



Relearning Vernacular Wisdom for Thermal Comfort: Assessing Climate-Responsiveness in Modern Housing Clusters of Banda Aceh

Cut Nursaniah^{*}, Laila Qadri^{}, Zahrul Fuady^{}

Architecture and Planning Department, Engineering Faculty, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia

Corresponding Author Email: cutnursaniah@usk.ac.id

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ABSTRACT

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traditional Acehese settlements, thermal landscape performance, climate-responsive architecture, modern housing clusters, Banda Aceh urban development, passive design strategies, thermal comfort evaluation, sustainable housing design

This study evaluates the thermal responsiveness of six modern housing clusters in Banda Aceh, Indonesia, by comparing their spatial and architectural patterns with traditional Acehese settlements. Field observations and photographic documentation were conducted by the research team using a standardized five-point scale to assess seven variables: building orientation, roof shape and ventilation, vegetation, openings, airflow, site condition, and wall color. Scoring was determined through team-based consensus and cross-checked with local climatic data to ensure consistency. Results show that southern clusters (P1WS and P2WS) achieved the highest thermal responsiveness scores (31 and 27), characterized by optimal orientation, ventilated roofs, and surrounding greenery. In contrast, northern clusters (P1WU and P2WU) scored the lowest (15 and 18) due to poor ventilation, dense layouts, and a lack of vegetation. Radar and bar chart analyses confirm that southern clusters better integrate passive design strategies aligned with Banda Aceh's wind patterns. The study concludes that incorporating vernacular principles, such as vegetation buffers, roof ridge ventilation, and north-south orientation into modern housing can significantly enhance thermal comfort and sustainability in tropical urban environments. These findings provide empirical benchmarks for integrating traditional climate-responsive design into contemporary housing development in post-disaster and climate-sensitive regions.

1. INTRODUCTION

Banda Aceh, located on the northern coast of Sumatra, Indonesia, experiences a humid tropical climate characterized by high humidity, elevated temperatures, and seasonal wind patterns influenced by the Andaman Sea [1, 2]. These environmental conditions require housing designs that can effectively respond to local climatic challenges. However, in recent decades, modern urban housing clusters in Banda Aceh have tended to emphasize aesthetics and market appeal over environmental adaptability, leading to increased dependence on mechanical cooling systems and reduced thermal comfort [3-5].

In contrast, the traditional Rumoh Aceh architecture embodies vernacular wisdom developed over generations, offering a rich repertoire of passive climate-adaptation strategies, such as elevated floors, cross-ventilation, and extended eaves, that effectively address the challenges of a humid tropical climate [6, 7]. Passive ventilation techniques, including maximizing natural airflow, providing shading from solar radiation, controlling indoor humidity, and protecting against rain, have been proven to achieve thermal comfort in a sustainable manner [8-10]. These strategies are deeply embedded in Rumoh Aceh, the region's traditional stilt houses, which typically feature large overhanging roofs, permeable wall structures, and raised floors designed for environmental

responsiveness [6, 11, 12].

Rapid urban development in Banda Aceh increasingly adopts generic architectural styles disconnected from local context and cultural identity [13-15]. As a result, contemporary housing often neglects proven vernacular passive design principles, leading to higher operational costs and environmental burdens. Integrating vernacular wisdom with modern construction techniques and materials presents an opportunity to create contextually responsive and sustainable housing solutions [16].

Previous research on vernacular architecture in tropical regions has largely focused on qualitative interpretations of traditional design wisdom [6, 13, 14, 17]. However, there remains a limited systematic and quantitative assessment of how these principles are retained, transformed, or neglected in modern residential environments, particularly in post-disaster and rapidly urbanizing contexts such as Banda Aceh.

Recent studies on climate adaptability of traditional buildings highlight various passive design approaches, ranging from thermal simulation and field measurement [18, 19] to computational ventilation analysis [20], but few have attempted to quantify their applicability within contemporary urban housing. Moreover, challenges persist in translating vernacular strategies into measurable design parameters due to differences in building materials, plot density, and construction regulations [21].

This research addresses these gaps by introducing a systematic, quantitative evaluation of modern housing clusters in Banda Aceh based on vernacular climate-adaptive benchmarks derived from traditional Acehese settlements. This study examines the extent to which passive ventilation strategies from Rumoh Aceh have influenced modern housing design in Banda Aceh, with the aim of enhancing indoor comfort, improving energy efficiency, and strengthening climate responsiveness [8]. It also identifies key vernacular elements that remain relevant today and proposes their integration into contemporary housing to achieve energy-efficient, comfortable, and culturally grounded living environments [17].

This study contributes both theoretically and practically: theoretically, by deepening understanding of how vernacular principles can inform contemporary tropical housing design; and practically, by providing quantitative benchmarks for architects and policymakers to enhance thermal performance through passive strategies. To clarify the research focus and scope, the specific objectives of this study are to:

1. Systematically evaluate the thermal responsiveness of six modern housing clusters in Banda Aceh based on seven vernacular-derived performance variables.
2. Identify and quantify the degree to which traditional climate-adaptive principles, such as orientation, ventilation, and vegetation, have been retained or neglected in contemporary housing design.
3. Propose design strategies for integrating vernacular wisdom into future urban housing development to enhance thermal comfort and environmental sustainability.

2. GEOGRAPHICAL CONDITIONS AND WIND DIRECTION IN THE STUDY AREA

Part of Banda Aceh lies within a coastal zone bordered by the vast Indian Ocean. Understanding prevailing wind directions and flow patterns is essential for optimizing building orientation in residential landscape design. To apply climate-responsive design principles in modern housing, this study incorporates an analysis of local weather conditions in Banda Aceh.

Figure 1 illustrates the monthly variation in maximum temperature across Banda Aceh, showing the number of days per month that reach specific temperature thresholds. The diagram highlights consistently high temperatures throughout the year, confirming the necessity of passive cooling strategies in residential environments.

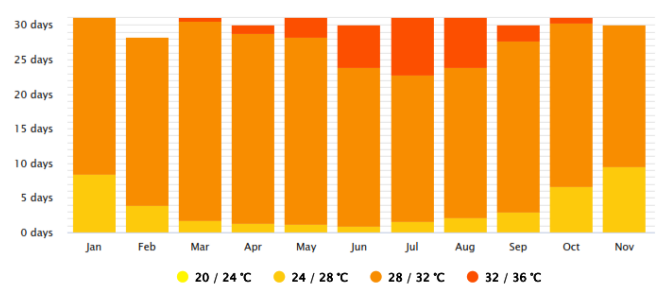


Figure 1. Temperature diagram of Banda Aceh [22]

Wind rose data, generated from ERA5T modeling for Banda Aceh, provide insight into local airflow patterns that are

crucial for evaluating cross-ventilation potential in housing clusters. As shown in Figure 2, the dominant wind directions originate from the southwest (SW) and southeast (SE), with prevailing wind speeds ranging from 1.39 to 2.78 m/s (5–10 km/h). This speed range is considered optimal for natural ventilation strategies in humid tropical climates, particularly for passive cooling through cross-ventilation [18].

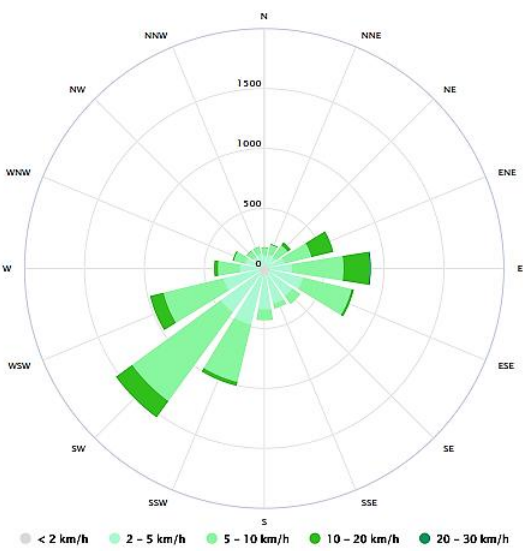


Figure 2. Wind rose of Banda Aceh City [22]

The Rumoh Aceh (vernacular house of Aceh) is typically oriented along the east–west axis, with its longest facades facing north and south. Major openings, such as windows and doors, are primarily located on the north and south elevations. This orientation minimizes direct solar heat gain from the east and west [18] while supporting comfortable indoor conditions through passive means.

Although the prevailing wind directions (SW and SE) do not perfectly align with the primary facade orientation, they approach the building at oblique angles that enable diagonal cross-ventilation. According to studies [6, 20], cross-ventilation can remain effective when wind approaches at an angle of up to 45° to the plane of openings, provided that inlet and outlet paths are unobstructed and adequately dimensioned.

The tilted structure of Rumoh Aceh allows for subfloor airflow, while high vents positioned beneath the roof ridge facilitate a stack effect, promoting upward airflow and heat release. A computational thermal study of Rumoh Aceh [19] confirmed that this architectural typology inherently supports passive cooling mechanisms aligned with Banda Aceh’s microclimatic conditions.

The combination of building orientation, strategic window placement, and elevated construction not only accommodates wind flows from the SW and SE but also enhances thermal comfort passively. This aligns with recent study [21], which demonstrate that passive designs rooted in traditional architecture can outperform modern designs when appropriately adapted to local climatic data.

These findings suggest that although the orientation and ventilation strategies of Rumoh Aceh originated from sociocultural practices, they are inherently adaptive to local microclimatic conditions. The integration of cross- and vertical-ventilation systems within the traditional design aligns closely with modern passive design principles, reaffirming the relevance of vernacular architecture as a

sustainable design reference for contemporary housing development [23].

3. MATERIALS AND METHODS

3.1 Materials

This study compares the characteristics of traditional Acehne settlements with those of six contemporary housing clusters located in Banda Aceh. Primary data were obtained through direct observation and field surveys in housing estates representing three distinct regions: the northern region (WU), the central region (WT), and the southern region (WS). Each region comprises two clusters, designated P1 and P2 (see Figure 3). The cluster selection was based on geographical representativeness (north–central–south distribution), housing typology, and construction period (2010–2020), ensuring coverage of diverse urban contexts and development patterns. Cluster mapping and coordinates were verified using satellite imagery to ensure the spatial accuracy of each case study.

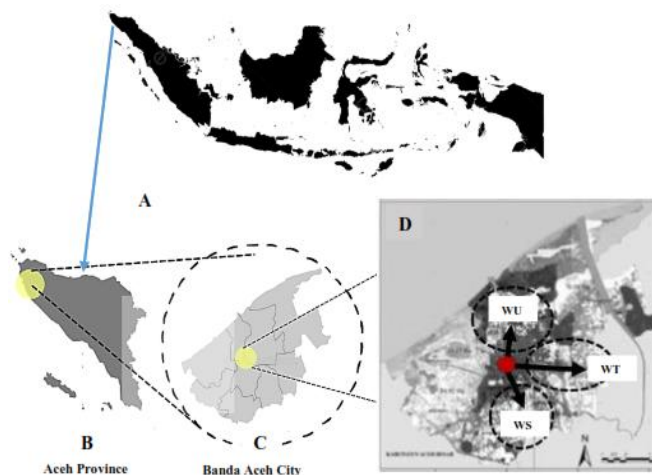


Figure 3. Study location map (A) Indonesia/Coordinates (0.7893° S, 113.9213° E), (B) Aceh/Coordinates (4.6951° N, 96.7494° E), (C) Banda Aceh/Coordinates (5.5483° N, 95.3238° E), and (D) The study areas are distributed across three administrative districts of Banda Aceh: Syiah Kuala (North Zone, WU: 5.5647° N, 95.3195° E), Ulee Kareng (Central Zone, WT: 5.5234° N, 95.3276° E), and Lueng Bata (South Zone, WS: 5.5301° N, 95.3199° E)

The traditional housing typology, known as Rumoh Aceh, is distinguished by climate-responsive spatial strategies such as elevated wooden floors, elongated east–west building orientation, permeable wall systems, and extensive vegetation surrounding the dwelling [6]. These traditional features provide the conceptual basis for selecting assessment variables relevant to the thermal performance of modern housing. To evaluate thermal landscape performance, seven core variables were adopted: (1) orientation, (2) roof shape and ventilation, (3) vegetation, (4) openings and ventilation, (5) airflow, (6) location and site, and (7) wall material and color. These variables were selected based on both theoretical frameworks and observable elements in vernacular and contemporary housing.

In traditional Acehne architecture (see Figure 4), spatial orientation plays a pivotal role in regulating solar exposure and maintaining indoor comfort. Most traditional houses are

aligned along a north–south axis, thereby minimizing east–west-facing walls and reducing solar heat gain. This practice aligns with climatic design strategies described by research [24], which advocate orientation-based solar control in hot–humid regions.

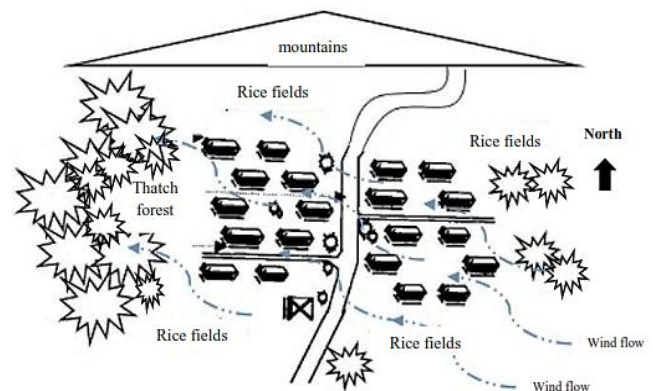


Figure 4. Landscape of traditional Acehne villages in the interior and wind flow illustration [13]

In coastal settlements, the spatial pattern also adopts a clustered configuration, primarily to mitigate the force of strong sea winds (Figure 5). Grouping houses helps disperse wind flow across the settlement, reducing the direct impact on individual buildings. Single-mass stilt houses are positioned between open green spaces and natural vegetation, which act as windbreaks [25].

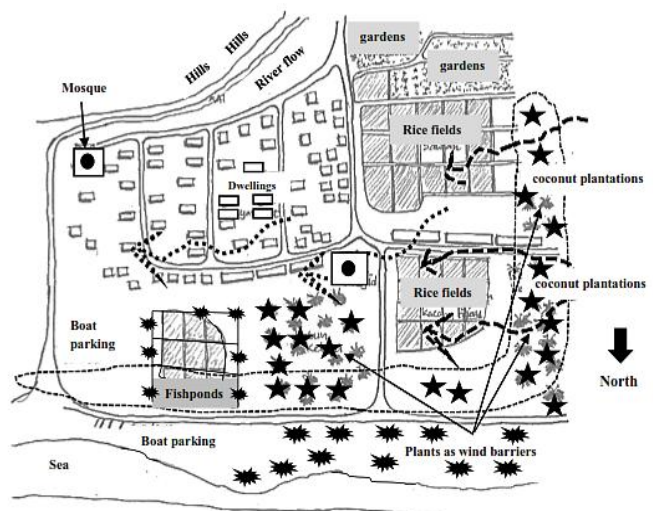


Figure 5. Landscape of traditional Acehne villages in coastal areas and wind flow illustration

The roof design of Rumoh Aceh typically features steeply pitched, elevated structures with ventilated ridges and extended eaves. These allow rising warm air to escape while shading the spaces below. This passive cooling mechanism supports the findings of studies [26–28], which demonstrated the role of ventilated and reflective roof systems in minimizing heat accumulation in tropical buildings.

Vegetation is another critical element in the thermal design of traditional Acehne compounds. Broad-canopied tropical trees and clustered greenery function not only as shading elements but also as natural thermal moderators through evapotranspiration [13, 29]. These landscape features enhance the microclimate, particularly in rural or coastal areas where

vegetation forms part of the ecological infrastructure.

Openings and ventilation are strategically integrated into traditional homes. Operable windows and perforated wooden panels promote cross-ventilation, allowing fresh air to circulate and reducing reliance on mechanical cooling. The Enerpos passive building principles highlight that the strategic placement of openings relative to prevailing winds can greatly improve indoor thermal comfort [30]. This principle is also evident in traditional Acehnese houses, where facade configurations support effective air circulation and thermal balance [31]. However, in many modern housing developments, this approach is often neglected, resulting in sealed façades with limited airflow.

Airflow within and around buildings is influenced by both micro-scale building arrangements and macro-scale site planning. In Acehnese settlements, housing clusters are arranged to deflect prevailing winds rather than block them [13, 31]. Such formations facilitate wind penetration and dispersal across dwellings, as supported by natural ventilation engineering principles [32]. Location and site characteristics also play an important role in thermal comfort. Traditional homes are sited with consideration for nearby rivers, forests, or hills, making use of natural wind corridors and shaded surroundings [13]. In contrast, modern site planning often overlooks these contextual relationships, increasing thermal stress in urban clusters. Finally, wall materials and colors strongly influence thermal absorption and reflectivity. Traditional homes favor light-colored organic materials, such as timber or bamboo, which have low thermal mass and high reflectance. Conversely, many modern buildings use dark masonry or concrete, which store heat throughout the day [24]. Proper selection of materials and surface colors is therefore critical to maintaining thermal comfort in tropical housing.

These seven variables provide an integrated framework for assessing thermal landscape performance in both traditional and modern contexts. Grounded in empirical evidence and culturally informed design practices, they serve as reliable indicators for evaluating the degree to which modern housing clusters in Banda Aceh adhere to sustainable thermal design principles. Derived from traditional settlement patterns and validated through prior studies on thermal comfort and vernacular architecture in tropical regions [25, 33, 34], these parameters highlight the interconnected roles of spatial

organization, materiality, and vegetation in moderating heat radiation, ventilation, shading, and microclimate. The integration of vegetation, orientation, and building configuration illustrates how traditional Acehnese wisdom provides measurable indicators for assessing thermal comfort performance in contemporary housing.

3.2 Methods

This study employed a descriptive-comparative approach that combined field observation, photographic documentation, and spatial mapping across six selected housing clusters representing the three geographic zones of Banda Aceh: north (WU), central (WT), and south (WS). Each zone comprises two housing clusters (P1WU and P2WU, P1WT and P2WT, P1WS and P2WS), resulting in a total of six case studies.

Data were collected through on-site visual assessment and systematic documentation, focusing on seven climate-responsive variables. A five-point Likert-type scale was used to evaluate the thermal performance of each variable in every housing cluster, based on observable physical attributes such as building orientation, roof form and color, vegetation coverage, openings, airflow, site conditions, and wall color.

A detailed scoring guide (Tables A1 and A2) was developed to define the operational criteria for each variable, ranging from very poor (1) to excellent (5). Each score level specifies measurable indicators, ensuring consistency, transparency, and replicability by other researchers. The assessment was conducted through on-site visual analysis by the research team, with internal cross-checking applied to maintain inter-observer reliability.

A score of 5 represents strong responsiveness to tropical climatic conditions (e.g., optimal orientation, effective natural ventilation, and extensive vegetation), while a score of 1 indicates poor thermal performance (e.g., inappropriate orientation, absence of shading, and restricted airflow).

The compiled scores were tabulated (Table 1) and visualized using bar charts, radar charts, and line graphs to compare both cumulative and variable-specific performances among clusters. These visualizations facilitated the interpretation of quantitative differences and the identification of spatial patterns in climate-responsive design adaptation.

Table 1. Comparison of housing landscape patterns to climate solutions

Variables	PIWU	P2WU	P1WT	P2WT	P1WS	P2WS
Building Orientation	2	4	5	1	5	3
Ventilation Openings and Cross-Ventilation	1	1	1	2	5	4
Vegetation and Shading	2	2	3	2	3	3
Roof Form and Ventilation	2	2	2	2	4	4
Building Color and Surface Reflectivity	2	2	3	5	4	4
Building Spacing and Density	2	3	3	2	5	5
Site Context and Environmental Integration	4	4	3	5	5	4
Total	15	18	20	19	31	27

The visual scoring was qualitatively cross-validated using available climatic data (e.g., prevailing wind direction and average temperature) from the Banda Aceh meteorological station. Although no direct on-site physical measurements were taken, the spatial consistency between observed design responses and local climatic patterns supports the credibility of the scoring results.

To ensure data reliability, triangulation was applied by cross-checking field observations with satellite imagery and

cadastral maps, verifying the spatial configuration, vegetation distribution, and surrounding environmental context of each cluster. This process enhanced both the validity and credibility of the scoring results.

Data synthesis and interpretation then focused on identifying essential passive design elements derived from Rumoh Aceh architecture that remain relevant and adaptable to modern housing constructed with contemporary materials and technologies.

By combining quantitative scoring, visual comparison, and spatial verification, this methodology provides a comprehensive and reproducible framework for assessing climate-responsive design quality across Banda Aceh's modern housing developments.

4. RESULTS AND DISCUSSION

4.1 Climate adaptation strategies of Aceh vernacular settlements

The layout of traditional Acehnese villages effectively responds to the hot and humid tropical climate by encouraging cross-ventilation through and around the houses, thus maintaining indoor thermal comfort. Furthermore, the clustered and vegetated patterns also serve as a disaster risk reduction strategy, acting as a buffer against the strong winds that frequently hit coastal and inland areas of Aceh [35]. Traditional settlement patterns in Aceh emerge as adaptive responses to both climatic and geographical factors [36]. The traditional landscape is organized into distinct functional zones: residential areas, communal facilities (such as the mosque), productive agricultural lands, and forests marking the village boundary. This zoning system reflects local wisdom that integrates building technology, climatic considerations, and the use of locally available resources, for example, sago forests, which serve as natural barriers against prevailing winds from the west or southwest.

The clustered settlement pattern, combined with deliberate vegetation placement, ensures effective cross-ventilation through building clusters, thereby reducing heat accumulation and enhancing overall thermal comfort. Simultaneously, this design approach strengthens resilience against environmental hazards by creating protective ecological layers around residential areas.

4.2 Transformation of vernacular settlement patterns

Over time, the climate-responsive landscape patterns of

traditional Acehnese settlements have undergone significant transformation. Rapid population growth in Banda Aceh (driven by both natural increase and urban migration) has led to the continuous expansion of residential areas. At the same time, evolving lifestyles and socio-cultural changes have increased demand for more space-efficient housing layouts capable of accommodating a wider range of modern activities.

As a result, many new housing developments have shifted away from clustered, climate-adaptive configurations toward denser, more compact urban layouts that often prioritize land-use efficiency over environmental responsiveness. This shift presents challenges for preserving traditional architectural wisdom, which historically balanced human needs with natural and climatic conditions.

4.3 Modern housing landscape design in Banda Aceh

Urban development in Banda Aceh is officially planned to expand toward the southern part of the city, supported by sub-centers in the central region. However, in practice, residential growth is concentrated in the northern (coastal) area due to its higher economic value [37], despite this zone being designated as a limited residential area in the Banda Aceh City Spatial Plan (RTRW) 2009–2029.

The P1WU and P2WU housing complexes are located in the northern part of the city (Figure 6), within a former tsunami-affected area built on reclaimed swamp land, which required substantial site modifications. In P1WU, building orientation follows the road network without consideration for solar path or cross-ventilation potential. Yards and circulation paths are fully paved with concrete and lack vegetation, leading to elevated ambient temperatures from direct solar radiation. While light-colored walls reflect heat, dark-colored roofs absorb it, intensifying indoor heat. Close building spacing and the absence of natural ventilation make thermal comfort highly dependent on mechanical cooling. Although the absence of a concrete perimeter fence could allow for cross-ventilation, this potential is lost due to non-optimal building orientation and the absence of other climate-responsive strategies.

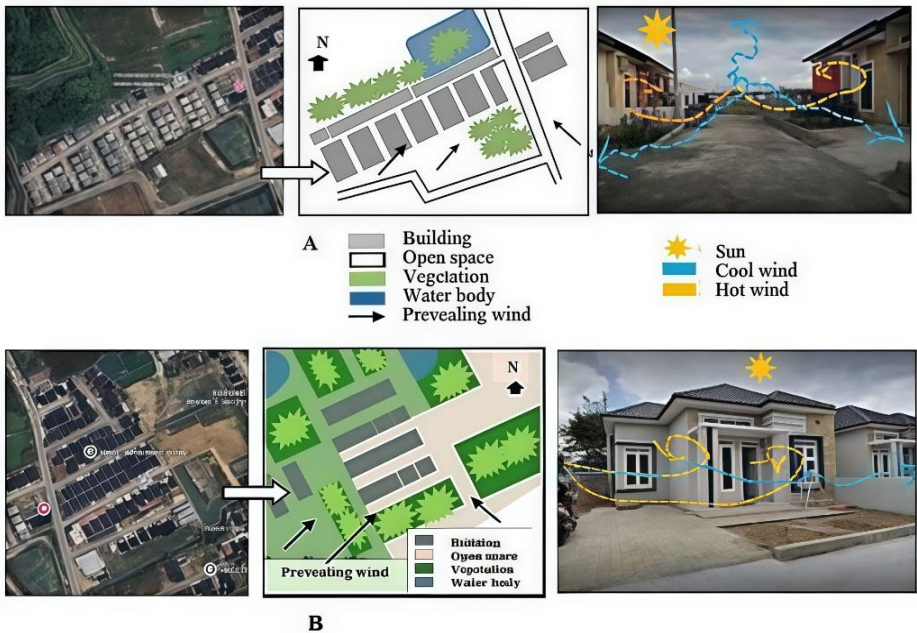


Figure 6. Plan view of housing landscape in the northern region and air flow illustration (A) P1WU and (B) P2WU

Similarly, P2WU faces comparable challenges, with houses oriented northwest and large glass openings placed on sun-exposed facades, resulting in a greenhouse effect. Outdoor paving consists of solid blocks with no shading from trees, while ventilation is minimal due to the absence of operable vents. The hip roof design lacks ventilation and is prone to leakage during heavy rainfall. Although a 1.5 m perimeter wall allows some wind entry, poorly oriented openings, non-responsive roof designs and colors, and additional internal fences further obstruct airflow.

The P1WT and P2WT housing complexes, both in the central part of Banda Aceh (Figure 7), were also constructed on reclaimed swamp land, requiring extensive surface modification for stability. P1WT is located between a swamp

forest and a river, but continued land reclamation and infill raise concerns over shrinking green open space and rising ambient temperatures. Although houses are oriented north-south, this potential advantage is not maximized due to minimal openings and the absence of effective cross-ventilation, with glass-covered vents further limiting airflow. The use of dark-colored walls and roofs increases heat absorption, while the tight spacing between buildings restricts wind movement. A 2 m-high perimeter wall and 5 m-wide street create outdoor wind corridors, providing some thermal relief in open areas. However, indoor comfort still relies on mechanical cooling, with only partial mitigation from shading provided by large-canopy fruit trees (e.g., mango, guava, longan) in the surrounding environment.

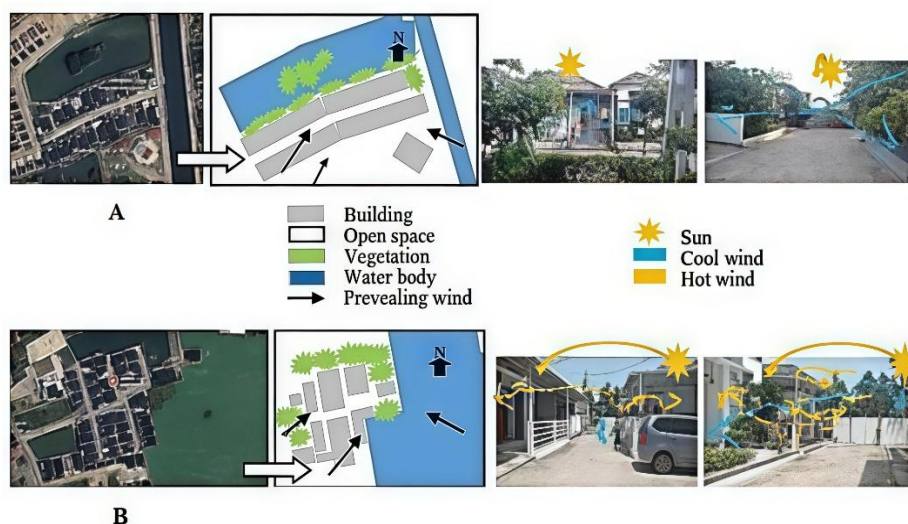


Figure 7. Plan view of housing landscape in the central area and air flow illustration (A) P1WT and (B) P2WT

Meanwhile, the P2WT housing complex is surrounded by water bodies that provide both aesthetic value and localized cooling effects. Despite the East–West orientation exposing openings to direct solar radiation, the spacing and height of buildings allow limited airflow around the structures. However, natural ventilation is largely ineffective due to glass-sealed vents, and cross-ventilation only occurs when doors and windows are kept open. The small yards predominantly feature ornamental plants, offering minimal shade from trees. Although the use of permeable paving blocks facilitates rainwater infiltration, the narrow 3 m-wide roads restrict wind movement. Similar to P1WT, this complex is enclosed by a 2 m-high perimeter wall; yet the absence of passive ventilation openings and shade trees means wind circulation occurs primarily in outdoor spaces, with indoor comfort remaining dependent on mechanical cooling systems.

The P1WS housing complex is located in the southern part of Banda Aceh City, developed on reclaimed rice fields within a relatively natural environment and in close proximity to a river. The site's inherent stability enabled construction with minimal land modification. Houses are oriented along a north-south axis, with most openings and ventilation aligned accordingly, enabling effective cross-ventilation between outdoor and indoor spaces. However, the longest building facades face East–West, increasing exposure to direct solar radiation and elevating indoor temperatures. The spacing and height of buildings facilitate optimal wind flow throughout the housing landscape, while saddle-shaped roofs with triangular

vents promote airflow within the roof cavity, reducing humidity and mitigating heat transfer to interior spaces. The use of light-colored walls and roofs further minimizes heat absorption, although shading vegetation within individual house lots is limited. At present, thermal comfort is supported by the surrounding forested areas and the nearby river; however, this condition may deteriorate if future development encroaches upon these green buffers.

The P2WS housing complex shares many architectural features with P1WS, including ventilated saddle roofs, active ventilation above doors and windows, and building spacing conducive to airflow. Nevertheless, most buildings are oriented East–West, following the road network, which positions openings directly toward solar exposure and results in greenhouse effects. Conversely, the North–South facades, which are more favorable for ventilation, lack adequate openings. Although the building design incorporates roof and wall vents that can support cross-ventilation, the absence of wide-canopy vegetation reduces outdoor cooling potential. As with P1WS, the current level of thermal comfort is largely attributable to surrounding open spaces. Nonetheless, the potential for effective cross-ventilation remains high and could be further enhanced through adjustments to building orientation in alignment with prevailing wind directions, coupled with the strategic addition of shade-providing vegetation. The residential landscape and prevailing wind patterns are illustrated in Figure 8.

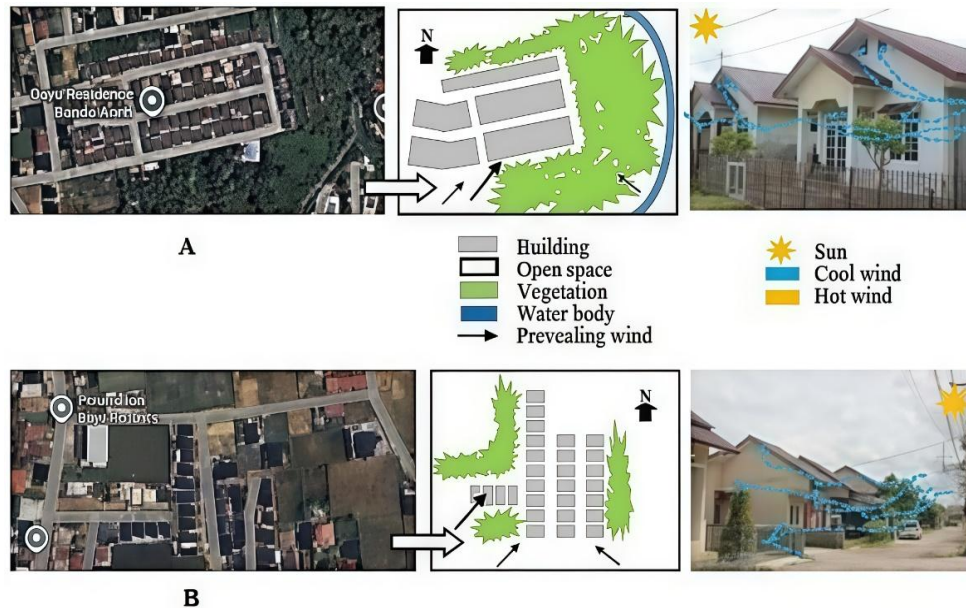


Figure 8. Plan view of housing landscape in the southern region and air flow illustration (A) P1WS and (B) P2WS

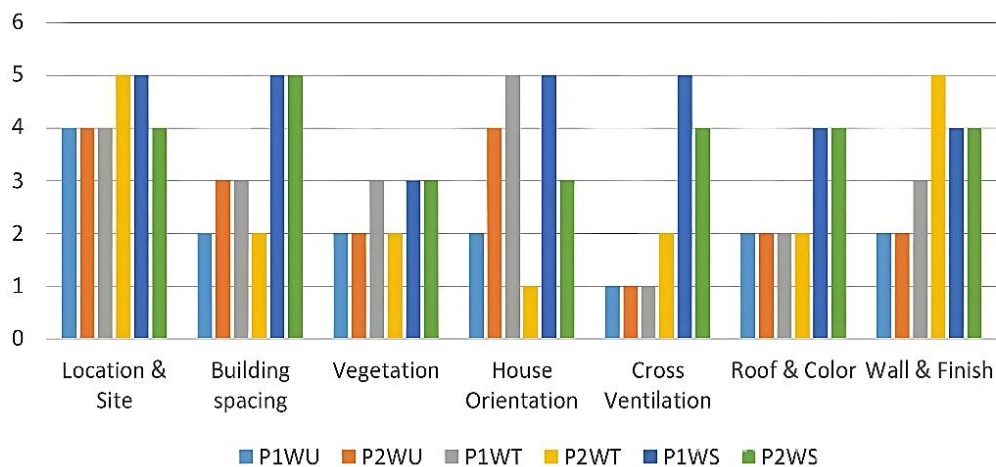


Figure 9. Climate-responsive housing design variables

4.4 Comparative analysis of housing clusters based on climate-responsive design variables

The Aceh traditional settlement patterns, commonly referred to as Gampong Aceh, were historically shaped by environmental wisdom and cultural practices developed over centuries. Characterized by organic layouts, house orientations aligned with prevailing winds, elevated timber structures, expansive pitched roofs, and abundant vegetation, these villages maximized natural ventilation and provided shaded spaces to mitigate tropical heat.

In contrast, modern housing clusters in Banda Aceh, such as the six examined in this study (P1WU, P2WU, P1WT, P2WT, P1WS, and P2WS), have emerged from rapid urbanization and market-driven planning. These developments often reduce spatial porosity and diminish vegetative layers, which were once integral to traditional thermal comfort strategies.

This study evaluated the six clusters using a 1–5 Likert scale across seven variables: site location, circulation pattern, road material, house orientation, cross ventilation, roof and color, wall and finish. The analysis revealed spatial differentiation influenced by location (see Figure 9).

Objects with extensive open space and the presence of water elements (P1WS, P2WT) achieved maximum scores in the location and site aspects. This aligns with the role of open space in improving air circulation, facilitating water infiltration, and reducing surface temperatures [29]. Conversely, locations in swampy or pond areas (P1WU, P2WU, P1WT) tend to face challenges such as high humidity and potential waterlogging.

Grid and linear patterns are found throughout the buildings, but the combination with road materials influences the results. Paving blocks (P1WT, P2WT) have better permeability than concrete (P1WU, P2WS), making them more effective in reducing stormwater runoff and the urban heat island effect.

North-south orientation, as in P1WT and P1WS, minimizes exposure to direct solar radiation during the day. However, thermal performance is largely determined by the quality of cross-ventilation. P1WS exhibits a good cross-ventilation system, while P1WU, P2WU, and P1WT experience limitations categorized as "very poor," impacting indoor thermal comfort.

The majority of buildings use dark-colored roofs (black or brown), which have high heat absorptivity. However, the

combination with light-colored and smooth walls (P2WT, P2WS) helps reflect solar radiation, reducing heat absorption on vertical surfaces [38].

Wind rose data for Banda Aceh indicate dominant southeast winds, with moderate seasonal southwest winds. Traditional Acehnese settlements, including inland villages, historically aligned houses and pathways to harness these breezes while incorporating vegetative buffers to create shaded, well-ventilated environments.

In the Northern Zone, clusters benefit directly from coastal breezes and ventilation (score 4). In the Central Zone, airflow is obstructed by dense urban fabric, resulting in lower ventilation (score 3) and slightly reduced orientation effectiveness (score 4). The Southern Zone retains suburban openness, enabling relatively higher ventilation (score 4) and wider building spacing (score 5), partially echoing traditional village principles.

The radar chart (Figure 10) compares the six modern housing clusters based on seven climate-responsive design variables. Several patterns emerge from this comparison. Clusters located in the southern part of the city (P1WS and P2WS) demonstrate relatively stronger adaptation to the hot-humid tropical climate. The use of gable roofs with ventilation openings and adequate building spacing promotes natural air circulation, contributing to improved thermal comfort. However, these clusters still lack substantial integration of vegetation and shading elements, which could further reduce ambient temperatures and enhance resilience against climate extremes.

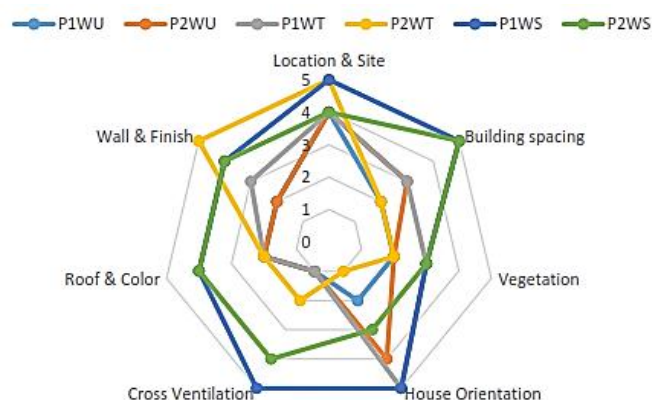


Figure 10. The climate responsiveness of six modern housing clusters

In contrast, the central clusters (P1WT and P2WT) demonstrate moderate performance across most variables. The presence of adjacent water bodies contributes marginally to lowering surrounding air temperatures. However, the houses are generally designed with limited operable openings, restricting cross-ventilation potential. The prevalent use of dark-colored roofs and heat-absorbing wall finishes exacerbates indoor heat gain, compelling residents to depend on mechanical cooling systems.

The northern clusters (P1WU and P2WU) exhibit the lowest performance in nearly all variables. Housing units are densely arranged with minimal spacing, and most yards are fully paved, which intensifies heat accumulation through surface radiation. Building orientation in these clusters follows the street layout rather than aligning with solar paths and prevailing wind directions, resulting in inadequate cross ventilation and a high dependence on air conditioning.

Although some clusters integrate selected climate-responsive features, the majority of modern housing developments in Banda Aceh still prioritize urban density and rapid construction over comprehensive passive design strategies. Across all case studies, extensive site modification, particularly the infilling of marshland, has substantially altered the natural landscape, potentially amplifying the urban heat island effect.

While clusters in the southern zone demonstrate better adaptation to the local hot-humid climate through improved building orientation and ventilated roof shapes, all six clusters share persistent deficiencies: insufficient vegetation coverage and limited passive cooling measures. These findings highlight the need to integrate more shade-providing vegetation, optimize building orientation, and enhance natural ventilation strategies to achieve genuinely climate-adaptive urban housing.

As illustrated in the line chart of total scores, a distinct performance gradient is evident across the six housing clusters, progressing from the western urban zone (WU) through the central transitional zone (WT) to the southern zone (WS). This pattern suggests a spatial trend of increasing environmental responsiveness from north to south, which aligns with variations in urban density, site morphology, and the degree of vernacular influence (Figure 11).

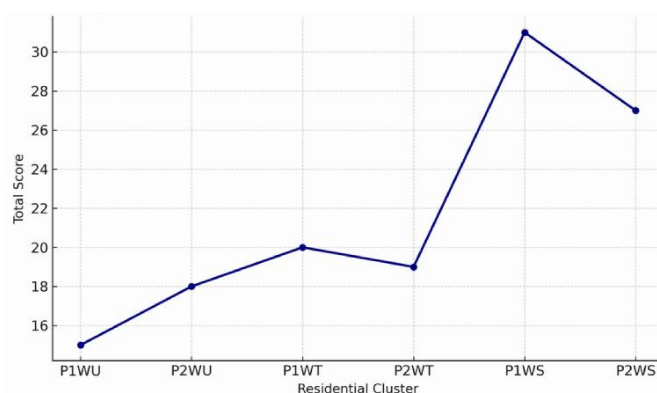


Figure 11. Climate responsiveness score per housing cluster

In the northern clusters (P1WU and P2WU), low scores are mainly attributed to high building density, limited vegetation coverage, and poorly oriented layouts that restrict natural ventilation. These developments represent highly urbanized environments where land value and plot efficiency are prioritized over climatic adaptation. As a result, passive design principles such as shading, airflow management, and orientation optimization are largely absent.

In contrast, the central clusters (P1WT and P2WT) exhibit moderate thermal adaptation. Although these areas have begun adopting modern materials and compact layouts, they still retain partial elements of vernacular design, such as north-south building orientation and selective use of vegetation. The P1WT cluster, in particular, shows a balanced integration of open spaces and building massing, which enhances cross-ventilation and microclimatic comfort. However, P2WT, despite similar spatial characteristics, shows lower performance due to reduced vegetative coverage and greater use of heat-absorptive materials. The transitional nature of these clusters reflects an ongoing shift from traditional to modern design paradigms, where climatic considerations are not entirely abandoned but are inconsistently applied.

Finally, the southern clusters (P1WS and P2WS)

demonstrate the highest adaptation to tropical climate conditions. Both clusters maintain wider spacing between buildings, generous vegetation buffers, and building orientations aligned with prevailing wind directions. These factors collectively enhance passive cooling and thermal comfort. Moreover, the surrounding environment in the southern zone, characterized by lower urban density and proximity to green and open areas, supports stronger ecological integration and climatic resilience.

Overall, the analysis indicates a correlation between spatial morphology and climatic responsiveness. The southern clusters benefit from contextual integration and vernacular continuity, while the northern ones represent the most modernized but least adaptive environments. The central zone (WT) functions as an intermediate typology, blending traditional climatic principles with modern construction methods. This gradient underscores how urbanization, planning policies, and landscape context collectively shape the environmental performance of contemporary housing in Banda Aceh.

4.6 Interpreting the north-south performance gradient: Policy, socioeconomic, and design perspectives

The stronger climatic performance of southern clusters arises from the interplay of planning policy, land value, and socioeconomic conditions. Southern areas developed after the 2009–2029 spatial plan retain wider setbacks and vegetated buffers that enhance ventilation and reduce surface heat. Northern reclaimed zones, by contrast, prioritize land efficiency and density due to higher market value, resulting in sealed surfaces and poor airflow.

Socioeconomic capacity further determines adaptability. Developers in southern zones target higher-income groups, enabling larger plots and landscape areas, while northern projects focus on affordable compact housing. Consequently, southern clusters preserve vernacular traits such as favorable orientation, permeability, and shading, whereas northern clusters rely on mechanical cooling.

Three obstacles continue to limit the adoption of vernacular wisdom in modern housing: (1) cost pressures that encourage compactness, (2) weak regulatory support for passive design, and (3) aesthetic preferences that equate traditional forms with rural imagery. Strengthening design codes and planning incentives for ventilation corridors, shaded streets, and vegetative integration would bridge this gap between modernity and climatic responsiveness.

4.7 Contextualizing the findings in the global south

The Banda Aceh case exemplifies broader challenges in the rapidly urbanizing Global South, where speed and cost often override climatic responsiveness. Similar to many tropical cities, post-disaster reconstruction and speculative development have encouraged compact, thermally inert housing typologies.

Yet, the findings demonstrate that vernacular principles remain adaptable within modern frameworks. Reinterpreting features such as elevated structures, porous layouts, and vegetative shading through contemporary materials and policy support can reduce thermal stress and energy demand. This shift from technology-driven to context-based adaptive design aligns with global sustainability goals and reinforces the enduring relevance of vernacular knowledge for resilient

urban housing in tropical regions.

5. CONCLUSIONS

This study demonstrates that Acehese vernacular settlements, both inland and coastal, embody adaptive wisdom that effectively responds to the region's tropical climate. Their clustered layouts, north–south-oriented stilt houses, and vegetated courtyards enhance cross-ventilation, thermal comfort, and social cohesion.

Analysis of six modern housing clusters in Banda Aceh revealed clear spatial and thermal contrasts. Southern clusters (P1WS, P2WS) achieved higher climate-responsiveness through better orientation, ventilation, and integration with the landscape, while northern clusters (P1WU, P2WU) performed poorly due to compact layouts, sealed façades, and a lack of greenery.

These patterns indicate that modern housing has largely departed from the passive logic of traditional design. Reintegration of vernacular strategies, such as shading vegetation, optimal orientation, roof ventilation, and airflow corridors, can significantly enhance thermal comfort and reduce energy dependence. The findings reaffirm the continued relevance of vernacular principles for developing sustainable and climate-responsive urban housing in tropical regions.

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APPENDIX

Table A1. Five-point Likert scale

Score	Description	Indicators
5	Strongly climate-responsive	Optimal orientation (N-S), extensive cross-ventilation, abundant vegetation, reflective roof materials
4	Moderately climate-responsive	Minor deviations, but generally well-adapted
3	Neutral/adaptive	Partial application of passive elements Limited shading,
2	Weakly responsive	suboptimal openings, poor airflow
1	Non-responsive	Fully sealed facades, dark materials, and inappropriate orientation

Table A2. Scoring guide for climate-responsive design variables

Variables	Assessment Criteria	Score 1 (Very Poor)	Score 2 (Poor)	Score 3 (Moderate)	Score 4 (Good)	Score 5 (Excellent)
Orientation	Building alignment relative to the sun path and prevailing wind	East-west orientation, no wind alignment	Partial misalignment, high solar exposure	Random orientation, limited adaptation	North-south alignment with minor deviation	Optimal N-S orientation, well-aligned with the dominant wind
Roof shape & ventilation	Roof form, pitch, and ventilation openings	Flat/concrete roof, no vents	Low-pitch roof, minimal ventilation	Medium pitch, partial vents	High pitch with ridge openings	Steep, ventilated roof with continuous airflow ridge
Vegetation	Presence and quality of shading and green cover	No vegetation	Sparse ornamental plants	Moderate greenery, limited shade	Sufficient trees and shrubs providing partial shade	Dense vegetation, full shading, and the evapotranspiration effect
Openings & ventilation	Window size, placement, and airflow potential	Small sealed windows	Limited openings, poor cross-ventilation	Moderate openings, partial airflow	Large openings, effective airflow	Strategically placed openings, optimal cross-ventilation
Airflow pattern	Spatial arrangement supporting wind circulation	Fully blocked by structures	Minimal openings between buildings	Moderate spacing allowing some airflow	Well-spaced with partial deflection	Optimal building spacing enabling diagonal cross-ventilation
Location & site setting	Relationship to topography, water bodies, and urban context	Poor siting, heat-trap zones	Minimal natural shading, poor drainage	Average siting, partial exposure	Strategic siting with natural wind corridors	Contextually responsive siting with landscape integration
Wall material & color	Surface reflectivity and thermal mass	Dark, dense concrete walls	Dark walls with limited reflectance	Light-colored masonry	Light surfaces, mixed materials	Light-reflective timber/bamboo with low heat absorption

Source: Adapted and synthesized from studies [24, 25, 28, 30, 32, 34].