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PREVENTING NOCTURNAL HEAT TRAPPING IN SEMI-OUTDOOR RETAIL CORRIDORS: RETROFIT HEURISTICS FROM HUMID-TROPICAL FIELD MEASUREMENTS

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ABSTRACT

In humid tropical cities, semi-outdoor retail corridors and promenades support daily activities by providing shade and walking spaces. However, high humidity and limited nocturnal cooling reduce effectiveness after sunset. Thus, 24-hour thermal performance becomes a practical design concern.
Objectives: To explain why semi-outdoor retail corridors in humid-tropical areas remain warmer than adjacent open areas at night. Specifically: (i) quantify the occurrence and magnitude of nocturnal inversion using ΔUTCI/ΔTmrt (node-outdoor); (ii) interpret patterns using a radiation-ventilation-storage (RVS) framework; and (iii) translate diagnosis into five retrofit heuristics (H1–H5) for design and operation.
Methodology and results: A multi-day field campaign in an Indonesian outlet recorded Ta, RH, and wind speed at outdoor and semi-outdoor nodes every 10 minutes. We derived UTCI and Tmrt, applied quality control, and aggregated the data to hourly medians. At matched timestamps, we computed ΔUTCI and ΔTmrt. During daytime, shaded corridors show clear relief (ΔUTCI < 0, ΔTmrt $\ll 0$). At night, deeper under-canopies tend to have smaller Δ and often have a positive Δ, indicating slower post-sunset cooling. More open edges return to outdoor conditions earlier.
Conclusion, significance and impact: Five retrofit heuristics are proposed: (H1) Raise local sky exposure; (H2) Split radiative roles; (H3) Enable night-purge paths; (H4) Reduce exposed thermal storage facing pedestrians; and (H5) Deploy vegetation, water, and fans for humid air. The findings emphasize the need for day–night design duality—shade by day and release by night—to

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mitigate nocturnal heat trapping and support safer, comfortable microclimates in humid tropical retail settings.

1. INTRODUCTION

In many tropical cities, daily life is increasingly organized around semi-outdoor and outdoor spaces, such as shaded sidewalks, podium decks, modern markets, food streets, and open-air retail promenades. These spaces are expected to provide relief from the heat during the day, while remaining comfortable in the evening when people go out to walk, shop, or meet with family after work. However, climate change and rapid urbanization are causing higher ambient temperatures, more frequent heatwaves, and stronger urban heat island effects, especially in large, dense urban areas across Southeast Asia. Recent reviews of outdoor thermal comfort emphasize that the microclimate of these spaces is not only governed by air temperature and humidity but also by radiant exchange, wind, and behavioral adaptation. These factors interact differently across climate zones and urban morphologies[1]. In humid tropical cities like Jakarta, where background humidity is high and nighttime cooling is limited, understanding the thermal behavior of semi-outdoor spaces over the full 24-hour cycle is critical for design rather than purely academic concern [1], [2]. A comprehensive review further stresses that outdoor comfort is multidimensional (physical, psychological, and behavioral), and is shaped by the combined roles of radiation, wind speed, humidity, and behavioral adaptation [3]. Recent field evidence also highlights mean radiant temperature and wind flow as dominant levers for mitigating heat-stress in real outdoor settings. This reinforces the importance of radiative exchange and ventilation as design variables rather than "secondary" effects [4].

A substantial body of work has demonstrated the significant impact of urban form on local microclimate and pedestrian thermal comfort. This impact is mediated by various parameters, including canyon geometry, aspect ratio, orientation, surface materials, vegetation, and water features [5]. Sky view factor (SVF) has emerged as a particularly important descriptor because it links three key processes: exposure to shortwave solar radiation, longwave exchange with the sky, and the potential for heat to dissipate vertically out of the urban canopy layer [6], [7], [8]. Studies in different climates report that lower SVF (i.e., more enclosed spaces) can improve daytime thermal comfort in the summer by reducing direct solar gains. However, it may also increase heat accumulation and reduce cooling potential in other seasons or at other times of the day [4], [5], [15]. Recent studies using remote sensing and field measurements show that SVF influences not only daytime conditions but also nighttime cooling rates and urban land surface temperature. This highlights the dual role of enclosure in both shading and heat release [9].

Within this broader literature, semi-outdoor spaces, such as colonnades, elevated podiums, overhead public spaces, and void decks, have been identified as effective solutions for mitigating outdoor thermal conditions in hot and humid climates. In dense, high-rise districts, these spaces at the podium or ground levels can provide shaded, ventilated environments that serve as transition zones between indoor and outdoor spaces [10]. Studies from Hong Kong, Singapore, and Shenzhen demonstrate that, when their geometry, orientation, and envelope treatment are carefully designed, semi-outdoor spaces can offer improved thermal comfort relative to fully exposed areas [10], [11], [12]. For example, elevated building forms and overhead public spaces can increase wind penetration and decrease radiant load; however, their effectiveness depends on SVF, corridor depth, soffit materials, and the presence of vegetation or water features [10], [11], [12]. However, semi-outdoor spaces are not automatically “comfortable.” Poor orientation, very low SVF, high emissivity thermal mass, and blocked wind paths can transform them into heat traps under prolonged heat loading.

In Indonesia, research on outdoor and semi-outdoor thermal comfort has expanded in recent years. This research has focused on city parks, green open spaces, streets, and different types of land covers. Reviews on walkability and microclimate in the tropics emphasize the importance of solar shading, greenery, and wind for achieving comfortable walking conditions, particularly in large metropolitan areas such as Jabodetabek [2], [13]. Field studies in North Sumatra at various altitudes and land covers have quantified how temperature-humidity-based indices respond to topography and land use. These studies illustrate that many locations experience heat stress for a large part of the day [14]. In coastal Jakarta, research on tourist areas has shown that outdoor thermal comfort conditions often fall within the “moderate” to “very strong” heat stress range during the day [15]. Concurrently, biometeorological studies on the Universal Thermal Climate Index (UTCI) emphasize that such indices must be interpreted carefully in hot, humid climates [16], [17]. Recent studies have begun recalibrating UTCI ranges for hot and humid Asian cities using year-round field surveys. These studies have shown that local clothing, activity patterns, and expectations may differ from those of temperate reference populations [17].

Despite the prevalence of semi-outdoor spaces in Indonesian retail architecture, such as open-air outlet malls, canopy-covered promenades, and mixed indoor-outdoor dining streets, there is still relatively little empirical evidence on how these spaces behave thermally at night. Retail complexes in and around Jakarta and its satellite cities often stay open until late evening, and many visitors come after sunset to avoid the harsh daytime sun. From a physical standpoint, however, the hours after sunset are not neutral: stored heat in building envelopes, pavements, and roofs is gradually released; long-wave exchange with the sky becomes the dominant radiative process; and wind speeds and directions can change relative to daytime conditions. International literature shows that SVF and urban geometry influence not only daytime solar access, but also nighttime cooling rates and urban heat island intensity [6], [9]. Yet, few studies examine whether semi-outdoor corridors designed for shading during the day might unintentionally trap heat and reduce comfort at night, especially in humid tropical retail settings.

This brief review reveals several gaps. First, most tropical and Indonesian studies focus on outdoor thermal comfort in open spaces, such as parks, streets, and squares. These studies pay less attention to semi-outdoor retail corridors, which combine overhead cover, lateral enclosures, and complex material palettes. Second, measurement campaigns and simulations usually focus on daytime peaks or daily averages. However, the nighttime period, when many people use semi-outdoor retail spaces, is addressed only indirectly or with a coarse temporal resolution [1], [2], [14], [15]. Third, although the literature recognizes the dual role of SVF and urban form in both shading and cooling, there is limited guidance on how to apply these insights to retrofit existing semi-outdoor corridors in humid tropical cities. Practitioners are often left with general advice, such as “add shading” or “increase greenery,” which may be insufficient when a corridor is heavily shaded and surrounded by massive, high-emissivity surfaces that store and re-radiate heat at night.

This study addresses these gaps by examining the thermal performance of semi-outdoor retail corridors at night in a large outlet complex in humid tropical Indonesia. A multi-day field campaign was conducted to measure microclimatic variables and derive the Universal Thermal Comfort Index (UTCI) and the mean radiant temperature (Tmrt) at multiple under-canopy and reference nodes linked to an on-site ambient weather station. The analysis focuses on the nighttime period and uses a radiation-ventilation-storage framework to interpret the observed “nocturnal inversions,” in which under-canopy nodes are warmer than adjacent open nodes. Building on these mechanisms, the paper proposes retrofitting heuristics to adjust the sky view factor, the radiative roles of roofs and soffits, purge vent paths, exposed thermal storage, and the calibrated use of water or mist at night. The goal is to provide designers and operators with

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a pragmatic playbook, rooted in field data from an Indonesian case study that can be applied to other humid-tropical cities. This playbook helps shift the focus from a “shade by day” to a 24-hour perspective, which involves shading during the day while enabling effective heat release at night.

2. RESEARCH METHODOLOGY

2.1 Site and Microclimate

The field study was conducted at The Grand Outlet in East Jakarta-Karawang. This large open-air outlet mall is located in the peri-urban corridor between Jakarta and Karawang, West Java, Indonesia. The site experiences a humid tropical monsoon climate with high humidity year-round, small diurnal air-temperature ranges, and weak to moderate winds, which are typical of the low-lying Java lowlands. The complex consists of semi-outdoor promenades, under-canopy corridors, an internal “green hub” with vegetation and water features, and exposed plazas and rooftops. These features create a variety of microclimatic conditions within the development. The measurement campaign targeted the transition from the dry to wet season, when daytime heat loads and nighttime humidity are both high, and retail activity extends into the evening. This period is typical of shopping and leisure trips in JABODETABEK, where visitors often prefer walking around after sunset rather than in the midday sun.

2.2 Monitoring Design and Measurement Points

We designed the monitoring to capture both ambient forcing and semi-outdoor microclimates relevant to the pedestrian experience and retrofit decisions in a retail context.

1) *Outdoor Reference.* Two Ambient Weather WS-2000 automatic weather stations (AWS) were installed on utility rooftops (Rooftop 1 and Rooftop 2) at approximately 9 meters above ground in unobstructed locations to monitor air temperature (Ta), relative humidity (RH), wind speed and direction, solar radiation, UV index, and daily rainfall.
2) *Semi-Outdoor Key points.* Five semi-outdoor/edge nodes were instrumented to represent typical user spaces and corridor morphologies:
    a. Green Hub (GH): A central semi-outdoor node with vegetation, a water feature, and larg fans.
    b. Under Canopy 1F (UC-1F): A shaded ground-floor corridor under a deep canopy that is partially enclosed by outlets and vegetation.

c. Under Canopy 2F (UC-2F): A second-floor corridor near a large void without vegetation that is more exposed to the sky and edge conditions.
d. Promenade (PR): A semi-open pedestrian zone with partial umbrellas and a visual connection to the central plaza.
e. Front Command Center (FCC): A semi-exposed entrance/transition node with limited shading and direct exposure to the vehicular forecourt.

These nodes were selected to span a gradient from well-shaded and vegetated (Green Hub) to exposed and minimally controlled (FCC), and to capture the vertical difference between the ground-floor and the second-floor under the canopy.

The selected monitoring locations were distributed across multiple microclimate conditions in both the outdoor rooftop zone and the under-canopy, semi-outdoor zones. See Figure 1 for the spatial distribution of these measurement points within the retail complex.

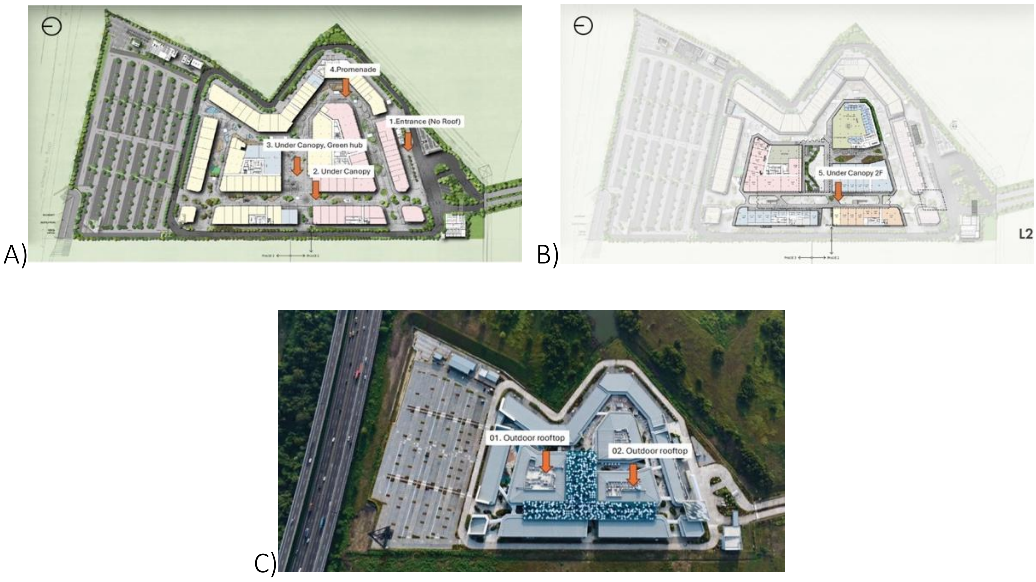

Fig. 1 Spatial distribution of rooftop and under-canopy measurement points inside the retail complex. **A)** First floor. **B)** Second floor. **C)** Rooftops for AWS

2.3 Instrumentation and Measured Parameters

At each semi-outdoor node, instruments were mounted on a single tripod at a height of approximately 1.1-1.5 m, which represents the height of a standing adult's head. The setup included:

1) Lutron AM-4234SD hot-wire anemometer: wind speed (m/s), air temperature (°C), relative

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humidity (%), and dew point (°C).

2) Lutron WBGT-2010SD meter: Wet Bulb Globe Temperature (WBGT, °C), black globe temperature (Tg, °C), air temperature (°C), relative humidity (%) and dew point (°C).
3) The T&D TR-74Ui data logger: measured air temperature (°C), relative humidity (%), and illuminance (lux).

The combined tripod configuration reduced deployment complexity and ensured that all microclimate parameters were sampled at nearly the same location and height. Aluminum foil was selectively placed around sensitive sensors to reduce direct solar load and prevent spurious heating, in accordance with standard procedures for outdoor thermal comfort studies [18].

The measurement period ran from November 26 to December 5, 2024. The TR-74Ui loggers were programmed to record at fixed intervals (e.g., 1-5 minutes), while the AWS units recorded at their factory-default interval. Data were downloaded daily from semi-outdoor instruments and periodically from the AWS, and a data log was maintained to document operational issues, such as power interruptions, instrument freezing, and relocation events.

2.4 Thermal indices and derived variables

Mean radiant temperature (Tmrt). Mean radiant temperature (Tmrt) is a key driver of outdoor thermal comfort because it integrates the combined effect of long-and short-wave radiation from the sky, ground, and surrounding surfaces [19], [20] In this study, Tmrt at the outdoor AWS point was estimated using the RayMan model. This model calculates short- and long-wave radiation fluxes on the human body based on Ta, RH, wind speed, global radiation, cloud cover, and geometrical configuration [21], [22] For semi-outdoor nodes, Tmrt was derived indirectly in two ways:

1) For nodes with full microclimatic input available (Ta, RH, wind speed, a global radiation proxy, and a simplified geometry), RayMan model was used in a “node-based” configuration to estimate Tmrt under typical sky obstruction patterns.
2) For locations where RayMan input was incomplete, globe temperatures (Tg) from the WBGT sensor were used together with air temperature and wind speed to estimate Tmrt using standard globe-temperature relationships, as in similar outdoor comfort studies.

These modeling choices are consistent with previous applications of RayMan in complex urban environments and with the recognition that Tmrt is often the most influential microclimate parameter for pedestrians[23], [24]

Universal Thermal Climate Index (UTCI). The Universal Thermal Climate Index (UTCI) was used as the main indicator of outdoor thermal stress because it integrates Ta, RH, wind and Tmrt through a sophisticated thermophysiological model. It can also be applied across climates and temporal scales. In this study, the UTCI was computed using the BioKlima software. The hourly Ta, RH, wind speed, and Tmrt (derived from RayMan) were supplied for each valid timestamp [16]. For each valid hour:

1) Tmrt (from RayMan or the Tg-based approximation) and AWS- or node-specific Ta, RH and wind speed were supplied to the BioKlima software to compute the UTCI.
2) Outdoor UTCI was computed from AWS1 (or the mean of AWS1 and AWS2) and served as the ambient reference.
3) Semi-outdoor UTCI was computed for Green Hub, Promenade, Under Canopy 1F, Under Canopy 2F (where sufficient wind data were available), and FCC. Due to the limitations in the dataset, UTCI could not be reliably computed for UC-2F for all hours because of missing air-velocity data. Therefore, this node was excluded from some UTCI-based analyses.

Nighttime subset and node comparison approach. Since the primary focus of this study is on nocturnal heat trapping under canopies, a nighttime subset was first defined from 6:00 p.m. to 6:00 a.m. local time. Hours with rainfall or missing data at either the weather station or any semi-outdoor node were excluded. For each remaining hour, we computed the difference:

$$\Delta UTCI_{node} = UTCI_{node} - UTCI_{outdoor.}\text{, and } \Delta T_{mrt,node} = T_{mrt,node} - T_{mrt,outdoor}$$

This ensures that each semi-outdoor node is directly compared with the ambient reference at the same moment. In the humid tropical context, over the roughly nine effective days of measurement, this difference-based approach sufficiently reduces the influence of day-to-day variations in background weather. This allows positive values to be interpreted as additional thermal stress generated by the corridor itself rather than by regional-scale conditions.

We then characterized nighttime performance at each node by the distribution of ΔUTCI and ΔTmrt (medians, interquartile ranges, and selected quantiles), and assessed differences between nodes using boxplots and simple statistical tests (one-way ANOVA or nonparametric equivalents, where appropriate). As a robustness check, nighttime hours were also inspected in broad categories of time of night (evening, midnight, and pre-dawn) and outdoor air temperature. However, no fine stratification by narrow temperature, relative humidity, and wind bins was imposed to retain sufficient sample size. This follows the pragmatic practice adopted in other outdoor and semi-outdoor comfort campaigns in warm-humid cities, where temporal coverage is limited but intra-site contrasts are of primary interest [2], [25], [26].

Qualitative documentation of node characteristics. In addition to the microclimate measurements described above, we documented the main architectural characteristics of each node to support the interpretation of the results later. For each semi-outdoor location (Green Hub, Under Canopy 1F, Under Canopy 2F, Promenade, and Front Command Center), we recorded the degree of overhead cover, apparent openness to the sky, visible wall and soffit construction, and the presence of vegetation, water features, and mechanical fans. We used site photographs, field notes, and architectural information provided by the operator to make these recordings. While these qualitative observations were not used as formal variables in the statistical analysis, they were drawn upon in the discussion to relate the observed nocturnal ΔUTCI and ΔTmrt patterns to known mechanisms involving sky view, ventilation, and thermal storage. They were also used to formulate the retrofit heuristics H1-H5 in combination with existing microclimate literature [2], [10], [11]

2.5 **Statistical Analysis**

All statistical analysis were performed using JMP 18.0 with an academic license. The descriptive analysis aimed to support the interpretation of the measured ΔUTCI and ΔTmrt patterns rather than to build a predictive model. The workflow included:

1) Descriptive statistics: Data preparation of 10-minute records resampled to hourly means, with predefined day (6:00 a.m. to 6:00 p.m.) and night (6:00 p.m. to 6:00 a.m.) windows; Δ-metrics computed only at synchronous timestamps.
2) Summaries: Medians and interquartile ranges (IQRs) were reported for temperature (Ta), relative humidity (RH), wind speed, wet bulb globe temperature (WBGT), temperature mean radiant temperature (Tmrt), and urban heat index (UTCI), and their Δ-metrics. Means were included only for comparability.
3) Visuals: Boxplots and hourly composites to show diurnal structure.
4) Associations: Spearman rank correlations (ρ) between outdoor and node variables. Simple least-squares trend lines are shown for guidance only (no inferential regression).
5) Contrasts & checks: Between-node differences are summarized as median differences with 95% percentile bootstrap confidence intervals (Cis). Key summaries are repeated after excluding dates with instrument issues or atypical weather.

The statistical analysis is used descriptively to support the interpretation of the measured patterns of ΔUTCI and ΔTmrt, as well as to highlight robust contrasts between nodes. It is not used to build a full predictive microclimate model. This approach is consistent with other design-oriented outdoor comfort studies in warm-humid cities that prioritize clear empirical evidence and simple metrics that can be easily understood by practitioners

3. RESULT AND DISCUSSION

This section presents and interprets the results of the field campaign, focusing particularly on the nighttime performance of the semi-outdoor corridors. First, we provide an overview of the measured microclimate and derived UTCI and Tmrt values during the monitoring period at the outdoor reference and semi-outdoor nodes. Next, we examine the behavior of ΔUTCI and ΔTmrt over the diurnal cycle. We highlight the emergence of nocturnal inversions, which occur when under-canopy nodes remain warmer than adjacent open areas after sunset. We interpret these patterns using a radiation-ventilation-storage lens and discuss them in the context of existing microclimate literature for warm-humid cities. Lastly, we link the observed node contrasts and nighttime behavior to a set of five qualitative retrofit heuristics (H1-H5) for semi-outdoor retail corridors, emphasizing their practical implications for design and operation in humid tropical Indonesia.

3.1 Overview of Measured Microclimate and Comfort Indices

Air temperature context. The distributions of 10-minute intervals by node and day demonstrate modest inter-node differences in relation to synoptic day-to-day variability (see Figures 2 and 3). Medians cluster around 26-28 °C across locations. The outdoor series follows a smooth diurnal envelope of 24 to 31 to 26 °C across the campaign.

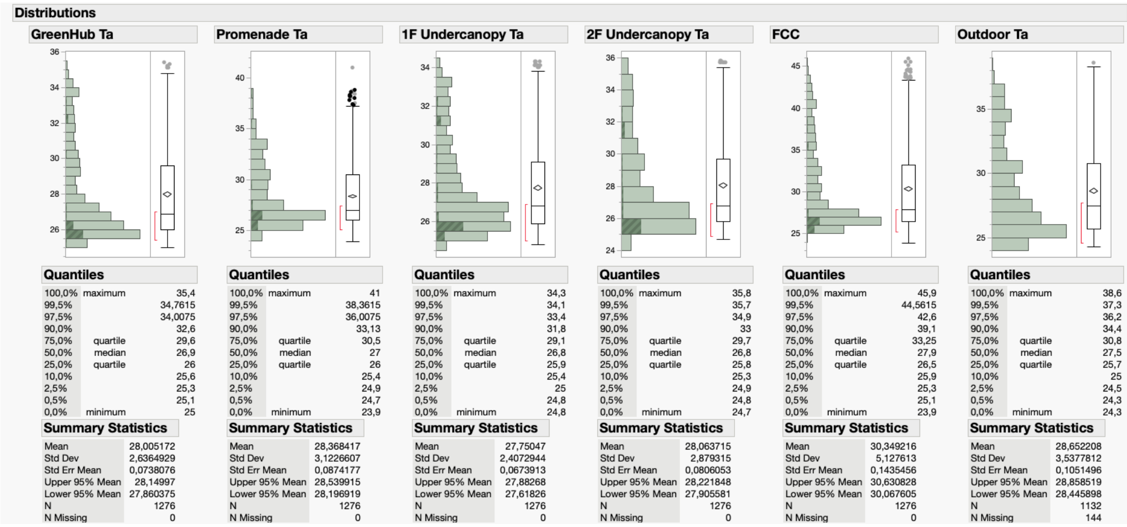

Fig.2 Air temperature context in research

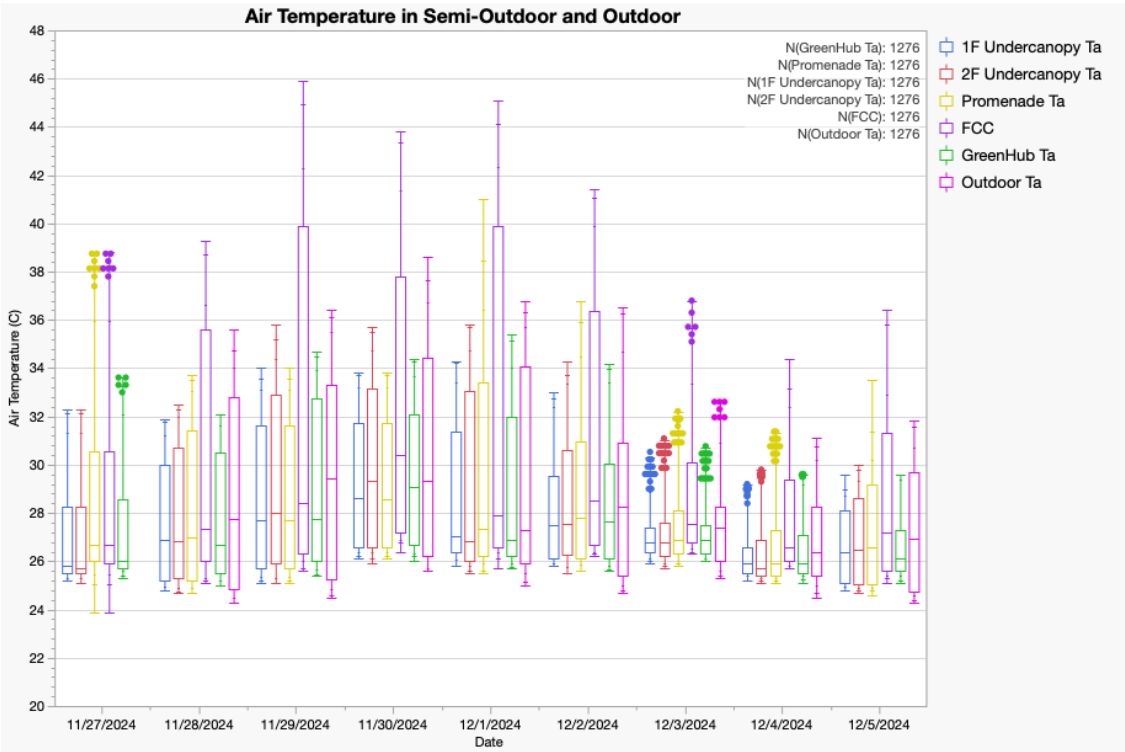

Fig.3 Air Temperature context in research

A small number of daytime outliers appear at FCC and, to a lesser extent, Promenade. Spikes above 40-45 °C are consistent with solar loading of the semi-outdoor Ta sensors. The primary figures use quality-controlled (QC) clean data. The corresponding raw plots in the supplement show that including these outliers modestly reduces the estimated daytime shading benefit but does not affect the nighttime inversion patterns. We include the raw outliers in the supplement to document typical instrument siting and shielding issues of semi-outdoor corridors. Future campaigns will incorporate aspirated shields and local wind at globe height to mitigate solar loading and improve Tmrt estimates.

Microclimate. Minute-resolution measurements from the semi-outdoor nodes and the rooftop weather station were first aggregated into hourly means. These means were then used as input for RayMan and BioKlima to derive Tmrt and UTCI. This temporal aggregation is consistent with the typical applications of RayMan/UTCI and other outdoor thermal comfort studies in warm-humid climates, which usually operate on hourly data [11], [23], [27]. Over the approximately nine effective days of monitoring, the hourly mean air temperature at the semi-outdoor nodes remained within a relatively narrow range characteristic of humid-tropical lowlands, typically between 25 and 29 °C (Figure 4). Relative humidity (Figure 4.B) stayed high throughout the campaign, often above 75-80 %, while wind speeds mostly stayed in the calm-to-light range, like previous urban and coastal observations in Indonesia[2], [14], [15].

Figure 4. A below shows the campaign mean diurnal cycle of air temperature for the five semi-outdoor nodes. All locations follow a similar 24-hour rhythm imposed by ambient forcing. Temperatures are warm shortly after midnight, increase slightly toward late morning and early afternoon, and then decrease slowly overnight. Within this common pattern, however, systematic offsets appear between nodes. The first and second floors under-canopy corridors are consistently the warmest, with hourly mean air temperatures typically around 27.5-28.5 °C. The Promenade and Green Hub tend to be cooler, mostly in the mid-25 to mid-26 °C range. The Front Command Center (FCC) occupies an intermediate position. Apart from a few anomalously low Green Hub values around midday—likely related to local sensor interference or strong fan and water effects—the curves for all nodes remain tightly clustered. This confirms that day-to-day variability in the background weather during the campaign was modest. These first-order patterns already suggest that the semi-outdoor corridors do not behave as a single, uniform microclimate despite being part of one retail complex. The two under-canopy nodes form a warmer group, while the Promenade and Green Hub are relatively cooler.

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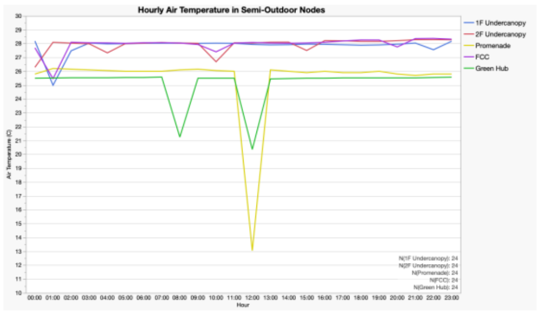
A)


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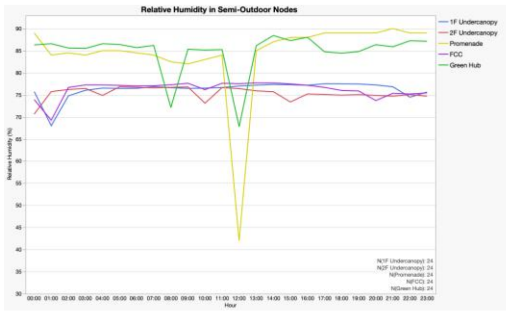

Fig.4 Line distribution of rooftop (Outdoor) and under-canopy (Semi-Outdoor) measurement nodes inside the retail complex. A) Hourly Air Temperature, B) Hourly Relative Humidity

Table 1. Qualitative attributes for each semi-outdoor node used to interpret measured microclimate contrasts

Node	Type	Shading/cover	Vegetation/water/fans	Expected behaviour
UC-1F	semi-outdoor, 1F	deep canopy, enclosed	yes/no/yes	potential heat storage
UC-2F	balcony/edge, 2F	canopy, edge	no/no/no	more exposed
PR	promenade	partial umbrellas	yes/no/no	mid condition
FCC	entrance/edge	partial umbrellas	yes/no/no	hottest
GH	semi-outdoor, central	high shade, open to void	yes/yes/yes	"designed cool spot"

The table above provides a framework for understanding the physical context of each instrumented node. It helps readers understand the type of space represented by each node, including how much sky it likely "sees," how air can purge at night, how much heat is likely to be re-radiated from the surface, and whether vegetation, water, or fans are present. The table does not introduce new variables or analysis. It simply sets expectations and provides a qualitative lens through which to interpret the upcoming Tmrt and UTCI comparisons across nodes. We will refer back to these attributes to explain why some corridors cool more slowly after sunset and how the later heuristics (H1-H5) target the same levers.

In the next subsections, we transition from air temperature to the indices Tmrt and UTCI, which are comfort-relevant and from raw values to ΔUTCI and ΔTmrt relative to the outdoor reference. This allows us to more clearly examine how these corridors modify thermal stress throughout the day and, particularly after sunset.

3.2 Day-Night Patterns of UTCI and Tmrt at Outdoor and Semi-Outdoor Nodes

Building on the node context in Table 1 and the overview in Section 3.1, we now examine how UTCI and Tmrt evolve over the 24-hour cycle at the outdoor reference node and the semi-

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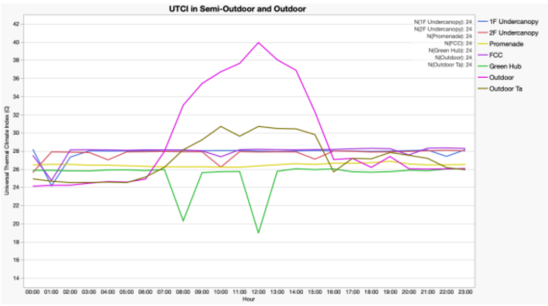
outdoor nodes. The aim is to show the daytime shading benefit and the post-sunset cooling behavior side by side before focusing on nocturnal inversions.

A)


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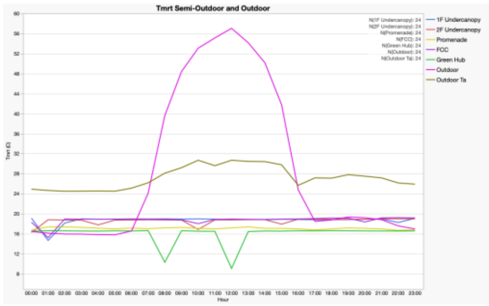

Figure 5.**A)** Hourly UTCI (0-23 h) at outdoor and semi-outdoor nodes. Shading strongly lowers daytime UTCI; under-canopies cool more slowly at night. **B)** Hourly Tmrt (0-23 h). Outdoor shows a strong solar arch; semi-outdoor Tmrt is compressed by shading.

Figure 5 summarizes the diurnal evolution of the UTCI and Tmrt at the outdoor reference and the semi-outdoor nodes. The outdoor reference node exhibits a typical humid-tropical cycle: UTCI rises from 27 °C after sunrise to 39-40 °C at midday, then declines at dusk; and Tmrt peaks near 56-57 °C around solar noon. The semi-outdoor nodes follow the same general pattern, but with systematic offsets. During peak sun hours, under-canopy and semi-outdoor nodes reduce UTCI by 8-10 °C relative to the outdoor node, consistent with their much lower Tmrt under shading. After sunset, however, divergences emerge. While the outdoor reference cools steadily, the deeper under-canopy nodes (e.g., UC-1F/UC-2F) show slower declines, and experience periods during night when the UTCI at the node meets or slightly exceeds the outdoor value. This is indicative of nocturnal inversion, or slower radiant and sensible heat release under canopies.

More open areas (e.g., Promenade and FCC) converge with outdoor conditions earlier in the night. Green Hub, with its vegetation, water, and fans, generally remains below the deeper canopies. However, quality-controlled anomalies around midday were excluded before summary plotting (see 2.5). Overall, the composites reveal the day-night duality that is central to this study. Shading mitigates daytime stress; however, some semi-outdoor corridors retain heat after sunset. This motivates the radiation-ventilation-storage analysis in Section 3.4.

3.3 Nocturnal ΔUTCI and ΔTmrt: Evidence of Under-Canopy Heat Trapping

Building on the diurnal composites in Section 3.2, we now express each node relative to the outdoor reference by calculating the hourly difference (ΔUTCI and ΔTmrt, node minus outdoor) at matched timestamps. This approach eliminates most day-to-day weather variation and isolates the effects of shading, enclosure, ventilation, and thermal storage on the corridor. First, we show the comfort outcome (ΔUTCI) and then the radiative driver (ΔTmrt) to test the central hypothesis of a nocturnal inversion-i.e., that spaces that are semi-outdoor are cooler than the outdoors by day but remain as warm or warmer after sunset.

We use UTCI because it represents the overall thermal comfort/stress experienced by a person walking at a standard pace. It combines air temperature (Ta), humidity (RH), wind speed, and the radiant environment (Tmrt) into a single equivalent-temperature outcome. We pair UTCI with Tmrt because Tmrt isolates the radiative driver (shortwave sunlight during the day and long-wave exchange with the sky and surfaces at night), which is typically the dominant local control in semi-outdoor corridors. Reading ΔUTCI alongside ΔT_{mrt} allow us to distinguish between "what people feel" and "why it happens," and directly links the evidence to design levers [27], [28]. According to Fiala's research on the multi-node thermos-physiological model, the index is defined as the equivalent air temperature that would elicit the same physiological response in a reference environment.

In this study, to isolate the corridor effect from day-to-day weather variations, we express each node relative to the outdoor reference at matched timestamps (see Section 2.4.3 and Figure 6 below). By construction, a negative $\Delta\mathrm{UTCI}$ means the node is more favorable than the outdoor environment (lower thermal stress) and a positive AUTCI means the node is less favorable than the outdoor environment (higher thermal stress).

A) B)

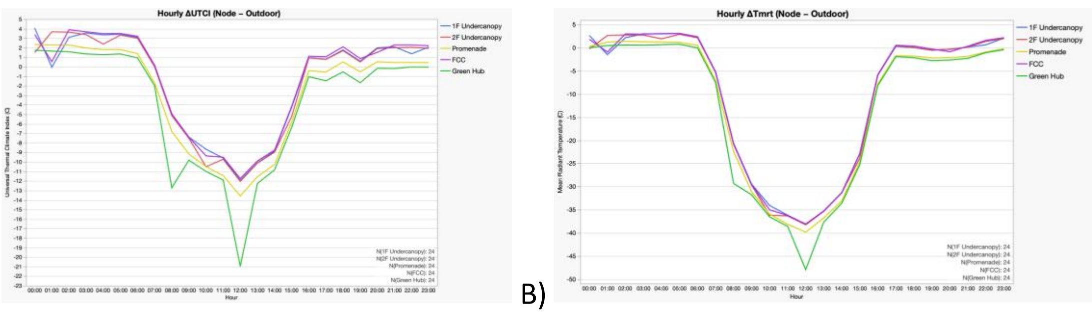

Fig 6 A) Hourly ΔUTCI (node − outdoor); negative = cooler than outdoor, positive = warmer. B) Hourly ΔTmrt (node − outdoor); negative = lower radiant load, positive = higher radiant load.

Figure 6A shows a strong day-night reversal. During the day, all semi-outdoor nodes provide clear relief compared to outdoor conditions. There are minimum temperatures around ΔUTCI =

−11 to -13 °C, at midday for UC-1F, UC-2F, PR, and FCC. GreenHub has a deeper through at -21 °C around 12:00, which is consistent with its dense shading and cooling features. After sunset, the curves climb toward zero and become positive at night for the deeper canopies. UC-1F and UC-2F reach approximately +1 to +3 °C between 8:00 p.m. and 2:00 a.m., indicating nocturnal inversion (the semi-outdoor environment is more stressful than the outdoor environment). The Promenade and FCC sit closer to parity (0 to +2 °C), while GreenHub typically stays the coolest at night (0 to +1 °C).

Figure 6B confirms the radiative mechanism behind these comfort outcomes. Daytime ΔTmrt is strongly negative, reflecting shortwave suppression under cover. UC-1F, UC-2F, PR, and FCC reach = -32 to -38 °C near noon, and GreenHub dips deeper (-48 °C), which is consistent with intense shading and local cooling. After sunset, all nodes rebound toward the outdoor reference. Under canopies hover near 0 to +2 °C throughout. Small positive ΔTmrt appearing from 9:00 p.m. to 11:00 p.m., consistent with limited sky cooling and re-radiation from warm soffits and façades. The more open areas (Promenade and FCC) tend to approach zero at night, indicating faster radiative release.

3.4 Interpretation through Radiation-Ventilation-Storage

The day-night patterns above are consistent with three coupled mechanisms:

1) *Radiation (R).* During the day, shading suppresses shortwave gains, which lowers Tmrt and UTCI at semi-outdoor nodes ($\Delta < 0$). After sunset, the limited sky view under deep canopies restricts longwave exchange with the cool sky. Meanwhile, warm soffits and façades re-radiate toward pedestrians, keeping Tmrt elevated and pushing ΔTmrt/ΔUTCI toward 0 or greater than 0.
2) *Ventilation (V).* Semi-enclosed geometries weaken nighttime purge flow. With low wind, sensible heat removal is slow, so nodes remain closer to their stored-heat state. More open edges (e.g., Promenade, FCC) couple better with ambient flow and return to outdoor conditions sooner.
3) *Thermal storage (S).* High-mass, high-emissivity surfaces (e.g., soffits and walls) absorb heat during the day and release it at night toward the corridor. This sustains elevated Tmrt and a modestly higher UTCI under the canopies compared to the outdoors.

Together, R, V, and S explain the observed duality: shade helps during the day, while restricted sky view, weak purge, and stored heat slow cooling at night. This framework directly informs the retrofit heuristics: (H1) increase local sky exposure; (H2) decouple the roof (sky-cooling) from the soffit (downward radiation); (H3) open night purge paths; (H4) reduce thermal storage exposed to pedestrians; and (H5) use vegetation, water, and fans judiciously in humid air.

3.5 Derivation and Discussion of Retrofit Heuristics (H1-H5)

The five retrofit heuristics (H1-H5) arise from three converging strands: (i) case-study evidence, such as the measured day-night patterns and the Δ-curves showing daytime relief (Δ<0) and nocturnal inversion under deep canopies (Δ≥0); (ii) a radiation-ventilation-storage (RVS) interpretation (3.4); and (iii) established microclimate literature on sky view, long and short-wave exchange, purge flow, and thermal storage in warm-humid settings. These heuristics are design translations, qualitative and practitioner-oriented, rather than a calibrated model based on geometric and material parameters in this dataset.

1) *Heuristics 1 (H1) - Raise local sky exposure (SVF) at night.* Introduce radiative slots, clerestory perforations, or controlled voids that increase a corridor's view to the cool sky while maintaining daytime shade. The expected result is that ΔTmrt and ΔUTCI become less positive after sunset, with little penalty to daytime comfort if the slots are placed above eye level or outside of sun paths.
2) *Heuristics 2 (H2) - Split radiative roles: cool roof, quiet soffit*. Allow the roof exterior to remain high-sky coupled for night cooling, while lining the underside with baffles to reduce downwelling longwave toward pedestrians. Expected signature: nighttime ΔTmrt falls without raising daytime shortwave, especially where warm soffits dominate the view factor.
3) *Heuristics 3 (H3) - Enable night-purge flow along prevailing winds*. Create cross-vent paths (side openings, high/low vents, and removable panels), remove dead-ends, and align apertures with night wind roses. The expected signature is faster post-sunset decay in UTCI (via higher local wind and sensible cooling), with ΔUTCI at night trending toward 0.
4) *Heuristics 4 (H4) - Reduce the amount of exposed thermal storage facing pedestrians*. Limit the massive, high-ε surfaces that "radiate back" at night (e.g., heavy concrete soffits or walls). Options include insulating rain screens, light claddings, and setbacks that decrease the view of the warm surface. The expected outcome is a lower nighttime ΔTmrt and a shorter duration of positive ΔTmrt after sunset.
5) *Heuristics 5 (H5) - Use vegetation, water, and fans calibrated for humid air*. Deploy radiant shielding (trees/trellises), modest water features or mist (evaporative cooling without

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saturating the air), and quiet fans (to raise the local air speed at pedestrian level). The expected signature is a more negative day ΔUTCI (due to extra shade) and a night ΔUTCI closer to 0 through combined radiative and convective effects. Avoid over-misting when the relative humidity (RH) is already high.

These heuristics are physically grounded and site-consistent, but they are not numerically calibrated to geometry/material parameters. They serve as a playbook to guide iterative design. Future work can quantify effect sizes by adding SVF estimates, material audits, or simple per-node regressions.

4. CONCLUSIONS

In humid tropical settings, semi-outdoor retail corridors exhibit a clear day-night duality. Shading lowers the daytime UTCI by suppressing Tmrt. However, deeper under-canopies often cool more slowly after sunset. This results in intervals of ΔUTCI ≥ 0 and ΔTmrt ≥ 0 relative to outdoor reference conditions. Framing this behavior in terms of radiation, ventilation, and storage clarifies the mechanisms: limited sky view restricts long-wave cooling; warm soffits and façades re-radiate toward pedestrians; and semi-enclosures impede purge flow. Guided by these findings, we propose five retrofit heuristics: (H1) increase local sky exposure at night; (H2) separate the radiative roles of the roof and soffit; (H3) enable night purge cross-ventilation; (H4) decrease thermal storage exposed to pedestrians; and (H5) install vegetation, water, and humid air-calibrated fans. These measures help retain daytime benefits while preventing nocturnal heat trapping. They offer a pragmatic playbook for operators and designers of semi-outdoor corridors in Indonesia and other similar climates

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