitch usually determines roof height, but in tiered pyramidal designs, roof segments increase height and create openings for ventilation and lighting without requiring steeper slopes. This design also enhances the stack throat (ventilation shaft) (Figure 8). Roof volume (m^3) is calculated by multiplying floor area by roof height, and higher ceilings provide larger air volume, directly impacting indoor temperature and thermal comfort.

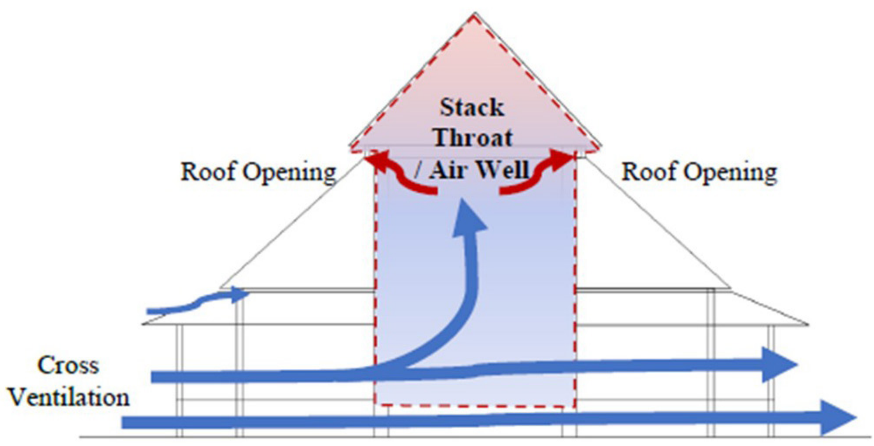
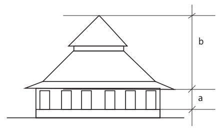
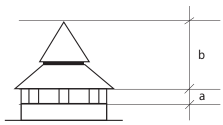
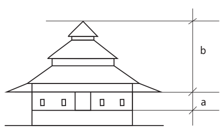
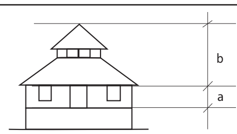
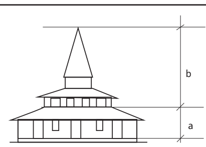


Figure 8. The roof segments place the roof openings and help to increase the height of the volume that influences the stack throat.

The height of the façade for each case study is different. This research has identified the height as ranging between 7.5m to 14.0m. Based on the ratio of height of the main prayer hall and roof in Table 2, it was significantly found that more than half of the total height belongs to roof design. Al-Obaidi et al. (2014) stated that roof design contributes for 70% of the total building's heat gain, making it crucial to identify the optimum roof design for improving indoor thermal comfort. Yang et al. (2017) also found that higher building heights are linked to lower average indoor air temperatures. Therefore, it is verified that the design of a tiered pyramidal roof that creates volume not only for aesthetic effect but also significantly contributes to lowering the mosque's indoor air temperature. Table 4 showed the mode ratio of height is 1:3.1-1:3.5 as displayed by Masjid Kampung Laut and Masjid Kampung Parit.

Table 4 *The ratio of height of the main prayer hall and roof*

	Mosque	Building Elevation	Height (mm) Prayer Hall	Height (mm) Roof	Volume (m³)	Ratio	Ratio Range 1:2.6 - 1:3.0	1:3.1 - 1:3.5	1:3.6 - 1:4.0	1:4.1 - 1:4.5	1:4.6 - 1:5.0
1	Masjid Kg. Laut		2800	9600	a - 707.9 b - 925.9	1:3.4		√			
2	Masjid Kg. Parit Istana		2500	8500	a - 254.1 b - 318.0	1:3.4		√			
3	Masjid Kg. Tuan		2700	10500	a - 153.6 b - 255.4	1:3.8			√		
4	Masjid Kg. Papan		2700	7500	a - 278.3 b - 251.5	1:2.7	√				
5	Masjid Tinggi, Bagan Serai		3000	14000	a - 724.8 b - 873.6	1:4.7					√
					Frequency		1	2	1	0	1

Wall to Opening Ratio (WOR)

Based on the finding of WOR at the main prayer hall (Table 5) show that the traditional vernacular mosques are within the recommended ratio range of 0.2-0.3 with Masjid Kg. Laut is 0.23 and Masjid Kg. Tuan is 0.22. Therefore, Masjid Kg. Laut and Masjid Kg. Tuan demonstrated the optimum inlet openings that allow the best airflow inside the main prayer hall to achieve the comfort level. However, Masjid Kg. Tuan has no roof openings in all the roof segments. Table 6 also demonstrated that Masjid Tinggi has the highest WOR at the outlet opening which is 0.09. Masjid Kg. Laut shows WOR result of 0.03, even though the result is still far from the optimum ratio, Masjid Kg. Laut will be the best sample to investigate further for the stack ventilation since the ratio of inlet openings was the optimum. It is believed that Masjid Kg. Laut will receive the optimum air to promote cross ventilation and further investigation will focus more on the stack ventilation strategies. Theoretically, similar size of the top and lower openings controls the balance of airflow of air inlet and outlet, resulting in efficient stack ventilation flow (Wahab et al., 2016).

Table 5 *Opening at main prayer hall wall (inlet opening)*

No.	Masjid	Total wall area at MPH (m²)	Total openings		Ratio
			(m²)	(%)	
1	Masjid Kg. Laut	217.27	49.60	22.83	0.23
2	Masjid Kg. Parit Istana	91.20	26.61	29.18	0.29
3	Masjid Kg. Tuan	94.4	21.08	22.3	0.22
4	Masjid Kg. Papan	99.92	18.81	18.83	0.19
5	Masjid Tinggi, Bagan Serai	176.58	46.09	26.10	0.26

*All types of doors, windows, void and opening on the façade are considered an opening area on the facade.

Table 6 *Opening at roof segments (outlet opening)*

No.	Masjid	Total Roof Area (m²)	R.S 1	R.S 2	Opening Percentage (%)	Ratio
			Total Opening (m²)	Total Opening (m²)		
1	Masjid Kg Laut	593.2	25.3	6.16	2.92	0.03
2	Masjid Kg. Parit Istana	245.6	1.9	0.0	0.77	0.08
3	Masjid Kg. Tuan	125.2	0.0	0.0	0.00	0.00
4	Masjid Kg. Papan	218.6	9.6	0.0	4.39	0.04
5	Masjid Tinggi, Bagan Serai	655.6	41.1	19.8	9.29	0.09

* R.S – Roof Segment

The rise in indoor air temperature is due to poor passive design. The upper part of the roof area is exposed to heat and accumulates heat during the daytime. Roslan et al. (2016) proposed a well-designed ventilated roof with a roof opening that helps to improve the over-heating condition at the upper part of the roof by eliminating the internal hot air (Siti Halipah et al., 2018). Therefore, these will become the variables that will be investigated as the optimum configurations that can help to improve the indoor thermal comfort of the mosque.

Roof Opening Height and Neutral Plane (NP)

Based on the previous equation, the study identified that most case studies have the neutral plane (NP) at the level of the main prayer hall beneath the roof (Table 7). This allows roof segment openings, particularly in roof segment 2, to act as outlets for hot air (Figure 9). Masjid Kg. Tuan did not have any openings at the roof area, instead has two levels of openings in the main prayer hall walls. The lower level act as inlets and the upper level act as outlets. The findings showed that NP was calculated at 1850 mm, below the outlet level but higher than the NP of Masjid Kg. Laut and Masjid Kg. Parit, due to its smaller inlet openings relative to the outlet openings.

Besides relying on cross ventilation, stack effect ventilation could also be exploited in giving benefit for building occupants. However, due to the unpredictability and inconsistency of the outdoor wind, the design of the building must provide higher height differences between the inlet and outlet openings in order to induce the air movement through the stack effect. This is essential to generate air movement through buoyancy (Izudinshah, 2016).

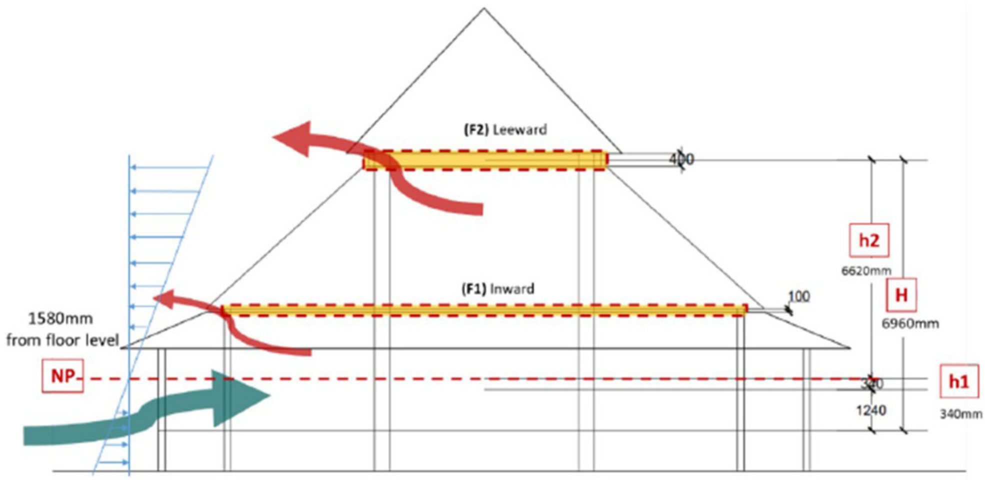
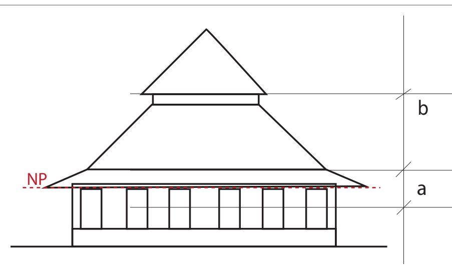
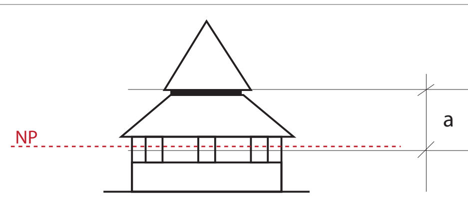
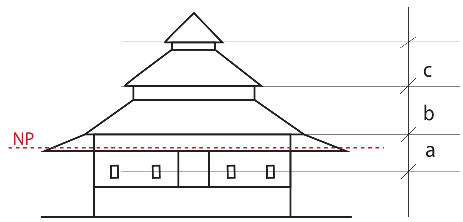
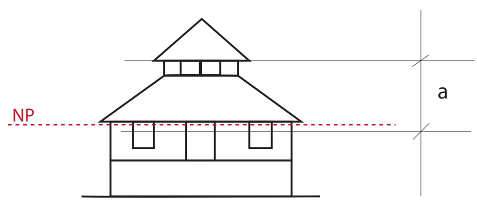
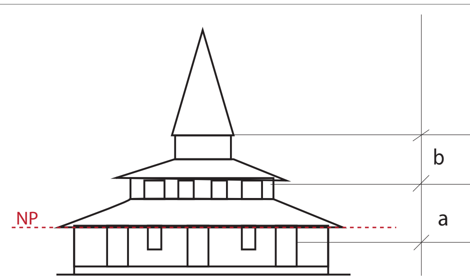


Figure 9. Cross section shows the neutral plane at Masjid Kg. Laut at 1.58m

Table 7 Height difference between inlet and outlet openings and NP for all case studies

	Mosque	Building Elevation	Height difference between the openings	Neutral Plane (from floor level)
1.	Masjid Kg. Laut		a – 2410 mm b – 4600 mm **H = 8250 mm**	1580 mm
2.	Masjid Kg. Parit Istana		a – **4420 mm** **H = 4420mm**	1130 mm

	Mosque	Building Elevation	Height difference between the openings	Neutral Plane (from floor level)
3.	Masjid Kg. Tuan		a – 1680 mm b – 1790 mm c – 2100 mm **H= 5750 mm**	1850 mm
4.	Masjid Kg. Papan		a – **4420 mm** **H = 4420mm**	2370 mm
5.	Masjid Tinggi, Bagan Serai		a – 3555 mm b – 3022 mm **H = 6576 mm**	2420 mm

LIMITATION AND RECOMMENDATION

This study provides insights into the role of tiered pyramidal roofs in facilitating natural ventilation within traditional vernacular mosques in Peninsular Malaysia. However, the findings are constrained by several limitations. Firstly, the methodology relied on field measurement and observational analysis, without incorporating computational simulations or occupant surveys, which limits the ability to quantify thermal performance, airflow patterns, and user comfort under real conditions. Secondly, the sample size is relatively small and by the focus primarily on roof geometry overlooking other critical factors such as site orientation, material properties, and surrounding microclimate, which may affect indoor thermal comfort.

Future research should expand the scope to include a wider range of mosque typologies and regions, supported by field measurement. The integration of Computational Fluid Dynamics (CFD) simulations and field measurement can provide detailed analysis of airflow, temperature distribution, and humidity, validate traditional passive strategies and enable optimization for contemporary mosque design. Such studies would bridge vernacular knowledge with modern performance-based approaches, offering evidence based strategies for sustainable architecture while respecting cultural and historical contexts.

CONCLUSION AND CONTRIBUTIONS

This research identifies key roof components that influence natural ventilation and indoor thermal comfort in traditional vernacular mosques, including the size, ratio, and position of roof openings, building volume, and the location of the neutral pressure plane (NPP). Lower average indoor air temperature associated with higher building height. The smaller scale of buildings tend to have higher air temperature, especially at the roof area and since the height is lower, the heat transfer occurs faster to occupants at the main prayer hall. Based on the ratio of the height of the main prayer hall and roof, it was found that more than half of the total height belongs to roof components. The mode ratio of the height of the main prayer hall to the roof is 1:3.4 (Masjid Kg. Laut and Masjid Kg. Parit).

WOR of traditional vernacular mosque in Malaysia is within the range of 0.20-0.30. Masjid Kg. Laut has the optimum WOR at the inlet opening, which is 0.23 meanwhile at the outlet opening is 0.12. The size and height difference of inlet and outlet openings then determined the NPP that influences the airflow pattern due to the stack effect. A higher neutral plane guarantees that fresh air enters the container to a larger extent. Masjid Tinggi has the highest NPP (2.42m), above the inlet opening height. This allows the openings at the main prayer hall to become the source of cool air to penetrate in.

By examining these roof components in relation to thermal conditions, this study proposes design strategies to enhance the thermal performance of prayer hall, reduce energy consumption, and promote sustainable mosque architecture. Beyond practical design applications, the research emphasizes cultural and heritage considerations, highlighting the need to integrate environmental improvements while preserving the authenticity, symbolism, and communal significance of traditional vernacular mosques. Future directions include testing these strategies across diverse mosque typologies and combining empirical measurements with simulation tools, thereby providing a framework that bridges traditional vernacular wisdom with contemporary performance-based design and contributes to both sustainable and culturally sensitive Islamic architecture in Malaysia.

ACKNOWLEDGEMENT

The paper is written based on the works done from Geran Galakan Penyelidikan Muda (GGPM-2024-019) research grant from the Ministry of Higher Education Malaysia.

REFERENCES

Abdul Majid, N. H., & Denan, Z. (2015). Ratio determination of solids and voids for traditional Malay carvings: A preparation for environmental performance. *International Journal of Engineering and Technology, 7*(2), 126–129. https://doi.org/10.7763/IJET.2015.V7.779

Abdul Manaf, M. Z., Mohamed, M. F., Mohamad Yusoff, W. F., & Mohd Sulaiman, M. K. A. (2020). A study on the thermal comfort of prayer hall based on the roof design of mosque with natural ventilation. *International Journal of Advanced Science and Technology*, *29*(9), 1900–1915.

Abdul Wahab, I., Ismail, L. H., & Kadir, A. (2016). Opening design and position effect on building natural stack effect and cross ventilation. *International Journal of Engineering and Technical Research, 5*(1), 13–21.

Ahmad, A. A., Ali @ Mat Zin, A., & Arbi, E. (2013). Typology of interior architecture for traditional mosques in Peninsular Malaysia from 1700-1900 AD. *Journal of Al-Tamaddun*, *8*(2), 89–100. https://doi.org/10.22452/JAT.vol8no2.8

Al-Obaidi, K. M., Ismail, M., & Abdul Rahman, A. M. (2014). Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review. *Frontiers of Architectural Research*, *3*(3), 283–297. https://doi.org/10.1016/j.foar.2014.06.002

ASHRAE. (2017). *ASHRAE Standard 55: Thermal environmental conditions for human occupancy*.

Azmi, N. A., Baharun, A., Arıcı, M., & Ibrahim, S. H. (2023). Improving thermal comfort in mosques of hot-humid climates through passive and low-energy design strategies. *Frontiers of Architectural Research, 12*(2), 361–385. https://doi.org/10.1016/j.foar.2022.07.001

Daghigh, R. (2015). Assessing the thermal comfort and ventilation in Malaysia and the surrounding regions. *Renewable and Sustainable Energy Reviews, 48*, 681–691. https://doi.org/10.1016/j.rser.2015.04.017

Eusof, Y. A., Denny, M., Mat Som, A. P., Mohd Jusan, M., & Ibrahim, B. (2015). An assessment of green mosque index in Peninsular Malaysia. *American-Eurasian Journal of Agricultural & Environmental Sciences*, *15*, 114–122. https://doi.org/10.5829/idosi.aejaes.2015.15.s.215

Green Building Index. (2009). *GBI assessment criteria for non-residential new construction* (1st ed.). Green Building Index Sdn. Bhd.

Hassan, A. S. (2011). Kampung Laut's old mosque in Malaysia: Its influence from Chinese building construction. *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies*, *2*(1), 27–52.

Ibrahim, S. H., Baharun, A., Nawi M. N. M., Junaidi E. (2014). Assessment of thermal comfort in the mosque in Sarawak, Malaysia. *International Journal of Energy and Environment (IJEE), 5*(3), 327–334.

Ibrahim, S. H., Roslan, Q., Affandi, R., Razali, A. W., Samat, Y. S., & Mohd Nawi, M. N. (2018). Study on the optimum roof type with 30° roof angle to enhance natural ventilation and air circulation of a passive design. *International Journal of Technology, 9*(8), 1692–1701.

Khalit, N. A., Abdul Majid, N. H., Abdul Rahim, Z., & Mohd Nawawi, N. (2017). Unveiling the secrets of passive design construction of Nusantara masjid architecture through the roof design for region's sustainability. *Journal of Ecology, Environment and Conservation, 23*(Special Issue), 78–83.

Khalit, N. A., Denan, Z., Sanusi, A. N. Z., & Mohd Nawawi, N. (2023). Assessment of indoor thermal condition on traditional vernacular masjid: A case study on Masjid Kampung Laut, Malaysia. *Jurnal Kejuruteraan, 35*(3), 647–655. https://doi.org/10.17576/jkukm-2023-35(3)-12

Kindangen, J. I., & Rogi, O. H. A. (2020). The role of attic ventilation to reduce indoor air temperature in zinc-roofed buildings in a humid tropical climate. In *Proceedings of the EduARCHsia & Senvar 2019 International Conference (EduARCHsia 2019)* (pp. 14–18). Atlantis Press. https://doi.org/10.2991/aer.k.200214.003

Maarof, S. (2014). *Roof designs and affecting thermal comfort factors in a typical naturally ventilated Malaysian mosque* [Doctoral dissertation, Cardiff University].

Malaysian Carbon Reduction and Environmental Sustainability Tool (MyCREST). (2020). *MyCREST reference guide: Design and construction stage*.

Mohammad Yusoff, W. F. (2020). Initial assessment of indoor environmental condition and thermal comfort of Malaysia heritage mosque. *Jurnal Kejuruteraan, 32*(2), 271–280. https://doi.org/10.17576/jkukm-2020-32(2)-11

Mohd Nawayai, S. S., Denan, Z., & Abdul Majid, N. H. (2020). Design strategies in passive design approach for thermal comfort in Malay vernacular masjids: A paradigm shift. *PalArch's Journal of Archaeology of Egypt/Egyptology, 17*(9), 7381–7397.

Mohd Rasdi, M. T. & Utaberta, N. (2010). The design of mosques as community development centers from the perspective of the Sunna and Wright's organic architecture. *Journal of Islamic Architecture, 1*(1), 1–7.

MS1525. (2019). *Energy efficiency and use of renewable energy for non-residential buildings*. Department of Standards Malaysia.

MS2577. (2014). *Architecture and asset management of masjid—Code of practice*. Department of Standards Malaysia.

Najafi, M, & Mohd Shariff, M. K. (2011). Factors influencing public attachment to mosques in Malaysia. *International Journal of Architectural Research, 5*(3), 7–25.

Othman, R. (2011). *Mihrab design and ornamentation of selected mosques in Malaysia* [Thesis, University of Malaya].

Rasli, N. B. I., Ramli, N. A., Ismail, M. R., Zainordin, N. S., & Razman, M. R. (2021). Effectiveness of ventilation strategies in reducing the temperature in the main prayer halls of mosques in Malaysia. *Journal of Engineering Science and Technology, 16*(4).

Roslan, Q., Ibrahim, S. H., Affandi, R., Mohd Nawi, M. N. & Baharun, A. (2015). A literature review on the improvement strategies of passive design for the roofing system of the modern house in a hot and humid climate region. *Frontiers of Architectural Research, 4*(1), 1–8. https://doi.org/10.1016/j.foar.2015.10.002

Shah, M. A., Arbi, E., & Keumala, N. (2016). Historiography of mosque architecture in Malaysia: Analysis of texts by 5 authors. *Journal of Design and Built Environment*, *16*(2), 44–54. https://doi.org/10.22452/jdbe.vol16no2.1

Sukawi, Dwiyanto, A., & Sari, S. R. (2015). The roof ventilation as alternative passive cooling for high density building in the humid tropics. *International Journal of Scientific and Research Publications*, *5*(12).

Tashoo, K., Thepa, S., Pairintra, R., & Namprakai, P. (2014). Reducing the air temperature inside the simple structure greenhouse using roof angle variation. *Journal of Agricultural Sciences*, *20*(2), 136–151. https://doi.org/10.15832/tbd.11840

Wang, S., Shen, Z., & Gu, L. (2012). The impact of roof pitch and ceiling insulation on cooling load of naturally ventilated attics. *Energies*, *5*(7), 2178–2196. https://doi.org/10.3390/en5072178