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Passive Cooling in Indonesian Traditional Dwellings and Its Relationship with Geographical Location

Zuber Angkasa[1] and Erfan M. Kamil[1*]

[1]Universitas Muhammadiyah Palembang, 30263 Palembang, Indonesia

*Corresponding author: erfanmk@gmail.com

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ABSTRACT

As efforts to maximize passive cooling for building cooling are growing, attention to traditional architecture is also increasing. Traditional houses have the potential to provide a variety of passive cooling solutions needed as a solution to the environmental impact of active cooling on urban heat islands and global warming. Indonesia is a country with huge cultural diversity. Each region has traditional houses that are proud and cared for. Despite the growing importance of traditional houses as a source of passive cooling design, the number of studies exploring passive cooling in traditional houses in Indonesia and its relationship with location is still very limited. This paper aims to provide an overview of passive cooling in traditional houses in Indonesia and its relationship with location based on peer-reviewed international scientific literature using a systematic literature review. The results reveal that most of the studies still do not optimally explore the passive cooling aspect of traditional houses. Few studies explicitly link passive cooling design to the location of the house. This research identifies several future research directions and offers several applications of passive cooling of traditional houses in modern designs.

1.0 INTRODUCTION

Population growth and the use of cooling technology to cool spaces in large cities have created an overheating problem. It is estimated that more than 400 cities in the world are currently experiencing overheating (Antoszewski, Świerk, and Krzyżaniak, 2020). If this is allowed to continue, excessive heat will cause physical, mental and spiritual health problems, both at the individual and community levels (Singh, Srinagesh, and Anand, 2020). It is estimated that the number of deaths of people over 65 years of age will double if the threshold temperature increases by 1°C (Buchin et al. 2016).

One solution geared towards overheating is to use passive cooling. Passive cooling is a technical effort to achieve thermal comfort by cooling the air temperature without using external energy consumption (Doi, 2022). Passive cooling techniques will improve energy efficiency and reduce noise and heat pollution in urban areas (Dugolli, 2023). Passive cooling techniques can range from very old strategies that have been architecturally inherited by societies throughout the ages to contemporary techniques that are sophisticated and still in the experimental stage (Erba, Sangalli, and Pagliano 2019). These types of passive cooling include shading, ventilation, shaded walls, thermal chimneys, ground shelters, ground air ducts, evaporative cooling, and courtyards (Cojocaru and Isopescu, 2021).

Old techniques in passive cooling have proven to be useful after natural selection in those societies that applied them to reduce thermal discomfort in their houses. These traditional techniques, of course, still have to be evaluated for their relevance to the modern world and improved so that they can be applied in modern designs (Freewan, 2019). Knowledge and improvement of passive cooling techniques in the context of traditional communities can not only help in modern design, but also increase the resilience of local communities in the face of rising temperatures even in rural areas (Kebir et al., 2022).

Indonesia is a tropical country with a very large population and very high cultural diversity. There are more than 500 ethnic groups and 752 languages and dialects spoken in Indonesia (Alesina, A., Gennaioli, C., & Lovo, 2019). Each region highlights cultural aspects such as traditional houses, traditional clothing, traditional musical instruments, and traditional weapons as regional identities. In line with this, there are many types of traditional houses that can be found in Indonesia (Wazir, 2019; Wazir & Indriani, 2020). These houses are generally under threat due to climate change and urbanization (Rajendra, 2021). There is a need for maintenance and inheritance, and in the case of this research, exploration of passive cooling technologies applied by these houses.

The aim of this study is to identify passive cooling techniques applied to traditional houses in Indonesia. Previous studies have not systematically approached this problem (Pramesti, Hasan, and Ramandhika, 2021). In addition, previous studies did not consider the climate diversity that exists in Indonesia. This study considers climate diversity as a relationship between buildings and the environment that provides an explanation for why a community takes certain steps to cool their houses.

1.1. Theoretical Foundation

Vernacular or traditional architecture is a residential work that is built within the influence of the traditions, culture, and climate in which it is built and uses local construction materials (Cojocaru and Isopescu, 2021). Traditional architecture is often referred to as architecture without architects because it is built collectively, or by individuals only on behalf of the community. Over time, traditional architecture undergoes changes, but these changes are very slow due to its strong attachment to the local culture.

Passive cooling is a commonly used cooling method in the tropics in traditional houses, in response to the humid, hot and sunlight-intensive climate characteristics (Zune, Rodrigues, and Gillott, 2020). Traditional dwellings in these regions must adapt to hot situations throughout the year, in contrast to dwellings in four-season regions that only optimize passive cooling in summer (Fernandes et al. 2019). In the four-season region, in winter, the strategy shifts to passive heating.

Due to the high ethnic diversity, it is important to dissect Indonesia's climate at a higher climate resolution. The Koppen-Geiger climate typology has a high resolution for distinguishing climate zones (Beck et al., 2018). Based on the Koppen-Geiger classification, the climate in Indonesia can be divided into seven zones. Almost all of Indonesia falls into the tropical zone in its three variants, rainforest (Af), monsoon (Am), and savanna (Aw). The dominant climate is the rainforest climate which covers Sumatra, West Java, Kalimantan, Sulawesi, Maluku, and the lowlands of Papua. This climate is characterized by high rainfall and hot air. The highest recorded rainfall is 4,824.10 mm in West Sumatra (Kunaifi, Veldhuis, and Reinders, 2020). The highest number of rainy days is 295 days per year in West Java (Kunaifi, Veldhuis, and Reinders, 2020). The hottest recorded temperature was 40.6°C in Banjarbaru, South Kalimantan in 1997 (CNN Indonesia, 2022), and the fastest average wind was 16.3 m/s in Gorontalo Province (Kunaifi, Veldhuis, and Reinders, 2020).

However, there are some regions that have a temperate climate in three variations, warm dry season dry season (Cwb), no dry season but warm (Cfb), and no dry season and cold (Cfc). Areas with this temperate climate are in the central parts of large islands such as the interior of Sumatra, Java, Kalimantan, Sulawesi and Papua. The polar tundra (ET) climate is found in just one place, the peaks of the Jayawijaya Mountains in Papua, where there is snow due to the extreme altitude.

Putra (Putra et al., 2022) developed a more detailed climate classification system for Indonesia. Based on observations of temperature patterns, wind speed, relative humidity, total cloud cover, global horizontal irradiance, and precipitation, eight climate zones in Indonesia were generated: equatorial (1A), sub-equatorial (1B), tropical highlands (2A), tropical very highlands (2B), monsoon (3A), sub monsoon (3B), savanna (4A), and sub-savanna (4B). The equatorial zone is widespread in Sumatra, Java, Kalimantan and Papua. The sub-equatorial zone is located on small islands around the equator. Tropical highland areas are in the center of Sumatra (Jambi), Java (Citeko, West Java), and Sulawesi (Toraja). The tropical very highlands are in the Jayawijaya Mountain in Papua. Monsoon areas are in Java, South Kalimantan, South Sulawesi, and North Sulawesi. The savanna region covers the Nusa Tenggara Islands. Table 1 below show the temperature, humidity, and wind speed range for each climate zone.

Table 1. Characteristics of each Climate Zone in Indonesia

No	Climate Zone	Temperature	Humidity	Wind Speed
1	Equatorial (1A)	23-34°C	54-99%	0-4 m/s
2	Sub-Equatorial (1B)	23-34°C	56-96%	0-5.5 m/s
3	Tropical Highlands (2A)	17-29°C	55-97%	0-3 m/s
4	Tropical Very Highlands (2B)	15-25°C	56-99%	1-7 m/s
5	Monsoon (3A)	21-34°C	50-95%	0-6 m/s
6	Sub-monsoon (3B)	22-35°C	48-99%	0-4 m/s
7	Savanna (4A)	20-34°C	50-95%	0-6 m/s
8	Sub-Savanna (4B)	25-35°C	46-93%	0-5.5 m/s

Source: Putra et al. (2022)

People living in these areas have different architecture. The literature study can reveal how architectural adaptation is done to improve thermal comfort using passive cooling techniques based on climate zones.

2.0 METHOD

This research uses architectural analysis using diagrams and pictures showing passive cooling techniques for traditional houses in eight climate conditions in Indonesia. To obtain the data on passive cooling strategies in traditional houses in Indonesia, an online search was conducted using the Scopus and Google Scholar electronic databases. Scopus was chosen because it is a global peer review database. Google Scholar was chosen as a complement because it can capture local articles that have not been indexed by Scopus.

English was used as the inclusion criterion in the Scopus database search. A combination of the keywords "Indonesia" and "cooling" and "house" (search string: TITLE-ABS-KEY) was used to obtain articles that had titles, abstracts, or keywords containing all three keywords. Without limiting the year of publication, 39 matching documents were found. However, after reviewing the titles and abstracts of the documents found, there were only three that were relevant to this research, which discussed traditional architecture. The rest was research in the context of modern buildings.

Having only found three relevant studies, the study searched Google Scholar for additional documents with the keyword combinations “Indonesia” and "cooling" and "house" and "traditional." When Google Scholar was used with these keyword combinations, 13,000 results were obtained. This is a huge number and far beyond the scope of the researcher's analytical capacity. To minimize the results, we limited them to articles published in 2019 and above. Even after being limited to articles published in the last five years (since 2019), Google Scholar still produced 6,160 results. Furthermore, the number of articles was limited to the first 10 pages of search results, meaning the top 100 articles obtained from Google Scholar. This restriction is not only to maintain the capacity of the analysis but is also relevant to the nature of the Google Scholar search engine which displays the most relevant articles on the front page and increasingly irrelevant towards the back. A review of the first 100 articles that appeared resulted in the finding that only 22 articles were actually relevant to traditional architecture. Furthermore, those relevant articles were found within the first 60 articles, indicating that the deeper one goes, the less relevant the articles appear.

Finally, a search was conducted for previous research in the reference lists of the reviewed articles. This process added 10 new articles. As a result, 35 articles were used for review (Table 1). Figure 1 provides an overview of the overall selection process.

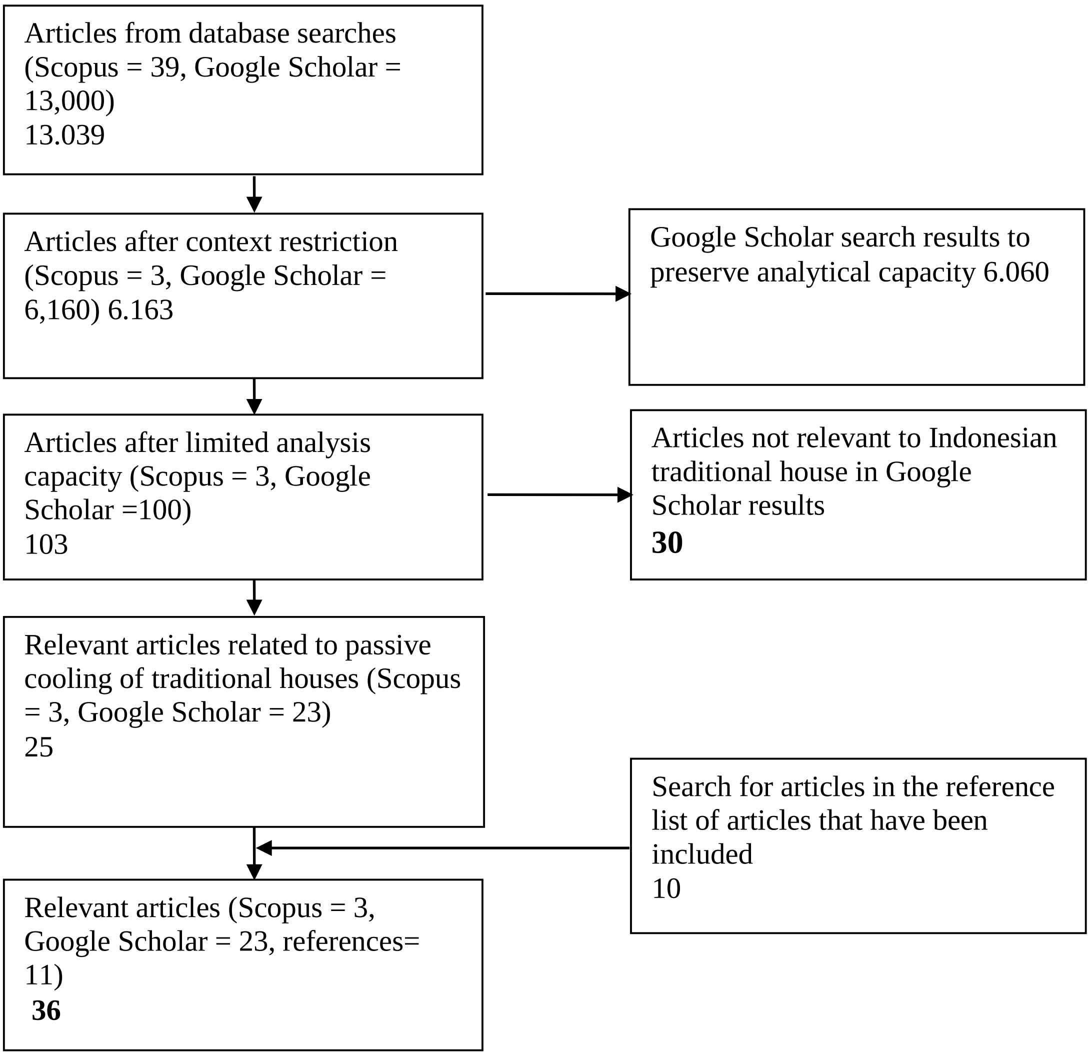

Figure 1. Overview of the Literature Selection Process. Source: Own Composition.

3.0 RESULTS AND DISCUSSIONS

A total of 36 pieces of literature were obtained describing studies on 50 residential groups spread across 27 ethnicities. The most studied ethnic houses are those of the Balinese, with seven dwelling groups in six studies. Javanese ethnicity was next, with five dwelling groups, followed by Aceh, with four groups. Malay was studied in three groups of dwellings. The following ethnicities were studied in two groups each: Flores, Bugis, Betawi, Gorontalo, Sunda, Banjar, Toba and Nias. The remaining ethnic groups were studied only once: Lampung, Toraja, Madura, Bawean, Sumbawa, Bengkulu, Timor, Palembang, Minahasa, Kaili, Seram, Leboya, Dani, Sasak, and Tobelo.

The distribution of house types studied along with the climate type of the location (Beck et al. 2018) is shown in Figure 2 below.

Figure 2. Distribution of Researched Traditional Houses in Koppen-Geiger Climate Regions (climate base map).
Source = (Beck et al., 2018)

Figure 2 shows that there are representatives of traditional dwellings on all major islands in Indonesia. The results can then be divided into four groups of dwellings based on the climate in which the house was built, namely tropical rainforest (Af), tropical monsoon (Am), tropical savanna (Aw), and cold temperate (Cfc). All dwellings found in Sumatra, Kalimantan and Sulawesi belong to the tropical jungle climate, as do dwellings from western Java such as Betawi (Setu Babakan) and Sundanese (Kampung Naga) dwellings. Dwellings in the tropical monsoon climate are found in the eastern part of Java and the island of Bali. The joglo (Java), limasan (Java), budaggan (Madura), and natah (Bali) houses belong to the monsoon tropical climate group. Houses from the Nusa Tenggara islands such as Ngada, Sumba, and Timor are houses in the tropical savannah climate.

The houses of the Dani tribe in Papua and the Mbaru Niang in Wae Rebo village, Flores, belong to the cool temperate climate because they are in the highlands. Basically, of these four climate types, the jungle tropics are the wettest (wet all year round) while the savannah tropics are the driest (dry all year round).

The tropical monsoon climate lies between the other two climate types, characterized by dry seasons and wet seasons. Temperate cold climates are cold all year round because they are in high mountains. The literature review did not produce traditional architecture for the other three climate regions (Cwb, Cfb, and ET). This finding is reasonable, as these three climate regions are very narrowly distributed and limited to high mountain areas. The ET climate even exists in Puncak Jayawijaya, where there are no people living in the area. The following describes the type of passive cooling practiced by traditional houses based on climate region.

However, if the research findings are mapped onto the integrated Indonesian climate typology (Putra et al., 2022), all climates are represented. Climate 1A includes Malay, Nias, Palembang and Minahasa. Climate 1B includes Aceh, Toba, Bengkulu and Seram. Climate 2A is represented by Toraja and Bali Aga while 2B by Dani and Wae Rebo. Climate 3A is represented by Betawi, Sunda, and Tobelo. Climate 3B by Bali, Java, Flores, Bugis, Gorontalo, Banjar, Lampung, Bawean, Kaili, and Sasak. Sumbawa, Timor, and Sumba fall into zone 4A while zone 4B is represented by Madura (Figure 3).

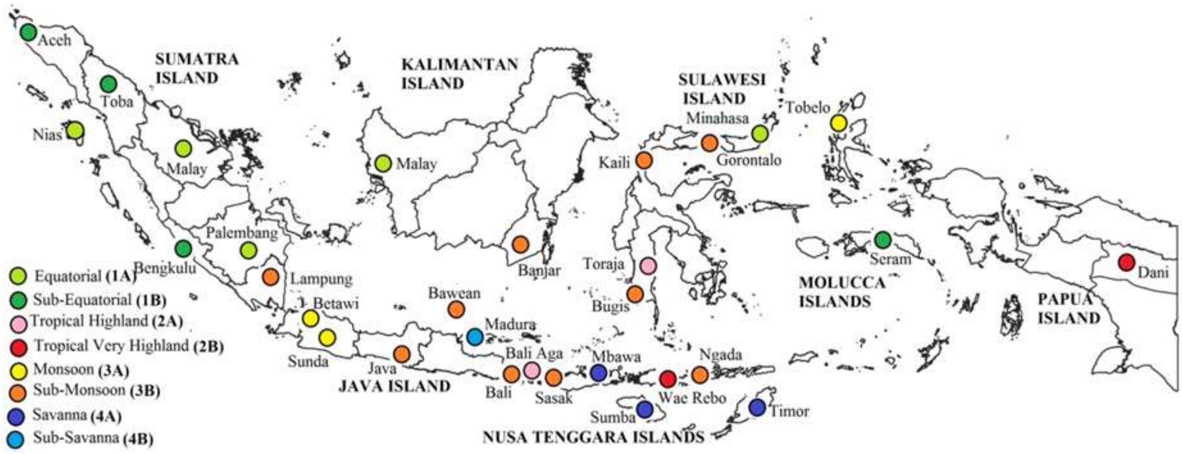

Figure 3. Distribution of the Researched Traditional Houses in Integrated Indonesian Climate Regions.

3.1. Passive Cooling of Equatorial Zone Traditional Houses

The climate of the equatorial zone is characterized by relatively moderate temperatures and irradiation, high humidity, cloud cover, precipitation, and low wind speeds. Equatorial zone areas obtained from samples include Malay (Wazir and Indriani, 2020) in West Kalimantan (Zain, Akbar, and Situmeang, 2021) and Riau (Samra and Imbardi, 2020), Nias traditional houses (F. Siahaan, 2020; Wazir and Indriani, 2020), Palembang limas houses (Anwar, 2019), and Minahasa houses (Wazir and Indriani, 2020).

The most prominent characteristic of traditional houses in the equatorial zone region is the presence of stilts to create cross ventilation that controls heating, cooling, humidity, and the instability of the internal environment, making the house cooler (Figure 4a). Limas houses from Palembang have tiered openings in the stilted floors (kekijing) that allow for additional cross-ventilation. In addition to ventilation through the underfloor of the stilts, there is ventilation through the walls via wooden gaps to help control the circulation of fresh air (Figure 4b). In Nias dwellings, wall ventilation is lattice shaped. Windows are generally large to support air circulation. The shape of the house is generally angled, but the Nias house has an oval shape making it more aerodynamic. This shape is said to be an adaptation to the mountainous terrain and earthquake risk on Nias Island. In addition, Nias houses have vertical vents that lift hot air upwards (Figure 4c). Some simple houses do not have partitions to maximize ventilation inside the house.

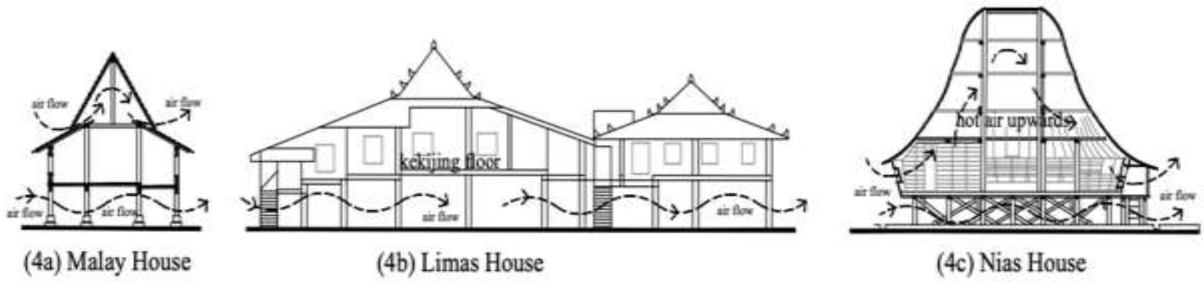

Figure 4. Passive cooling system in equatorial climate dwellings (4a) Malay, (4b) Palembang, (4c) Nias.

Passive cooling using ventilation in houses in equatorial climates is appropriate when the density of the houses is low. When the house environment is too dense such as in urban areas, the natural ventilation applied is reduced in effectiveness. In addition, equatorial climates have low passive cooling potential using ventilation (Putra et al., 2022). Low passive cooling potential indicates a climate zone where natural, passive methods are less effective in maintaining comfortable indoor temperatures due to unfavorable diurnal variations in temperature, high relative humidity, and low wind speeds. This explains why traditional houses in equatorial climates use ventilation extensively. Various ventilation techniques are used to maximize the cooling that is difficult to obtain.

3.2. Passive Cooling of Sub-Equatorial Zone Traditional Houses

The sub-equatorial zone is characterized by very high cloud cover, moderate humidity and wind speed, and low temperature, irradiance and precipitation. This research sample for traditional houses in the sub-equatorial climate zone includes Aceh, Bengkulu, Toba and Seram houses. These traditional houses also have a stilt shape (Wazir and Indriani, 2020). The Aceh house even has an underfloor of up to 2.5 meters, allowing cold humid air to enter the house through the floor. On the other hand, these houses use lightweight roofs such as thatch as a heat insulator (Maulinda, 2023). Hot air is directed out through perforated gable screens under the roof or the absence of ceiling (Izziah et al., 2021). The window and door gaps of the house are made large to obtain cooling (Jannah, 2021). There is a large enough yard to direct natural air movement to cool the house (Figure 5a). Toba Batak houses have well-organized greenery using bamboo, hariara, and jackfruit trees to maintain cool air during the summer (N. M. Siahaan and Suwantoro, 2019) (Figure 5b). Vegetation is also intensive in Aceh houses. The orientation of the house is more adaptive by pointing towards the axis of the wind, rather than the road or river.

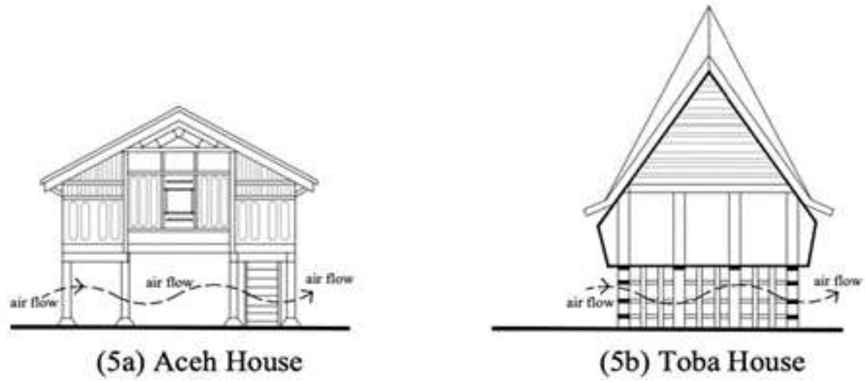

Figure 5. Passive cooling system in sub-equatorial climate dwellings (5a) Aceh (5b) Toba

Natural ventilation techniques are more efficient in sub-equatorial regions than equatorial regions (Putra et al., 2022). The ventilation techniques used in houses in sub-equatorial regions are the same as those in equatorial regions, with the additional use of vegetation to manage the wind. In addition, because the winds in the sub-equatorial region are higher than those in the equatorial region, wind splitting is an important technique.

3.3. Passive Cooling of Tropical Highland Zone Traditional House

The climate of the tropical highlands is characterized by low temperature and irradiance, moderate humidity, and high cloud cover and precipitation. On the other hand, the wind speed in this region is very low. The minimum altitude of the tropical highland area is 700 meters (Putra et al. 2022). There are two areas in the tropical highland climate in the sample: The Toraja house (Suhendri and Koerniawan 2017) and the Bali Aga house.

Temperatures in the tropical highland climate zone are low, so what is needed is heating, rather than cooling. The researchers found that this house more optimal in terms of passive heating. The floors had a height difference that prevented the wind from reaching the lower floors. The difference in height is because the wind is not as fast as it is in the equatorial region. In addition, the shape of the roof blocks the incoming wind (Figure 6a).

Since there is no burden to cool the house, the design of Toraja houses is optimized for cultural purposes. (Wazir and Indriani 2020) reveal that Toraja house designs are made to accommodate large numbers of people in communal banquets and the roofs are built to symbolize social status.

The Bale Gajah Tumpang Salu traditional house in Sidatapa village is an anomaly. It belongs to the Bali Aga ethnicity, which has cultural differences with the Balinese. Ethnic Balinese houses are modular while Bali Aga is a single mass. The Bali Aga people live in the central mountains of Bali, so their house designs also reflect tropical highland climate houses rather than sub-monsoon climates (Wazir and Indriani, 2020). The sample houses in the reviewed research are in Sidatapa village, Banjar sub-district, Buleleng regency which is at an altitude of 450-600 meters above sea level (I Gede Mudita et al. 2022). This altitude is the beginning of the tropical highland zone. Moreover, when referring to the Koppen-Geiger classification, there is a CwB temperate climate pocket in the central area of Buleleng regency, thus justifying the placement of Bali Aga ethnic houses as adapted houses for mountain climate (Figure 6b).

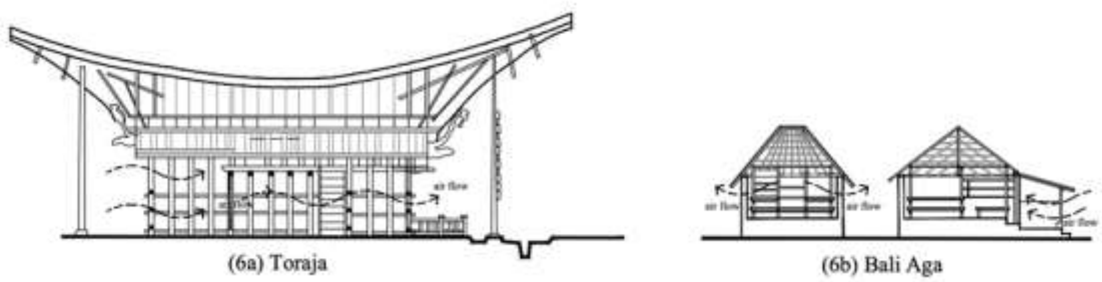

Figure 6. Passive cooling system in tropical highland climate dwellings (6a) Toraja, (6b) Bali Aga

A characteristic of a Bali Aga house is that it has a kitchen in the center of the house. The heat from the stove warms the entire room that is limited by the earthen wall, making sleeping more comfortable. However, the vents on the left and right of the house. The wooden pillars (saka) that make up the main construction of the building serve one of the functions of maintaining room temperature. The strategy of using wood from certain species to maintain air humidity inside the house is also shown by Bugis houses using ironwood, merbau and bayan (Naing and Hadi, 2020).

3.4. Passive Cooling of Tropical Very Highland Zone Traditional House

The tropical very highland climate zone is above 1,600 meters. This area is characterized by very low temperatures and irradiance, while humidity, winds peed, and rainfall are very high. The cloud cover is moderate. Given the very low temperature in this region, the concept of passive heating is more relevant. The sample house in this region is a Dani tribe house from the mountains of Jayawijaya, Papua (Wazir and Indriani 2020). Dani houses are circular to reduce shredding vortices and friction with the wind (Pinassang, Harsritanto, and Sari 2021). Dani houses also lack ventilation as a form of protection against very heavy rain, very high humidity, and very strong winds. The kitchen in a Dani house is right in the center of the house, just like Bali Aga's house in Bali central mountain, and the occupants sit around the stove to get heat which increases thermal comfort (Wazir and Indriani 2020) (Figure 7a).

If the Koppen-Geiger climate typology is used, the Mbaru Niang, Wae Rebo houses from West Manggarai Regency, Flores, could also fall into the same climate as the Dani houses, namely the cool temperate region (CfC). The traditional houses of Wae Rebo are located at an altitude of 1,200 meters above sea level. This area is not included as a tropical highland area in the integrative typology because the measurement station is not located in the Wae Rebo area.

This similarity can also be seen from the shape of Wae Rebo houses. Wae Rebo houses have a circular shape, just like the Dani tribe's houses. However, Wae Rebo houses still have ventilation in the form of windows on the sides, bamboo walls, plank floors, and 1.5 to 2 meters underfloor, as is characteristic of houses in equatorial climates (Figure 7b). This design is understandable given that the Wae Rebo area is not as high as the Dani area, so the climate zone faced is the transition between the tropical highland zone and the tropical very highland zone. The main distinguishing characteristic of these two zones is the wind speed, where the windspeed in the tropical highland zone is very low while in the very highlands it is the opposite, very high. The Wae Rebo area is between these two zones and can be said to be sufficient in wind speed so that it can be utilized for cooling needs.

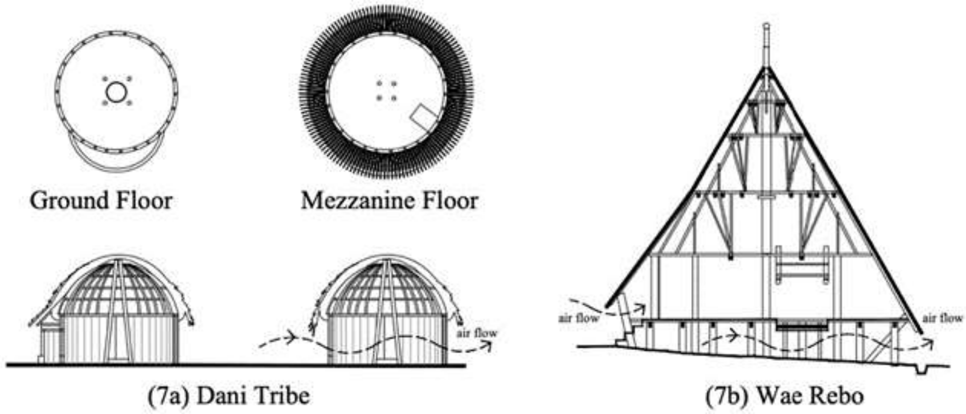

Figure 7. Passive cooling system in tropical very highland climate dwellings (7a) Dani, (7b) Wae Rebo.

3.5. Passive Cooling of Monsoon Zone Traditional Houses

The monsoon zone is characterized by moderate temperatures, irradiance and rainfall, low humidity and little cloud cover, and high wind speeds.

Traditional dwellings that fall into the monsoon climate category in this research include Sundanese, Betawi and Tobelo (North Halmahera) houses. Traditional houses in the monsoon zone are characterized by insulating roofing materials such as woven palm fiber, palm leaves overlaid with tepus (genus Stachyris) leaves, or roof tiles, to retain heat during the day and cool the house at night (Nurislaminingsih, Komariah, and Yudha 2022).

The door of the house has a hollow cavity or corner for air ventilation (Wardana; Basuki Dwisusanto 2019) (Figures 8a, 8b). Houses can have an underfloor but not as high as in equatorial regions. Typical underfloor of houses in monsoon zone is 0.5 to 1 meter, lower than typical underfloor of houses in equatorial zone which could be 2 to 3 meters high. This helps in cooling the space above (Asriningpuri 2020). However, the main function of the underfloor is to evade floods, not as living space, barns, parking space, or storage such as in equatorial zone. If there is no underfloor, the floor is also eliminated so that the cold from the ground can be felt directly (Asriningpuri 2020). The roof is gable-shaped with a bamboo ceiling to let hot air pass through. The gable roof helps cooling as the lower part of the room is affected by the rain flow.

Despite being in the same climate zone, the Tobelo house seems to be an anomaly. It is relatively closed with the back completely enclosed, making ventilation difficult to obtain. The reason for choosing this shape seems to be more cultural, for example to protect the privacy of the family. The residents adapt to this closed house condition by doing outdoor activities more often, especially around the bamboo table in front of the house (Wazir and Indriani 2020) (Figure 8c).

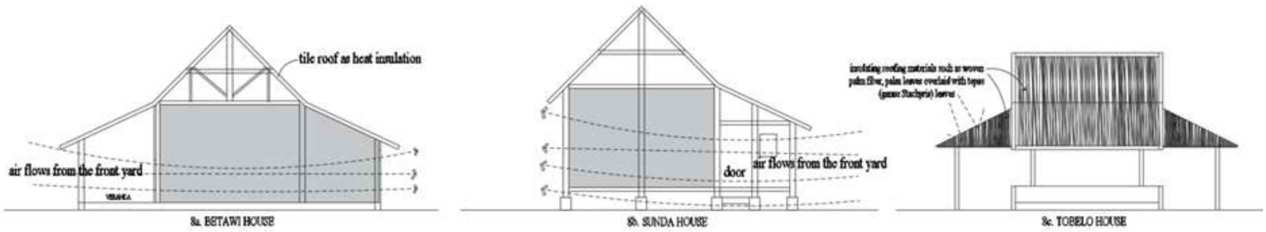

Figure 8. Passive cooling system in monsoon climate dwellings (8a) Betawi, (8b) Sunda, (8c) Tobelo.

3.6. Passive Cooling of Sub-Monsoon Zone Traditional Houses

The sub-monsoon zone has very high temperatures, high humidity and irradiance, moderate cloud cover and rainfall, and low wind speeds. Houses in this region are most in need of passive cooling. Included in the sub-monsoon zone region in this research are Lampung, Java, Bugis, Bawean, Bali, Gorontalo, Banjar, Ngada, Kaili and Sasak. These houses have asymmetrical internal layouts (Suhendri and Koerniawan 2017; Wazir and Indriani, 2020; Rahmayanti and Haisah, 2020). There are certain parts of the house that are not touched by air flow (Tajuddin, 2019). Cooling needs are obtained from cross ventilation between the left and right sides of the house. In addition, in Bawean houses, there is an open durung (barn) in front of the house which functions as an air corridor to channel the wind into the house (Samodra, F., Mappajaya, A., Kharismawan, R., Muchlis, N., & Nasution, 2019) (Figure 9a).

Balinese houses are modular type houses. Each house is a complex of several separate buildings. Each building serving typical room functions. There are two types of building arrangements in each house complex: linear form (tri mandala) and compact form (sanga mandala). The tri mandala configuration uses a linear form in the arrangement of buildings within the house complex. This configuration is better able to distribute temperature and wind flow to accelerate the cooling process compared to the compact configuration (sanga mandala) (Susanti and Damayanti, 2019). Compact houses can counteract the lack of cooling by planting vegetation (Waisnawa, I. M. J., & Padmanaba, 2022) and leaving the center of the complex (natah) open to keep the air warm on cold nights (Wiryomartono, 2014; Yudantini, 2021) (Figure 9b, 9c).

The compactness and asymmetries of houses in the sub-monsoon zone seem to be aimed at blocking the scorching sunlight from entering frontally into the house. Although the irradiance in this zone is actually not high, the sunlight brings very hot temperatures. This temperature must be diverted immediately. The Banjar Bubungan Tinggi house diverts these temperatures with a high roof shape so that the hot air is lifted upwards, although it eventually accumulates around the upper corners of the building (Ikhsan, Ol Siska, and Hidayah, 2021) (Figure 9d). Sasak houses are even extensively covered by roof extensions on two sides facing the direct sun, while ventilation is on the other two sides (Wazir and Indriani, 2020) (Figure 9e).

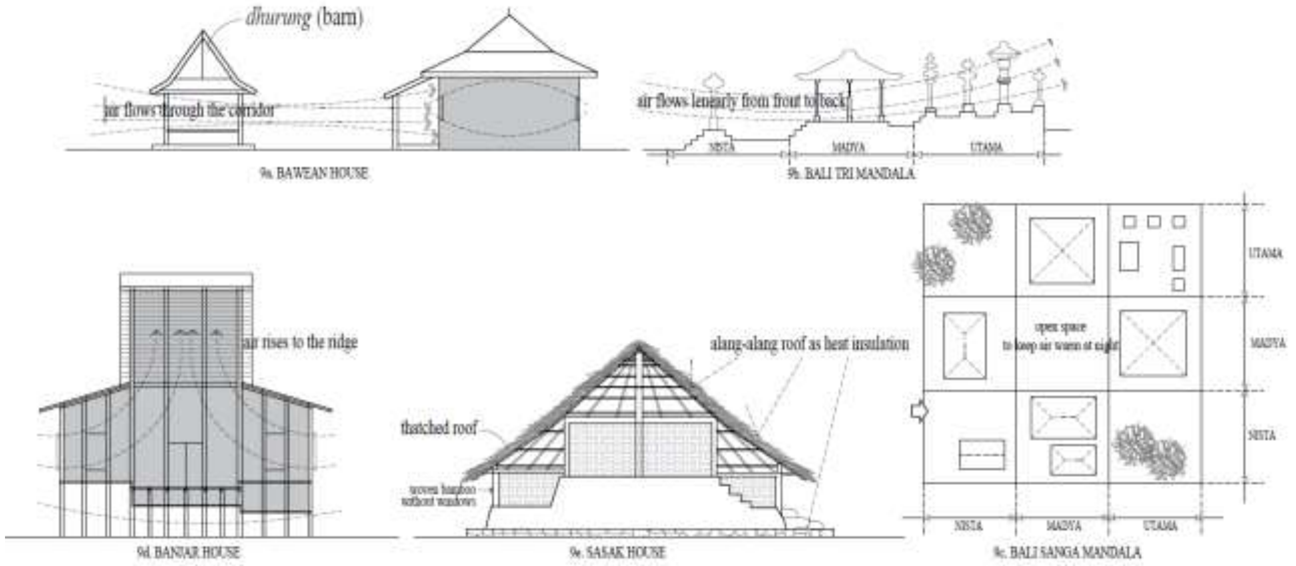

Figure 9. Passive cooling system in sub-monsoon climate dwellings (9a) Bawean, (9b) Bali, tri mandala style, (9c) Bali, sanga mandala style, (9d) Banjar, and (9e) Sasak.

Ceilings are removed to allow hot air to escape between the walls and roof (Asriningpuri 2020; Norvia 2021). Some houses have walls of woven bamboo to improve ventilation and allow natural air circulation indoors (Mustika, F. T., Azizah, S., & Laksono, 2020). These walls are varied with wooden and brick walls and roofs of tiles or reeds to negotiate between privacy and ventilation (Idham 2018; Lahji et al., 2020).

3.7. Passive Cooling of Traditional Savanna Zone Houses

The savanna zone in Indonesia is in most parts of East Nusa Tenggara. This zone 4A corresponds to climate zone Aw in the Koppen-Geiger climate. The temperature and wind speed in this region are high while humidity and cloud cover are low. Solar irradiation is very high while rainfall is very low.

The Uma Khubu house from Central Timor, Uma Lengge from Mbawa Village in West Nusa Tenggara, and Leboya house from Sumba stand in an area with a savanna climate (Figure 10). The main characteristic of houses from this area is the use of alang-alang (Imperata cylindrica) roofs to insulate heat from entering the house (Pratiwi, Hamzah, and Mulyadi, 2020). These houses are 0.1 - 1.8°C cooler than the air outside. To adapt to high-speed winds, houses use underfloors to pass the wind (Wazir and Indriani, 2020).

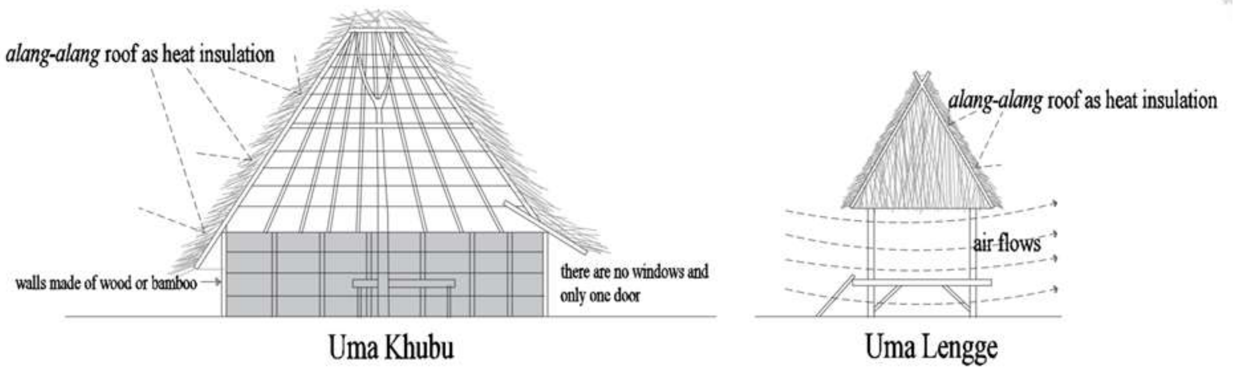

Figure 10. Passive cooling system in savanna climate dwellings: Sumba.

3.8. Passive Cooling of Sub-Savanna Zone Traditional Houses

The last climate zone is the sub-savanna zone. This zone is only found on Madura Island. The sub-savanna climate also has high temperatures like the savanna climate but high irradiation, but not as high as the savanna. The level of humidity and cloud cover in the sub-savanna climate is very low, lower than the savanna area. While wind speed is moderate, not as fast as savanna, and rainfall is higher than savanna, although still relatively low.

Madurese houses adapt to this sub savanna climate by orienting the building mass to the south and using wall colors that reflect solar radiation. Thermal insulation is shown by the large roof space and walls made of bricks (Figure 11).

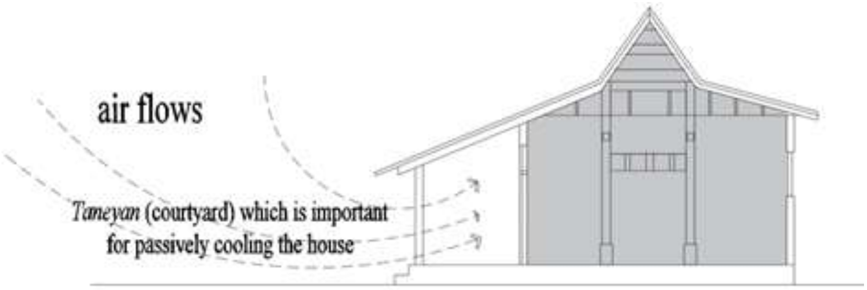

Figure 11. Passive cooling system by expanding the yard in sub-savanna climate dwellings: Madura.

However, Madurese houses are not optimal in passive cooling because they prioritize large courtyards that minimize vegetation, which is important for passively cooling the house. Window openings lack major shading while floor and roof covering materials are less able to absorb air moisture (Nugroho, 2021).

4.0 CONCLUSION

Indonesian traditional houses, as elsewhere in the world, can survive until now because of their ability to respond to the surrounding environment, including the local climate. Of course, some elements of traditional houses are still not optimal in responding to the environment, including in the aspects of passive cooling and thermal comfort improvement. This study is the first to review traditional Indonesian dwellings in terms of passive cooling based on climate type. Previous studies generalized Indonesia's climate as humid tropical, without disaggregating regions based on their climatic peculiarities. This generalization makes it difficult for scholars to build a typology of traditional Indonesian dwellings because the diversity of existing house types seems to have no similarities that can be drawn as a basis for categorization. This study uses an integrative climate typology as the basis for categorization and generates traditional Indonesian dwelling types and assesses the ability of each type to promote passive cooling. This novelty is an important contribution to the study of Indonesian traditional dwellings and their role in sustainable development.

Three further research agendas are proposed by this study. First, there are still pockets of specialized climates in the region that have not been adequately sampled. These special climate pockets are generally located in the highlands in the interior of Sumatra, Java, Sulawesi and Papua. Special studies on traditional dwellings in these climatic areas need to be improved and associated with the concept of thermal comfort. Secondly, studies so far tend to be biased towards local wisdom so that aspects of weaknesses or design flaws of traditional houses are not explored. Future studies need to look at the weaknesses of traditional houses in creating thermal cooling. This step does not mean to underestimate the quality of traditional architecture, but rather as an effort to optimize the benefits that can be obtained by residents and make traditional houses an object of sustainable development. Third, studies on the translation of traditional residential architectural designs into modern residential and building designs need to be reproduced with an emphasis on optimizing passive cooling.

The practical implication of this research for architects and planners in general is the utilization of passive cooling elements of traditional houses to build or retrofit modern houses or buildings according to the climate.

For example, circular designs can be applied to public buildings in savannah climates, while stilt designs with wooden floors can be used to aid passive cooling in buildings with educational functions.

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