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Research Article

Thermal Performance of Semi-Outdoor Buildings in a Coastal Tropical Environment

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Abstract

This study aims to evaluate the thermal performance and comfort levels of semi-outdoor timber buildings in a tropical coastal environment through an integrated approach combining field measurements and CFD simulations. Key thermal parameters—including air temperature, relative humidity, wind speed, Mean Radiant Temperature (MRT), Effective Temperature (TE), and thermal comfort indices (PMV and PPD)—were measured at three semi-outdoor spaces of Maha Corner Café during peak operational hours. These empirical data were used to construct detailed airflow and temperature simulations in ANSYS Fluent to analyze ventilation behavior and thermal distribution. The results show that air temperatures remained relatively stable (29–30 °C), while TE values indicated warmer perceived conditions due to high humidity and solar exposure. PMV values ranged from slightly warm to warm (+0.7 to +1.8), with corresponding PPD values between 18–48%, indicating reduced comfort acceptability for most occupants. Wind speeds varied substantially across building zones, where areas with direct sea-breeze exposure demonstrated better thermal sensation alignment with PMV predictions. CFD outputs showed strong agreement with field measurements and revealed airflow patterns highly influenced by spatial configuration and coastal microclimate factors. Overall, the study highlights that thermal comfort in semi-outdoor coastal buildings depends primarily on natural ventilation effectiveness, shading, and microclimate exposure, while timber contributes to moderating surface-temperature fluctuations as part of broader passive design strategies.

Keywords: Thermal Performance; Semi-Outdoor Timber Buildings; Coastal Microclimate; Thermal Comfort (TE–PMV–PPD); CFD Simulation.

Introduction

The continuous rise in air temperature across Indonesia has intensified the occurrence of heat-wave events, emphasizing the urgent need for buildings capable of maintaining adequate thermal comfort in tropical environments [1,2]. Concerns regarding thermal comfort have grown significantly, as reflected in the increasing number of studies evaluating comfort conditions in various building types and in lightweight tropical structures through field measurements and

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CFD simulations [3,4]. While research has historically centered on fully enclosed indoor spaces, semi-outdoor environments have increasingly gained attention due to their role as transitional zones that substantially influence user comfort and spatial experience [5].

In coastal regions such as Lhoknga in Aceh Besar, thermal comfort challenges are amplified by the combined effects of strong sea breezes, high humidity, and intense solar exposure, all of which shape occupants' thermal perception [6,7]. Maha Corner Café—one of the most frequented semi-outdoor public facilities along the coastline—utilizes extensive timber elements and natural ventilation in its design. Although visually appealing, the thermal performance of such semi-open timber structures remains highly dependent on coastal microclimate conditions, creating uncertainties regarding how effectively they maintain comfort under fluctuating environmental forces.

Existing studies on cafés in Indonesia have largely focused on urban settings, emphasizing indoor comfort assessment through physical measurements and user perception analyses [8-10]. However, empirical investigations specifically targeting semi-outdoor cafés in coastal tropical environments remain scarce, and previous works have not examined how timber-based semi-open structures respond thermally to coastal microclimates. Moreover, the integration of short-term field measurements with CFD simulations—which is essential for capturing airflow behavior and spatial temperature distribution in open tropical buildings—has rarely been applied in this context, leaving a gap in understanding how these spaces perform under real environmental exposure. To address this gap, the present study evaluates the thermal performance of semi-outdoor timber buildings in a coastal tropical environment through combined field measurements of air temperature, relative humidity, wind speed, and WBGT, MRT, ET complemented by CFD simulations to visualize airflow patterns and thermal distribution. The recommended indoor temperature range is 22.8-25.8 °C, as specified SNI 036572-2001 [11]. In addition, relative humidity is a critical parameter due to its close association with human health; the ideal range lies between 55–60%. Excessively high humidity levels may promote the growth of mold and bacteria, whereas excessively low levels can lead to skin irritation and respiratory discomfort. Air movement also influences indoor environmental quality, as it carries heat, dust, and moisture; thus, its regulation is essential for maintaining comfort as well as energy efficiency [12]. Air circulation is influenced by the pressure differences between the outdoor and indoor environments and can be enhanced through either natural or mechanical ventilation. The recommended ventilation rate is 0.15–0.25 m/s per occupant, as specified in SNI 036572-2001 [11]. This integrated methodological approach enables a more comprehensive and robust interpretation of ventilation performance and microclimate responsiveness compared to studies that rely solely on physical measurements. Building on this foundation, the study is guided by a set of research questions that seek to clarify how thermal conditions vary within semi-outdoor timber buildings in coastal environments, how accurately CFD simulations can replicate the measured thermal and airflow conditions, and which spatial or environmental factors most strongly influence thermal behavior in these settings. By framing the investigation around these questions, the study aims to generate evidence-based insights that can inform the development of climate-responsive design strategies for semi-outdoor timber architecture.

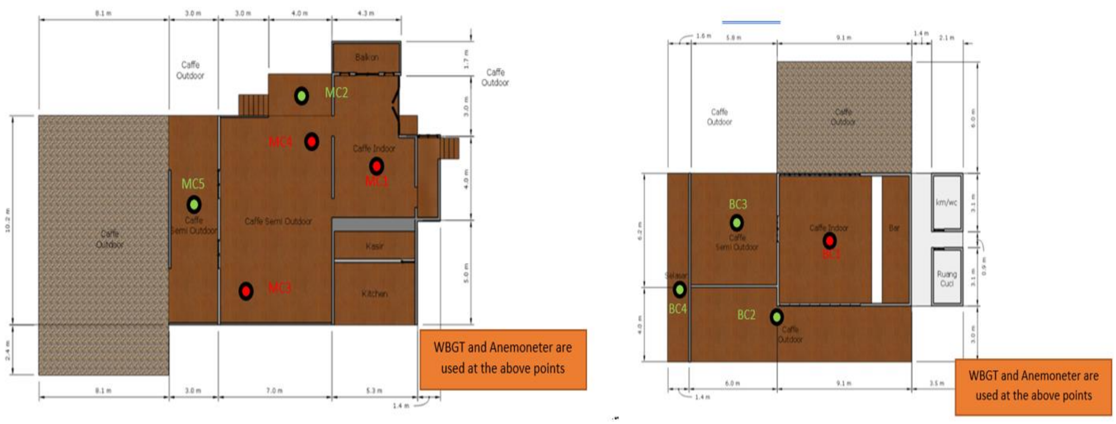
The primary contribution of this study lies in providing empirical data and simulation-based analysis for a building typology and climatic context that remain underrepresented in the literature. The novelty of this research is reflected in its explicit focus on semi-outdoor timber cafés in coastal climates, its integration of field measurements with CFD modeling to examine airflow–temperature interactions, and its effort to translate these findings into transferable design guidelines for passive thermal improvement in tropical coastal architecture. Through this approach, the study offers a scientific foundation for enhancing thermal comfort and environmental performance in semi-outdoor timber structures located in coastal regions.

Materials and Methods

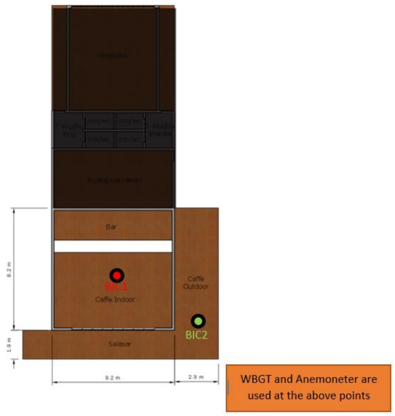
This research employs a quantitative method using a case study approach. The quantitative method is applied to numerically validate the findings through statistical analysis [13]. The collected data include measurements of thermal conditions, which were subsequently simulated for each space using ANSYS software.

Figure 1. Map of the Research Location and 3D Perspective of Maha Corner Café

The study was conducted at the Maha Corner Café, located in Mon Ikeun, Lhoknga District, Aceh Besar Regency, Aceh, Indonesia (**Figure 1**). The research covered three semi-outdoor buildings within the complex: the Bar Coffee, situated closest to the shoreline; the Bar Ice Cream, positioned farthest from the sea but located at the highest elevation among the three; and the Main Café, which is situated adjacent to the Bar Coffee.



(a) **(b)**



(c)

● = Indoor

● = Outdoor

MC = Main Café

BC = Bar Coffee

BIC = Bar Ice Cream

Figure 2. Measurement Points at the Maha Corner Café
(a)Bar Coffee, (b)Bar Ice Cream, (c)Main Café

In this study, "semi-outdoor" determined in a room that has walls or partitions on four sides of the room and is covered by a ceiling or roof, while "outdoor" is determined in a room that has a ceiling or roof but does not have walls on four sides of the room (**Figure 2**). By establishing these measurement points, the study was able to obtain a more representative depiction of the thermal comfort conditions at the Maha Corner Café. The measurement locations were determined based on the dimensions and area of each space so that the distribution of data collection could accurately reflect the actual thermal conditions within the study area. Measurements were conducted under clear to slightly cloudy weather conditions. Data collection took place during weekends (Saturday and Sunday) within the café's operating hours, from 12:00 to 20:00 local time per 60 minutes. All sensors were positioned at a height of 1.2 m above the floor to represent the breathing zone, consistent with standard practices in field studies that typically employ heights of 1.1–1.2 m in thermal comfort research involving both pedestrians and seated occupants [14]. Instrumentation specifications were documented to ensure reproducibility. Air temperature, Temperature Globe, Relative Humidity, and WBGT were measured using a Lutron WBGT-201 Heat Stress Monitor (accuracy ±0.5 °C; RH ±3%; globe temperature ±1 °C; response time 60 s). Wind speed was measured using the Benetech GM8908 digital anemometer testo 400 (accuracy ±0.1 m/s; range 0–30 m/s; response time <1 s). Measurements were conducted over two consecutive days during peak operational hours (12:00–20:00). Data were logged at 1-minute intervals, with each recording representing an instantaneous reading. In total, 495 datasets per parameter were collected at each point per day.

Although PET and UTCI are widely applied for outdoor and transitional environments, TE and PMV–PPD were chosen in this study because they provide a more direct representation of the microclimatic variables measured on-site (air temperature, relative humidity, and air velocity), allowing consistent integration with CFD-derived parameters and enabling a clearer comparison across semi-outdoor zones with different exposure levels. Moreover, TE and PMV–PPD remain among the most established indices in thermal comfort research for warm–humid regions, making them suitable for assessing the combined effects of humidity, air temperature, and airflow in coastal semi-outdoor café settings

The airflow and thermal distribution simulations were performed using ANSYS Fluent 2024 R1. The energy equation was activated (Energy = On), and the SST k–ω turbulence model was employed under the viscous settings. A pressure-based solver was selected and executed in steady-state mode. The computational domain was constructed based on the actual building geometry and meshed using the default ANSYS meshing tool with a global element size of 0.2 m. Boundary conditions were assigned according to the designated zones in the model, including the inlet (represented as a velocity inlet), outlet, wall boundaries, and interface/internal regions for zone connections. Solution initialization was conducted using the hybrid initialization method, and the simulation was terminated after 300 iterations.

The field measurements were conducted over two consecutive days during peak operational hours to capture representative thermal conditions under typical usage scenarios. Although the measurement duration is relatively short, this approach was intentionally adopted to obtain a focused snapshot of thermal behavior under dominant coastal weather conditions. Short-term measurements have been widely applied in thermal comfort studies of semi-outdoor and transitional spaces, particularly when combined with numerical simulations. In this study, the limitation of measurement duration is mitigated by integrating CFD analysis, which enables a more comprehensive understanding of airflow dynamics and thermal distribution beyond the measurement period.

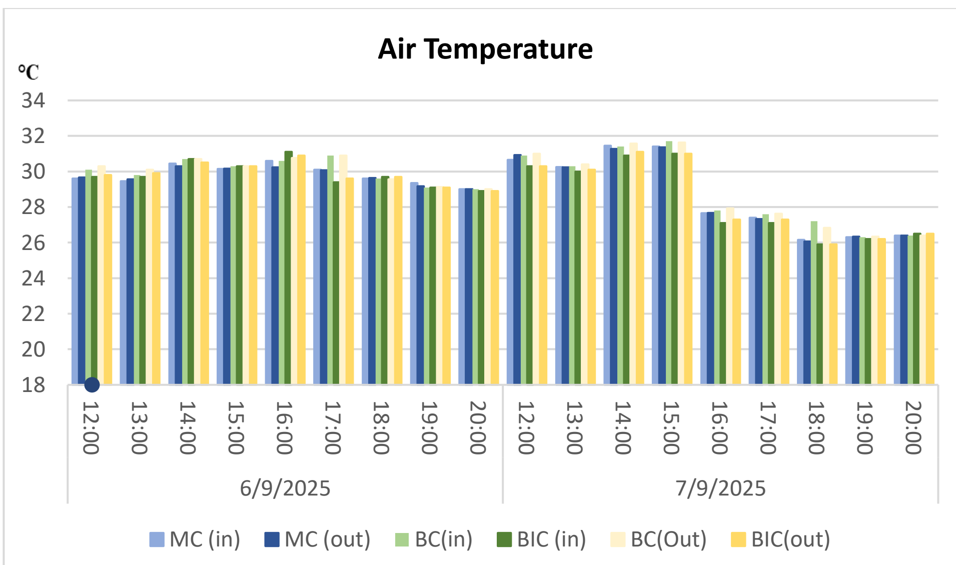


Figure 3. Air Temperature Measurements at the Maha Corner Café

Results

Air Temperature

Based on the measurements obtained using the Wet Bulb Globe Temperature (WBGT) device, the air temperature patterns across the three buildings at the Maha Corner Café exhibited noticeable fluctuations during the two-day observation period (**Figure 3**). On 6 September 2025, air temperature remained relatively stable under slightly cloudy hot weather conditions, with an average of 29.89 °C. On 7 September 2025, hot and cloudy conditions during midday followed by rainfall in the late afternoon led to a temperature decrease, producing an average of 28.61 °C. The highest temperatures were recorded in the interior of the Bar Coffee (BC) building at 31.70 °C and in the exterior area at 31.63 °C at 15:00 local time on the second day. This condition was attributed to the BC's position closest to the shoreline, resulting in greater exposure to solar radiation. Conversely, the lowest temperatures were observed in the interior of the Main Café (MC) at 26.15 °C and in the exterior area at 26.07 °C at 18:00 local time on the second day. These lower values were associated with the MC's greater distance from the coast and the presence of dense surrounding vegetation, which provided a natural cooling effect.

The higher air temperature observed in the Bar Coffee building can be attributed to its proximity to the shoreline and direct exposure to solar radiation, combined with limited shading from surrounding vegetation. The semi-open configuration allows solar heat gain to dominate during peak hours, while the timber material helps moderate extreme fluctuations rather than significantly lowering peak temperatures. This finding suggests that in coastal semi-outdoor buildings, material properties alone are insufficient to ensure thermal comfort without complementary passive strategies such as vegetation shading and optimized orientation.

Relative Humidity

A similar pattern is observed in the relative humidity parameter (**Figure 4**). On 6 September 2025, the relatively stable weather resulted in minimal variation in the humidity graph, with an average of 64.04% Rh. In contrast, 7 September 2025 showed a significant increase in humidity due to the sudden change in weather—specifically, rainfall—which raised the average humidity to 73.4% Rh. The highest humidity levels were recorded in the exterior area of the Bar Ice Cream (BIC) building at 86.50% Rh and the interior area at 86.40% Rh at 18:00 local time on the second day. This condition is influenced by the BIC's location at the highest elevation among the three buildings, making it more exposed to sea breezes and the moist atmospheric conditions following the rainfall. Conversely, the lowest humidity levels were observed in the exterior of the Bar Coffee (BC) at 58.77% Rh and its interior at 57.90% Rh. These lower values align with the higher temperatures recorded at those times, as increases in air temperature lead to a reduction in relative humidity.

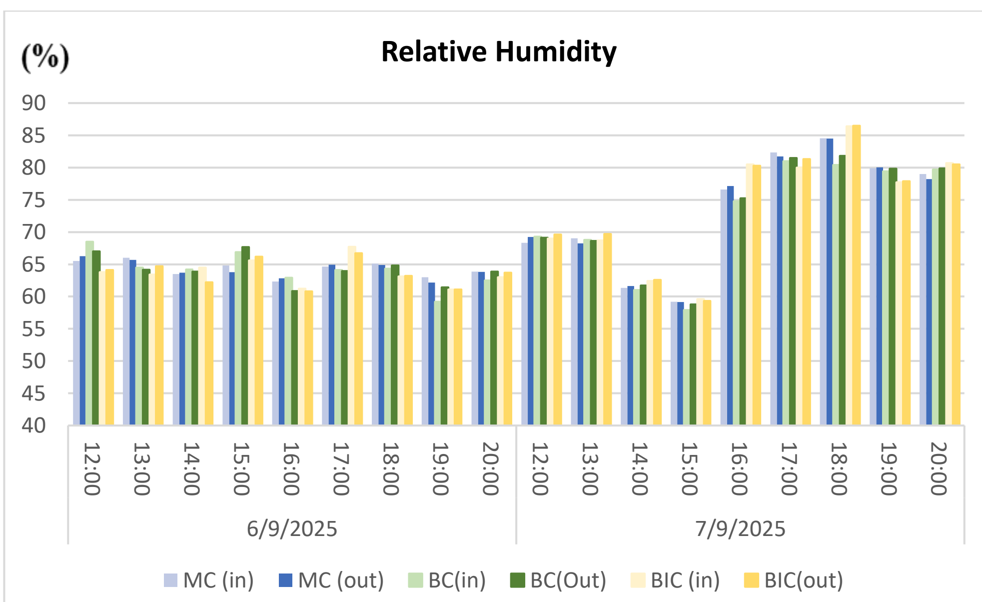


Figure 4. Relative Humidity Measurements at the Maha Corner Café

Figure 5 illustrates the variation in relative humidity across the three buildings at the Maha Corner Café, classified according to the comfort criteria established by SNI 03-6572-2001 [11]. Over the two-day observation period, most humidity values fell within the uncomfortable category, exceeding the ideal threshold of 55–60% Rh. On 6 September 2025, humidity levels were relatively stable despite slight fluctuations within the 60–70% Rh range, remaining slightly above the comfort limit. However, on 7 September 2025, a significant increase in humidity was observed, particularly after afternoon rainfall, with values surpassing 85% Rh across all buildings. The BIC building—located at the highest elevation and receiving greater exposure to sea breezes—recorded the highest humidity levels compared to the other structures. Meanwhile, the BC building tended to show lower humidity values due to higher temperatures at those times, which consequently reduced relative humidity. Overall, the chart demonstrates that coastal humidity conditions and rapid weather changes play a major role in placing humidity levels within the uncomfortable category across all semi-outdoor buildings in the study area.

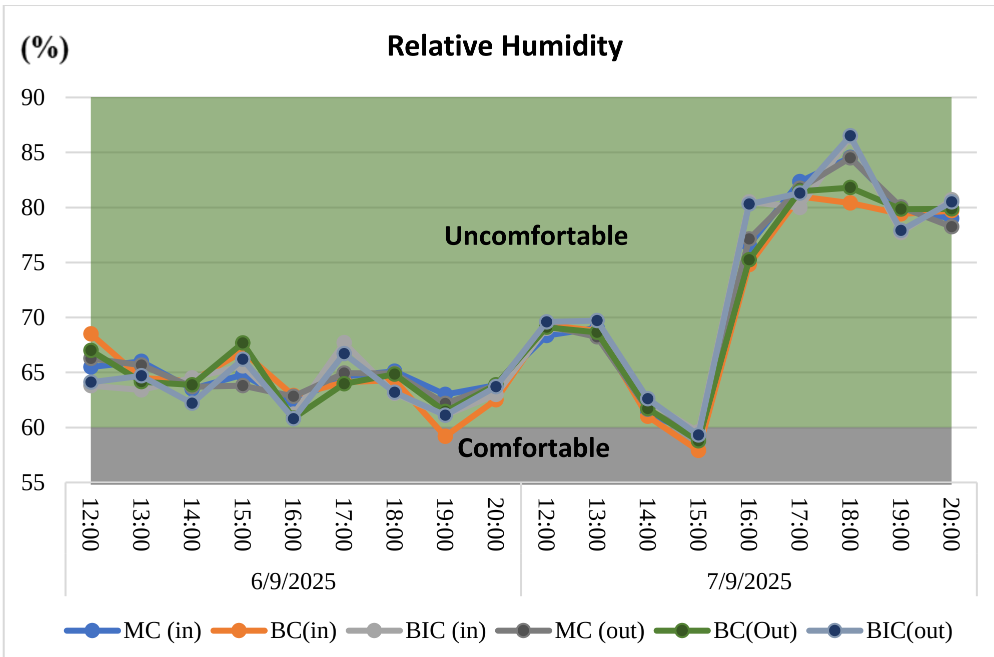


Figure 5. Relative Humidity Classification Based on Comfort Criteria SNI 03-6572-2001 [11]

Wind Speed

Weather conditions during the measurement period had a direct influence on the wind speed values obtained (**Figure 6**). On 6 September, the average wind speed was approximately 0.5 m/s. In contrast, on 7 September, an increase was observed, with the average reaching 0.85 m/s, reflecting daily atmospheric variations that affected airflow patterns at the study site. The highest wind speeds were recorded in the interior of the Bar Coffee (BC) building at 2.51 m/s and in the exterior area at 2.05 m/s at 16:00 local time on the second day. This was influenced by the BC's position closest to the shoreline, resulting in greater exposure to sea breezes, compounded by rainfall conditions that contributed to increased wind speeds at that time. Conversely, the lowest values were found in the interior of the Bar Ice Cream (BIC) at 0.07 m/s and its exterior at 0.09 m/s at 19:00 on the same day. These low wind speeds corresponded to the atmospheric conditions in the early evening, when air movement typically weakens due to the stabilization of air temperature.

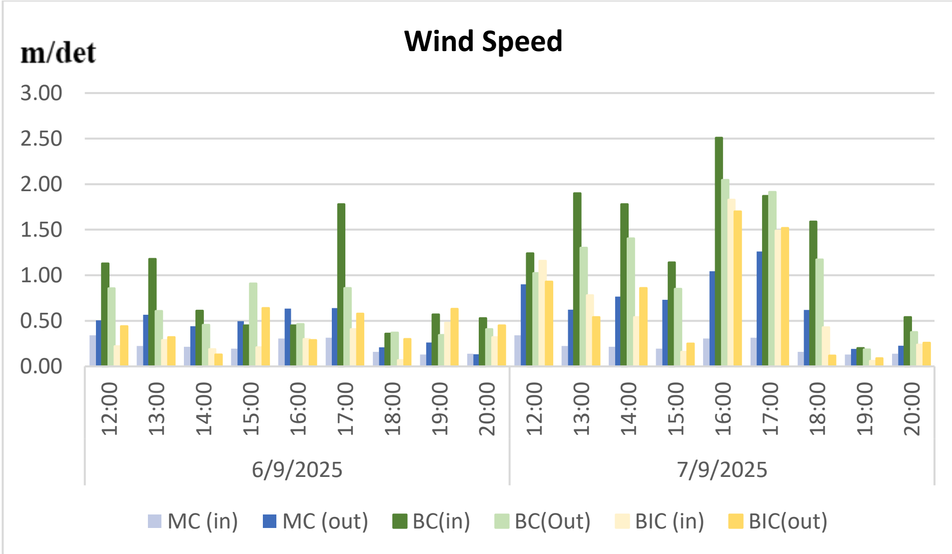


Figure 6. Wind Speed Measurements at the Maha Corner Café

The higher wind speeds recorded in the Bar Coffee area indicate strong exposure to prevailing sea breezes. While increased airflow can enhance convective cooling, excessive wind speeds may exceed the comfort threshold and reduce occupant satisfaction. This highlights the importance of balancing openness and wind control in semi-outdoor coastal buildings, where unrestricted exposure may lead to discomfort despite adequate ventilation.

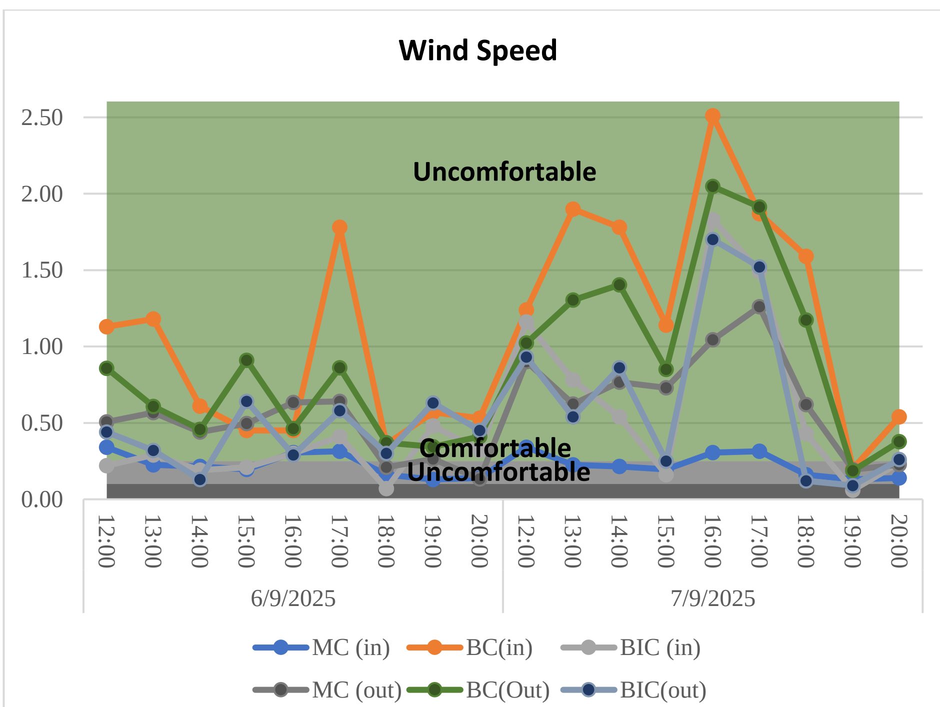


Figure 7. Wind Speed Classification Based on Thermal Comfort SNI 03-6572-2001

Figure 7 illustrates the variation in wind speed across the three buildings at Maha Corner Café based on the comfort classification established by the Indonesian Ministry of Health (2023). Overall, most wind speed values fall within the uncomfortable category, as they exceed the recommended comfort range of 0.15–0.25 m/s, particularly on 7 September 2025 when atmospheric conditions shifted due to rainfall and increased sea breezes. The Bar Coffee (BC) building, located closest to the shoreline, consistently records the highest wind speeds at nearly all observation times, both indoors and outdoors, indicating significant exposure to direct coastal winds. In contrast, the Bar Ice Cream (BIC) and Main Café (MC) buildings display lower wind speeds, especially during the evening when airflow typically weakens. The fluctuations shown in the graph highlight that location, building orientation, and daily weather conditions play crucial roles in shaping airflow patterns within semi-outdoor spaces in coastal environments.

Table 1. Average Thermal and Airflow Conditions in Bar Coffee, Bar Ice Cream, and Main Café

Average Air Temperature (°C)	BC(in)	BC(out)	BIC(in)	BIC(out)	MC (in)	MC (out)
	29.43	29.47	29.09	29.13	29.22	29.19
Average Wind Speed (m/s)	**BC(in)**	**BC(out)**	**BIC(in)**	**BIC(out)**	**MC (in)**	**MC (out)**
	1.10	0.86	0.51	0.56	0.23	0.57

The comparison in **Table 1** reveals that the Bar Coffee (BC) consistently exhibits higher air temperature and wind speed compared to the Bar Ice Cream (BIC) and Main Café (MC). This condition is primarily influenced by BC's direct proximity to the shoreline, which increases exposure to solar radiation and dominant sea breezes. The semi-open configuration of BC allows wind to penetrate freely, resulting in higher airflow intensity but also greater thermal fluctuation during peak hours. In contrast, the BIC building—although located at a higher elevation—is positioned farther from the shoreline and experiences reduced direct solar exposure, leading to lower temperatures and more moderate airflow. Meanwhile, the MC benefits from surrounding vegetation and partial enclosure, which attenuate wind velocity and limit heat gain, resulting in more stable thermal conditions. These findings indicate that in coastal semi-outdoor buildings, spatial positioning, orientation, and environmental shielding play a more decisive role in shaping thermal performance than material properties alone.

Table 1 indicates that the air temperatures at BC (in) and BC (out) fall within nearly identical ranges, namely 29.43 °C indoors and 29.47 °C outdoors, reflecting stable thermal conditions across both areas. The temperature simulation visualization of the Bar Coffee building likewise displays a relatively uniform distribution pattern around the structure, with color gradients illustrating the natural dispersion of heat within the semi-open environment (**Figure 8**). Overall, the integration of the tabulated data and simulation results suggests that the thermal conditions in this area remain fairly constant without any notable temperature fluctuations, thereby facilitating the analysis of heat transfer patterns and the potential level of thermal comfort within the Bar Coffee space.

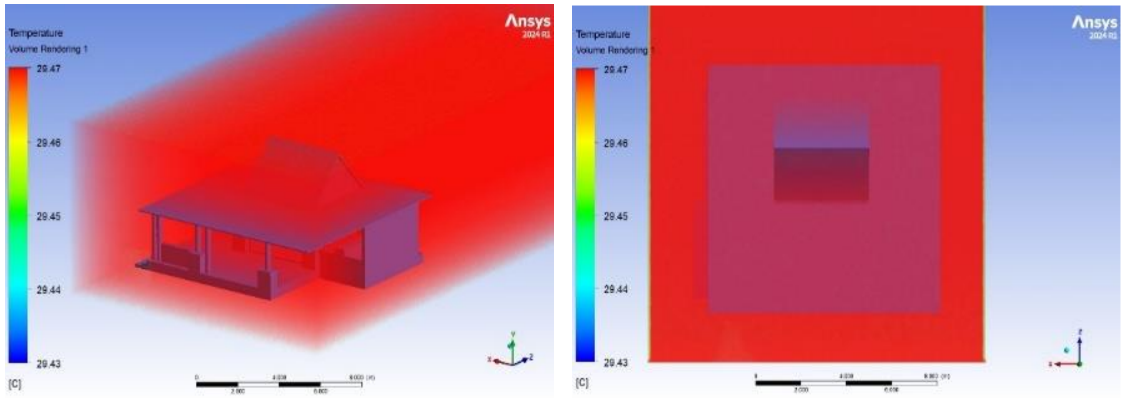


Figure 8. Air Temperature Simulation in the Bar Coffee Area

Table 1 shows that the wind speed at BC (in) reaches 1.10 m/s, slightly higher than BC (out), which records 0.86 m/s. This indicates a difference in airflow intensity as air enters and exits the bar area. The velocity simulation illustrates airflow patterns entering through the openings and subsequently dispersing throughout the interior, with velocity gradients showing stronger airflow near the inlet that gradually decreases toward the inner parts of the building (**Figure 9**). Overall, the integration of the tabulated data and simulation results demonstrates that the airflow consistently moves from the entry zone toward the exit, while the presence of architectural elements creates resistance that reduces wind speed and results in a lower and more uniform airflow distribution within the Bar Coffee interior.

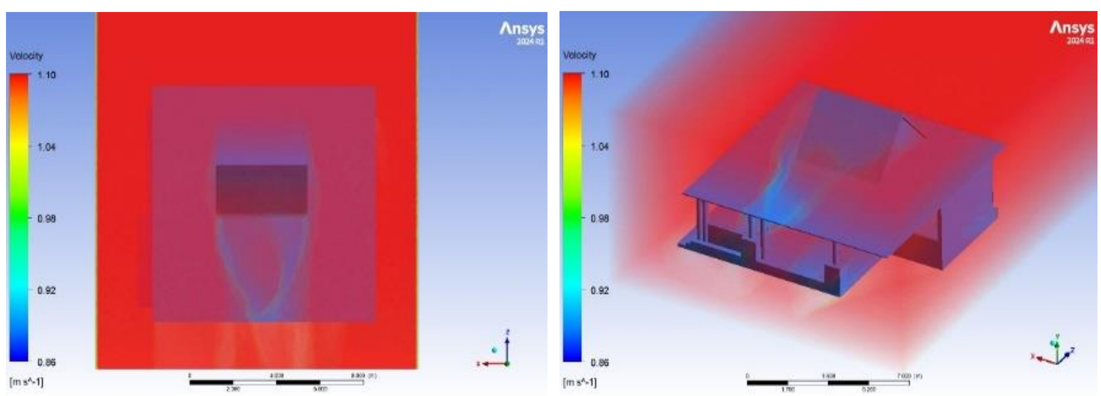


Figure 9. Velocity Simulation in the Bar Coffee Area

The temperature simulation (**Figure 10**) illustrates the distribution pattern resulting from the interaction between the thermal characteristics of building materials, indoor air conditions, and the influence of the external environment. Based on the simulation results, the average temperatures recorded on 6 and 7 September were 29.03 °C for the indoor area and 29.13 °C for the outdoor area. These values fall within the thermal comfort range for tropical climates as defined by the 2023 Ministry of Health standard on indoor thermal comfort. The dominance of light-green tones in the legend indicates zones with temperatures close to these average values, suggesting that most areas remain within a stable and comfortable thermal condition.

The relatively uniform temperature distribution within the interior indicates that the building design is capable of maintaining thermal balance between the outdoor environment and the indoor space. This suggests that the combination of construction materials used and the application of natural ventilation contribute effectively to achieving strong passive thermal performance, thereby reducing the reliance on mechanical cooling systems.

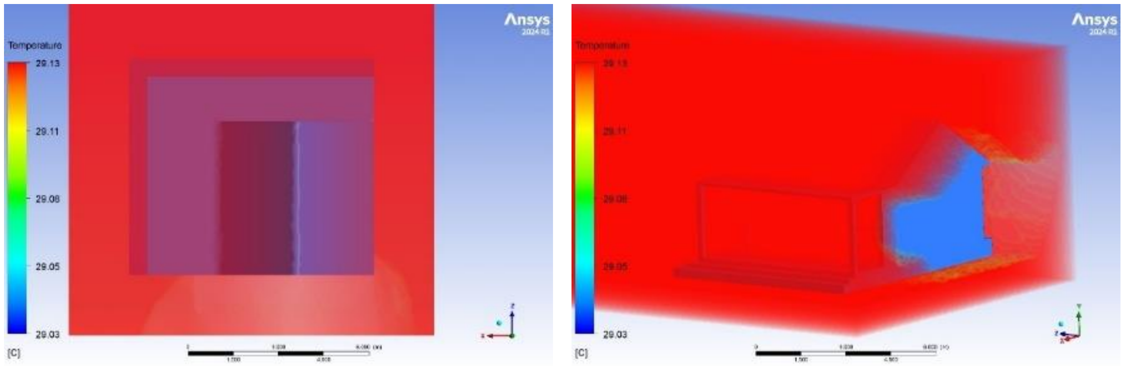


Figure 10. Air Temperature Simulation Bar Ice Cream

The visualization (**Figure 11**) illustrates the wind-speed simulation in the Ice Cream Bar area using ANSYS 2024 R1, showing the airflow distribution within the space based on thermal conditions and natural ventilation mechanisms. The simulation analysis recorded a maximum wind speed of 1.83 m/s and a minimum of 0.06 m/s, with average values of 0.51 m/s for the indoor area and 0.56 m/s for the outdoor area. The highest velocities appear in the central to upper portions of the building, indicating more active air movement driven by pressure differences and the influence of the roof geometry. Conversely, lower velocities are observed in corner zones and near the lower parts of the room, reflecting areas with minimal airflow. This distribution pattern suggests that the opening configuration and spatial layout of the Ice Cream Bar are sufficiently effective in generating cross-ventilation, thereby supporting passive thermal comfort without reliance on mechanical cooling systems.

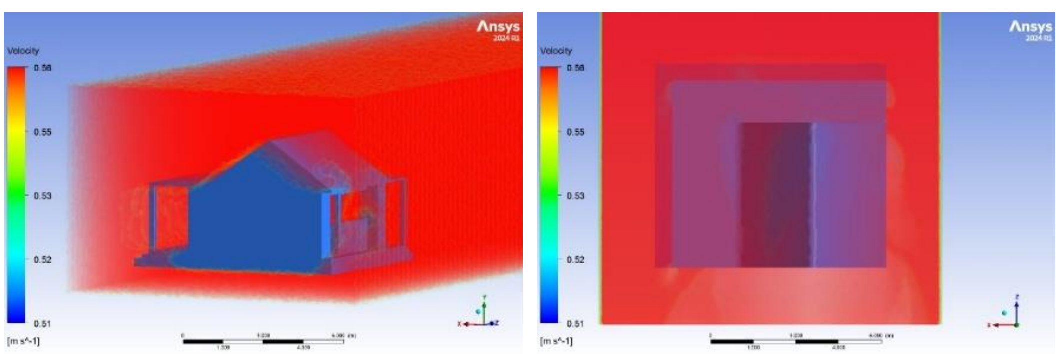


Figure 11. Simulation Velocity pada Bar Ice Cream

The CFD simulation results exhibit strong consistency in representing the thermal conditions of the studied building. The thermal images show a generally uniform distribution of surface temperatures with several warmer spots caused by radiation or indoor activities, aligning with the tables indicating stable average temperature ranges across the buildings. The temperature and wind-speed simulations further confirm these patterns by presenting temperature distributions and airflow dynamics that correspond closely to field conditions. The simulation outputs indicate that indoor temperatures fall within the same range as the thermal measurements, while the airflow patterns reflect how structural elements and opening design influence wind movement within the space.

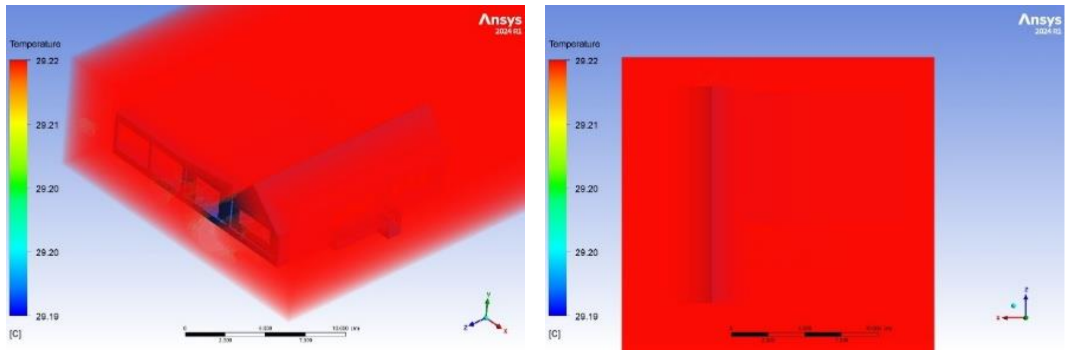


Figure 12. Main Café Air Temperature Simulation

Table 1 shows that the average indoor temperature of the Main Café is 29.22 °C, only slightly higher than the outdoor temperature of 29.19 °C. This minimal difference indicates that the thermal conditions in both areas are nearly equivalent. This finding is consistent with the visualization presented in **Figure 12**, where the CFD simulation displays a temperature distribution ranging from 29–32 °C throughout the building from multiple viewpoints. The color variations indicate zones that are relatively warmer or cooler, likely influenced by solar radiation intensity, shading from building elements, and spatial configuration characteristics. Overall, the integration of tabulated data and simulation results provides a comprehensive understanding of the Main Café's thermal conditions, characterized by a predominantly uniform temperature distribution across both interior and exterior areas.

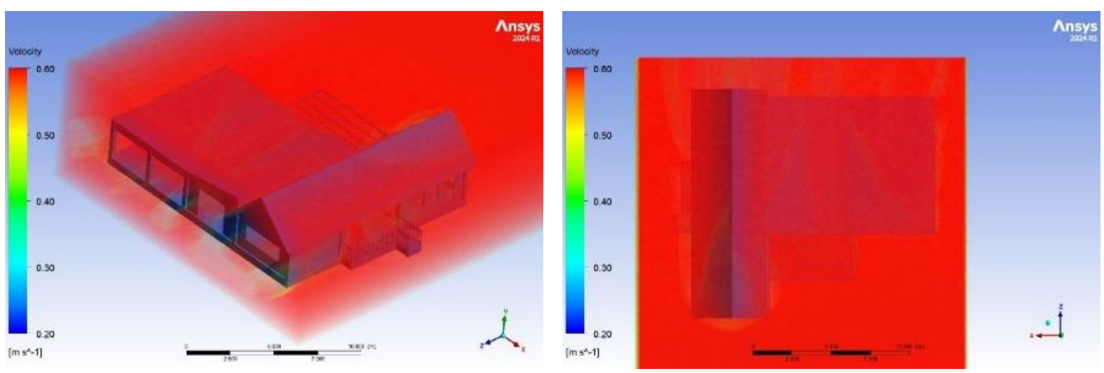


Figure 13. Simulation Velocity Main Café

The wind-speed table for the Main Café shows that the indoor area (MC in) records an average velocity of 0.23 m/s, while the outdoor area (MC out) reaches 0.57 m/s, indicating that air movement outside the building is more unrestricted due to the absence of spatial barriers. This corresponds with **Figure 13**, where the velocity simulation illustrates higher and more dispersed wind speeds in the outdoor zones—represented by stronger color intensities—while the interior exhibits lower velocities due to obstructions created by walls, openings, and spatial arrangements. The observed pattern also indicates that part of the airflow enters the building through the openings but decelerates as it moves further inside, creating zones with minimal air movement. Overall, the integration of the table and simulation results provides a clear understanding of airflow dynamics in the Main Café, with a distinct contrast between indoor and outdoor areas driven primarily by building structure and ventilation design, which limit wind-speed distribution within the interior.

The tabulated data and CFD visualizations demonstrate strong consistency in representing the thermal conditions and airflow patterns in the Main Café. The thermal images show a relatively homogeneous temperature distribution with several slightly warmer spots, consistent with tabulated results indicating that indoor and outdoor temperatures remain within a similar range, approximately 29 °C. The temperature-distribution simulation reinforces these findings, with color gradients representing a 29–32 °C range that aligns with field observations. Meanwhile, the difference in wind-speed values—where outdoor airflow is higher than indoor—is further confirmed by the velocity simulation, which displays stronger airflow outdoors that weakens progressively as it enters the interior.

In addition to air temperature, relative humidity, and wind speed, another important indicator for assessing thermal conditions is the comfort and heat stress index, which is represented by the Wet-Bulb Globe Temperature (WBGT) value (**Figure 14**). According to [15], WBGT is an index recognized by the International Organization for Standardization (ISO) as a tool for assessing the level of heat stress on humans. Heat stress occurs when the accumulation of heat within the body exceeds its ability to dissipate it, which can be influenced by physical activity as well as environmental conditions such as air temperature, humidity, solar radiation, and wind speed. Based on the measurements conducted, the following data were obtained:

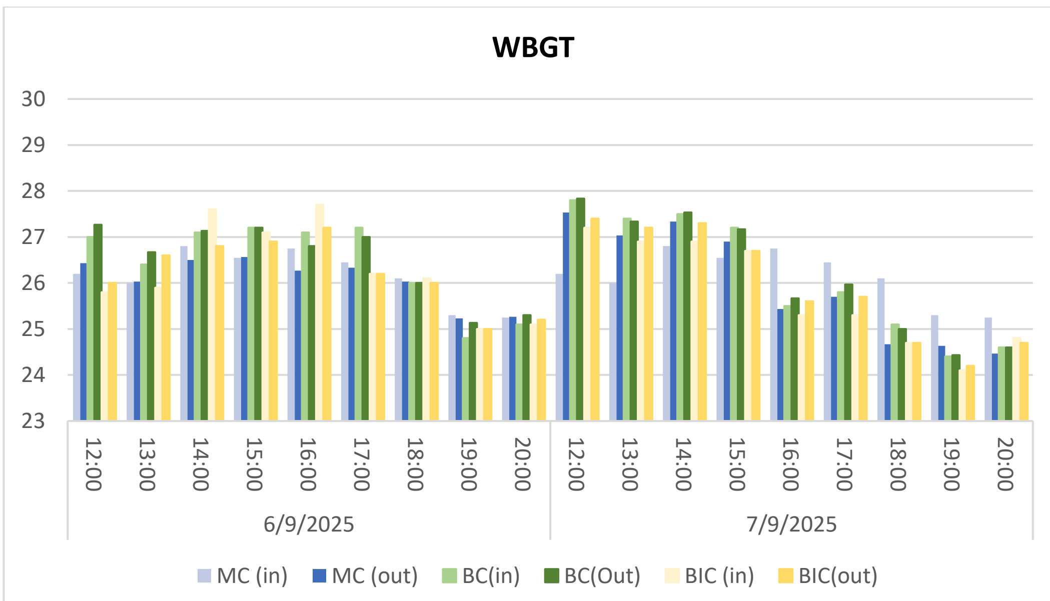


Figure 14. WBGT Measurements at the Maha Corner Café

Based on the WBGT graph, all three buildings (MC, BC, and BIC), in both their indoor and outdoor areas, exhibit WBGT values within the range of 24–28 °C. This range indicates moderate heat conditions that are still considered safe for activities in semi-outdoor spaces. WBGT values increase between 13:00 and 15:00 and begin to decrease toward late afternoon. The peak values occurred between 12:00 and 13:00 on the second day, coinciding with heightened solar radiation in the coastal environment. Given the buildings' location along the shoreline and their function as semi-outdoor spaces, the relatively uniform WBGT pattern across all three buildings suggests that thermal conditions are influenced more strongly by coastal weather factors than by the specific characteristics of each building.

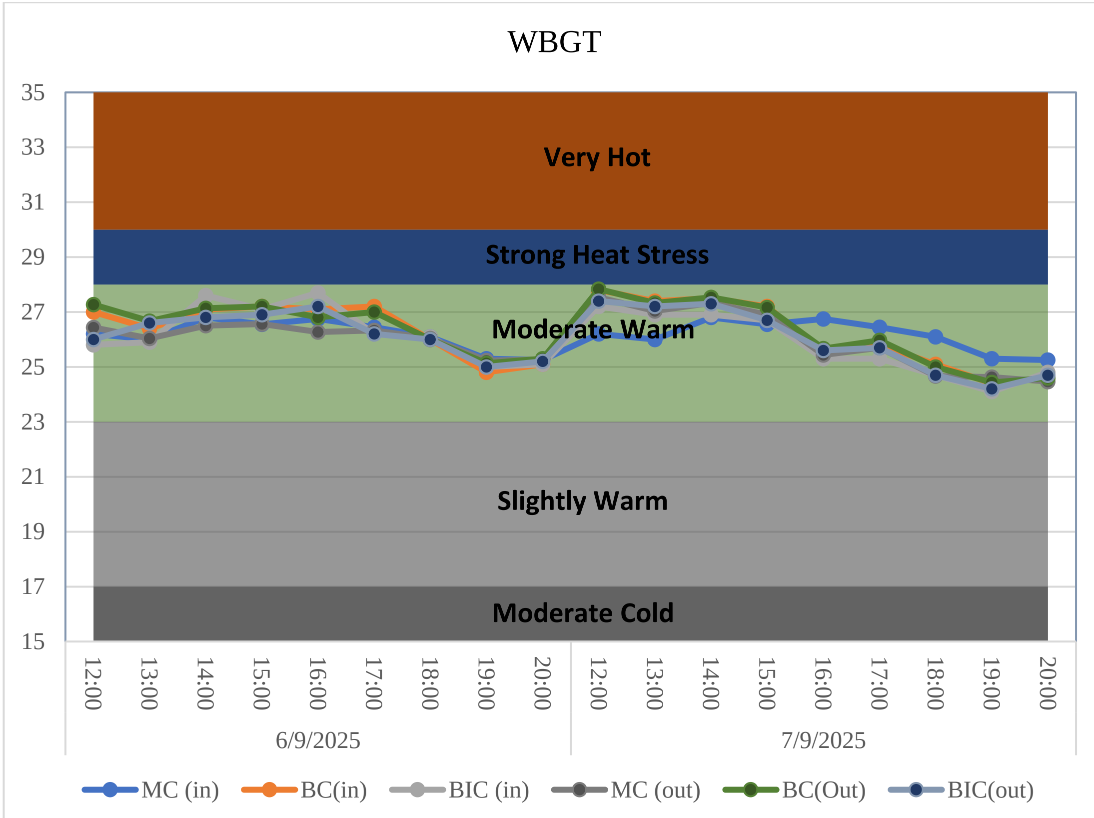


Figure 15. WBGT Comfort Classification [16]

Based on the WBGT measurements and the thermal comfort zone classification proposed by Rachid [16], all observed areas—Main Café, Bar Coffee, and Bar Ice Cream—consistently fall within the Moderate Warm category (23–28 °C), with a proportion of 100% at each location (**Figure 15**). This finding aligns with the WBGT graph, which shows stable values ranging from 25 to 28 °C, with no indication of shifting toward the Strong Heat Stress zone (28–30 °C) or the Very Hot category (>30 °C). Accordingly, all three areas can be considered to be within a safe thermal condition for work and activity, although they remain in a thermal range that requires monitoring to prevent potential exceedance into higher-risk categories.

Mean Radiant Temperature (MRT)

Based on the graph in **Figure 16**, the highest Mean Radiant Temperature (MRT) was recorded at 14:00 WIB at point BC (in) on the second day of measurement, reaching 38.83 °C. In contrast, the lowest MRT value at the same location occurred at 18:00 WIB on the second day, with a value of 23.81 °C. This pattern indicates a decreasing trend in MRT from midday to the late afternoon period. The decline is primarily attributed to the reduction in short-wave solar radiation intensity after the daily radiation peak, resulting in diminished direct solar exposure on building surfaces.

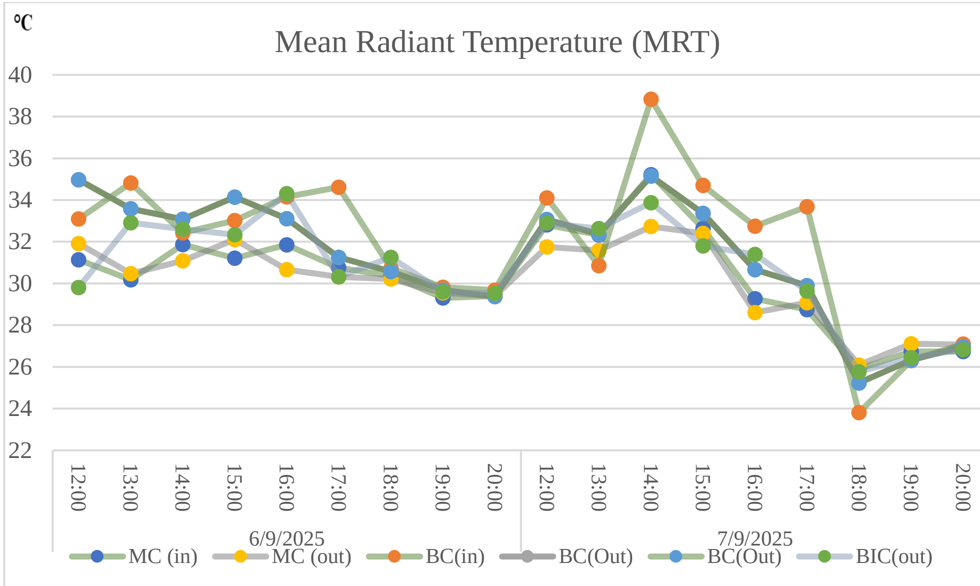


Figure 16. Mean Radiant Temperature (MRT)

Temperature Effective (TE)

Based on **Figure 17**, the average effective temperature (ET) during the measurement period was 25.02 °C. The highest ET was recorded at MC (in) at 14:00 WIB on the second day of measurement, reaching 30.75 °C. Meanwhile, the lowest ET was observed at BC (in) at 16:00 WIB on the second day of measurement, with a value of 20.20 °C.

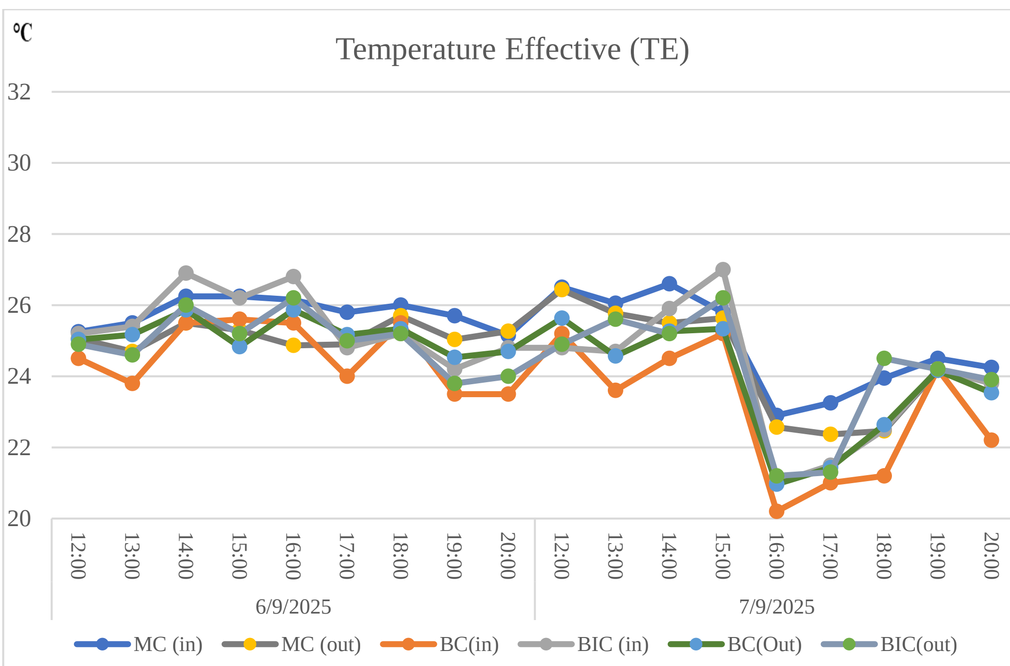


Figure 17. Temperature Effective (TE)

Table 2. TE value according to SNI 036572-2001

TE	Standard	Percentage (%)						Total (%)
		MC (in)	MC (out)	BC (in)	BC (out)	BIC (in)	BIC (out)	
Cool and Comfortable	20.5-22.8 °C	0	2.80	3.7	2.8	2.7	1.9	14.00
Optimal Comfort	**22.8-25.8 °C**	**10.41**	**12.9**	**12.9**	**12.1**	**9.29**	**12.0**	**69.5**
Comfortable Warm	25.8-27.1°C	6.5	0.9	0	1.85	4.6	2.8	16.00
Threshold	>27.1°C	0	0	0	0	0	0	0
			Total					100

Based on the **Table 2**, the effective temperature (ET) values across the three buildings show that the highest percentage, **62.03%,** falls within the **optimal comfort category**.

PMV and PPD

Based on the results of the thermal comfort analysis calculations that have been carried out (**Table 3**), a data recapitulation is produced to conclude the thermal comfort of PMV and PPD using the CBE Thermal Tool.

Tabel 3. Adaptive Thermal Comfort Recapitulation

Parameter	**SNI 03-6572-2001 & ASHRAEE-55**	**Mean**					
		MC(in)	MC(out)	BC(in)	BC(out)	BIC(in)	BIC(out)
Operative Temperature (TE)	-	29.7	29.6	30.6	30.3	29.8	29.9
Relative Humidity (%)	55-60 %	68.8	68.7	68.3	68.5	68.8	68.9
Air Velocity (m/s)	0.15 – 0.25	0.3	0.5	1.1	0.86	0.51	0.55
Clothing Insulation (Clo)	-	0.61	0.61	0.61	0.61	0.61	0.61
Metabolism (MET)	-	1.0	1.0	1.0	1.0	1.0	1.0
PMV Value	-0,5 – +0,5	1.18	0.86	0.85	0.85	0.92	0.92
PPD (%)	0% - 10%	34%	20%	20%	20%	23%	23%
Sensation	-	Slightly Warm	Slightly Warm	Slightly Warm	Slightly Warm	Slightly Warm	Slightly Warm

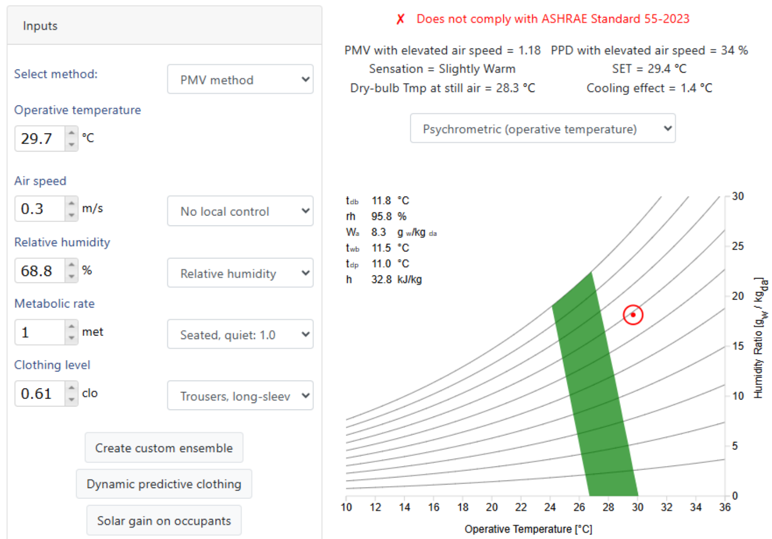


Figure 18. CBE Thermal Comfort

The Operative Temperature value is taken from the combined average of air temperature and MRT, while the Air Humidity and Wind Speed values are taken from the average of direct measurements. Meanwhile, the Clothing Insulation value is taken from the majority of respondents using "Perfectly Covered Head, Top, and Bottom," following **Table 3**, resulting in a Clo value of 0.67 Clo. Meanwhile, the MET value, as seen in **Figure 18**, shows that the majority of respondents engaged in the "Sitting Quiet" activity, resulting in a MET value of 1.0 MET. Based on the results of the thermal comfort parameter calculations (**Table 3**) in the Maha Corner (MC) and Banda Corner (BC) areas, both indoors and outdoors, the operative temperature was found to be in the range of 29.6–30.6°C with air humidity of around 68%. Wind speed varied between 0.3–1.1 m/s, while the Clo and metabolic values were relatively consistent at 0.61 and 1.0 MET, respectively. The evaluation results show that the PMV value is in the range of 0.85–1.18, which indicates slightly warm thermal conditions, with PPD between 20–34%, thus exceeding the ASHRAE 55 comfort limit which requires PMV –0.5 to +0.5 and a maximum PPD of 10%. Thus, it can be concluded that all measurement points are still in the **Slightly Warm category.**

Discussion

The combination of field measurements and CFD simulations provides a comprehensive understanding of the thermal behavior of semi-outdoor buildings in a coastal tropical environment. Across all three building zones—Bar Coffee, Bar Ice Cream, and Main Café—the measured air temperatures remained relatively stable around 29–30 °C, indicating that the semi-open configuration facilitates continuous heat exchange with the outdoor environment. This aligns with Psomas et al. [17], who emphasize that semi-outdoor thermal conditions are predominantly shaped by external microclimates rather than indoor interventions. In the context of the study site, coastal humidity, solar exposure, and sea breezes emerge as the primary drivers of thermal variability. Airflow patterns from the CFD simulations further reinforce these observations. Buildings positioned nearer the shoreline experienced stronger wind speeds, reflecting direct exposure to prevailing sea breezes. Meanwhile, areas with vegetation buffering or partial enclosure exhibited lower and more stable airflow intensities. These patterns are consistent with Wahab & Ismail [18], who highlight that spatial orientation and opening configuration exert significant influence on airflow distribution in tropical buildings.

The role of timber in this study appears as a contributing factor in moderating surface-temperature fluctuations. Rather than significantly reducing peak temperatures, the thermal capacity of wood allows it to absorb and release heat gradually, thereby dampening rapid temperature changes. This behavior is in line with Pervan [19], which describes wood as having higher thermal inertia compared to non-organic materials. However, the findings make clear that such moderation operates within the broader interactions of shading, ventilation, solar exposure, and coastal climate influence. Thus, timber should be understood as part of a composite passive design strategy rather than a determinant of thermal comfort on its own. Overall, the good agreement between measured data and CFD outputs strengthens the reliability of the study's interpretation. The consistency of results across both methods confirms that achieving thermal comfort in semi-outdoor coastal buildings is primarily dependent on effective natural ventilation, appropriate spatial zoning, and microclimate-responsive design rather than solely on material selection. This reinforces the relevance of integrated passive design approaches for coastal tropical architecture.

Conclusion

This study concludes that semi-outdoor buildings in a coastal tropical environment can maintain relatively stable thermal conditions, with average temperatures near 29–30 °C despite exposure to fluctuating coastal weather. While humidity levels consistently exceed comfort thresholds due to inherent microclimatic characteristics, natural ventilation remains effective in supporting thermal regulation across the three building zones analyzed. The CFD simulations show strong alignment with field measurements, confirming that airflow and temperature distribution are shaped mainly by spatial configuration, openness, vegetation shading, and coastal wind conditions. Timber elements contribute to moderating surface-temperature fluctuations but function as part of an integrated passive design system rather than as a singular controlling factor. These findings underscore the importance of climate-responsive design strategies—particularly ventilation planning, shading, and spatial orientation—in enhancing the thermal performance of semi-outdoor buildings in coastal tropical settings. Future research could explore variations in timber species, broader seasonal measurements, and user perception to provide a more holistic understanding of thermal comfort in similar environments.

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Conflict of Interest

The authors declare that there are no conflicts of interest.

Author Contribution Statement

Ade Riskia: Conceptualization, Investigation, Writing – original draft. **Muslimsyah**: Methodology, Supervision. **Laina Hilma Sari**: Software, Validation. **Siti Norbaya Mohd Konar**: Writing – review & editing.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics Approval

Not required.

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