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# Outdoor Thermal Comfort and Microclimate Adaptation in Coastal Tourism: Evidence from Indonesia

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**Abstract**

Outdoor thermal comfort (OTC) has become a crucial topic, particularly due to global warming and growing public interest in outdoor tourism. This study evaluated OTC conditions at Lampuuk Beach, Aceh Besar Regency, Indonesia, using field measurements of climate parameters and a visitor thermal perception survey conducted over three days in May 2023. A total of 288 respondents participated, while air temperature, relative humidity, wind speed, and solar radiation were simultaneously recorded. The findings indicated that most visitors experienced moderate-to-severe heat stress, with thermal sensation ratings predominantly ranging from warm to hot. Nevertheless, more than 50% of respondents considered the conditions acceptable or comfortable, suggesting relatively high thermal adaptation to tropical outdoor environments. Among the evaluated parameters, air temperature was the dominant factor influencing thermal comfort indices. Physiological Equivalent Temperature (PErtmentT) showed a stronger correlation with thermal sensation and Predicted Mean Vote (PMV) than Universal Thermal Climate Index (UTCI), indicating its suitability for assessing outdoor thermal comfort in tropical coastal environments. The findings highlight the thermal tolerance of people living in warm-humid climates and provide useful insights for improving outdoor thermal comfort in tourism areas under rising temperatures.

**Keywords:** Coastal tourism, Outdoor Thermal Comfort, Physiological Equivalent Temperature, Thermal sensation, Universal Thermal Climate Index

## 1. Introduction

Outdoor thermal comfort (OTC) is a significant concern, especially given the current rise in global temperatures. [1], [2]. It is also an important issue in providing comfort for outdoor tourism activities. The outdoor environment also influences the micro-climate, which determines the indoor thermal comfort [3]. Rising air temperatures necessitate providing comfortable outdoor thermal conditions to encourage outdoor tourism activities, thereby increasing the country's income.

It has been shown that the high rate of urbanization persuades people to have leisure, especially in nature [4]. Urban residents seek natural views and want to experience the local climates of tourist destinations [5], [6]. In tourist areas, climate influences visitor numbers [5], [7]. Outdoor thermal comfort studies have been conducted largely in public spaces such as plazas, parks, streets, playgrounds, and shaded areas. Among those, the most frequently studied areas are plazas and green spaces such as parks and streets. However, developing nations, especially in tropical regions, have been understudied relative to developed nations [8], creating significant research opportunities in these regions. Recent studies on outdoor thermal comfort in Southeast Asia (SEA) have been limited to a few, mostly in Malaysia and Singapore. Most of the OTC studies were carried out in urban parks, lake areas, dense commercial areas, and some resting areas. In Indonesia, there are only a few studies on OTC, all conducted in the capital city of Jakarta, in urban parks and superblock areas [8]. Understanding OTC at the beach has not been widely studied, especially in SEA. The coastal area is also one of the most visited tourist destinations, second only to the mountains. Coastal environments are characterized by sea breezes, which may provide slightly different outdoor thermal comfort from other areas. Therefore, this study works on the beach case in Indonesia.

Located in a tropical region, Indonesia is one of the world's largest archipelagic countries [9] with a coastline of up to 99,000 km [10]. This means that Indonesia is affected by both the coastal climate and the warm, humid tropics. Aceh, in the northern part of the island of Sumatra in Indonesia, has several beaches, such as Lampuuk. It is one of the most visited coastal tourism areas in Aceh. It faces the Indian Ocean on the west, with a 5 km shoreline. In 2017, the number of visitors reached 1,075,626, with growth of 4.75% each year since then [11]. Therefore, regarding outdoor thermal comfort, Lampuuk Beach, as a tourist activity area, is significant enough to warrant investigation. This study concentrates on the coastal microclimate, tourists' perceptions of thermal conditions, and the rate at which these conditions are thermally accepted. This study sought to (1) identify the neutral air temperature (Ta) and assess the effectiveness of the Physiological Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI); (2) evaluate tourists' thermal acceptability at Lampuuk Beach; (3) explore tourists' thermal preferences; and (4) determine the key microclimatic variables affecting thermal comfort.

Although there have been many studies on outdoor thermal comfort, most have been conducted in temperate and subtropical climates. Research in tropical regions remains limited; therefore, this study fills this gap by examining outdoor thermal comfort conditions at Lampuuk Beach, the main tourist destination in Aceh, located at the northern tip of Sumatera Island, Indonesia.

The primary contribution of this study is its focus on tropical coastal environments, a setting that has received little attention in outdoor thermal comfort research. It combines field measurements (air temperature, relative humidity, and air speed) with visitors' thermal comfort responses. This study provides a more complete understanding of how people experience outdoor environments under realistic coastal conditions. It also expands the geographic scope of outdoor thermal comfort studies. It evaluates how well commonly used thermal indices, i.e., PET, UTCI, and Predicted Mean Vote (PMV), perform in tropical coastal climates.

However, this study is limited to one beach (i.e., Lampuuk beach), one climatic period (i.e., May), and a cross-sectional survey design.

## 2. Outdoor Thermal Comfort

Outdoor thermal comfort (OTC) is a multifaceted research area that has been extensively investigated, encompassing theoretical developments and practical applications in building and urban environments, while facing increasing challenges from climate change [12]. OTC is also shaped by the combined effects of environmental conditions, including climate, and psychological factors. [13]. As mentioned previously, OTC is characterized by the climate. Studies of outdoor thermal comfort across various climates indicate that comfort varies by climate and depends on the microclimate [14]. Various typologies of outdoor public spaces also create unique microclimates, which help explain how climate influences people's thermal perceptions across different locations.

OTC is also regarded as the interaction between human behavior or activity and the built environment [12], [15]. In many surveys, various human activities have been observed, with the most common being walking, standing, and sitting. Several thermal indices are commonly used in OTC studies, including Thermal Sensation Vote (TSV), which focuses on human perception and behavior [16], [17]; Predicted Mean Vote (PMV) [18], [19]; Physiological Equivalent Temperature (PET) [16], [17]; and Universal Thermal Climate Index (UTCI) [8], [19]–[21]. Atmospheric conditions, including solar radiation, ambient temperature, air velocity, and relative humidity, influence all of these thermal indices. PET and UTCI account for human sensation and behavior; therefore, these indices consider gender, age, height, weight, clothing type, and metabolic activity at the time of measurement [17], [22], [23].

The PET value (Table 1) was calculated using RayMan 1.2 software, developed from applied climatology research conducted by Dr Andreas Matzarakis and Dr Frank Rutz at Albert Ludwig University of Freiburg, Germany [6]. PET requires mean radiant temperature (Tmrt) data, which are calculated using globe temperature (Tg), air velocity (v), air temperature (Ta), globe diameter (D), and globe emissivity (ε) (1).

$$Tmrt = \left[(Tg + 273)^4 + \left((1.1 \times 10^8 \times V^{0.6})/((\varepsilon D)^{0.4})\right) \times (Tg - Ta)\right]^{0.25} - 273 \qquad (1)$$

However, in this study, Tmrt was also generated directly using RayMan 1.2, which automatically calculates Tmrt based on the available global radiation data.

PET values between 18 and 23 °C indicate thermally neutral, comfortable conditions with no thermal stress. In contrast, higher PET values indicate increasing heat stress, ranging from slight to extreme as conditions shift from slightly warm to very hot. Conversely, PET values below 18 °C indicate progressively cooler conditions, ranging from slight to extreme cold stress as temperatures decrease.

The Universal Thermal Climate Index (UTCI) is a relatively recent thermal comfort index, yet it has become widely used in recent OTC studies [20], [21], [24]. UTCI represents the perceived ambient temperature, reflecting how the human body experiences atmospheric conditions. It is defined as the air temperature (Ta) under standardised reference conditions that would produce the same physiological response as the actual environmental condition [20]. The difference between UTCI and the measured air temperature depends on several environmental factors, such as air temperature (Ta), mean radiant temperature (Tmrt), wind speed (va), and moisture conditions, which are represented by water vapor pressure (vp) or relative humidity (RH) (2). UTCI is calculated using the following equation:

$$UTCI = f(Ta; Tmrt; va; vp) = Ta + Offset(Ta; Tmrt; va; vp) \quad (2)$$

The value of UTCI between 9 °C and 26 °C indicates thermally neutral environments with no thermal stress, while values outside this range represent increasing levels of heat or cold stress.

PMV is Predicted Mean Vote where the value is based on the equations in ASHRAE Standard 55 (3), which considers of several thermal variables, including metabolic rate (M), mechanical work (W), clothing insulation (fcl), air temperature (ta), mean radiant temperature (tr), air velocity (var), water vapor pressure (Pa), convective heat transfer coefficient (hc), and clothing surface temperature (tcl) [18]. PMV is implemented in simplified form via engineering simulation software such as RayMan.

$$PMV = (0.303e^{-}0.0336M + 0.028) \times (M - W) - 3.5 \times 10^{-}3[5733 - 6.99(M - W) - pa] - 0.42(M - 58.5) - 1.7 \times 10^{-}5 \times M(5867 - pa) - 0.0014M(34 - ta) - 3.96 \times 10^{-}8fcl[(tcl + 273)^4 - (tr + 273)^4] - fcl \times hc(tcl - ta) \quad (3)$$

The PMV (Predicted Mean Vote) scale describes how people perceive the thermal environment, with negative values indicating cold conditions and positive values indicating warm or hot conditions. The value ranges from -3 to +3, where -3 to –0.5 indicates very cold to slightly cool, 0 represents neutral, whereas +0.5 to +3 describes conditions ranging from slightly warm to very hot.

The Thermal Sensation Vote (TSV) is also based on the ASHRAE thermal sensation scale. The value is also similar to PMV; however, TSV is commonly obtained through large-scale surveys conducted simultaneously with thermal parameter measurements [25]. TSV (equation 4) reflects the influence of air temperature (Ta), relative humidity (RH), air velocity (v), and mean radiant temperature (Tmrt) [26].

$$TSV = 0.398Ta + 0.023RH - 0.329v + 0.038Tmrt - 14.061, R^2 = 0.801 \quad (4)$$

## 3. Lampuuk Characteristics

This research is a case study of Lampuuk Beach in Aceh Besar, Indonesia. Lampuuk Beach is located at 5o29'21" N, 95°13'44" E (Fig. 1). The beach is categorized as an intermediate coastal type, situated between cliffed high coasts and low-lying coasts [27]. The recorded air temperature ranges from a maximum of 32°C to a minimum of 23 °C (Fig. 2). The highest wind speed reaches up to 8 m/s in July, and the lowest is 1.3 m/s in April (Fig. 3).


**Figure 1.** The map of Lampuuk beach (5°29'21" N, 95°13'44" E). Source: Authors (2025).

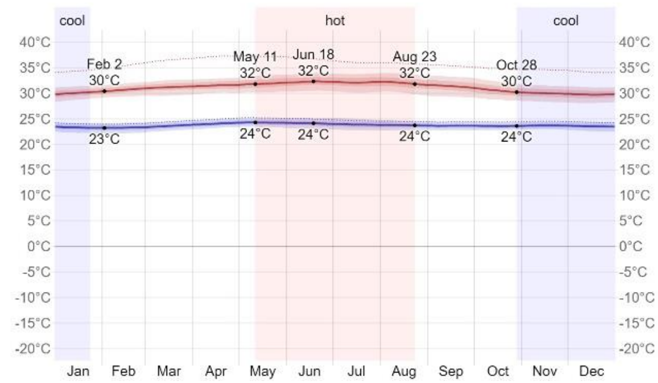


**Figure 2.** Average High and Low Temperature in Lampuuk [28].

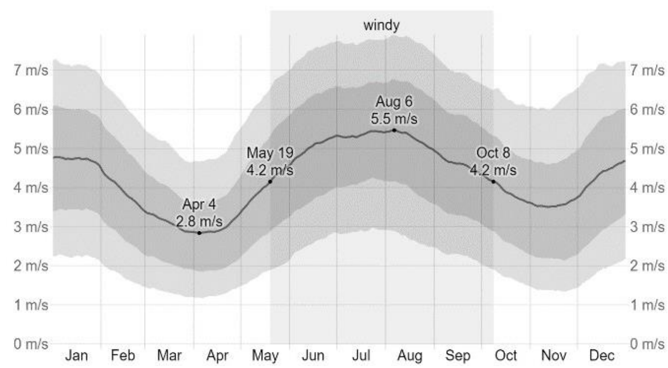


**Figure 3.** Average Wind Speed in Lampuuk [28].

The terrain within a 3-kilometer radius of Lampuuk is generally flat, with elevation differences of no more than 20 meters and an average elevation of about 8 meters above sea level. It is characterized by cropland (71%) and trees (18%). Within 16 kilometers, the area is essentially flat (782 meters of elevation change), which is covered by water (43%) and cropland (31%). Within 80 kilometers, there are large variations in elevation (2,305 meters of change), with water (74%) and trees (15%) [28].

## 4. Methodology

Data were collected using a cross-sectional study design that combined micrometeorological measurements with questionnaire surveys. University students conducted the field survey during periods of tourist activity on predominantly sunny days, although brief light rain showers occurred at times. The survey site was alongside Lampuuk Beach, where visitors were sitting, lying on the sand, and walking. Some surrounding areas contained gazebos where people relaxed and entertained themselves with an open view of the beach. The survey was carried out among tourists sitting or walking along the beach and those sitting in the gazebos.

### 4.1. Data Collection

Outdoor Thermal Comfort is assessed using the thermal indices PET, UTCI, and PMV. As previously mentioned, those indices require the mean radiant temperature (Tmrt), which was calculated with the RayMan software. When running the calculation, RayMan software requires data on air temperature (Ta), relative humidity (RH), wind speed (v), and other meteorological parameters. Those parameters were obtained from the Professional Wifi Weather Station WS2320CE (Fig. 4). The weather station also recorded outdoor illuminance (lux) and rain rate (mm/h).


**Figure 4.** Professional Wifi Weather Station WS2320CE

The field measurement was conducted from 6 to 8 May 2023. The selection of this period was justified because Aceh is located at 5°N, very close to the equator, resulting in minimal annual climate variation. May, June, July, and August share similar meteorological characteristics and reach the year's highest air temperatures. Although May is considered one of the warmest months, the rains eventually come; thus, the field measurement in May is acceptable as a representative of the year. The meteorological parameters were recorded every 5 minutes from 9 am to 5 pm. The instruments were placed at a height of 1.1 m above the ground in accordance with ASHRAE Standard 55-2017 (Fig. 5).

### 4.2. Validation and Instrumentation Accuracy

To ensure the reliability of environmental data, all meteorological parameters in this study were recorded using the Professional WiFi Weather Station WS2320CE. The instrument was installed in accordance with ASHRAE Standard 55-2017, with sensors positioned 1.1 meters above ground to reflect the average height of the human body's center of thermal perception in outdoor standing or seated conditions. The WS2320CE sensors have the following manufacturer-reported accuracies: air temperature ±0.5°C, relative humidity ±5%, wind speed ±0.3 m/s, and global solar radiation ±5%. Regular calibration checks were performed before and after data collection to confirm the consistency of sensor readings. Data were collected at 5-minute intervals and averaged to 30-minute means to minimize short-term fluctuations and reduce random measurement error. Given these tolerances, the potential error margins for the derived thermal indices (PET and UTCI) are estimated at ±1.5°C, which is acceptable for field-based outdoor thermal comfort studies.

**Figure 5.** The weather station installation. Source: Authors (2025).

### 4.3. Questionnaire/Survey

Besides indicating the thermal comfort indices as explained above, the subjective thermal comfort survey was also carried out with the beach visitors (Fig. 6). The questionnaires in the study were adopted from the outdoor thermal comfort questionnaire used by Zhang in her study 'Outdoor Thermal Comfort of Urban Park-A Case Study [6]. The questionnaire began with the data filled in by the surveyor. The data consisted of the survey date, time, and location. Further, the surveyor must record the activities the respondents engaged in, such as reclining, sitting quietly, walking, or running. Furthermore, the questionnaire collected demographic information such as age, gender, height, weight, and type of clothing worn by the respondents, with the following choices: shorts, light clothing, or heavy clothing. The final section focused on outdoor thermal comfort perception, which used the human transient thermal sensation vote to describe the actual situation during the survey. Interviewees were required to mark the value at the corresponding position on the scale based on their current thermal sensation. The first question in this part asked about what the interviewees felt during the survey. Question 2 asked about the interviewee's thermal sensation using the 7-point ASHRAE thermal scale (i.e., −3, cold; -2, cool; −1, slightly cool; 0, neutral; 1, slightly warm; 2, warm; 3, hot). Questions 2, 3, 4, 5, 6, and 7 required the interviewee to rate their willingness to experience various thermal changes in air temperature, relative humidity, airspeed, and solar radiation, respectively. At the end of the questions, the interviewees were asked to indicate their overall feeling of the thermal environment and their acceptance of it.

**Figure 6.** The survey/ interviewing process results. Source: Authors (2025).

Table 1 shows the meteorological data recorded during three days, i.e 6, 7, and 8 May 2023, from 8 am to 7 pm. During those days, the average temperature (Ta) was 30.65°C, with maximum and minimum values of 35°C and 26.1°C, respectively. The mean air velocity (V) was 1.06 m/s, with the maximum value reaching up to 5.07 m/s. The average solar radiation was 630.43 w/m2. Weather conditions were generally sunny, although some periods were partly cloudy, with an average illuminance of 76,394 lux. The maximum rain rate was 36.6 mm/h, followed by 0.16 mm/h and 0 mm/h for the average and minimum values, respectively.

**Table 1.** Recorded meteorological conditions during the survey time.

| Parameter | Avg | Max | Min | SD |
|---|---|---|---|---|
| $T_a$ (°C) | 30.65 | 35 | 26.10 | 1.77 |
| RH (%) | 77 | 95 | 64 | 6.69 |
| V (m/s) | 1.06 | 5.07 | 0.20 | 0.67 |
| G (W/m$^2$) | 630.43 | 777.98 | 523.88 | 54.82 |
| E (lux) | 76,394.20 | 131,900 | 4,150 | 33,501.57 |
| Rainrate (mm/h) | 0.16 | 36.6 | 0 | 2.20 |

## 5. Results and Discussion

A total of 288 valid sets of raw data were collected during the field survey in Lampuuk Beach. Characteristics of the respondents surveyed are presented in Table 2, with gender distribution at 46% male and 53% female. The interviewees' ages ranged from an average of 31 for males and 28 for females. The average height was 165.76 cm for males and 155.75 cm for females, whereas the average weight was 63.07 kg and 57.57 kg for males and females, respectively. During the survey, 86.5% of the interviewees wore light clothing (mean clo 0.47). 8.6% wore heavy clothing (mean clo 0.62), and another 4.5% wore shorts (mean clo 0.06).

**Table 2.** Summary of basic information of interviewees in the questionnaire survey.

| | Male | Female |
|---|---|---|
| Number | 133 | 156 |
| **Age** | | |
| Max | 74 | 56 |
| Min | 15 | 15 |
| Avg | 31.3 | 27.78 |
| SD | 12.05 | 10.07 |
| **Height (cm)** | | |
| Max | 182 | 175 |
| Min | 150 | 135 |
| Avg | 165.76 | 155.75 |
| SD | 6.28 | 6.18 |
| **Weight (kg)** | | |
| Max | 121 | 144 |
| Min | 32 | 20 |
| Avg | 63.07 | 57.57 |
| SD | 13 | 14.50 |

### 5.1. Thermal Sensation Vote

Figure 7 shows respondents' perceptions of the thermal environment (Table 1). Field measurements at Lampuuk Beach recorded an average air temperature of 30.65°C (maximum: 35°C) and a high average relative humidity of 77%, confirming the warm, humid tropical coastal climate of the site. These meteorological conditions were consistent with the questionnaire responses, with most respondents reporting warm to hot thermal sensations; however, they felt the conditions were acceptable or very acceptable. These responses show the thermal adaptation to the local climate. The average wind speed was 1.06 m/s, with peaks up to 5.07 m/s, consistent with respondents' preference for steady or stronger winds. This indicates the importance of the cooling effect of sea breezes. High solar exposure was also observed, with an average global radiation of 630.43 W/m² and an illumination level exceeding 76,000 lux, which may explain why some respondents preferred dimmer sunlight. The preference for lower air temperatures is consistent with measured thermal conditions, particularly during peak daytime periods. Overall, the integration of climate measurements and perception-based responses suggests that, despite Lampuuk Beach experiencing intense heat and solar radiation, the availability of wind is crucial for maintaining outdoor thermal comfort.

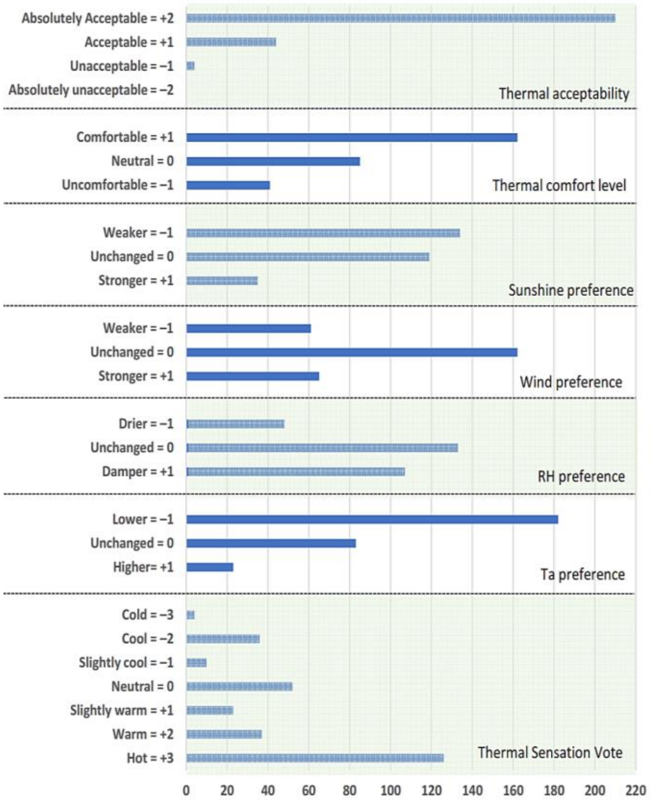


**Figure 7.** Summary of questionnaire results.

Figure 7 shows that although respondents generally experienced warm-to-hot thermal sensations, the outdoor environment at Lampuuk Beach was still perceived as comfortable and acceptable. Preferences for stronger wind, slightly lower air temperature, and reduced sunshine highlight the critical role of natural ventilation and shading in enhancing outdoor thermal comfort in tropical beach destinations.

### 5.2. Thermal Indices

In this study, thermal conditions were evaluated using the Physiological Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI). Both indices were calculated using the RayMan model based on respondents' clothing insulation and metabolic rate, along with the relevant meteorological variables for each location. Meteorological data were recorded at 30-minute intervals, while clothing insulation and metabolic activity data were entered into the RayMan model at the corresponding times to compute PET and UTCI values. As shown in Table 3, the mean PET value is 31.44 °C, corresponding to a warm thermal sensation and indicating moderate heat stress. Meanwhile, the average UTCI is 34.34 °C, indicating conditions associated with strong heat stress.

**Table 3.** PET and UTCI obtained in the study.

| Parameter | Avg | Max | Min | SD |
|---|---|---|---|---|
| PET (°C) | 31.44 | 37.60 | 24.30 | 2.95 |
| UTCI (°C) | 34.34 | 39.50 | 26.55 | 2.56 |

Source: Author (2025)

### 5.3. Correlation between Thermal Indices and TSV

In this study, the correlation between the two thermal indices was assessed against TSV and PMV. Ta was also correlated to TSV and PMV to indicate the linear relationship. Fig. 7 shows that the higher the Ta, PET, and UTCI, the higher the TSV rated by the interviewees. Based on Fig. 7, the linear relationship of Ta, PET, and UTCI is indicated (Table 4). When the TSV is zero, the human-body neutral temperatures corresponding to Ta, PET, and UTCI are determined, yielding PET neutral-temperature values of 27.97°C, 25.66°C, 29.48°C, and 20.19°C. When the TSV is between −0.5 and 0.5, which is determined to be in the neutral PET range, the neutral PET range is 26.95-28.98°C; 24.85 °C- 28.47 °C; and 27.65-31.32°C, respectively, for Ta, PET, and UTCI.

The thermal perception of 24.85°C to 28.47°C (the neutral temperature of PET based on TSV) is defined as slightly warm (slight heat stress). This value is higher than the neutral temperature range for PET, which is 18°C to 23°C. The neutral temperature of UTCI obtained from the field survey (TSV), i.e., 27.65°C to 31.32°C, is also higher than that recommended in the standard (Tables 1 and 2). It is considered moderate heat stress, which is higher than the no-heat-stress range of the standard, i.e., 9°C to 26°C.

**Table 4.** Linear Relationship between Thermal Indices and TSV.

| Thermal Indices | Linear relationship with TSV | Neutral Temperature | | |
|---|---|---|---|---|
| | | –0.5 | 0 | +0.5 |
| $T_a$ | $TSV=0.4935T_a$-13.804 ($R^2$ = 0.2221) | 26.95 | 27.97 | 28.98 |
| PET | TSV= 0.2765 PET-7.3723 ($R^2$=0.1934) | 24.85 | 26.66 | 28.47 |
| UTCI | TSV=0.2727UTCI-8.0415 ($R^2$ = 0.1403) | 27.65 | 29.48 | 31.32 |

Source: Authors (2025)

### 5.4. Correlation between Thermal Indices and PMV

Table 5 shows the linear relationship between Ta, PET, and UTCI, which is regressed from Fig. 8. The neutral temperatures for the four parameters are as follows: 25.38 °C for Ta; 23.32 °C for PET; and 25.34 °C for UTCI. The comfortable temperatures within the -0.5 to +0.5 range are 24.11°C to 26.66°C for Ta, 21.36°C to 25.28°C for PET, and 23.16°C to 27.52°C for UTCI. However, compared to the ASHRAE standard, the neutral temperatures for PET and UTCI are partially within the comfortable range. PET with the PMV votes of -0.5 and 0, corresponding to 21.36°C and 23.32°C, are thermally perceived as neutral (comfortable) and have no thermal stress. At the same time, PMV+0.1 for PET (25.28°C) is considered slightly warm, with slight heat stress. UTCI has the same characteristics: the neutral temperatures obtained from PMV votes of -0.5 and 0, i.e., 23.16°C and 25.34°C, are considered comfortable without heat stress.

However, the PMV +0.5 neutral temperature is perceived as slightly warm. UTCI is similar to PET, in which votes of -0.5 and 0 (PMV) fall into the "no thermal stress" temperature category. A PMV of +0.5, corresponding to a temperature of 27.52°C, indicates moderate heat stress. In contrast, the neutral temperature obtained from PMV, namely 14.87°C to 16.87°C, is thermally perceived as cool and poses a moderate hazard. Only the PMV of +0.5 (neutral temperature: 18.87°C) is considered comfortable.

**Table 5.** Linear Relationship between Thermal Indices and PMV.

| Thermal Indices | Linear relationship with PMV | Neutral Temperature | | |
|---|---|---|---|---|
| | | –0.5 | 0 | +0.5 |
| $T_a$ | PMV=0.3933x-9.9842 ($R^2$ = 0.8264) | 24.11 | 25.38 | 26.66 |
| PET | PMV=0.2547x-5.9404 ($R^2$ = 0.9615) | 21.36 | 23.32 | 25.28 |
| UTCI | PMV=0.2298UTCI-5.8238 ($R^2$ = 0.5842) | 23.16 | 25.34 | 27.52 |

Source: Authors (2025)

### 5.5. R Square Value

In general, Fig. 7 shows that the R2 value for the correlation between TSV and the thermal indices is low. Among the thermal indices, TSV shows the closest correlation with Ta (R2 = 0.22), followed by PET and UTCI (0.19 and 0.14, respectively). The low R-squared value is accepted because of the TSV voted on by the people. In this study, we found that human behavior typically exhibits $R^2$ values below 50%, reflecting that people are far more difficult to predict than physical systems or processes.

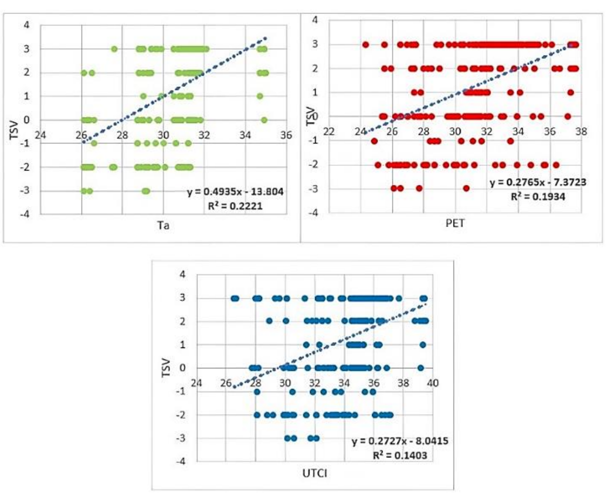


**Figure 8.** The correlation between Ta, PET, UTCI, and TSV.

In contrast, the thermal indices show a stronger correlation with PMV than TSV (Fig. 9). PET (i.e., $R^2$ = 0.96) has a stronger correlation with PMV than Ta ($R^2$ = 0.83) and UTCI ($R^2$ = 0.58). Figs. 7 and 8 indicate that, as air temperature increased, the TSV values were consistently lower than the corresponding PMV values. This discrepancy is expected, as the PMV model is derived from experiments conducted under steady-state thermal conditions, where subjects are assumed to be in thermal equilibrium [25].

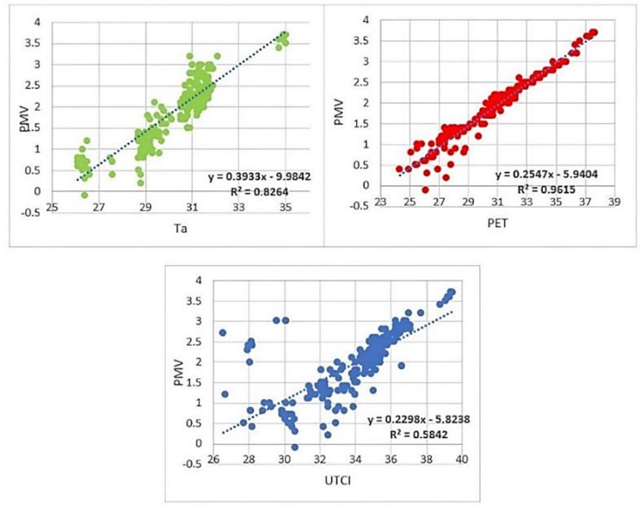


**Figure 9.** Correlation between Ta, PET, UTCI, and PMV.

### 5.6. Influence of Air Temperature, Air Velocity and Relative Humidity on PET and UTCI

In this study, we also investigated the correlation between air temperature, Air velocity, and relative humidity and PET and UTCI. Fig. 10 shows the linear trendline for the correlation between Air velocity and the indices, i.e., PET and UTCI. Even though the $R^2$ is rather low (i.e., less than 0.5), we find that higher air velocity is associated with lower thermal indices. Despite the low R-squared value, Air velocity has a slightly higher correlation with PET (i.e., 0.23) than with UTCI (Fig. 10).

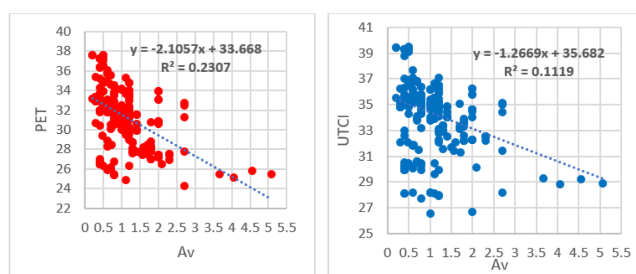


**Figure 10.** Correlation between PET, UTCI and Air velocity.

Relative humidity (RH) is also correlated to those thermal indices. Fig. 11 shows that there is a stronger correlation between RH and PET, and between RH and UTCI, than between RH and air velocity. RH has a stronger correlation with PET compared with UTCI. The R-squared is 0.59. The higher the relative humidity, the lower the PET and UTCI values (Fig. 11).

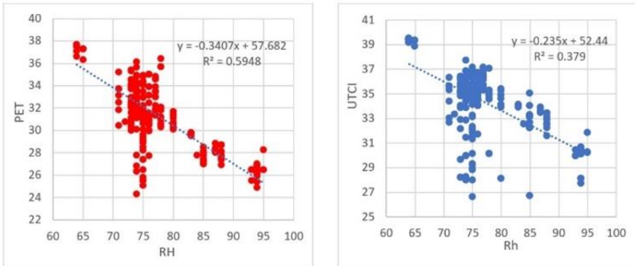


**Figure 11.** Correlation between PET, UTCI, and Relative Humidity.

This study indicates that among air temperature (Ta), relative humidity (RH), and air velocity (Av), Ta is the thermal parameter that has a strong correlation with PET and UTCI. The R-squared values are 0.78 and 0.62 for PET and UTCI, respectively. The linear trend line increases with rising air temperature (Fig. 12).

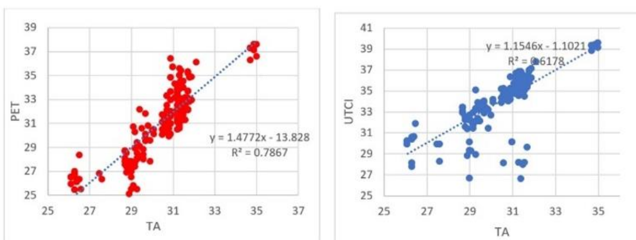


**Figure 12.** Correlation between PET, UTCI and Air temperature.

The findings of this study indicate that the conventional environmental standards, i.e., PET and UTCI, cannot be relied on as the only outdoor thermal parameters, as their values classify the resulting thermal data as moderate to strong heat stress. At the same time, the majority of respondents reported that, although their thermal sensation votes are mostly hot, they can tolerate it.

Beach visitors can tolerate, and even accept, higher thermal stress levels because of their recreational purposes, the visual connection to the sea, and the cooling effect of the breeze.

Another finding was that PET showed a stronger correlation with participants' thermal perceptions than UTCI and PMV, suggesting that PET is better able to capture the combined influence of environmental factors in naturally ventilated coastal outdoor environments. Nevertheless, PET still could not fully explain the thermal comfort responses observed in this study, indicating that existing thermal indices may require further refinement for application in tropical outdoor settings.

## 6. Discussion

This study indicates that environmental conditions, adaptive human responses, and contextual coastal characteristics influence outdoor thermal comfort at Lampuuk Beach. Although the measured PET and UTCI values generally indicated moderate to strong heat stress, most respondents still perceived the environment as acceptable or comfortable. This suggests that conventional thermal comfort standards, largely developed under controlled indoor or steady-state conditions, may not fully capture human thermal perception in dynamic tropical outdoor environments.

Several adaptive thermal behaviors exhibited by visitors in the tropics include their presence on beaches well-suited to coastal environmental challenges, such as high air temperatures and intense solar radiation. Light clothing (mean clo 0.47), sitting under the shaded trees, and playing with water also make the environment acceptable. The sea breeze helps visitors accept the thermal conditions, with PET and UTCI indicating moderate to strong heat stress. Air movement also enhanced evaporative cooling and improved thermal acceptability.

Further, the results indicate that air temperature is the most influential environmental parameter on PET and UTCI values, followed by relative humidity and air velocity. However, despite the strong influence of temperature, airflow played a critical role in outdoor comfort conditions. This study also indicates that TSV and thermal indices (PET, UTCI) have a weak relationship. This is because outdoor thermal perception is influenced not only by environmental conditions but also by physiological adaptation to the local climate, psychological expectations, behavioral adjustments, and the surrounding environmental context. However, among the thermal indices used in the study, PET shows the strongest correlation with subjective responses, indicating that PET is better suited to evaluating thermal comfort in outdoor coastal settings.

This research also provides input for the development of coastal tourism areas by increasing wind accessibility, preserving open coastal airflow corridors, and increasing shaded rest areas [29]. Coastal thermal comfort can also be enhanced by integrating vegetation or lightweight shelter structures, which can significantly increase outdoor thermal comfort, in accordance with prior research [29].

## 7. Conclusion

This study examined outdoor thermal comfort (OTC) at Lampuuk Beach, Indonesia, through field measurements and a thermal perception survey involving 288 visitors. Findings indicate that thermal conditions at the beach, as indicated by PET and UTCI, are moderate to strong.

Despite visitors' perceived heat of the TSV and preference for lower temperatures, most respondents still perceived the environment as thermally comfortable, indicating a high level of thermal adaptation in a tropical beach environment. Air temperature was identified as the dominant factor influencing thermal sensation, while airflow significantly enhanced perceived comfort. Among the indices evaluated, PET showed a stronger relationship with TSV and PMV than UTCI, indicating its greater suitability for assessing OTC in tropical beach environments.

This study also demonstrates that conventional thermal comfort standards alone cannot fully explain human thermal perception in tropical outdoor environments, where behavioral adaptation, environmental expectations, and natural ventilation significantly influence comfort responses.

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**Conflict of Interest Statement**

The authors confirm that this study was carried out without any personal, commercial, or financial interests and declare that there are no conflicts of interest with the funding bodies.

**Author Contribution**

Laina Hilma Sari formulated the research problem and developed the theoretical framework.

Chaham Alalouch validated the analytical methods, while Era Nopera Rauzi carried out the investigations.

Evalina Zuraidi oversaw the findings. All authors discussed the results and contributed to the preparation of the final manuscript.

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