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EVALUATING THERMAL COMFORT MODELS IN HIGH-ALTITUDE RURAL AREAS OF THE PERUVIAN ANDES

EVALUACIÓN DE MODELOS DE CONFORT TÉRMICO EN ZONAS RURALES DE GRAN ALTITUD DE LOS ANDES PERUANOS

AVALIAÇÃO DE MODELOS DE CONFORTO TÉRMICO EM ÁREAS RURAIS DE GRANDE ALTITUDE DOS ANDES PERUANOS

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RESUMEN

Los ambientes interiores fríos en las viviendas rurales de los Andes generan preocupaciones sobre el confort térmico, pero la aplicabilidad de los modelos existentes a estos contextos sigue siendo poco examinada. Este estudio comparó las predicciones de cinco modelos de confort térmico, incluidos PMV, aPMV y enfoques regionales, con datos obtenidos en terreno. La información se recopiló de 154 residentes de Langui (3,969 m s. n. m.) mediante encuestas culturalmente adaptadas y mediciones ambientales. El modelo aPMV mostró la mayor concordancia con los votos de sensación térmica, alcanzando un 58,4 % de precisión (± 1 categoría) y permitiendo definir un rango de confort entre 14 °C y 25 °C. Los resultados resaltan la necesidad de criterios de diseño locales que aborden las condiciones de frío interior en las viviendas andinas.

Palabras clave
viviendas rurales, viviendas de montaña, viviendas sociales, condiciones de habitabilidad

ABSTRACT

Cold indoor environments in rural Andean housing raise concerns about thermal comfort, yet the applicability of existing comfort models to these contexts remains insufficiently examined. This study has compared predictions from five thermal comfort models, including PMV, aPMV, and regional approaches, against field data. Data were collected from 154 residents of Langui (3,969 m.a.s.l.) through culturally adapted surveys and environmental measurements. The aPMV model showed the highest agreement with thermal sensation votes, achieving 58.4% accuracy (±1 category), and enabled the definition of a comfort range between 14 °C and 25 °C. The results emphasize the need for local design criteria that address cold indoor conditions in Andean housing.

Keywords
rural housing, mountain housing, social housing, habitability conditions

RESUMO

Os ambientes internos frios nas habitações rurais andinas suscitam preocupações quanto ao conforto térmico, mas a aplicabilidade dos modelos de conforto existentes a esses contextos ainda não foi suficientemente examinada. Este estudo comparou as previsões de cinco modelos de conforto térmico, incluindo PMV, aPMV e abordagens regionais, com dados de campo. Os dados foram coletados de 154 residentes de Langui (3.969 m.a.n.m.) por meio de questionários culturalmente adaptados e medições ambientais. O modelo aPMV apresentou a maior concordância com as avaliações de sensação térmica, alcançando 58,4% de precisão (±1 categoria), e permitiu definir uma faixa de conforto entre 14 °C e 25 °C. Os resultados enfatizam a necessidade de critérios de projeto locais que abordem as condições de frio interno nas habitações andinas.

Palavras-chave
habitação rural, habitação de montanha, habitação de interesse social, condições de habitabilidade

INTRODUCTION

High-altitude Andean regions present distinct challenges to thermal comfort due to low temperatures, large diurnal thermal fluctuations, and limited housing quality (Molina et al., 2023). In communities such as Langui (Cusco, Peru), persistent indoor cold affects well-being and increases respiratory risks, particularly among older adults (Canales Gutiérrez et al., 2021). Although residents demonstrate strong cultural and behavioral adaptation, such as wearing heavy clothing, these strategies often fail to mitigate discomfort during winter nights (Massler, 2004). Indoor environmental quality is especially problematic in low-income rural households, where inadequate construction materials, minimal insulation, and the use of biomass fuels amplify exposure to cold temperatures and pollution (Subri et al., 2024). Despite these risks, most widely used thermal comfort models, particularly the Predictive Mean Vote (PMV), were developed under controlled laboratory conditions in temperate, urban environments (Fanger, 1972), limiting their relevance in high-altitude rural settings.

Adaptive comfort research has demonstrated that occupants of naturally ventilated buildings accept a broader temperature range closely linked to outdoor conditions and recent thermal history (De Dear & Brager, 2002; Humphreys et al., 2013). This divergence from laboratory models has been reported in other high-altitude regions. For example, comfort temperatures ranging from 10 to 23 °C have been documented on the Tibetan Plateau (Yu et al., 2017), while studies in the Himalayan settlements report neutral temperatures near 10.7 °C (Rijal, 2021; Thapa, 2020). These contexts are shaped by heavy traditional clothing (up to 2.67clo) and high-calorie diets (Rijal, 2021; Thapa, 2020; Yu et al., 2017; Zhao et al., 2023). Together, these findings support the use of adaptive models such as the Adaptive Thermal Comfort (ATC) model (Nicol et al., 2012) and the adaptive Predictive Mean Vote (aPMV) (Yao et al., 2009), both of which incorporate behavioral and physiological adaptation.

Within the Andes, however, very few field studies have examined comfort responses or evaluated the performance of existing comfort models under high-altitude conditions (Molina et al., 2023; Pari-Quispe et al., 2024). Recent studies in the Peruvian highlands illustrate substantial variability in neutral temperatures, ranging from 12.4 °C (Molina et al., 2023) in Imata to 21.98 °C in Lake Titicaca (Pari-Quispe et al., 2024), highlighting the influence of local climate, housing characteristics, and cultural practices. While experimental projects on passive heating and envelope improvements show promise (Aza-Medina et al., 2025; Mejia-Solis et al., 2023; Wieser et al., 2021; Yang et al., 2025), progress is limited by the absence of locally validated comfort criteria. Without these benchmarks, it is difficult to define performance targets or guide cost-effective housing interventions.

This study aims to (1) evaluate the predictive accuracy of five comfort models in Langui and (2) define a localized comfort temperature range to support design guidelines for high-altitude rural housing. To achieve this, we conducted a comprehensive field study using a culturally adapted survey in Spanish and Quechua, combined with concurrent indoor measurements. The analysis compares PMV, aPMV, and ATC, and two regional models against residents´ Thermal Sensation Votes (TSV) and examines demographic and dwelling characteristics influencing thermal perception.

A brief overview of the study context is necessary to situate these findings. Langui (14°25′57″S 71°16′22″W), located at 3,969 masl in the Cusco region, has a subtropical highland climate with dry winters and moderate summers, experiencing substantial daily temperature swings.

A brief overview of the study context is necessary to situate these findings. Figure 1 introduces the high-altitude setting of Langui and its built environment. The district (14°25′57″S 71°16′22″W; 3,969 masl) has a subtropical highland climate with dry winters and moderate summers, conditions that shape residents' daily thermal exposure. The district's economy is agrarian, and most residents are Quechua-speaking subsistence farmers who rely on dwellings with low thermal performance. Figure 2 shows examples of the main housing typologies, typically built with minimal insulation and poor airtightness, which often result in cold indoor environments. Recent social housing programs have introduced insulated metal roofs and improved materials, yet thermal comfort challenges remain (Mejia-Solis et al., 2023).

METHODS

This study employed an integrated methodological approach combining subjective thermal perception data with objective environmental measurements. A culturally adapted survey, administered in Spanish and Quechua, was used to collect information on thermal sensation, adaptive behaviors, daily routines, and dwelling characteristics. Indoor environmental parameters were measured concurrently with each interview following ASHRAE Standard 55 guidelines, while a meteorological station recorded outdoor climatic conditions throughout the study period. These data were used to analyze the influence of demographic and building characteristics on thermal comfort and to evaluate the predictive performance of five existing thermal comfort models, including international standards, locally calibrated models, and regional adaptive models.

(a) (b)

Figure 1. The high-altitude setting of Langui: (a) Panoramic view, and (b) town square.

Figure 2. Housing typologies in Langui: (a) one-story dwelling; (b) two-story dwelling; (c) and (d) social housing units; (e) multi-volume household.

SURVEY

The survey was based on the ASHRAE Standard 55 instrument but culturally adapted to ensure linguistic and conceptual clarity for residents of Langui. The adaptation process included six community assemblies and six workshops conducted in Spanish and Quechua, which helped identify misunderstandings related to technical terms such as relative humidity, air velocity, and thermal comfort.

Some concepts could not be translated reliably, leading to the removal of questions on indoor air velocity, relative humidity perception, and categorical comfort ("comfortable/uncomfortable"). The ASHRAE seven-point thermal sensation scale was retained, and the Thermal Sensation Vote (TSV) was recorded using its standard categories.

The final survey collected demographic information, thermal perception, adaptive behaviors, daily routines, and dwelling characteristics. Surveys were conducted between July 23 and August 10, 2023, and interviewers were trained to explain unfamiliar concepts in both Spanish and Quechua to ensure consistent data collection.

This study was reviewed and approved by the Research Ethics Committee for Social Sciences, Humanities, and Arts of the Pontificia Universidad Católica del Perú (PUCP), approval number 048-2023-CEI-CCSSHHYAA/PUCP (July 6, 2023). All participants provided informed consent. Verbal consent, documented through audio recordings, was used instead of written consent to accommodate cultural practices, varying literacy levels, and the bilingual context (Spanish and Quechua). This procedure ensured a clear understanding and participant comfort and was explicitly approved by the ethics committee.

SAMPLE

The final dataset consisted of 154 valid interviews out of an initial 160. Participants were selected by local authorities as a prerequisite for conducting fieldwork in the area. While this facilitated community engagement, the resulting sample may not fully represent the broader population of Langui. The valid sample comprised 91 women and 63 men, with average ages of 54.7 and 60.9, respectively (Figure 3).

Most respondents lived in one-story adobe dwellings with corrugated metal roofs and dirt floors, and ceilings were found only in part of the housing stock. Insulation was scarce, and none of the surveyed dwellings had heating or air-conditioning systems. Public housing participation was limited (n=20, 13%).

FIELD MEASUREMENTS

Outdoor climatic conditions were monitored throughout the survey period using a meteorological station that recorded air temperature, relative humidity, wind speed, wind direction, and solar radiation at 15-minute intervals (Table 1). The solar radiation sensor had intermittent data gaps (Figure 4).

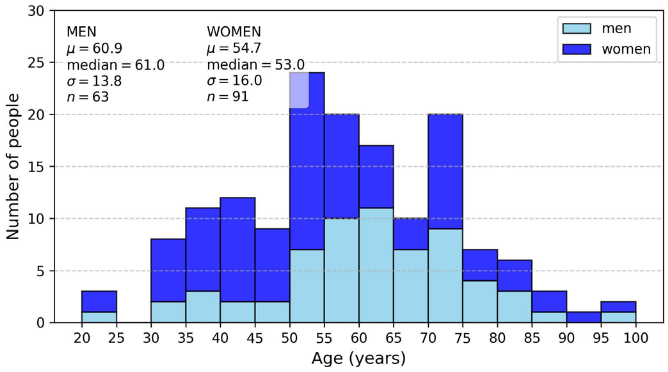

Figure 3. Age and sex distribution of interviewees.

Table 1. Specifications of the instruments used for environmental monitoring.

Parameter	Instrument	Range	Accuracy
Indoor air temperature	Extech HT200 Heat Stress WBGT Meter	0 - 50°C	±0.8°C
Indoor air relative humidity	Extech HT200 Heat Stress WBGT Meter	1 - 99%	±3%
Globe temperature	Extech HT200 Heat Stress WBGT Meter	0 - 80°C	±0.6°C
Air velocity	Testo 425 Hot-wire anemometer	0 - 20m/s	±0.03m/s
Solar radiation	ONSET smart sensor S-LIB-M003	0 - 1280 W/m2	±10W/m2
Outdoor air temperature	ONSET S-THC-M002	-40°C - 75°C	±0.20°C
Outdoor air relative humidity	ONSET S-THC-M002	0 - 100%	±2.5%
Wind speed	ONSET S-WCF-M003	0 to 76 m/s	±1.1 m/s
Data logger	HOBO RX3004 Remote Monitoring Station	-	-

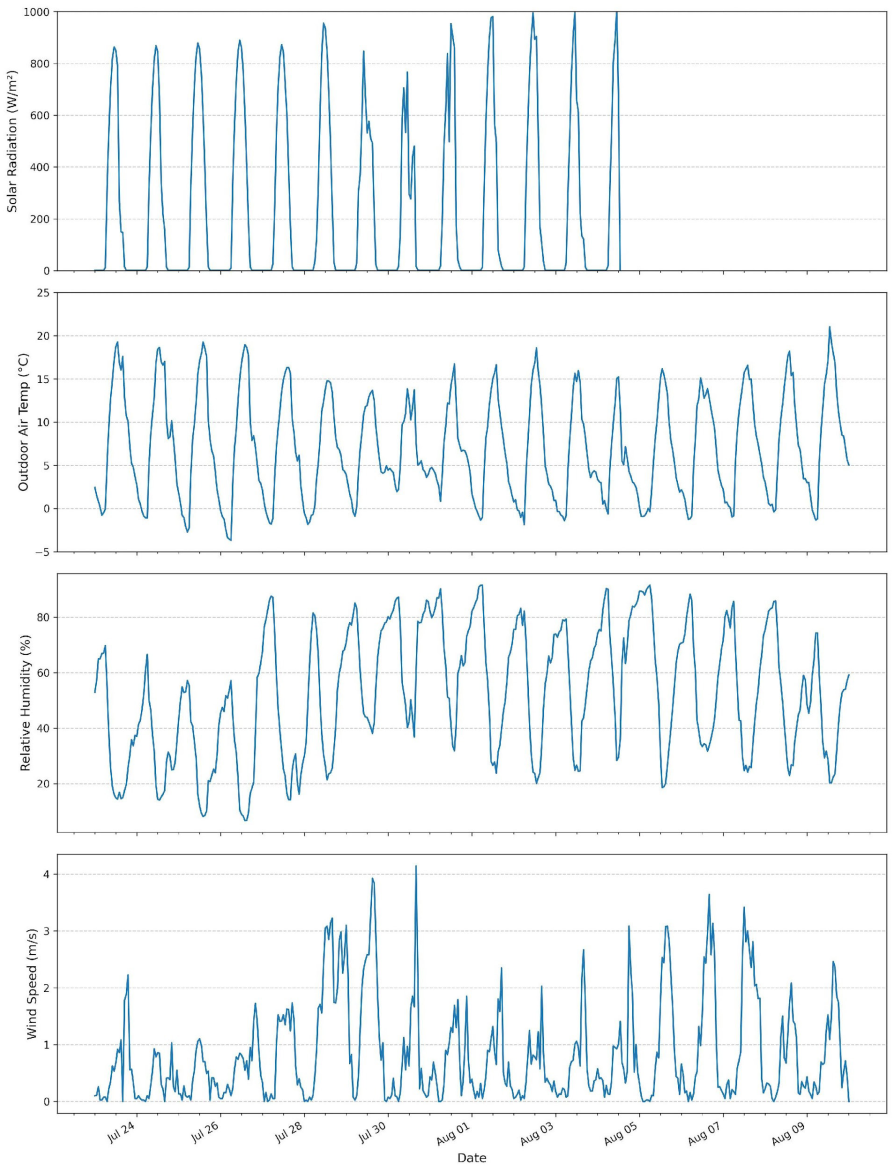

Figure 4. Hourly meteorological data in Langui during the surveys.

Indoor environmental measurements were conducted alongside each interview following ASHRAE Standard 55 guidelines. Indoor air temperature (T_a), globe temperature (T_g), relative humidity, and air velocity were recorded with portable instruments positioned approximately 1 meter above the floor to reflect the participant's seated posture. Prior to each interview, participants remained seated for 15 minutes to allow thermal conditions to stabilize. Clothing insulation values were assigned using standard reference tables, with reasonable estimates applied to traditional garments not documented in existing literature.

STATISTICAL ANALYSIS OF THERMAL COMFORT METRICS AND ADAPTATIVE BEHAVIORS

The statistical analysis was designed to quantify the influence of demographic (sex, age) and building characteristics on two primary indicators of thermal comfort: the Mean Thermal Sensation Vote (TSV), and the mean neutral temperature (T_n). TSV was obtained directly from participant responses on the 7-point ASHRAE scale. , which represents the operative temperature at which the TSV is zero, was calculated using the Griffiths method [19] (Equation 1):

$$\bar{T}_n = \frac{1}{n}\sum_{i=1}^{j}\left(T_{g,i} - \frac{TSV_i}{a}\right) \qquad \text{(Equation 1)}$$

where

$T_{g,i}$: globe temperature for the i-th subject.
TSV_i : Thermal Sensation Vote for the i-th subject.
a: regression coefficient equal to 0.5.
j: number of subjects in the subgroup.

A value of a = 0.5 was chosen due to its widespread use

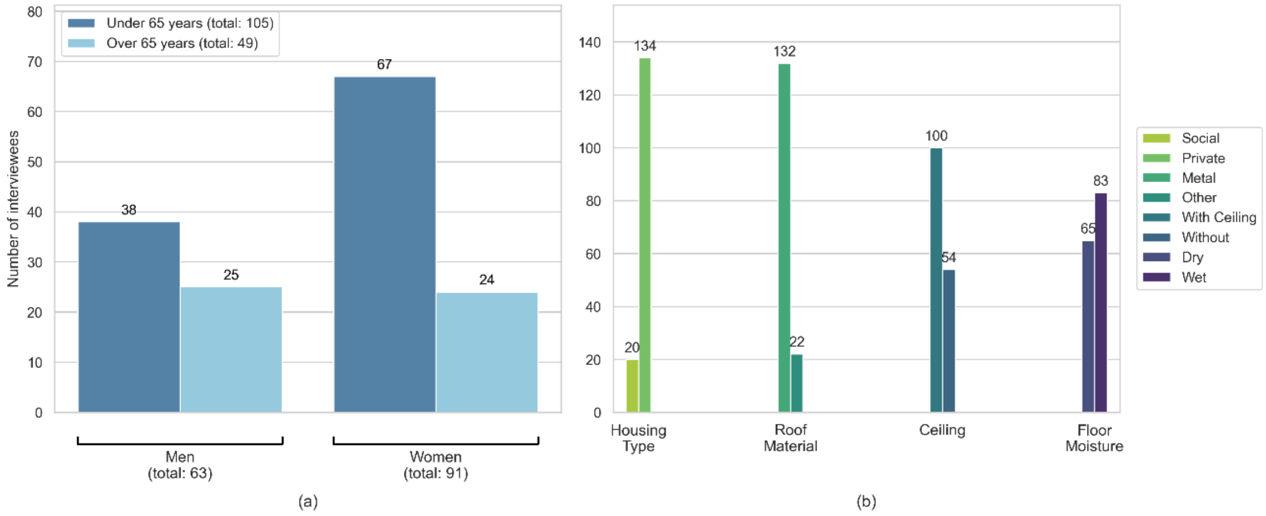

Figure 5. Distribution of interviewees according to (a) sex and age, and (b) building characteristics.

in adaptive comfort research (Humphreys et al., 2010). Although other studies have employed different values or calculated them empirically, the assumption that a 2 °C change in operative temperature corresponds to a one-unit shift in TSV provides a reasonable approximation for field surveys such as this.

Demographic effects were evaluated using variance-based tests appropriate for unequal sample sizes (Figure 5). Building characteristics were evaluated through predefined pairwise comparisons (Figure 5). Potential demographic imbalances were checked to avoid confounding effects: a Welch's t-test was used to compare the mean age of the occupants, and a Chi-squared test of independence was used to compare the sex distribution.

Adaptive behaviors were summarized descriptively to contextualize the quantitative comfort indicators.

COMPARATIVE ANALYSIS OF THERMAL COMFORT MODELS

The primary objective of this analysis was to evaluate the accuracy of five thermal comfort models in predicting the TSV of the surveyed population. The PMV model was included as a benchmark; two locally calibrated models: aPMV and ATC; and two models developed from field studies in the Peruvian highlands. Predicted TSV (TŜV) using the PMV model (TŜV_{PMV}) were calculated for each participant. PMV was included as a benchmark because of its widespread use in thermal comfort research, despite well-documented limitations in buildings with high indoor temperature swings and no mechanical conditioning, where adaptive models such as ATC generally provide more accurate predictions (Nicol et al., 2012).

TŜV using aPMV, that refines the PMV calculations by incorporating an adaptive coefficient (λ) taken from field studies, was (Equation 2, Equation 3, Equation 4):

$$\widehat{TSV}_{aPMV} = aPMV = \frac{PMV}{1+\lambda\times PMV} \qquad \text{(Equation 2)}$$

where λ was calculated as:

$$\lambda = \frac{\sum_{i=1}^{n}(TSV - PMV)}{n} \qquad \text{(Equation 3)}$$

where
n: number of interviewees [-]
TŜV from the ATC model calculated with our data was:

$$\widehat{TSV}_{ATC} = a \times \left(T_g - \underline{T}_n\right) \qquad \text{(Equation 4)}$$

where a and $\underline{T}$n were defined in Equation 1.

The first adaptive comfort model from surveys in the Peruvian Andes was developed by Molina et al. (2023). It used a five-point thermal sensation scale where $T_{n,Molina}$ is a function of the monthly mean outdoor temperature ($\underline{T}$m) (Equation 5):

$$T_{n,Molina} = 0.5\underline{T}_m + 11.8 \qquad \text{(Equation 5)}$$

To define TŜV_{Molina} on the standard seven-point scale, we calculated $\underline{T}_m$ using the outdoor air temperature recorded during the 30 days preceding the survey day. This participant-specific $\underline{T}_m$ was then used to compute the corresponding $T_{n,Molina}$ for Langui ($T_{n,Molina,Langui}$). The distribution of was 7.3 °C (95% CI: 7.3–7.3 °C; SD = 0.1 °C). Applying a sensitivity of 0.5 scale units per degree Celsius, TŜV_{Molina} was calculated as (Equation 6):

$$\widehat{TSV}_{Molina} = 0.5 \times (T_g - T_{n,Molina,Langui})$$ (Equation 6)

The second regional benchmark was from Pari-Quispe et al. (2024). They employed the seven-point scale and reported a specific T_n for the winter period of 21.98 °C, determined using the Griffiths method with a coefficient of 0.50. $\widehat{TSV}_{Pari\text{-}Quispe}$ was defined as (Equation 7):

$$\widehat{TSV}_{Pari-Quispe} = 0.5 \times (T_g - 21.8)$$ (Equation 7

The following metrics were calculated to evaluate each model.

- Mean Absolute Error (MAE) (Equation 8):

$$MAE = \frac{1}{n}\sum_{i=1}^{n} \lfloor y_i - \hat{y}_i \rfloor$$ (Equation 8)

where
n: total number of observations,
y_i: i-th observed TSV,
y_i:i -th predicted TSV.

- Root Mean Square Error (RMSE) (Equation 9):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}$$ (Equation 9)

- Classification Accuracy (Equation 10):

$$Accuracy(\delta) = \frac{100}{n}\sum_{i=1}^{n} \mathbb{I}\lfloor y_i - \hat{y}_i \rfloor \leq \delta$$ (Equation 10)

where
δ : tolerance used to determine how close predictions were to the observed TSV,
I: indicator function, which equals 1 if the condition is true and 0 otherwise.

Accuracy was evaluated at three tolerance levels: exact matches (δ=0), predictions within ±0.5 scale units (δ=0,5), and those within ±1.0 scale units (δ=1.0).

- Bias (Equation 11):

$$Bias_i = \hat{y}_i - y_i$$ (Equation 11)

The distribution of these bias values was then examined by calculating the median bias and the Interquartile Range (IQR) to assess the central tendency and spread of the errors.

Finally, to understand how model accuracy changes with thermal conditions, the survey data were grouped into 2 °C bins based on the T_g measured . For each bin, the Mean Bias (MB), MAE, and Classification Accuracy (a δ= 0.1) were calculated and plotted against aT_g to visualize performance across a spectrum of colder to warmer environments. To ensure the stability and reliability of this binned analysis, only bins containing five or more surveys were included.

RESULTS

The T_g averaged 16.8 °C (95% CI: 16.3-17.2; SD = 2.9), across all surveyed dwellings, with values ranging from 9.8 °C to 27.3 °C (Figure 6). T_i closely matched T_g, showing a strong linear association (R^2= 0.96). In contrast, the relationship between T_i and T_0 was weak (R^2 = 0.27), although remained generally higher.

Observed (TSV) reflected most participants (n=111, 72%) in the comfort region (Slightly Cool, Neutral, or Slightly Warm), and a notable portion experienced cold discomfort (Cool or Cold; n=39, 25%) (Figure 7a). Reports of nighttime discomfort in the preceding three months were common, with 83% of respondents reporting feeling cold at night and only 14% reporting comfort. The relationship between TSV and T_g was weak, with a linear regression yielding R^2=0.05 (Figure 7b).

T_n across demographic subgroups revealed no statistically significant differences based on age or sex. Each subgroup $\underline{T}_n$ clustered around the overall sample $\underline{T}_n$ of 18.2 °C (95% CI: 17.6-18.7; SD: 3.2) (Figure 8). Statistical testing indicated no significant differences among subgroups (Levene's test: p = 0.026; Welch ANOVA: F(7, 137.1) = 0.11, p = 0.998). TSV was similarly consistent across subgroups. $\underline{TSV}$ values remain close to -0.7, the overall sample mean (Figure 9), with no significant differences detected (Levene's test: p = 0.640, ANOVA: F(7, 139.6) = 0.15, p = 0.993).

Differences in $\underline{T}_n$ across the four building-related comparisons (social vs. private housing, roof material, ceiling presence, and floor moisture) were generally small (Figure 10). A significant effect was observed only between social and private housing (p = 0.001), with no confounding influence from sex or age. The remaining comparisons did not show statistically significant differences in T_n. However, a significant difference in the mean age of participants was identified between the groups for both 'Roof Material' (p = 0.042) and 'Ceiling Presence' (p = 0.024). TSV did not differ significantly across any of the building characteristics evaluated (Figure 11).

Participants reported a range of adaptive behaviors to mitigate cold discomfort. The sample exhibited high levels of clothing insulation (I_{cl}= 1.97 clo; 95% CI: 1.86-2.08; SD = 0.67), and a negative correlation between I_{cl} and T_g (Figure 12). Women reported slightly higher insulation

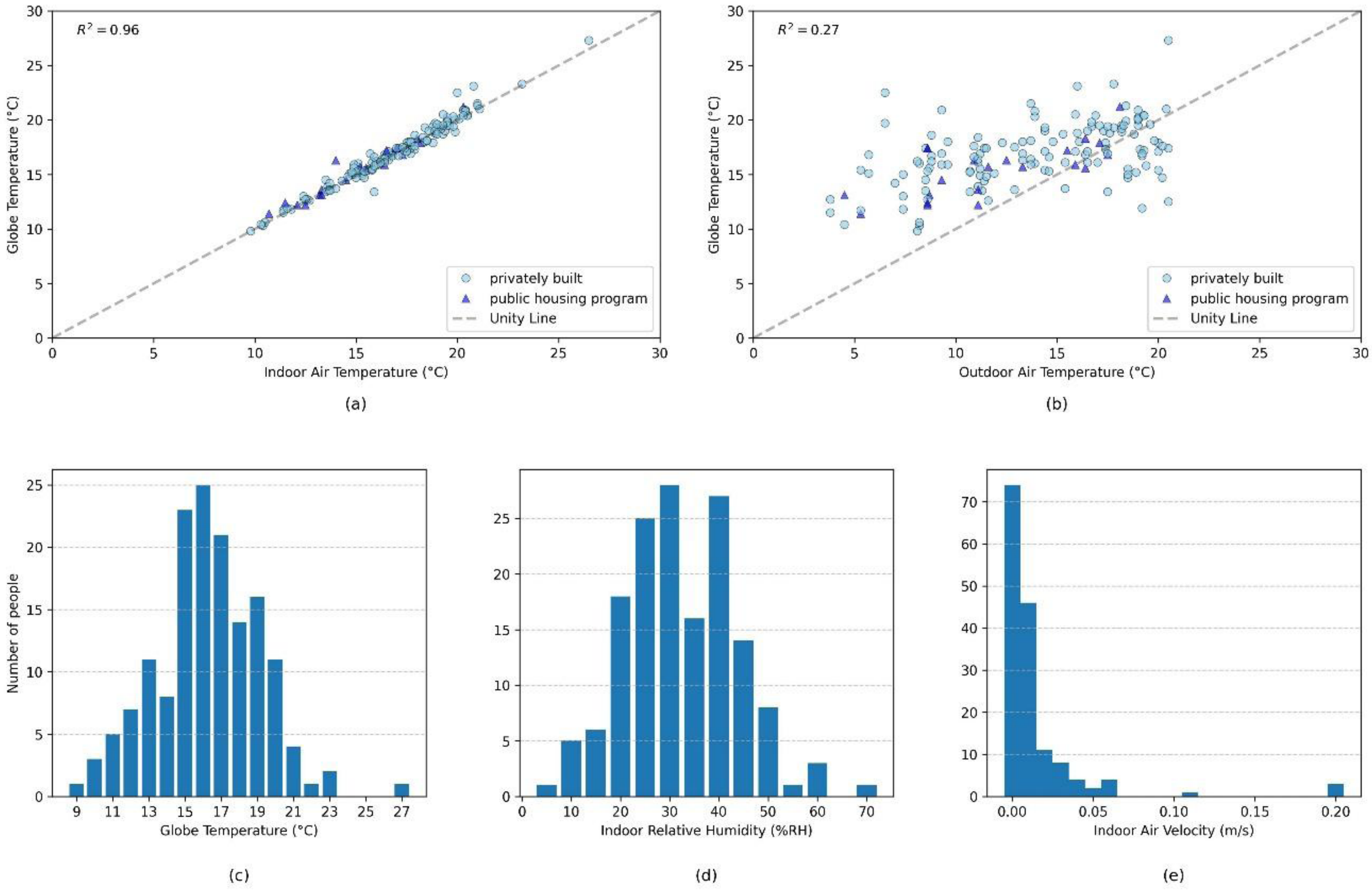

Figure 6. Environmental data during the surveys: Relationship between (a) T_i and T_g, and (b) T_o and T_g; and distributions of (c) T_g, (d) indoor relative humidity, and (e) indoor air velocity.

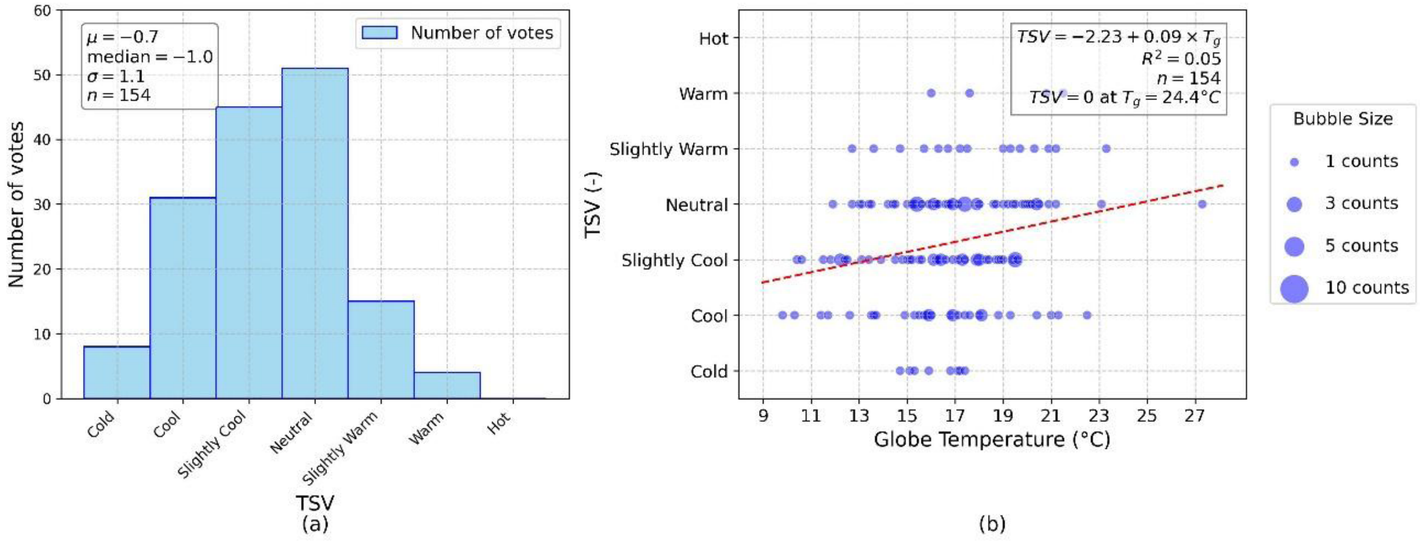

Figure 7. (a) TSV distribution, and (b) TSV and T_g relationship.

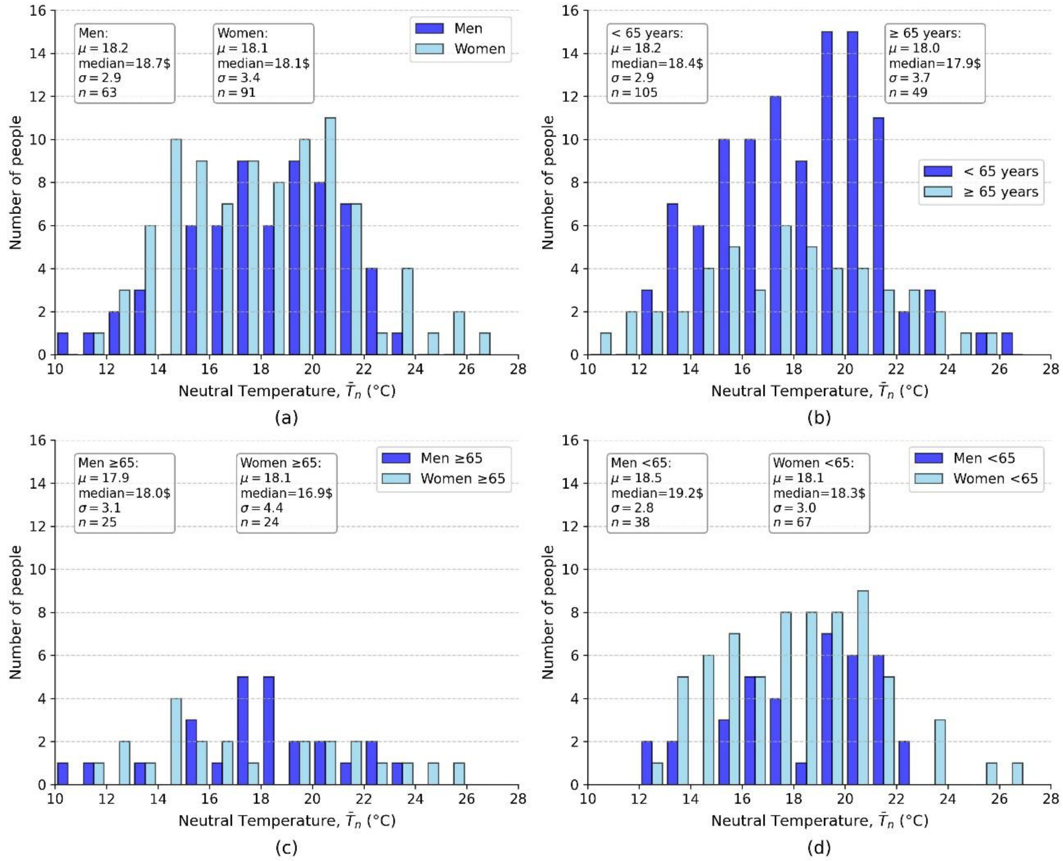

Figure 8. T_n distribution for demographic subgroups.

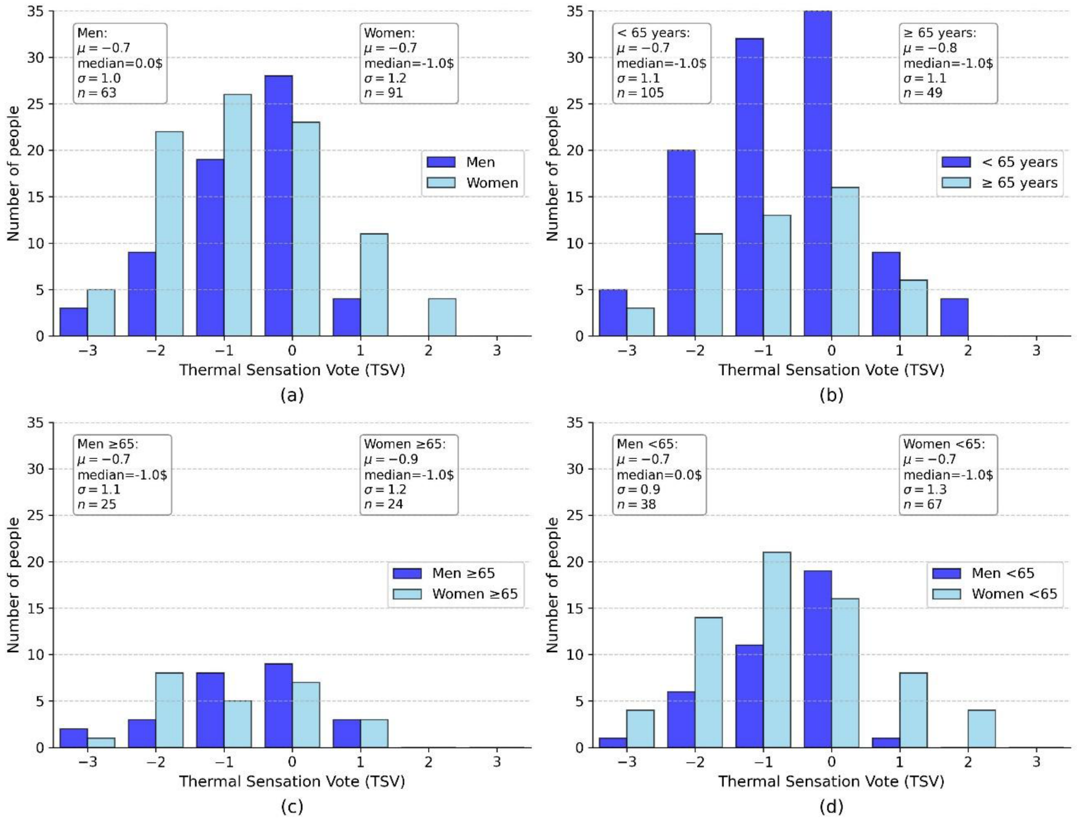

Figure 9. TSV distribution for demographic subgroups.

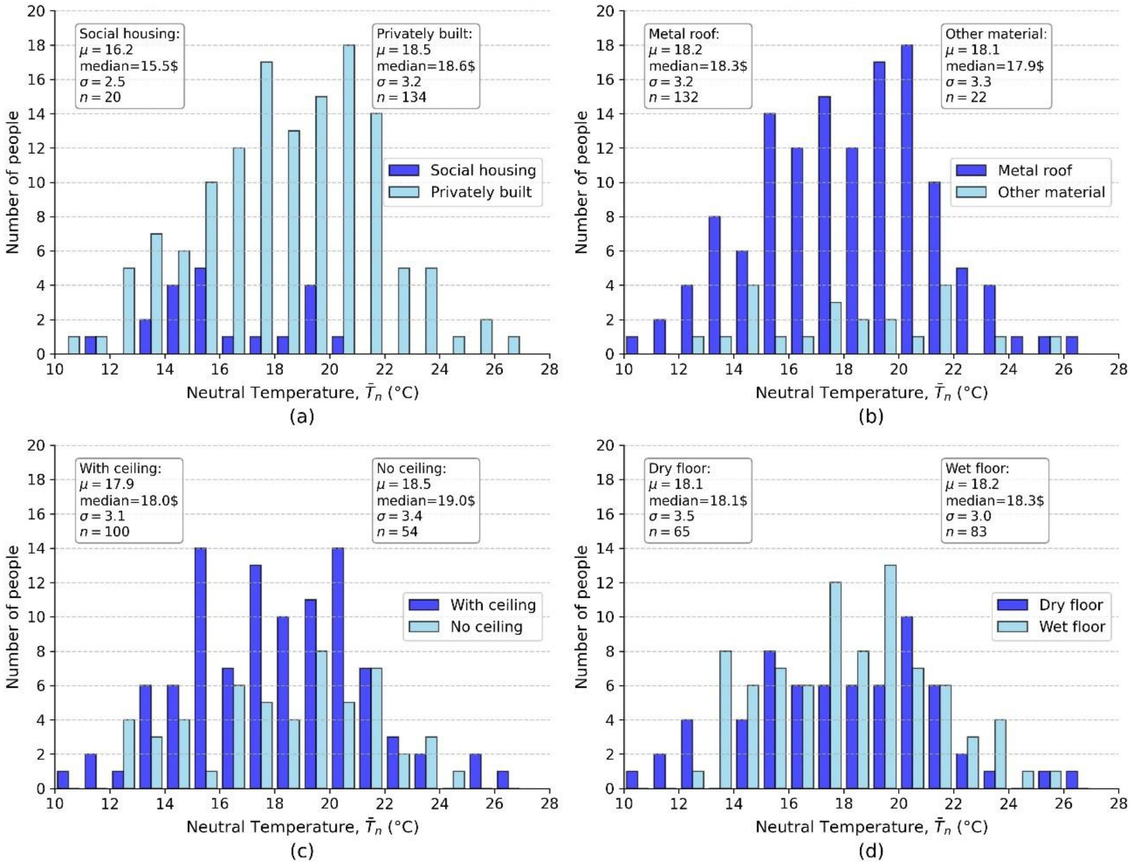

Figure 10. Distribution across building characteristic subgroups.

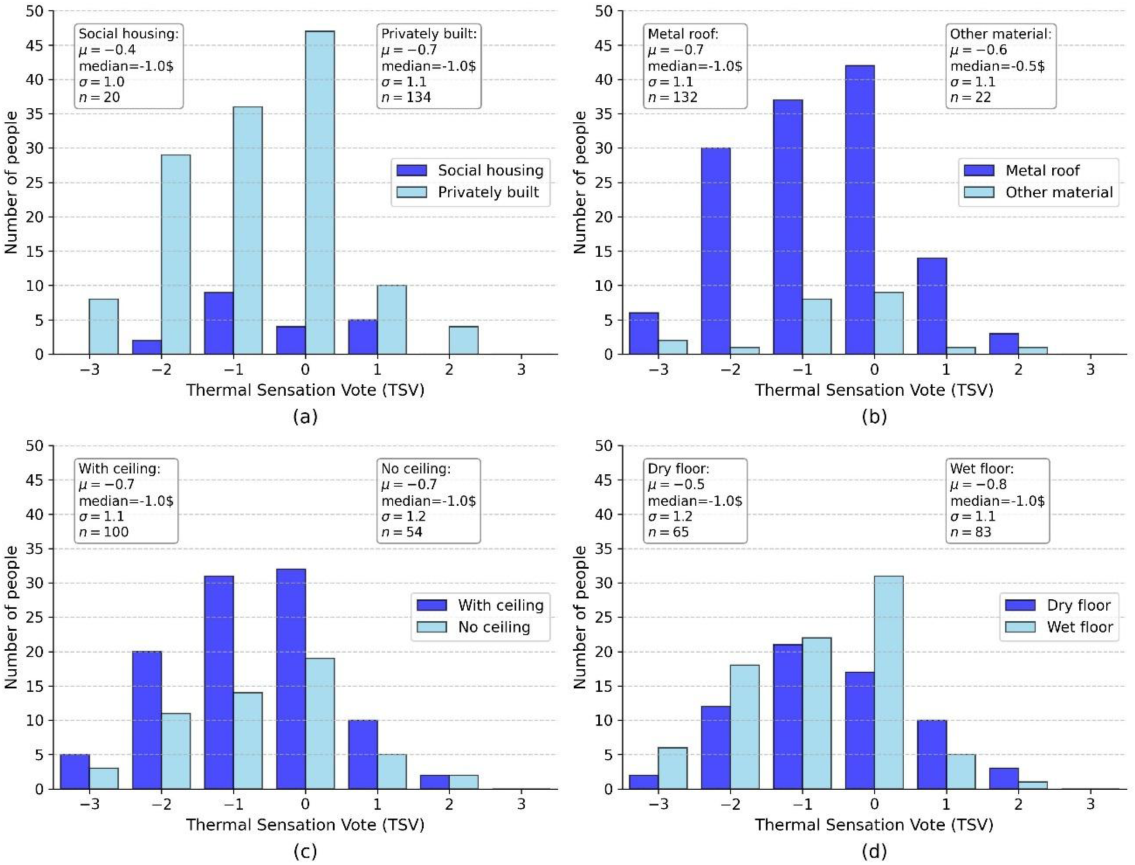

Figure 11. TSV distribution across building characteristic subgroups.

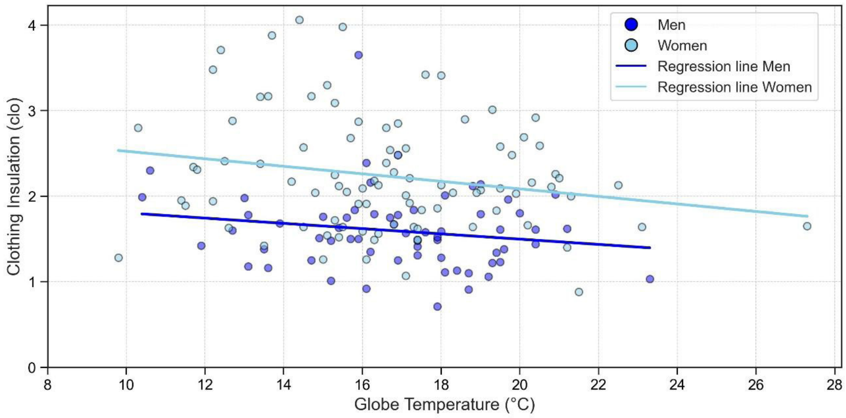

Figure 12. Relationship between $I_{cl,}T_{g}$, and sex.

Table 2. Performance metrics for the five thermal comfort models.

Benchmark Models	**MAE**	**RMSE**	**Median Bias**	**IQR**	**Accuracy (Exact)**	**Accuracy (±0.5)**	**Accuracy (±1.0)**
PMV Model	1.06	1.26	-0.85	1.26	23.08%	23.08%	48.72%
Molina Model	1.61	1.95	1.14	2.40	18.18%	18.18%	35.06%
Pari-Quispe Model	2.01	2.43	-1.78	2.39	14.94%	16.23%	32.47%
Locally developed models							
aPMV Model	1.02	1.31	0.26	1.68	29.87%	29.87%	58.44%
Adaptive Model	1.32	1.61	0.03	2.39	19.48%	20.78%	44.16%

levels than men. Other common strategies to combat the cold included using additional clothing or blankets (94% of participants), consuming warm beverages or food (48%), and using cooking stoves for warmth (13%).

A comparative analysis of the thermal comfort models revealed that the aPMV model, developed from the local survey data, obtained a of -0.26 and demonstrated the best overall predictive performance (Table 2). It achieved the lowest MAE (1.02) and highest practical accuracy, with 58.4% of its predictions falling within ±1.0 scale units of the observed TSV. The distribution of its prediction bias was centered close to zero, with a slight positive median bias of 0.26 (Figure 13b).

Notably, the standard PMV model had the smallest IQR = 1.26 and a similar MAE (1.06) (Table 2). However, consistently underpredicted TSV, with a median bias of -0.85 (Figure 13a). In contrast, the locally derived ATC, that was TSV_{ATC}=0.5×(T_g-18.2 °C), was the most unbiased of all models (median bias = 0.03), though it had a wider error distribution (IQR = 2.39). The two regional benchmark models performed poorly. Both the Molina and Pari-Quispe models had high error rates and displayed the largest systematic biases, albeit in opposite directions (median bias of +1.14 and -1.78, respectively) (Figure 13d, Figure 13e). These systematic deviations indicate the limited transferability of regional models to the conditions observed in Langui.

The aPMV model maintained a relatively stable MAE and the highest overall accuracy across the T_g range of 14-20 °C (Figure 14 a). The standard PMV model also showed stable error but exhibited a consistent negative bias, predicting colder sensations than observed (Figure 14 b). In contrast, the other models displayed strong

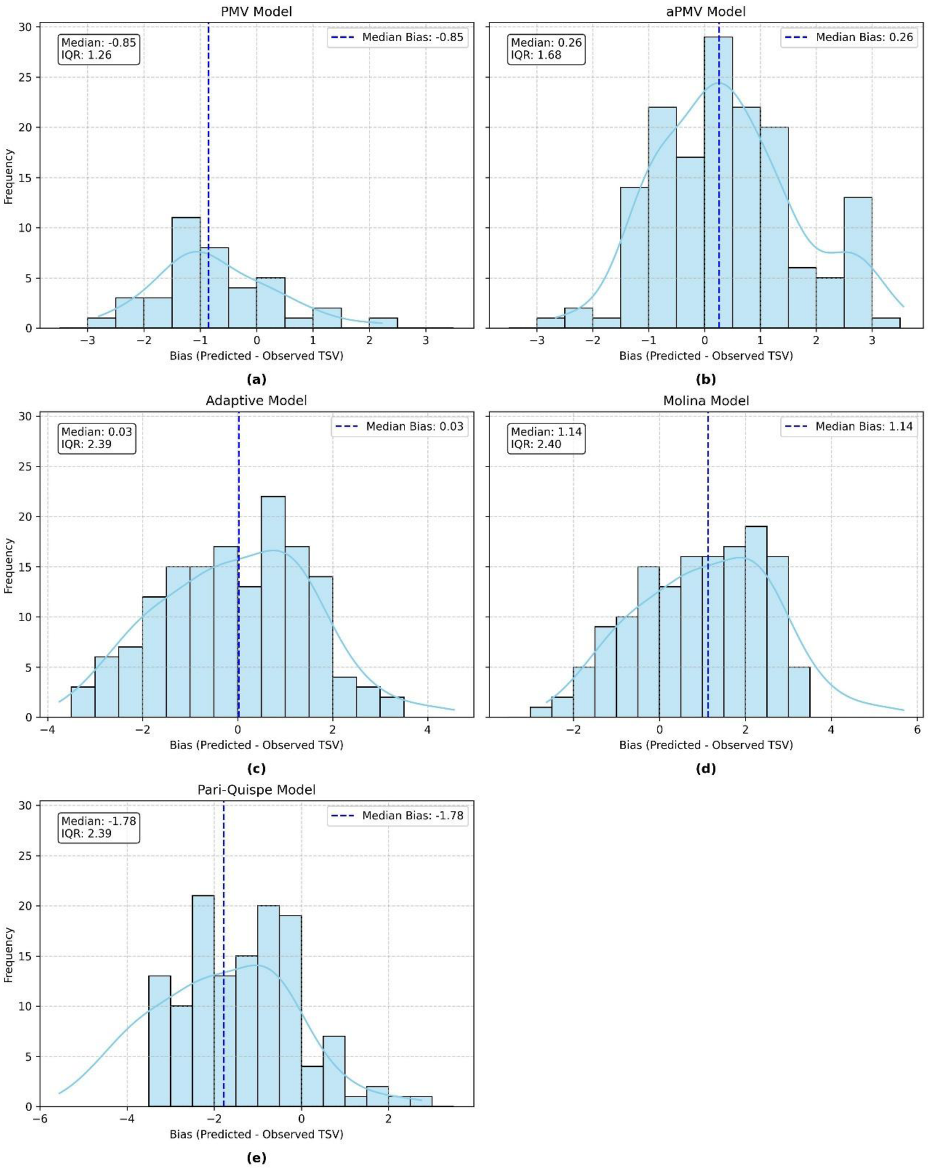

Figure 13. Distribution of prediction bias (Predicted - Observed TSV) for the (a) PMV model, (b) aPMV model, (c) Adaptive model, (d) Molina model, and (e) Pari-Quispe model.

temperature-dependent biases (Figure 14 c, d y e). Based on its superior predictive performance (Table 2), the aPMV model was used to establish a localized comfort temperature range. The 90% occupant-satisfaction range, corresponding to predicted votes between -0.5 and +0.5, was calculated to be 14 °C to 25 °C. This comfort range is valid under the average conditions observed during the survey: of 1.97 clo, a metabolic rate of 1.0 met, a mean radiant temperature of 16.8 °C, an air velocity of 0.01 m/s, and a relative humidity of 35%.

DISCUSSION

This study's primary finding is that the aPMV model, with a locally derived adaptive coefficient (λ = -0.26), emerged as the most accurate predictor of thermal sensation for residents in Langui. Using this model, we established a localized comfort temperature range of 14-25 °C, and the calculated using the Griffiths method was 18.2 °C. This preference showed no significant variation across age or sex; however, it was significantly lower among social housing (T_n: 16.2 °C) compared to those in privately built homes (T_n: 18.5 °C). These findings reflect behavioral adaptation mechanisms consistent with adaptive comfort theory, where clothing (I_{cl}:1.97 clo), routines, and expectations shape thermal perception in naturally ventilated dwellings.

This study has several limitations. Comparisons across some building-related subgroups were affected by age imbalance, although age was not found to influence thermal sensation or T_n in the sample. Nevertheless, results for these specific comparisons should be interpreted cautiously. Sampling was also influenced by the involvement of local authorities, which may have

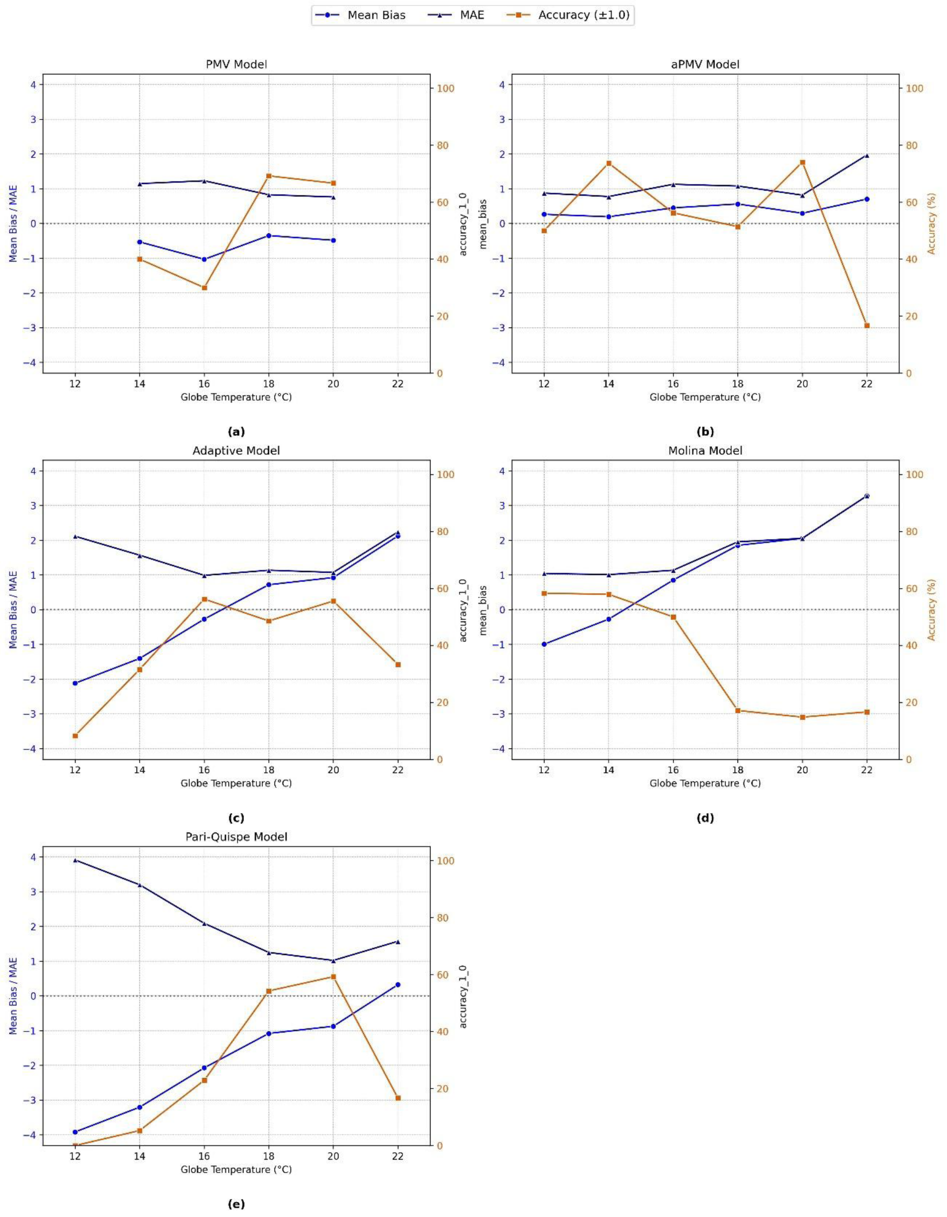

Figure 14. Model performance metrics as a function of T_g. Each subplot shows the Mean Bias, Mean Absolute Error (MAE), and Classification Accuracy (±1.0) for the (a) PMV model, (b) aPMV model, (c) Adaptive model, (d) Molina model, and (e) Pari-Quispe model, calculated in 2 °C temperature bins.

shaped the demographic composition of participants and the low representation of social housing residents. Despite substantial efforts to culturally adapt the survey instrument, some subtle misunderstandings of the thermal sensation scale may have persisted. In addition, preference and acceptability items from the original ASHRAE survey could not be retained due to translation challenges, so the analysis relies exclusively on TSV. Even so, the final sample size and analytical approach were adequate for the study objectives. Despite these constraints, this study provides one of the few systematic evaluations of thermal comfort models in the Peruvian highlands, supported by culturally adapted data collection and comparative model testing.

The performance of the aPMV model aligns with findings from similar high-altitude regions, suggesting that this approach captures adaptive behaviors more effectively than other models under these environmental conditions. The calculated adaptive coefficient (λ = -0.26) is remarkably consistent with the λ of -0.34 reported for residential buildings on the Tibetan Plateau, a region with analogous conditions of high daily temperature fluctuations and a lack of centralized heating (Yu et al., 2017). While the standard ATC model underperformed in our predictive analysis, its general utility for determining comfort temperatures in naturally ventilated buildings with high occupant adaptability remains well-documented in a wide range of studies (Nicol et al., 2012).

Because λ in the aPMV model was calibrated using the same dataset, its predictive performance may be slightly optimistic. This also applies to the ATC model, which relies on correlations between TSV and T_o. However, only aPMV outperformed PMV, despite both ATC and aPMV being dataset-derived. The ATC model, while nearly unbiased (median bias = 0.03), showed higher dispersion, reducing its performance in MAE, RMSE, and accuracy metrics. PMV, in contrast, showed lower MAE and RMSE because its systematic underprediction produced tightly clustered errors. These results do not contradict previous studies reporting stronger ATC–TSV correlations than PMV–TSV; rather, they highlight the value of complementing correlation analysis with multiple performance metrics when comparing comfort models.

T_n observed in Langui (18.2 °C) falls between values reported in two recent Peruvian studies in a similar high-altitude context (12.4 °C in (Molina et al., 2023) and 21.98 °C in (Pari-Quispe et al., 2024). The lower temperature in (Molina et al., 2023) was taken from a study focused on young residents using a five-point thermal sensation scale, whereas the higher temperature in (Pari-Quispe et al., 2024) reflects a winter-specific survey in vernacular totora houses. These differences underscore the need for standardized methods nationwide. Developing a national thermal comfort database would enable consistent comparisons, support calibration of adaptive models, and provide more robust evidence for building guidelines.

Consistent with research from other high-altitude regions, our findings confirm that comfort temperatures in Langui are lower than those predicted by international standards such as ASHRAE 55. Studies in Nepal (Shahi et al., 2021) (Rijal et al., 2010) similarly report winter comfort temperatures between 13 °C and 24 °C, reflecting adaptation to cold indoor environments. The high clothing insulation values and reliance on behavioral strategies reflect the core mechanisms of adaptive comfort theory, where occupants broaden their acceptable temperature range through sustained exposure and adaptation (Rijal et al., 2010; Yu et al., 2017). The absence of demographic differences in thermal sensation was unexpected and different from other field studies (Thapa, 2020; Yuan et al., 2022). This absence may reflect the homogenizing influence of high insulation levels, which can reduce the physiological distinctions typically observed between age and sex groups.

Differences in T_n between residents of social and private housing suggest that dwelling characteristics may influence thermal perception, although this finding is difficult to interpret. The T_o measured in social housing during the survey were within the same range as those of privately built dwellings, indicating that the lower T_n cannot be attributed to differences in thermal conditions at the time of measurement. Although a reporting bias related to gratitude for receiving subsidized housing could influence self-reported comfort, our data does not allow us to verify this or other interpretative mechanisms. Potential demographic confounders were examined and ruled out. Future research is needed to determine whether long-term exposure conditions or contextual factors help explain these differences.

Given its superior predictive performance in our comparative analysis, aPMV emerges as a suitable index for evaluating indoor thermal conditions in high-altitude rural housing and for guiding the assessment of building interventions. The comfort range of 14–25 °C calculated in our study provides one of the first empirically grounded benchmarks for high-altitude rural buildings in Peru and can be used to assess whether current dwellings meet residents' comfort needs. The fact that 83% of participants reported nighttime cold discomfort underscores the need to prioritize improved indoor thermal conditions as a public health concern. In this context, the lower threshold of 14 °C offers a practical reference for supporting building designs or retrofit strategies in housing programs, as well as for guiding residents who wish to improve their own homes to address the prevailing experience of nocturnal cold discomfort.

Based on the study's findings, several directions for future research emerge. Further work is needed to identify the design features of social housing that may contribute to improved thermal comfort and to understand how comfort preferences evolve over time in such dwellings. Expanding demographic representation would help clarify the thermal needs of children and other vulnerable groups. Finally, additional methodological research is required to refine culturally appropriate thermal sensation scales for high-altitude populations. Strengthening these areas of inquiry will contribute to the development of housing solutions that improve comfort and health outcomes in the Andes.

CONCLUSION

This study evaluated the performance of five thermal comfort models in the high-altitude Andean community of Langui. The aPMV model, calibrated with a local adaptive coefficient (λ = -0.26), showed the highest agreement with reported thermal sensation, supporting a comfort temperature range of 14–25 °C. Despite strong behavioral adaptation, the widespread nighttime cold indoor environment indicates that current dwellings do not meet basic thermal needs.

The study provides one of the first contextualized assessments of comfort model applicability in the Peruvian highlands and offers indicators that can support future evaluation of Andean housing. While limitations include non-random sampling and the low representation of social housing, the results provide a solid basis for further work. Future research should examine long-term performance in social housing, broaden demographic representation, and refine culturally adapted survey instruments to strengthen comfort assessments in high-altitude contexts.

AUTHOR CONTRIBUTION CRediT

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