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Thermal transmission reduction through bio-based insulated walls, weather-based data analysed for passive cooling in tropics

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Abstract

An experimental and analytical investigation on the potential of bio-based insulation on heat transmission reduction and natural ventilation for passive cooling in the tropics was carried out. Thailand has a tropical climate that is commonly hot and humid all year around. Wall insulation can reduce heat transmission into buildings, resulting in lowering energy demand for cooling as well as providing occupant comfort. Biologically based insulations can be employed to not only provide good thermal characteristics, comparable with conventional commercial products, but are also environmentally friendly. In this article, simple bio-based insulation materials were produced from bamboo fibers and blady grass fibers and their thermal conductivities were compared to commercial insulation. The thermal characteristics of insulated walls using natural fiber materials and commercial materials was tested, in a hot and humid outdoor climate, and compared. Finally, weather data from three cities in Thailand was analyzed to examine the wind speed and direction for locating the optimal building opening for passive ventilation. In brief, the bio-based insulation had quality equal to the commercial materials in terms of thermal conductivity and density, the building insulation could prevent heat gain through the walls by as much as 33% with indoor temperatures 2.4°C lower than the base case, according to the experimental results of the bamboo fiber insulation. The prevailing wind for the three case study provinces in Thailand varied depending on their topography; however, it was found the southern wind was the strongest in all three regions.

Keywords: Natural fiber, Temperature, Comfort, Hot and humid

1. Introduction

Scientists report that the effects of climate change will impact many aspects of the climate, such as more natural disasters and increased global temperatures. This will increase building energy demands for cooling [1]. Thailand is located near the equator and has a tropical climate that is hot and humid for most of the year. It has few months that are cooler than average, between October and February that is considered the winter season. In 2021, the winter had an annual mean temperature of 25.8°C and an annual mean maximum temperature of 31.5°C, while the summer had an annual mean temperature of 29.1°C and an annual mean maximum temperature of 34.8°C [2]. A study on the air temperature trends in Thailand for the last 50 years found that the surface air temperatures were significantly increased and can be an indicator of climate change [3]. The climate impact affected the areas along the eastern, central and western parts of Thailand the most. Buildings are used to control their internal environment, to protect people from the unpleasant and dangerous effects of an extremely hot environment. In tropical climate countries that have recently reached middle income status, like Thailand, many air conditioning systems have been installed over the last few decades. Many families can afford to have at least one air conditioner in their house. Energy consumption in buildings is dominated by air conditioning systems and other electrical appliances used to make the interior more comfortable i.e., fans, evaporative coolers, and refrigerators, which accounts for 60% of energy use [4]. Heat transfer via windows, walls and roofs is the major cause of cooling load in buildings [5]. This can be cut down by means of an efficient thermal insulation material on the building envelope. A simple solution to reduce electrical usage on air conditioning is to reduce heat transmission through walls, using insulation. The lower the heat gain, the lower the cooling energy consumption needed to provide indoor comfort. Among several passive design practices, using insulation is applicable and attractive for both new and existing buildings. Insulation fills in cavities between an external and internal wall, and can be positioning close to either the inner or outer wall. Studies shows that placing insulation board at difference positions in the cavity causes different thermal protection [6]. The optimum composite material to use for an external building wall was investigated using modelling to select the appropriate wall materials in the hot and humid climate of Iran. When emphasizing energy conservation, thinner walls were better for the winter where they helped warm the house in the morning, but thicker composite walls made with extruded polystyrene close to the outer wall was the best option for keeping the homes cool in the summer. An analytical examination of various types of insulation materials and installation patterns showed that placing the insulation board in the external section was slightly better than internal section of the composite wall [7]. Recycled glass fiber, with a thermal conductivity of 0.031W/m.K and a density of 450 kg/m^3, was recommended as the best to use in both winter and summer according to its overall performance [7]. The high-density insulation sheet was considered the best for the summer but the worse one for the winter season. This study also showed recycled glass fiber was better than polyisocyanurate insulation sheets with a thermal conductivity of 0.022 W/m.K and a density of 30 kg/m^3, although the latter is better in terms of having a low thermal conductivity. In our previous study, blady grass fibers were prepared and formed an insulation sheet using natural rubber latex [8]. Based on the thermal conductivity, blady grass insulation is comparable to commercial insulation, such a fiberglass. Several bio-based materials have been studied to produce insulation sheets in which compression, and binding processes were adopted [8-15]. These materials were bamboo fibers, coconut fibers, vetiver fibers, blady grass fibers, and rice straw. Their thermophysical properties were investigated. It was found that the bio-based insulations have low thermal conductivity with various densities which depended on the production process and combination of materials. Bamboo and blady grass are abundant in Thailand. There are a few studies on the bamboo and blady grass insulators while other unconventional insulation materials such as bagasse, corn cob, rice straw and straw bale are widely studied [16]. Bambusa blumeana, bamboo species, contains holocellulose 65.7-72.6 %, Alpha-cellulose 40.3-45.1 %, lignin 20.5-22.7 % [17]. This bamboo is one of 10 important bamboos species in Thailand [18]. In general, the whole bamboo is comprised of 40-50% Alpha-cellulose that is similar to softwoods (40-52%) and hardwoods (38-56%) [17]. Similarly, imperata cylindrica, blady grass, contains high holocellulose as 69.4% and cellulose 37.1% [19]. This makes bamboo and blady grass fibers a potentially suitable raw material for insulation; therefore, they were selected to be raw bio-materials for the current study. The study will be beneficial to building insulation manufacturers where those materials are available.

There are several passive cooling techniques that were recommended in the city of Tamil Nadu, India where the climate is warm and humid [20]. The design principals of the buildings included free flowing air from large openings, the long side of the building being oriented north - south, exterior shading by vegetation and shading devices, light color for exterior surfaces of the building, installation of insulation, facing the predominate wind direction for low rising buildings to avoid absorbing radiation on walls, large overhangs for wall protection and pitched roofs to have a lower roof exposure area. In addition, passive ventilation is one of the passive cooling techniques that can be utilised at no cost to provide cool breezes to overcome an uncomfortable hot and humid climate. It was realised that the natural free running ventilation is an effective passive cooling for residential house in Malaysia where the range of temperatures was 27% lower than is acceptable, based on the adaptive thermal comfort standard [21]. In order to achieve a higher percentage, a mixed mode ventilation was recommended. Efficient natural ventilation relies on the local weather to recognise the prevailing wind according to its speed and direction and also the outdoor air temperature. The incoming air needs to be lower than the indoor temperature for space cooling or removing heat from the interior [22]. Passive cooling techniques are attractive because they require no energy thus cutting down building energy demand. This technique should be widely promoted to provide indoor thermal comfort. Another advantage is to reduce carbon emission from electricity generation by fossil-fuel combustion.

In the current study, the bio-based insulation and passive ventilation, two passive techniques, were investigated. Bamboo and blady grass were used to produce bio-based insulation. Their thermal conductivities and apparent densities were compared with commercial insulations. The two bio materials are widely available in Thailand and have not been studied much on their feasibility as building insulation. Thermal characteristics of insulated walls from both insulation types were investigated and experimentally carried out under Phitsanulok's climate. In addition, the building opening direction for optimized natural ventilation was suggested from the weather analysis for three provinces; Chiangmai, Ubon Ratchathani, and Phitsanulok. A promising result showed the potential of proposed passive cooling techniques in tropical climate to reduce building energy consumption for cooling. This study may lead to practical applications from these experiments to the construction of buildings in the tropics.

2. Materials and methods

Two passive cooling techniques were investigated in this study:

Passive cooling technique 1, insulation: Two bio-based materials, namely Bambusa blumeana J.H. Schultes and *Imperata cylindrica* (L.) were collected in the area of Phitsanulok province. The samples were cut into smaller pieces, treated with NaOH, washed by water, dried, and bound with natural rubber in a wooden frame to form insulation sheets. The bamboo insulation sheet was further investigated for its thermal protection for walls under the hot and humid climate of Phitsanulok. The other 3 commercial insulators were also tested using the chambers that were placed on the flat roof of the Physics building, Naresuan University. Four identical demonstrated houses with the same type of temperature sensors in the same positions provide sufficient information for comparing the thermal protection trends.

Passive cooling technique 2, free ventilation: weather data was collected and analyzed to investigate the potential of wind speed, wind direction and temperature for free ventilation through building openings.

2.1 Bio-based thermal insulation

Bambusa blumeana J.H. Schultes is the scientific name of the bamboo that was adopted in this study. The bamboo fibers were first processed before being formed into insulation sheets. The bamboo was cut to a length of approximately 5 cm and was soaked in sodium hydroxide with a concentration of 15% for 8 h. After that the pieces of sliced bamboo were taken from the solution and washed with water. Next, the sliced bamboo was sun dried for a day before being placed in a blender. The blended bamboo fiber was now ready to make insulation sheets, as shown in Figure 1. The bamboo fibers were combined using natural rubber latex. In the production process, the liquid rubber latex was sprayed on the thin layers of fibers that were laid down and the process repeated with additional layers on a wooden frame to form a sheet with dimensions of 0.45 m × 0.45 m × 0.025 m (width × length × thick) to fit the wall of the chamber (demonstrated house). The bamboo fiber thermal insulation sheet can be seen in Figure 3A.

(A) **(B)** **(C)**

Figure 1 The bamboo fiber preparation from (A) sliced, (B) washed to, and (C) blended bamboo.

Secondly, samples of *Imperata cylindrica* (L.) or blady grass were cut between 10-15 cm before being boiled in a solution of NaOH (25% by mass) for 4 h, cleaned with water, then dried in the sun as shown in Figure 2. The blady grass fibers were combined using natural rubber latex as a binder, before being placed in the wooden frame to make the blady grass insulation sheet of size 0.20 m × 0.20 m × 0.025 m (width × length × thick). Lastly, the insulation sheets were dehumidified in a hot air oven. The blady grass fiber thermal insulation sheet is shown in Figure 3B.

(A) **(B)** **(C)**

Figure 2 The blady grass fiber preparation from: (A) sliced, (B) boiled in NaOH 25%, and (C) dried fiber.

(A) (B)

Figure 3 Bio-based insulation: (A) The bamboo insulation sheet, and (B) The blady grass insulation sheet.

A longer period of time is required in the NaOH solution if a lower concentration of NaOH is used but a shorter period can be used for higher NaOH concentrations and temperatures [15]. Unfortunately, there is not a publication that identifies the exact NaOH concentration to use for the fibers used in the current research. The closet is on varying the NaOH concentration between 10 and 25% for bamboo fiber processing on bamboo with a higher percentage of cellulose II [23]. The current research applied a lower NaOH concentration of 15% at room temperature for bamboo and 25% at an elevated temperature for blady grass. The fiber obtained from both materials were found suitable and can be bound with natural rubber latex to form insulation sheets. Moreover, bamboo and blady grass fibers were well produced using the chemical treatment methods and have good distribution of fibers to allow layering without clogging while forming the insulation sheets.

The thermal conductivity of the bamboo insulation sheet was investigated using Pasco's thermal conductivity apparatus to identify the rate of thermal conduction [24]. The thermal conductivity of the bamboo insulation was measured from the heat transferred using the mass of the ice melted, the material thickness and area, time, and temperature difference were calculated using Equation 1.

$$k\left(\frac{\text{cal}}{\text{cm.s}^{\circ}\text{C}}\right) = \frac{\text{h.m.L}}{\text{A.}\Delta\text{T. }\Delta\text{t}} \tag{1}$$

where h is the sample thickness, m
m is the mass of the melted ice, g
L is the latent heat of fusion for ice (80 cal/g)
A is the area of ice where conduction takes place, m^2
Δt is the time when the ice melted, s
ΔT is the temperature difference between the sides of sample, °C

The difference method was employed to find the thermal conductivity of the blady grass insulation sheet due to the Pasco's laboratory equipment being unavailable at the time the sample was produced, the thermal conductivity of the blady grass insulation sheet was tested using the American Society for Testing and Materials C 177 or ASTM C 177 standard specified by the Institute for Scientific and Technological Research and Services. The apparent density can be determined by the ratio of mass to volume.

2.2 Experimentation on thermal characteristics of the bamboo wall insulation

Four experimental rigs for measuring the heat transmission through the insulated walls were constructed and tested under Phitsanulok's climate, as shown in Figure 4. The chamber wall was constructed with a gypsum board on the outside and plywood on the inside with an air gap between for the base case, while the other three chambers had an insulation sheet of 2.5 cm thickness placed before the inner wall as shown in Figure 4 A-D. 3 commonly used commercial insulators were chosen to compare with the bio-based insulation for their thermal protection. Three insulation sheets of fiberglass, polyethylene or bamboo fibers were used in the 3 test chambers. The insulated wall was facing south during the experiment. Thailand is located in the northern hemisphere and the path of the sun changes daily according to the geographic location. Therefore, the insulated wall faced south as to receive as much solar radiation as possible. A wooden frame 1.5 cm wide and 7.5 cm long was used for the top and bottom of the chamber, while the other three sides, except the one with the testing insulation, were insulated with an EPS, Expanded Polystyrene, foam sheet as shown in Figure 4E.

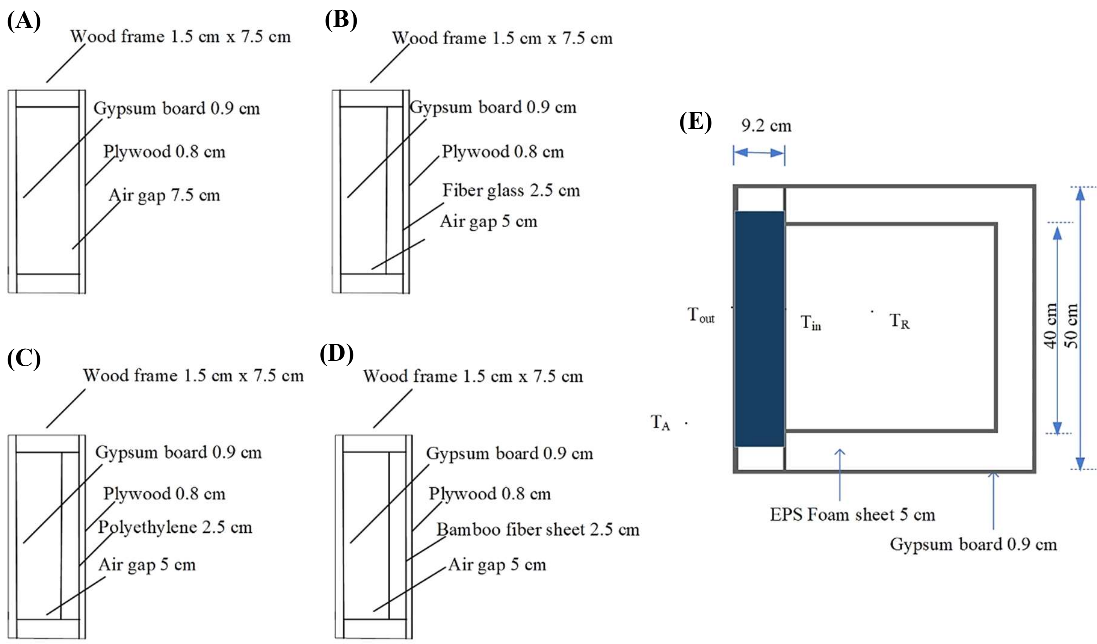

Figure 4 (A) Wall without insulation, (B) Wall with fiber glass insulation, (C) Wall with polyethylene insulation, (D) Wall with bamboo insulation, and (E) Insulated wall test rig and temperature measuring points.

Heat transmission through the wall could be defined as:

$$Q = UA\Delta T \tag{2}$$

where U is the overall heat transfer coefficient, W/(m^2.K)
A is the area the heat transmitted through, m^2
ΔT is the temperature difference across the wall, K

2.3 Weather data analysis

The outdoor temperature and wind speed and direction were taken from the meteorological department of Thailand for Chiangmai, Ubon Ratchathani and Phitsanulok and were analysed for the annual maximum, average, and minimum hourly temperatures. The wind direction and speed were calculated by converting the number of degrees to the letter of the direction, such as 180^o to South (S), and 90^o to East (E). The percentage of time each recorded speed was counted and wind rose diagrams were plotted with the data in Microsoft excel. Tabulation analysis was used to calculate the number of hours where the outdoor temperature was lower than upper temperature limit for adaptive thermal comfort for the three provinces to look at the possibility of passive ventilation.

3. Results and discussion

3.1 Thermophysical properties of bio-based and commercial insulation

The two insulation samples were analyzed for their thermophysical properties. The thermal conductivity of the bamboo fiber insulation was 0.038 W/m.K and the apparent density was 255 kg/m^3. The lowest thermal conductivity obtained for a blady grass thermal insulation sheet was at a ratio of 9:1 (blady grass fiber: natural rubber latex). Its thermal conductivity was 0.0489 W/m.K and an apparent density of 100 kg/m^3. More information of blady grass insulation can be found in our past report [8]. Table 1 shows comparisons among the current test samples, bio-based materials from past research and commercial materials. It can be seen that the insulation sheet made from bamboo fiber and natural rubber latex has a thermal conductivity 50% lower than bamboo fiber alone and a lower thermal conductivity than bamboo fiber and bone glue. Compared to other bio-based materials, both bamboo fiber with natural rubber latex, and blady grass fiber and natural latex offers lower thermal conductivity than other materials namely, coconut fiber, coconut fiber and durian peel, coconut fiber and sugar cane, vetiver fiber and natural rubber latex, and rice straw. The present insulating materials are comparable to other commercial and conventional materials, since they have a similar thermal conductivity. Both insulation samples have a density of over 100 kg/m^3, thus they could be adopted as building insulation for walls and provide good thermal performance in tropical regions, as seen in other research reports [9-10,13-14]. A literature study of expanded polystyrene (EPS) showed that the thermal conductivity increased from 0.031 to 0.037 W/m.K as the density increased from 15 to 75 kg/m^3 , showing that higher density insulation can, in some cases, increase performance [7].

Table 1 Thermophysical of present research insulation and other bio-based and commercial insulation sheets.

Insulation materials	Density (kg/m^3)	Thermal conductivity (W/m.K)
Bamboo fiber and natural rubber latex	255	0.038
Blady-grass fiber and natural rubber latex	100	0.0489
Bamboo fiber [9]	431	0.077
Bamboo fiber and bone glue [10]	645	0.118
Coconut fiber without additive [11]	N.A.	0.046-0.068
Coconut fiber and sugar cane [12]	500-700	0.14-0.17
Coconut fiber and durian peel [13]	856	0.0764-0.1342
Rice straw [14]	250	0.051-0.053
Vetiver fiber and natural rubber latex [15]	250	0.0564
Gypsum plasterboard [25]	2200	0.1-0.3
Fiberglass [26]	12-48	0.028-0.070
Polyurethane matrix with wood fiber/bamboo fiber/rice husk [27]	105-178	0.045-0.065
Polyethylene foam [28]	35-40	0.017-0.023

N.A. = not applicable.

3.2 Thermal characteristics of insulated wall

The experimental results showed that the chamber with a polyethylene insulated wall (PIW) had the highest reduction of heat transmission through the wall followed by the bamboo fiber sheet insulated wall (BIW) and fiberglass insulated wall (FIW) as shown in Figure 5. The three walls, the PIW, the BIW and FIW, all had a similar thermal effect on the chamber. The temperature difference between the outer and inner wall shows the highest difference in FIW at 17°C, followed by BIW at 16°C and lastly the PIW at 15°C. Moreover, it was found that the room temperature of the three chambers was lower than the base case by 3.2°C, 2.4°C and 1.6°C respectively. The use of BIW is promising with a 33% heat reduction being achieved. Thus, the bamboo fiber insulation can prevent building heat gain to a greater extent than the fiberglass material in an environmentally friendly way.

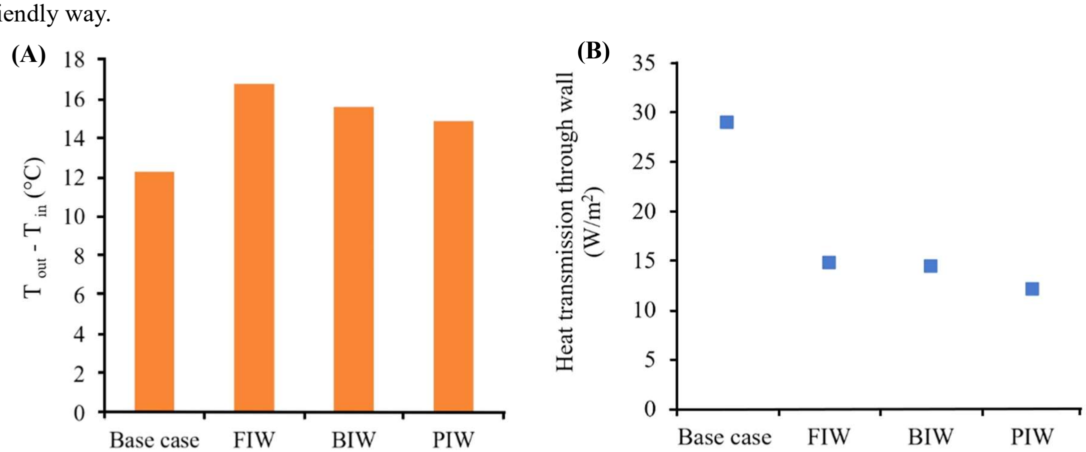

Figure 5 Insulated wall experiment in a tropical climate, Phitsanulok; Base case, Fiberglass insulated wall (FIW), Bamboo fiber insulated wall (BIW), Polyethylene insulated wall (PIW) (A) Temperature different across the wall and (B) Heat transmission through the wall.

3.3 Passive ventilation

To find potential times of the day when the outdoor air temperature is cool enough to be used for natural ventilation, the maximum temperature, average temperature and minimum temperatures are graphed in Figure 6. Temperatures were lowest from 1:00 to 6:00., then they gradually increased to peak around 14:00 - 16:00, and then they continually decreased for the rest of the day. Annual minimum temperatures are the lowest in Chiangmai with temperatures just above 10ºC throughout the day. Phitsanulok and Ubon Ratchathani also had an annual minimum temperature just above 10ºC in the early morning hours between midnight and 7:00, though they experienced higher minimum temperatures latter in the daytime.

Next, the percentage of the days that the air temperature was between the minimum and average hourly temperatures, but lower than 27°C (the upper limit of the adaptive thermal comfort zone) was quantified. For example, the number of days when the temperature recorded at 1:00 had a value lower than the average temperature, but not above 27°C, were divided by the number of days in the year and multiply by 100 to look at the potential for using passive ventilation. This showed that 80% of the time before 6:00, in Chiangmai, the temperature was in the comfortable range, but this decreased to lesser than 20% of the time after 10:00. This period where there is a high percentage of days that are naturally cool could lower the number of operating hours needed for air conditioning which would lower energy demand. The trend was similar in Ubon Ratchatani and Phitsanulok but the percentage of time that could potentially use passive ventilation was less. From 10:00 to 17:00 most days were too hot to allow for passive cooling, in the three provinces of Thailand.

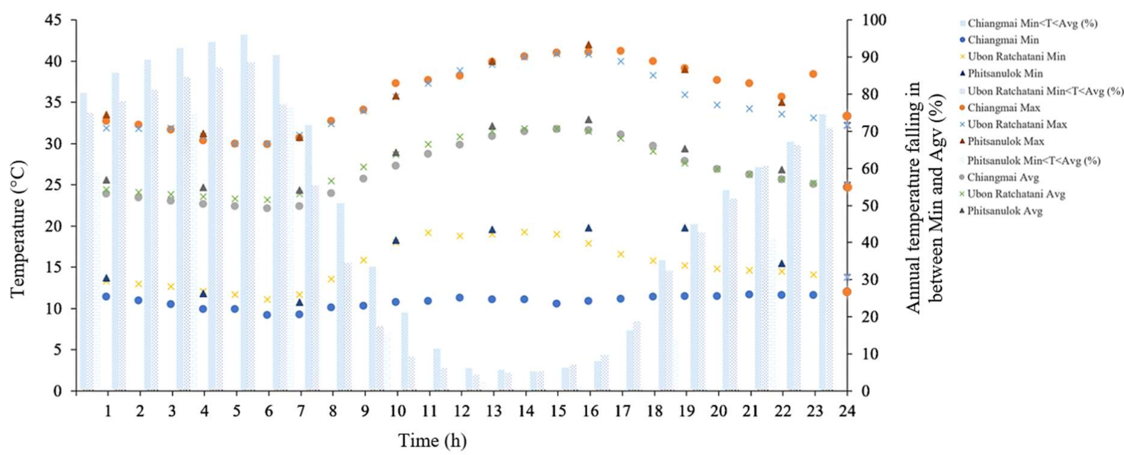

Figure 6 Hourly annual temperature classified for minimum, average, and maximum in Chiangmai, Ubon Ratchathani and Phitsanulok.

Finally, the wind speed and direction were studied for their potential for natural ventilation, the tabulated data analysis indicated that the maximum winds speeds are from the south for Chiangmai and Phitsanulok and from both the north-east and south for Ubon Ratchathani, as can be seen in Figure 7.

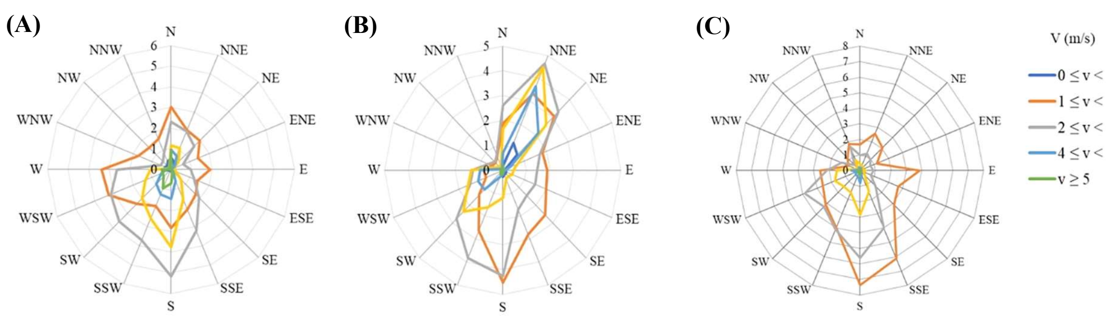

Figure 7 Wind speed and direction plot in percentage of total incident number (A) Chiangmai, (B) Ubon Ratchatani, and (C) Phitsanulok.

The radius labels in Figure 7 show the percentage of time the wind speed is in the velocity range and direction. The prevailing wind speeds of 1-3 m/s in Phitsanulok, 1-4 m/s in Ubon Ratchatani and, 1-3 m/s in Chiangmai were observed. Wind speeds were above 2 m/s 62.6% of the time in Chiangmai, 65.3% of the time in Ubon Ratchathani and 52.7% of the time in Phisanulok. That accounted for 5,484 h, 5,720 h, and 4,616 h respectively during the year. An outdoor wind speed of 1.9 m/s combine with building opening options e.g., operable windows and balcony doors can receive an air change rate high enough to allow for natural ventilation [29]. This allows passive ventilation which not only conserves energy by achieving thermal comfort at lower energy consumption, but also improves indoor air quality during a pandemic.

3.4 Limitations of the study

The current study focuses on only two passive cooling techniques where more techniques could be employed in further research to reduce the building energy consumptions in hot and humid climates. The strength of this research is that the results of the thermal conductivity of both blady-grass insulation and bamboo insulation show their performance is comparable with synthetic fiber insulation but is more beneficial to the environment, health, safety and wellbeing. A longer period of observation would be useful to learn the effects of the climate on bio-insulation.

4. Conclusion

In this research, bamboo fiber insulation and blady grass fiber insulation were investigated and found comparable to commercial insulation with low thermal conductivities of 0.038 W/m.K and 0.0489 W/m.K, respectively, and high densities of 255 kg/m^3 and 100 kg/m^3, respectively. An outdoor test to simulate a building wall incorporating the bamboo fiber insulation or two walls insulated with commercially available materials (fiberglass and polyethylene) showed equal thermal protection; hence, bio-based insulation offers efficient thermal protection. Lastly, analysis of the weather data showed the prevailing wind speed and direction could be applied for natural ventilation in the three provinces in the case study; Chiangmai, Ubon Ratchathani and Phitsanulok where the wind speed was higher than 2 m/s for 5,484 h, 5,720 h, and 4,616 h per year respectively. In addition, air temperatures lower than the upper limit of adaptive thermal comfort could be reached during the nighttime and morning, allowing comfortable passive ventilation. Other passive cooling techniques shall be explored in further research to reduce the building energy consumptions in hot and humid climate.

5. Acknowledgements

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