LOCAL WISDOM, 18 (2): 94- 112 , 2026
Local Wisdom Scientific Online Journal
ISSN: 2086-3764

Tropical Vernacular Strategies of Kobuang Limo House for Sustainable Thermal Performance in Society 5.0 Era

Mulfakli*, **Desy Aryanti**[1*]
[1] *Department of Architecture, Universitas Bung Hatta, Sumatera Barat, Indonesia.*
*Corresponding Author: desyaryanti@bunghatta.ac.id

Keywords:
Malay House; Tropical Architecture; Thermal Comfort; Sustainability; Vernacular Design.

Abstract

This study addresses the challenge of achieving thermal comfort in hot-humid tropical climates, where buildings increasingly rely on energy-intensive cooling systems. Vernacular architecture offers passive strategies, yet their performance remains insufficiently quantified under real conditions. This research evaluates the thermal performance of Kobuang Limo houses and examines how their architectural elements function as an integrated passive cooling system. Field measurements were conducted in four traditional houses in Riau, Indonesia, over three consecutive days across seven spatial (room) zones and three daily intervals. Effective Temperature (ET) was calculated from air temperature, relative humidity, and air velocity. The results show that indoor spaces maintain ET within the warm-comfort range (26–27 °C) and are more stable than outdoor conditions. Houses with ceilings exhibit lower ET than those without, while moderate wall-opening ratios (15–25%) provide optimal performance. These findings demonstrate that Kobuang Limo houses operate as integrated passive systems, offering empirical insights for sustainable, climate-responsive design in tropical regions.

Article History
Received : Jan 13, 2026
Accepted : April 3, 2026
Published : July 15, 2026

1. INTRODUCTION

In hot-humid tropical regions, maintaining indoor thermal comfort remains a persistent challenge due to high air temperatures, elevated relative humidity, and limited air movement. These conditions increase dependence on mechanical cooling systems, contributing significantly to energy consumption and carbon emissions in the building sector. Globally, buildings account for nearly 39% of total CO_2 emissions, largely driven by operational energy use for cooling (Ali et al., 2020; Bertoldi et al., 2022; IEA, 2023). In Indonesia, this issue is exacerbated by the widespread use of air conditioning in buildings that are not climatically adapted (Rosianasari et al., 2027; Triani et al., 2023). This condition highlights a critical limitation in contemporary architectural practice, which tends to rely on energy-intensive systems rather than climate-responsive design strategies. However, climate-responsive strategies in tropical contexts have not been sufficiently quantified in terms of measurable thermal performance, particularly under real environmental conditions.

Tropical vernacular architecture offers an alternative through passive environmental adaptation. Previous studies have identified key strategies such as cross-ventilation, elevated floors, permeable materials, and spatial layering that enhance airflow and reduce heat accumulation (Anand et al., 2023; Gamero-salinas et al., 2021). However, most vernacular studies remain predominantly qualitative, focusing on typology and cultural aspects rather than measurable environmental performance (Karyono, 2016; Rapaport, 1969). In contrast, studies on passive cooling strategies often rely on simulation-based models or generalized climatic assumptions rather than on in situ (Anand et al., 2023; Gamero-salinas et al., 2021). As a result, the relationship between architectural configuration and actual thermal performance in vernacular buildings has not been systematically established.

The evaluation of thermal comfort in naturally ventilated tropical buildings also requires appropriate analytical indicators. Conventional models, such as Predicted Mean Vote (PMV), are designed for controlled indoor environments and are less representative of open tropical conditions (Fanger, 1972). In contrast, Effective Temperature (ET), which integrates air temperature (Ta), relative humidity (RH), and air velocity (Va), provides a more suitable indicator for assessing thermal comfort in naturally ventilated environments (Coccolo et al., 2016; Hermawan & Švajlenka, 2021). These studies indicate that thermal performance in tropical buildings is strongly influenced by interactions among Ta, RH, and Va, as well as by architectural factors such as ventilation openings and vertical spatial configuration. These variables, therefore, form the basis for evaluating thermal performance in this study using the ET index.

Within this gap, the *Kobuang Limo* house in Riau, Indonesia, represents a relevant case for empirical investigation. This traditional Malay stilt house exhibits consistent spatial characteristics, including elevated flooring, controlled wall-opening proportions, and attic-based ventilation systems. These features enable direct examination of how architectural elements influence thermal performance under real climatic conditions. Despite its relevance, quantitative studies that explicitly relate these spatial characteristics to measured thermal performance remain limited, particularly for *Kobuang Limo* houses.

In the context of Society 5.0, where technological advancement is expected to integrate with environmental intelligence, vernacular architectural knowledge can be reinterpreted as a source of adaptive, low-energy design strategies. Rather than being viewed as static heritage, it can be understood as a measurable environmental system that informs contemporary sustainable design, particularly in reducing reliance on energy-intensive cooling systems.

Therefore, this study aims to empirically evaluate the thermal performance of *Kobuang Limo* houses using Effective Temperature (ET) as the primary indicator of thermal comfort, in accordance with SNI 03-6572-2001 (Badan Standardisasi Nasional, 2001)for naturally ventilated buildings. ET is derived from air temperature (Ta), relative humidity (RH), and air velocity (Va). The objectives of this study are: (1) to measure and compare thermal conditions across spatial zones and house units; (2) to analyze the influence of architectural elements, including wall-opening ratios and ceiling conditions, on thermal performance; and (3) to examine how these elements operate as an integrated passive cooling system in a humid tropical environment.

2. LITERATURE REVIEW

Conversely, traditional tropical architecture has long incorporated adaptive climatic systems through classical bioclimatic principles first articulated by (Olgyay, 2015). Principles such as cross-ventilation, wind-oriented building orientation, high-pitched roofs, porous local materials, and shading vegetation have proven to maintain thermal balance without mechanical energy input (Anand et al., 2023; Bema & Ozarisoy, 2024; Gamero-salinas et al., 2021; Mahadzir & Ismail, 2025; Zune et al., 2020). Xu et al. (2024) demonstrated that bioclimatic strategies could reduce indoor temperatures by 3 - 5 °C compared to sealed modern buildings, while Rasha A et al. (2023) confirmed that natural ventilation can save up to 45% of cooling energy. Thus, the passive strategies embedded in vernacular architecture have long functioned as natural environmental technologies (bioclimatic intelligence) long before the emergence of the green building concept.

The effectiveness of passive strategies in tropical architecture is closely related to the selection of thermal comfort indices for evaluating building performance. The Predicted Mean Vote (PMV) model and Fanger's thermal comfort scale, developed for closed air-conditioned spaces in temperate climates, assume homogenous and stable air temperature and flow (Fanger, 1972). These assumptions make the model less representative of tropical buildings that rely on open, naturally ventilated environments. Several adaptive models, such as Physiological Equivalent Temperature (PET), Effective Temperature (ET), and Universal Thermal Climate Index (UTCI), highlight the necessity of incorporating air velocity (Va) and relative humidity (RH) to evaluate thermal comfort in tropical contexts accurately (Albatayneh et al., 2019; Coccolo et al., 2016; Jing et al., 2024). In the Indonesian context, the national standard SNI 03-6572-2001 and numerous empirical studies suggest that Effective Temperature (ET) is a more representative indicator for assessing comfort in open tropical buildings (Hermawan & Švajlenka, 2021). ET integrates three main parameters: air temperature (Ta), relative humidity (RH), and air velocity (Va) (Blazejczyk & Epstein, 2012), making it more sensitive to natural airflow than PMV, which assumes a closed system. Therefore, ET is more appropriate for evaluating "breathing" tropical buildings such as vernacular stilt houses that employ cross ventilation, large openings, and shading vegetation as natural cooling systems (Angkasa & Kamil, 2024; Hermawan & Švajlenka, 2021; Mulfakli et al., 2025).

Various studies in Indonesia reaffirm the relevance of environmental technology for cross-sectoral carbon mitigation. Triani et al. (2023) projected that CO_2 emissions from the building sector could increase by over 35% by 2035 without the adoption of energy-efficient design. (Agnes & Naqash, 2025) showed that the implementation of green infrastructure as a nature-based solution for water resource management can reduce surface temperature and enhance energy efficiency in urban drainage systems. Fatah et al. (2025) found that the use of 60 MW wind turbines for data centers in West Java could reduce emissions by up to 125,000 tons of CO_2 annually, while Rahim et al. (2025) reported that waste-to-energy systems lower emissions in the waste sector by up to 40% compared to conventional open systems.

The novelty of this research lies in its quantitative empirical approach that frames vernacular houses as natural environmental technology systems, energy-efficient and adaptive to climate change. This study emphasizes that spatial and material intelligence embedded within tropical architecture can serve as a foundation for developing low-carbon, intelligent design paradigms in the Society 5.0 era. The evaluation of four *Kobuang Limo house* units in *Pulau Belimbing Village*, Kampar Regency, with variations in wall-opening ratios, floor areas, and ceiling conditions, enables the identification of the relationship between tropical architectural configurations and indoor thermal performance as an actualization of sustainability principles in tropical architecture.

3. METHODS

3.1 Research Design

This study employs a quantitative-descriptive approach, combined with a comparative case study strategy, to evaluate the thermal performance of tropical vernacular architecture under real-world environmental conditions. The quantitative approach enables the measurement of thermal variables without experimental manipulation, while the case study strategy allows in-depth analysis of architectural configurations within their real-life context (Crowe et al., 2011).

A comparative analysis was conducted across four *Kobuang Limo* house units to examine how variations in architectural elements influence indoor thermal conditions. The selected variables include wall-opening ratios, floor area, and ceiling conditions, which are hypothesized to affect natural ventilation and thermal stability.

3.2 Study Location and Objects

The study was conducted in *Pulau Belimbing* Village, *Kuok* District, *Kampar* Regency, Riau Province, Indonesia (0°23′ S; 101°10′ E), which is characterized by a hot-humid tropical climate with average temperatures ranging from 26–33 °C, relative humidity above 60%, and low wind velocity (< 0.5 m/s).

Four *Kobuang Limo* house units were selected based on the following criteria: architectural authenticity above 90%, similar environmental and microclimatic conditions, and variation in wall-opening ratios and ceiling presence. These criteria enable controlled comparison of thermal performance under comparable climatic exposure.

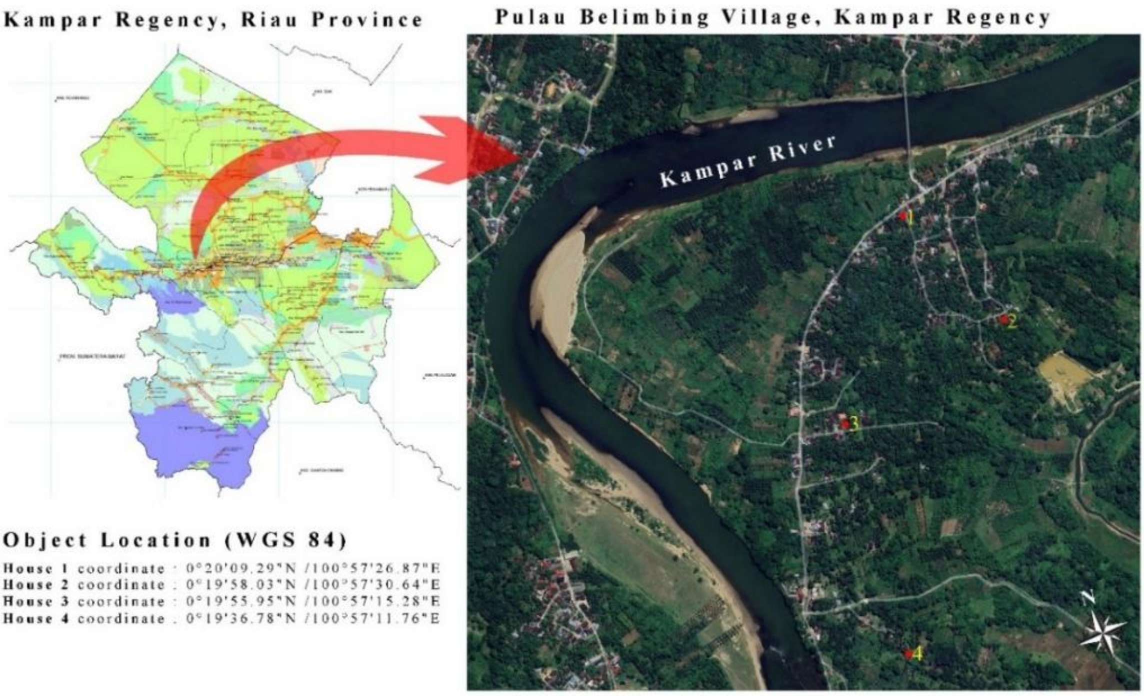

Figure 1. Illustrates the study area, showing the location of Pulau Belimbing Village and the distribution of five *Kobuang Limo* houses along the Kampar River.
Source: RTRW Kampar, 2019 - 2039; Google Earth, 2025

The research focuses on four *Kobuang Limo House* units within the village. Each house is over six decades old, with high levels of authenticity in form, materials, and structure (over 90%). However, one unit has been converted into storage and is no longer inhabited. All houses are oriented along a north-south axis, allowing direct comparison of variations in openings, roofing materials, and surrounding vegetation.

Table 1. Documentation of the five observed *Kobuang Limo* houses in Pulau Belimbing Village

Object	Description and Information		Figure
House 1	Built year	1954	
	Clan Owner	Domo	
	Function	Residential	
	Façade material	Wooden planks	
	Roof Material	Zinc	
House 2	Built year	1920	
	Clan Owner	Piliang	
	Function	Residential	
	Façade material	Wooden planks	
	Roof Material	Zinc	
House 3	Built year	1934	
	Clan Owner	Caniago	
	Function	Residential	
	Façade material	Wooden planks	
	Roof Material	Zinc	
House 4	Built year	1918	
	Clan Owner	Piliang	
	Function	Storage house	

Object	Description and Information		Figure
	Façade material	Wooden planks	
	Roof Material	Zinc	

Source: Author's Field Documentation, 2024

3.3 Research Procedure

The research was conducted through the following sequential stages:

- Identification of research problems and variables (Ta, RH, Va, architectural configuration)
- Selection of case study objects based on predefined criteria
- Architectural documentation and zoning of observation points
- Field measurement of thermal variables (Ta, RH, Va)
- Calculation of Effective Temperature (ET) based on SNI 03-6572-2001
- Intra-unit analysis of thermal distribution across spatial zones
- Inter-unit comparative analysis based on architectural variations
- Interpretation of passive cooling mechanisms as an integrated system

The research was conducted through the following sequential stages, as illustrated in Figure 2 below.

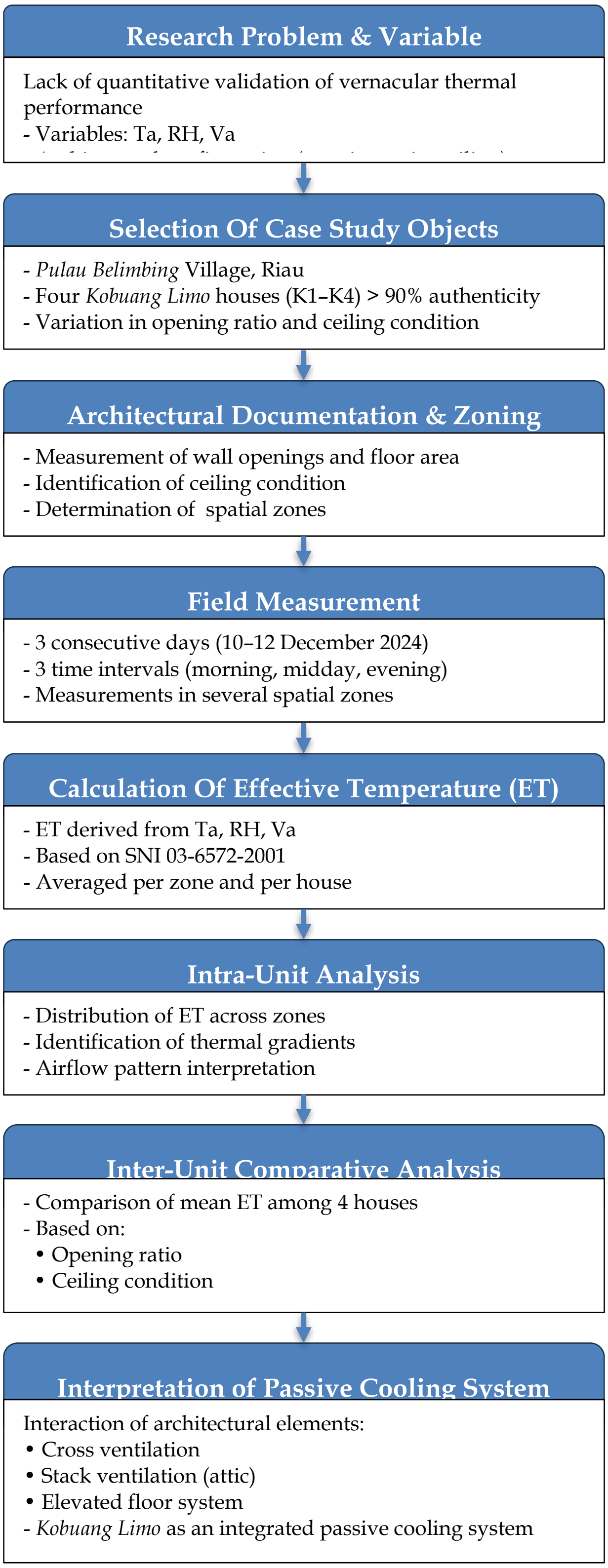

***Figure* 2.** Research procedure of the study, including data collection and analysis stages.
Source: Author, 2025

3.4 Data Collection

Data were collected through field measurements and architectural observation over three consecutive days (10-12 December 2024) under stable weather conditions. Measurements were conducted across seven representative (room) area: the yard as an outdoor reference, the underfloor space, front porch, living room, bedroom, rear porch, and kitchen. These zones were selected to represent variations in spatial configuration, airflow conditions, and thermal exposure within the building.

Observations were carried out at three daily intervals to capture diurnal variations in thermal conditions, consisting of morning (07:00 - 10:00), midday (12:00 - 15:00), and evening (19:00 - 21:00). The measured variables included air temperature (Ta, °C), relative humidity (RH, %), and air velocity (Va, m/s). Air temperature and relative humidity were recorded with a digital thermo-hygrometer, while air velocity was measured with a hot-wire anemometer.

All measurements were conducted in accordance with SNI 03-6572-2001 standards for naturally ventilated buildings.

3.5 Thermal Data Processing

Thermal performance was evaluated using Effective Temperature (ET) as the primary indicator of thermal comfort. ET integrates air temperature (Ta), relative humidity (RH), and air velocity (Va), making it suitable for naturally ventilated tropical environments.

The concept of ET was first introduced by Missenard (1933), empirically developed by, and later reformulated by Blazejczyk et al. (2012) as follows:

$$\mathrm{ET} = 37 - \frac{37 - \mathrm{Ta}}{0.68 - 0.0014\mathrm{RH} + \frac{1}{1.76 + 1.4\mathrm{Va}^{0.75}}} - 0.28\mathrm{Ta}(1 - 0.01\mathrm{RH})$$

ET = Effective Temperature
37 = Maximum body temperature of a healthy human (°C)
Ta = Air temperature (°C)
Rh = Relative humidity (%)
Va = Air velocity (m/s)

The ET values were calculated for each observation point and time interval. Subsequently:

- ET values across the seven spatial zones were averaged to obtain the mean ET per house
- Mean ET values were grouped by:
  - spatial zone
  - time interval
  - house unit

3.6 Data Analysis

The analysis was conducted at two levels:

1. Intra - unit analysis: To examine the distribution of ET across spatial zones within each house, identifying thermal gradients and airflow patterns.

2. Inter - unit comparative analysis: To compare mean ET values among the four houses based on wall-opening ratios, floor area, and ceiling conditions.

The results were evaluated against the thermal comfort range defined by SNI 03-6572-2001 (25–27 °C) to determine the effectiveness of passive thermal strategies.

3.7 Analytical Framework

The final stage interprets the relationship between measured thermal data (ET) and architectural configuration. This includes:

- airflow dynamics
- spatial layering
- material characteristics

The analysis is grounded in:

- bioclimatic design principles (Olgyay, 2015)
- vernacular architecture theory (Rapoport, 1969)
- tropical architectural adaptation (Karyono, 2016)

This framework allows the *Kobuang Limo* houses to be understood as an integrated passive thermal system within a humid tropical context.

4. RESULTS AND DISCUSSION

The results are derived from field measurements conducted in four *Kobuang Limo* house units, focusing on the relationship between thermal conditions and architectural configuration under a humid tropical climate. The analysis is structured to examine thermal distribution across spatial zones, compare performance among houses, and interpret how architectural elements contribute to passive cooling. Figure 3 illustrates the spatial configuration and measurement points used in this study.

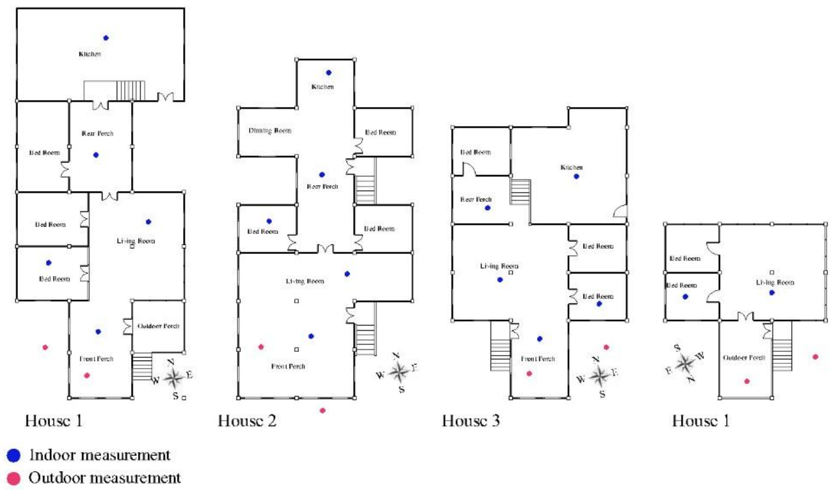

Figure 3. Floor plans of the four *Kobuang Limo House* units show orientation and thermal measurement points.
Source: Author's field survey and redrawing, 2024

4.1 Thermal Distribution Across Spatial Zones

The thermal conditions of the *Kobuang Limo* houses were evaluated using Effective Temperature (ET) measured across seven spatial zones and three daily time periods. The values presented represent the average results of measurements conducted over three consecutive days, providing a reliable representation of thermal conditions under stable climatic exposure.

Table 2. Comparison of Effective Temperature (ET) across rooms and time periods in four units of *Kobuang Limo* House, based on SNI 03-6572-2001.

Object	Time	Outdoor		Indoor				
		Yard	Under floor	Front porch	Living room	Bed room	Rear porch	Kitchen
House 1	Morning 07.00-10.00	25.13	25.22	25.14	25.55	25.39	24.40	25.93
	Noon 12.00-15.00	26.56	26.72	26.76	26.99	26.72	26.15	27.30
	Evening 19.00-21.00	26,07	26.04	26.07	26.68	26.33	25.65	26.52
House 2	Morning 07.00-10.00	25.41	25.66	25.61	25.85	26.24	26.08	26.07
	Noon 12.00-15.00	27.38	27.05	26.81	27.00	27.12	26.96	27.12
	Evening 19.00-21.00	26.27	25.91	25.98	26.51	26.47	26.58	26.26
House 3	Morning 07.00-10.00	26.61	26.69	26.43	26.55	26.83	26.41	26.46
	Noon 12.00-15.00	28.01	27.86	26.80	26.72	27.62	26.86	27.37
	Evening 19.00-21.00	26.21	26.19	26.42	26.80	26.63	26.75	26.78
House 4 (non ceiling)	Morning 07.00-10.00	26.91	26.81	26.64	26.91	27.16	-	-
	Noon 12.00-15.00	27.50	27.53	26.82	27.61	27.91	-	-
	Evening 19.00-21.00	26.09	26.33	26.04	26.91	26.99	-	-

Based on SNI 03-6572-2001

The optimal comfort range is an Effective Temperature between 22.80 °C and 25.80 °C.

The Warm - comfort range is an Effective Temperature between 25.80 °C and 27.10 °C.

Thermal discomfort occurs when ET exceeds 27.10 °C.

Source: Author's field measurement and analysis, 2025

The results show that most indoor spaces fall within the warm-comfort range (25.8-27.1 °C) according to SNI 03-6572-2001. Lower ET values are consistently observed in the underfloor zone and semi-open areas such as the front and rear porches. In contrast, higher values are recorded in enclosed spaces, particularly the bedroom and kitchen, during midday. This distribution indicates that zones with greater airflow exposure maintain lower thermal conditions, whereas enclosed spaces tend to accumulate heat.

A clear temporal pattern is also observed, with ET values increasing during midday (12:00 - 15:00) and decreasing in the evening. The average daily fluctuation is approximately ±1.3-1.5 °C, indicating that solar radiation is the primary factor influencing thermal variation, while the building configuration moderates the intensity of heat gain.

To obtain a generalized representation of the thermal distribution, the ET values from the three ceilinged houses (Houses 1-3) were averaged across all observation periods and spatial zones over the three-day measurement period.

Table 3. Mean Effective Temperature (ET) across rooms (average of three ceilinged *Kobuang Limo house* units).

Object	Time	Outdoor		Indoor				
		Yard	Under floor	Front porch	Living room	Bed room	Rear porch	Kitchen
Mean ET H1 - H3	Morning 07.00-10.00	25.72	25.85	25.73	25.98	26.15	25.63	26.15
	Noon 12.00-15.00	27.32	27.21	26.79	26.90	27.15	26.65	27.26
	Evening 19.00-21.00	26.18	26.05	26.16	26.66	26.48	26.33	26.52

Note: Values represent mean ET of ceilinged units (House 1–3); House 4 excluded due to absence of ceiling.
Source: Author's Analysis, 2025

The averaged results reveal a consistent spatial pattern. The underfloor zone and semi-open areas maintain lower ET values (approximately 26.0-26.3 °C), while core indoor spaces such as the living room, bedroom, and kitchen exhibit higher values (approximately 26.6-27.4 °C). This pattern reflects a layered thermal structure, in which peripheral and lower zones serve as cooling buffers, while the main occupied spaces retain moderate heat.

The diurnal variation of thermal conditions is illustrated in Figure 4, which shows the changes in mean ET across spatial zones throughout the day.

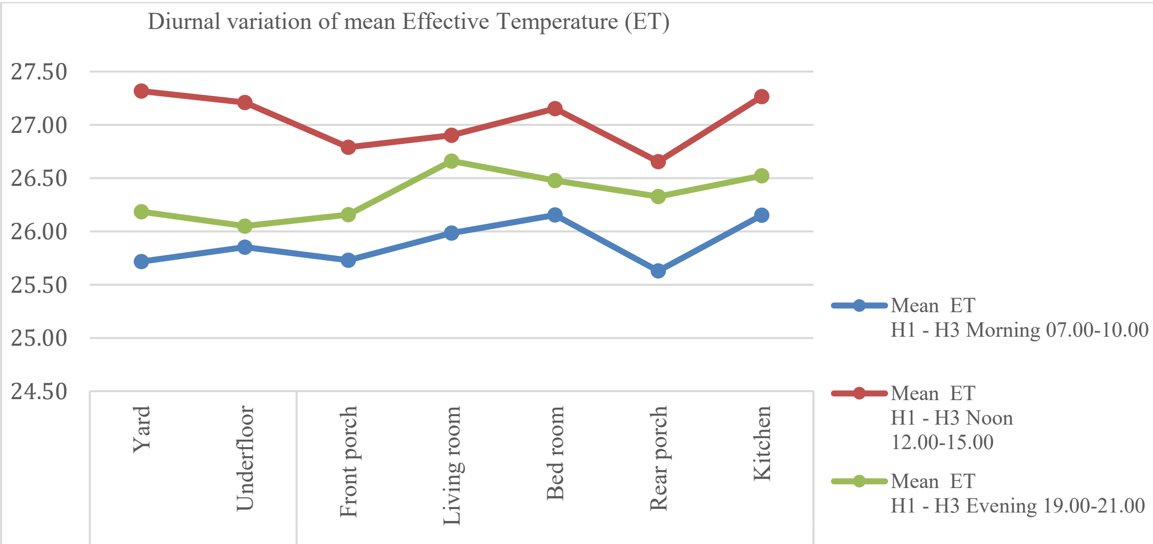

Figure 4. Diurnal variation of mean Effective Temperature (ET) across rooms of three ceilinged Rumah *Kobuang Limo* units (H1–H3).
Source: Author's Analysis, 2025

4.2 Effect of Ceiling Presence on Thermal Performance

A comparative analysis was conducted to evaluate the thermal performance of the four *Kobuang Limo* house units, with particular attention to the influence of a ceiling as a vertical thermal control element. The analysis is based on the average indoor Effective Temperature (ET) values derived from three-day measurements.

Table 4. presents the average indoor ET values for each house across three daily observation periods

House	Morning 07.00-10.00	Noon 12.00-15.00	Evening 19.00-21.00
House 1 (ET) (°C)	25.28	26.78	26.25
House 2 (ET) (°C)	25.97	27.00	26.36
House 3 (ET) (°C)	26.54	27.07	26.68
House 4 (ET) (°C)	26.90	27.45	26.65

Source: Author's Analysis, 2025

The results indicate that the three ceilinged houses (Houses 1-3) maintain relatively stable thermal conditions, with mean ET values ranging from 26.3 to 26.7 °C. In contrast, House 4, which lacks a ceiling, consistently records higher ET values across all time periods, with an average increase of approximately +0.7 °C compared to the ceilinged houses.

This difference becomes more pronounced during the midday period, when House 4 reaches peak ET values exceeding 27.4 °C, while the ceilinged houses remain closer to 26.6-27.0 °C. The higher thermal exposure in House 4 indicates a reduced capacity to buffer solar heat, particularly during peak radiation hours.

The comparison of thermal performance among the houses is illustrated in Figure 5, which shows the variation of indoor mean ET values across the three observation periods.

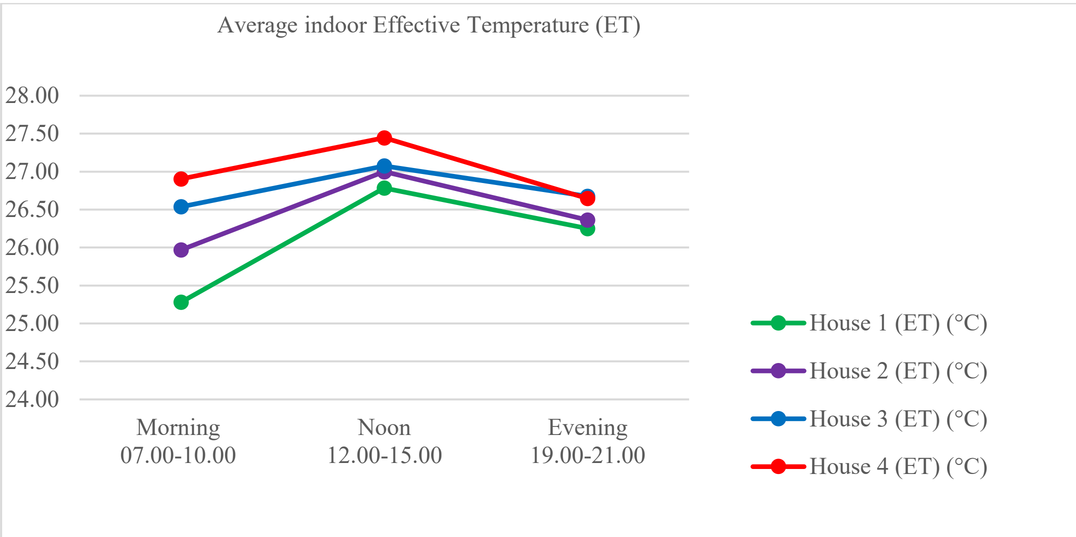

Figure 5. Average indoor Effective Temperature (ET) recorded in the morning, noon, and evening across four traditional *Kobuang Limo* houses.
Source: Author's analysis, 2025

Figure 5 highlights a consistent trend: all houses experience an increase in ET during the daytime, followed by a decline in the evening. However, House 4 exhibits the highest peak and the least moderated thermal profile. This pattern indicates that the absence of a ceiling allows direct radiative heat transfer from the roof into the interior space, significantly increasing indoor thermal load.

In contrast, the presence of a ceiling in Houses 1–3 serves as an intermediate thermal layer that reduces heat transfer from the roof and helps maintain more stable indoor conditions. This finding demonstrates that the ceiling is not merely a structural or aesthetic element but plays a critical role as a vertical thermal buffer in regulating indoor temperature.

Overall, the comparison confirms that thermal performance in *Kobuang Limo* houses is strongly influenced by vertical spatial configuration. The presence of a ceiling enhances the building's ability to moderate heat gain and maintain thermal stability, whereas its absence increases thermal exposure despite similar environmental conditions.

4.3 Relationship Between Wall-Opening Ratio and Thermal Performance

A comparative analysis was conducted to examine the relationship between wall opening ratio and thermal performance across the four *Kobuang Limo* house units. The analysis incorporates floor area, wall-opening area, and mean indoor Effective Temperature (ET), based on three-day averaged measurements.

Table 5. Floor area, wall opening area, and opening-to-wall ratio of four *Kobuang Limo House* units.

Room	Floor area (m2)	Wall opening area (m2)	Opening to wall ratio (%)	Mean indoor ET (°C)
House 1	134.00	29.04	22%	26.10
House 2	105.00	16.27	15%	26.44
House 3	105.00	16.27	15%	26.76
House 4 no ceiling (excluding open porch)	41.40	13.00	31%	27.00

Source: Author's Analysis, 2025

The results show that houses with moderate wall-opening ratios (15-22%) exhibit more stable thermal performance, with mean ET values ranging from 26.1 to 26.7 °C. House 1, despite having the largest floor area, records the lowest mean ET (26.1 °C), indicating that an appropriate balance between opening size and spatial configuration contributes to effective thermal regulation.

In contrast, House 4 presents a different pattern. Although it has the highest opening ratio (31%), it records the highest mean ET (27.0 °C). This finding indicates that increasing the proportion of openings does not necessarily improve thermal performance. Instead, the effectiveness of openings depends on their integration with other architectural elements, particularly vertical thermal control components.

The relationship between wall-opening ratio and mean indoor ET is illustrated in Figure 6, which shows the correlation across the four houses.

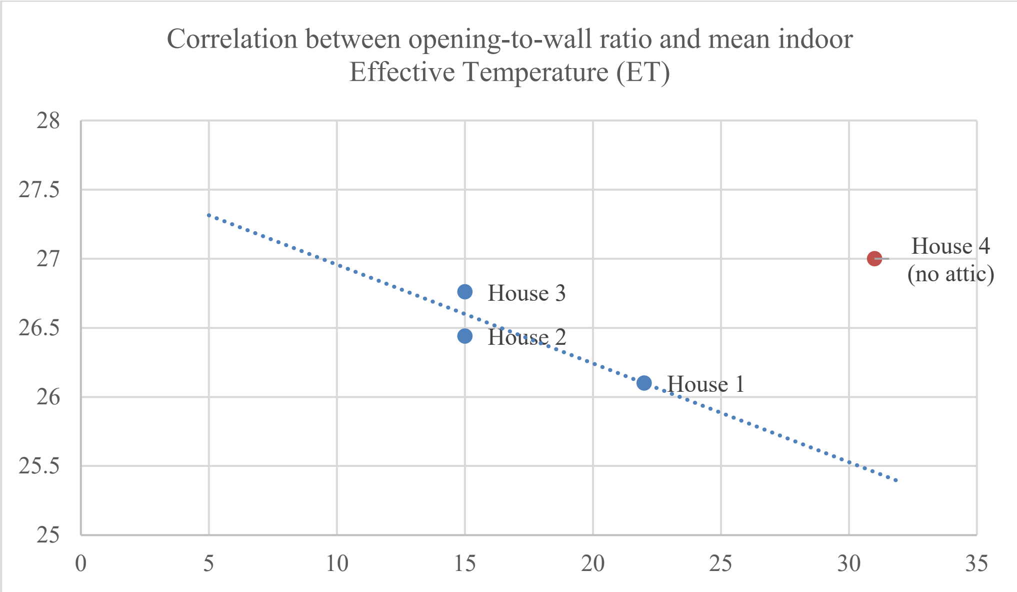

Figure 6. Correlation between opening-to-wall ratio and mean indoor Effective Temperature (ET) across four Rumah *Kobuang Limo* units.
Source: Author's Analysis, 2025

Figure 6 indicates a general trend: thermal performance improves with increasing opening ratio within a moderate range (approximately 15-25%). Within this range, larger openings enhance airflow and contribute to heat dissipation, resulting in lower ET values. However, beyond this range, the relationship becomes non-linear. In the case of House 4, the absence of a ceiling reduces ventilation effectiveness, leading to greater heat accumulation despite the larger opening area.

This finding demonstrates that the wall-opening ratio cannot be interpreted as an independent variable in determining thermal comfort. Instead, it must be understood in relation to the overall architectural configuration, including the presence of ceilings, spatial layout, and airflow pathways. The interaction of these elements determines whether increased openings contribute to cooling or lead to additional heat gain.

Overall, the results suggest that a moderate wall-opening ratio (approximately 20-25%), combined with adequate vertical thermal buffering and controlled airflow, provides the most effective configuration for maintaining stable indoor thermal conditions in *Kobuang Limo* houses.

4.4 *Kobuang Limo* House as an Integrated Passive Cooling System

The findings presented in the previous sections demonstrate that the thermal performance of the *Kobuang Limo* house cannot be attributed to a single architectural element but rather emerges from the interaction of multiple spatial and material components that operate as an integrated passive cooling system. This system is shaped by the combined influence of building orientation, wall-opening configuration, vertical layering, and material properties, which together regulate airflow, heat distribution, and indoor thermal stability.

The north–south orientation of the house plays a fundamental role in minimizing direct solar exposure on the longitudinal façades while facilitating continuous cross ventilation along the main spatial axis. This configuration allows airflow to move effectively from one end of the building to the other, particularly through the calibrated wall openings and semi-open transitional spaces such as the front and rear porches. As demonstrated in Sections 4.1 and 4.3, spaces with greater airflow exposure consistently exhibit lower Effective Temperature (ET), confirming that ventilation is a primary mechanism for thermal regulation in this context.

The elevated floor system further enhances this process by introducing an additional airflow layer beneath the building. The underfloor space serves as a thermal buffer zone, reducing heat transfer from the ground while promoting air circulation that helps cool the occupied spaces above. This condition is reflected in the consistently lower ET values observed in the underfloor and peripheral zones, which act as intermediary layers that moderate thermal conditions before heat reaches the core interior spaces.

Vertical thermal regulation is achieved through the presence of a ceiling and attic space, which together form a critical heat-buffering system. As shown in Section 4.2, houses with ceilings have lower, more stable ET values than houses without ceilings. The attic space traps heat accumulated from solar radiation on the roof, while upper ventilation openings (such as *singap* and jalousie vents) allow this heat to be gradually released. This mechanism reduces direct radiant heat transfer to the living spaces below and prevents excessive increases in indoor temperature during peak solar periods.

Material properties also contribute significantly to this integrated system. The use of timber with relatively low thermal conductivity enables faster heat release during the evening, supporting the diurnal cooling cycle observed in Figure 4. This characteristic allows the building to recover from daytime heat accumulation more effectively than structures with high thermal mass, thereby maintaining a more stable indoor thermal environment.

Importantly, the results demonstrate that these elements do not function independently. For example, increasing wall-opening ratios alone does not necessarily improve thermal comfort, as shown by the higher ET values in House 4 despite its larger openings. Instead, the effectiveness of openings depends on their interaction with vertical buffering elements, spatial configuration, and airflow pathways. This confirms that thermal performance in *Kobuang Limo* houses results from a coordinated system rather than from isolated design features.

The integration of these spatial and environmental mechanisms is illustrated in Figure 7, which summarizes the interactions among orientation, airflow, thermal buffering layers, and material behavior in maintaining indoor thermal balance.

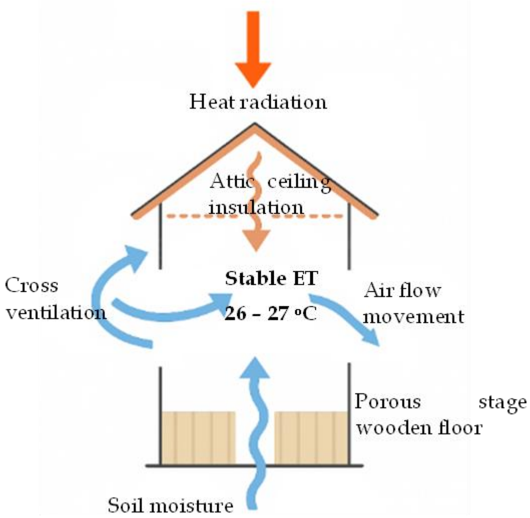

Figure 7. Schematic diagram of passive thermal interaction
Source: Author's Illustration, 2025

This integrated system reflects fundamental principles of tropical architectural adaptation, in which the balance among airflow, shading, and heat control determines thermal comfort. The findings support the view that vernacular architecture embodies a form of environmental intelligence, in which spatial configuration and material selection are inherently aligned with climatic conditions.

In the context of contemporary sustainable design, the *Kobuang Limo* house can therefore be understood not merely as a traditional form but as a functional environmental system that reduces reliance on mechanical cooling. Its passive strategies offer relevant insights for the development of low-energy buildings in humid tropical regions, particularly in addressing current challenges related to energy consumption and carbon emissions.

5. CONCLUSION

This study demonstrates that the *Kobuang Limo* house maintains relatively stable indoor thermal conditions under a hot-humid tropical climate. Based on Effective Temperature (ET) measurements averaged over three consecutive days, most indoor spaces remain within the warm-comfort range defined by SNI 03-6572-2001, generally between 26 and 27 °C, while the highest heat accumulation occurs in the attic and during midday periods. These findings confirm that the house can moderate external thermal stress and maintain more stable indoor conditions than exposed outdoor areas.

The comparative analysis further shows that thermal performance is strongly influenced by architectural configuration. Houses equipped with ceilings maintain lower and more stable ET values than the unit without a ceiling, with the non-ceilinged house recording an increase of approximately +0.7 °C. Similarly, houses with moderate wall opening ratios, particularly within the range of about 15–25%, exhibit better thermal performance than houses with excessive openings but without adequate vertical thermal buffering. These results indicate that the presence of ceilings and calibrated openings plays a decisive role in reducing indoor heat accumulation and improving thermal stability.

More importantly, the findings show that the thermal effectiveness of the *Kobuang Limo* house does not arise from isolated elements, but from the interaction of multiple spatial and material components. The north-south orientation, elevated floor system, semi-open transitional spaces, controlled wall openings, attic ventilation, and timber envelope work together as an integrated passive cooling system. In this sense, the *Kobuang Limo* house should be understood not merely as a cultural artifact, but as a form of spatial and material intelligence embedded in tropical vernacular architecture.

Nevertheless, this study has certain limitations, including a small number of household samples and a short measurement period. Future research is recommended to explore seasonal thermal variations and to incorporate occupants' perceptions to enrich the understanding of experiential thermal comfort. Such efforts will enhance the relevance of the findings and strengthen the position of tropical vernacular strategies as an adaptive, low-energy design model for future architecture.

Overall, this study provides quantitative empirical evidence that vernacular tropical architecture can function as an effective low-energy environmental system under real climatic conditions. The *Kobuang Limo* house demonstrates that thermal comfort can be achieved through spatial configuration, airflow regulation, and material adaptation without reliance on mechanical cooling. These findings position vernacular architecture not merely as cultural heritage, but as a relevant model for developing sustainable and climate-responsive design strategies in contemporary tropical contexts.

ACKNOWLEDGMENT

The author expresses sincere appreciation to *Yayasan Kandil Kemilau Emas*, the custodian of the Museum Rumah Lontiak Kandil Kemilau Emas, for providing access, guidance, and archival information during the fieldwork. Appreciation is also extended to the Pulau Belimbing Village administrators and the homeowners who generously facilitated spatial observations and on-site thermal measurements. This research received no specific grant from any funding agency, public or commercial.

REFERENCES

Agnes, M., & Naqash, M. T. (2025). Green Infrastructure as Nature-Based Solutions For Water Resources Management in Indonesia. *Indonesian Journal of Urban and Environmental Technology*, *8*(1), 15–25. https://doi.org/https://doi.org/10.25105/urbanenvirotech.v8i1.21415

Albatayneh, A., Alterman, D., Page, A., & Moghtaderi, B. (2019). *The Significance of the Adaptive Thermal Comfort Limits on the Air-Conditioning Loads in a Temperate Climate*. https://doi.org/10.3390/su11020328

Ali, K. A., Ahmad, M. I., & Yusup, Y. (2020). Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector. *Sustainability*, *12*(7427), 1–11. https://doi.org/https://doi.org/10.3390/SU12187427

Anand, V., Kadiri, V. L., & Putcha, C. (2023). Passive buildings : a state - of - the - art review. *Journal of Infrastructure Preservation and Resilience*. https://doi.org/10.1186/s43065-022-00068-z

Angkasa, Z., & Kamil, E. M. (2024). *Passive Cooling in Indonesian Traditional Dwellings and Its Relationship with Geographical Location*. *24*(01), 1–16. https://doi.org/https://doi.org/10.22452/jdbe.vol24no1.1

Badan Standardisasi Nasional. (2001). *SNI 03-6572-2001: Tata Cara Perancangan Sistem Ventilasi dan Pengkondisian Udara pada Bangunan Gedung.* https://sispk.bsn.go.id/

Belding, H. S., & Hatch, T. F. (1955). *Index for evaluating heat stress in terms of resulting physiological strains.* https://doi.org/https://api.semanticscholar.org/CorpusID:138297469

Bema, N., & Ozarisoy, B. (2024). Bibliometric Review of Passive Cooling Design Strategies and Global Thermal Comfort Assessment : Theories, Methods, and Tools. *Sustainability*, *16*(9629), 1–39. https://doi.org/https://www.mdpi.com/2071-1050/16/22/9629

Bertoldi, P. B., Kihila, J. M., Lucena, A. F. P., Mata, É., Mirasgedis, S., Novikova, A., & Saheb, Y. (2022). Buildings. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 953–1048). Cambridge University Press. https://doi.org/10.1017/9781009157926.011

Blazejczyk, K., & Epstein, Y. (2012). *Comparison of UTCI to selected thermal indices*. 515–535. https://doi.org/10.1007/s00484-011-0453-2

Coccolo, S., Kämpf, J., Scartezzini, J.-L., & Pearlmutter, D. (2016). Outdoor human comfort and thermal stress: A comprehensive review on models and standards. *Urban Climate*, *18*, 33–57. https://doi.org/https://doi.org/10.1016/j.uclim.2016.08.004

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A., & Sheikh, A. (2011). The case study approach. *BMC Medical Research Methodology*, *11*(100), 1–9. https://doi.org/https://doi.org/10.1186/1471-2288-11-100

Fanger, P. O. (1972). *Thermal comfort. Analysis and applications in environmental engineering.* McGraw-HIll Book Company.

Fatah, I., Hakam, D. F., & Nugraha, D. B. (2025). Techno-Economic Feasibility and Emission Reduction of 60 MW Wind Power Plants for Data Centers in West Java, Indonesia. *Indonesian Journal of Urban and Environmental Technology*, *8*(1), 157–176. https://doi.org/https://doi.org/10.25105/urbanenvirotech.v8i1.22628

Gamero-salinas, J., Monge-barrio, A., Kishnani, N., López-fidalgo, J., & Sánchez-ostiz, A. (2021). Energy & Buildings: Passive cooling design strategies as adaptation measures to reduce indoor overheating risk in tropical climates. *Energy & Buildings*, *252*, 111417. https://doi.org/10.1016/j.enbuild.2021.111417

Hermawan, H., & Švajlenka, J. (2021). The Connection between Architectural Elements and Adaptive Thermal Comfort of Tropical Vernacular Houses in Mountain and Beach Locations. *Energies*, *14*(7427), 1–19. https://doi.org/https://doi.org/10.3390/en14217427

IEA. (2023). *Tracking Clean Energy Progress*. https://www.iea.org/reports/tracking-clean-energy-progress-2023

Jing, W., Qin, Z., Mu, T., Ge, Z., & Dong, Y. (2024). Evaluating thermal comfort indices for outdoor spaces on a university campus. *Scientific Reports*, 1–16. https://doi.org/10.1038/s41598-024-71805-5

Karyono, T. H. (2016). *Arsitektur tropis: bentuk, teknologi, kenyamanan, dan penggunaan energi*. Penerbit Erlangga.

Mahadzir, M. S., & Ismail, M. A. (2025). Effectiveness of Passive Design Elements in a Malaysian Modernist Tropical Cottage. *Journal of Design and Built Environment*, *25*(01), 17–36. https://doi.org/https://ejournal.um.edu.my/index.php/jdbe

Mulfakli, Zulherman, & Fuadi, A. B. (2025). Thermal Comfort in Kobuang Limo House: Evaluating Tropical Architectural Elements. *Journal of Architectural Research and Design Studies*, *9*(2), 129–142. https://doi.org/10.20885/jars.vol9.iss2.art4

Olgyay, V. (2015). *Design with climate: bioclimatic approach to architectural regionalism*. Princeton University Press.

Rahim, I. R., Sari, K., Mukrim, M. I., Iman, A. Z., Taweesan, A., & Swe, Z. A. (2025). Assessment of Carbon Emissions From The Waste Management Sector in Ajatappareng Region, South Sulawesi, Indonesia. *Indonesian Journal of Urban and Environmental Technology*, *8*(2), 690–711. https://doi.org/https://doi.org/10.25105/urbanenvirotech.v8i2.24071

Rapaport, A. (1969). *House Form and Culture*. Prentice-Hall Inc. https://bibliodarq.files.wordpress.com/2016/05/rapoport-amos-house-form-and-culture.pdf

Rasha A, A., Naglaa A, M., Merhan M, S., & Hassan, A. M. (2023). Natural ventilation as a passive cooling strategy for multi-story buildings: analytic vertical skycourt formations. *City, Territory and Architecture*, *10*(28), 1–16. https://doi.org/10.1186/s40410-023-00212-6

Rosianasari, N., Hustim, M., Aly, S. H., Alimuddin, H., & Husna, F. (2027). Quantifying Greenhouse Gas Emissions From Corporate Office Operations: PT PLN (PERSERO) Unit Induk Distribusi (UID) Kalselteng Case Study. *Indonesian Journal of Urban and Environmental Technology*, *8*(2), 576–596. https://doi.org/https://doi.org/10.25105/urbanenvirotech.v8i2.23094

Triani, M., Dewi, K., & Ediansjah, A. S. (2023). Prediction of Carbon Dioxide Emission From Electricity Generation in ASEAN. *Indonesian Journal of Urban and Environmental Technology*, *6*(1), 20–35. https://doi.org/https://doi.org/10.25105/urbanenvirotech.v6i1.14810

Xu, W., Wang, Q., Deng, H., & Id, Z. Z. (2024). *PLOS ONE Research on the sustainable design strategies of vernacular architecture in Southwest Hubei — A case study of the First Granary of Xuan ' en County*. 1–20. https://doi.org/10.1371/journal.pone.0316518

Zune, M., Rodrigues, L., & Gillott, M. (2020). Vernacular passive design in Myanmar housing for thermal comfort. *Sustainable Cities and Society*, *54*, 101992. https://doi.org/https://doi.org/10.1016/j.scs.2019.101992