Integrating regenerative design with adaptive thermal comfort: insights for sustainable rural housing in India's composite climate

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Abstract

The architectural characteristics of traditional rural habitats in India, characterised by greater openness to the external environment, offer residents a more dynamic means of regulating indoor thermal conditions compared to modern urban apartments. This research integrates regenerative design principles with thermal comfort studies to better understand how adaptive thermal comfort strategies can inform sustainable development in rural settings. Specifically, it explores rural residents' perceptions and adaptive behaviours within India's composite climate, which remains understudied in thermal comfort literature. Field studies conducted in June and July 2020 involved 315 survey responses from 105 participants across eight villages in Bulandshahr district, Uttar Pradesh (India). They were paired with concurrent environmental measurements in typical rural dwellings. Surveys were conducted three times daily to capture shifts in comfort responses and adaptive measures such as moderating indoor air movement, reducing activity levels, and resting to restore thermal comfort.

The study revealed that rural residents rely heavily on adaptive strategies, including region-specific attire and open housing layouts, despite limitations posed by socio-cultural factors, particularly for women. The analysis identified a neutral temperature of 30.38°C and a comfort zone between 27.98°C and 32.79°C. Interestingly, even as measured conditions often exceeded comfort standards, residents accepted their indoor environments and tolerated high temperatures, underscoring their unique thermal expectations. Findings indicate that these adaptive responses not only fulfil immediate comfort needs but also align with regenerative design principles by optimising natural ventilation, minimising mechanical cooling demands, and promoting sustainable living in rural settings. Insights from this study offer valuable guidance for energy-efficient rural housing design under the Pradhan Mantri Awas Yojana (PMAY) – Rural scheme, promoting regenerative approaches that enhance indoor thermal comfort and foster resilient, climate-responsive habitats in India's composite climate.

Introduction

The well-known trajectory of environmentally responsive design[1], developed over the last few decades, generally distinguishes anthropocentric (technological) and biocentric (ecological) models of sustainability Fig. 1.

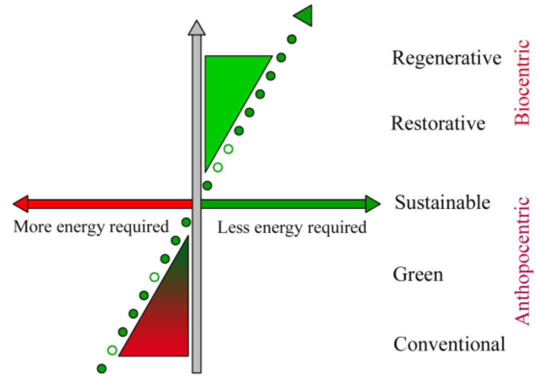

Fig. 1. Environmentally responsive trajectory

While aspiring for net-zero or optimized environmental load in terms of waste, water, carbon, or energy are important objectives, the built environment should go beyond. The built environment must not merely focus on preserving/conserving; instead, it should aim to revitalize and regenerate to have a net positive environmental impact while correcting destruction and pollution.

Energy consumption in the domestic sector is about 26% of the total energy consumed in India; their demand and usage are continuously increasing[2]. Most of this domestic energy is consumed for lighting and cooling to ensure visual and thermal comfort indoors. United Nations' Sustainable Development Goal 3 also emphasizes "Health and Wellbeing." It is, therefore, entails that a dwelling is required to afford indoor conditions for human thermal comfort, which strongly influences occupant health and wellbeing and energy conservation.

The regenerative design of a dwelling and the choice of building materials depends a great deal on the prevailing external climate and the thermal comfort necessities of occupants. As the first step to systematic dwelling design, it is, therefore, necessary to assess the external climatic variables and articulate the indoor conditions that are likely to be desirable and the conditions that have to be avoided. These conditions serve as guidelines in assessing the range of values of physical parameters in which one would feel thermally comfortable.

Thermal comfort

ASHRAE[3] handbook defines Thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment." Thermal comfort is a complex function of the physiological factors: metabolic rate (level of activity) and clothing and the environmental factors, viz. air temperature, humidity, air movement, and radiation[4]. The other contributing factors which may determine how thermally comfortable a person senses in a given context are: living habits, acclimatization, body shape, subcutaneous fat, age, gender, food and drink. Generally, thermal comfort is categorized according to the type of environment: indoor, semi-outdoor or outdoor. The provision of thermal comfort indoors is a fundamental objective of building professionals.

The present discussion mainly involves two distinct theoretical models to understand scientifically and predict thermal comfort and thermal sensation more practically. The first is the constancy model established by Fanger for air-conditioned environments in the 1970s based on the steady-state energy balance of the human body[5]. Fanger's PMV index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. PMV is calculated using five indoor environmental factors (air temperature, relative humidity, mean radiant temperature, air velocity, and water vapour pressure) and occupants' two personal factors (metabolism and clothing). After estimating the PMV, the predicted percentage dissatisfied (PPD) with a condition can also be calculated, where dissatisfied is defined as anybody not voting -1, +1 or 0. The PMV-PPD model was adopted by the ISO standard 7730[4] and ASHRAE 55 standards[6] and widely used and accepted for design and field assessment of comfort conditions in air-conditioned environments.

The second is the adaptive thermal comfort model, which assumes an adaptation to the thermal environment to a certain level. The adaptive thermal comfort model is an empirical model developed based on a series of in-situ studies. This model correlates people's responses to quantifiable environmental factors. The thermal adaptation can be accounted for through occupants' adjustments to the surrounding environment, involving physiological acclimatization, psychological expectation or habituation, and behavioural considerations[7,8].

The adaptive thermal comfort model is recommended by numerous national and international standards, for instance, ASHRAE standard 55-2020[9], EN 15251-2007[10], EN 16798[11], ISO 17772[12] Chinese standard GB/T 50785-2012[13], National Building Code of India-2016[14], IEA Annex 69[15], and others, Table 1.

Table 1: Preliminary details of five adaptive thermal comfort standards

S. No.	Thermal comfort standard	Description	Limitations	Acceptable operative temperature		Applicable scope
				Upper limit	Lower limit	
1.	ANSI/ASHRAE 55-2020 [8] (adaptive model)	The database of 21,000 samples was collected worldwide from 160 buildings in nine countries as part of the ASHRAE project RP-884[16]	This model applies only to naturally conditioned spaces.	T_{op} = 0.31. T_{rm} + 21.3 (80% acceptability) T_{op} = 0.31. T_{rm} + 20.3 (90% acceptability)	T_{op} = 0.31. T_{rm} + 14.3 T_{op} = 0.31. T_{rm} + 15.3 (90% acceptability)	10<= T_{rm} <=33.5°C
2.	EN 15251-2007 [10]	The Smart Control and Thermal Comfort project (SCATs), commissioned by the European Commission, is the basis of this standard	It applies to both: buildings in free-running mode and mechanically cooled buildings.	T_{op} = 0.33. T_{rm}+ 20.8°C (category I 90% acceptability) T_{op} = 0.33. T_{rm} + 21.8°C (category II 80% acceptability) T_{op} = 0.33. T_{rm} + 22.8°C (category III 65% acceptability)	T_{op} = 0.33. T_{rm} + 16.8°C (Category I 90% acceptability) T_{op} = 0.33. T_{rm} + 15.8°C (category II 80% acceptability) T_{op} = 0.33. T_{rm} + 14.8°C (category III 65% acceptability)	10<= T_{rm} <=30°C
3.	EN 16798 [11] ISO 17772 [12]			T_{op} = 0.33. T_{rm} + 20.8°C (Category I 90% acceptability) T_{op} = 0.33. T_{rm} + 21.8°C (category II 80% acceptability) T_{op} = 0.33. T_{rm} + 22.8°C (category III 65% acceptability)	T_{op} = 0.33. T_{rm} + 15.8°C (Category I 90% acceptability) T_{op} = 0.33. T_{rm} + 14.8°C (Category II 80% acceptability) T_{op} = 0.33. T_{rm} + 13.8°C (Category III 65% acceptability)	10<= T_{rm} <=30°C
4.	Chinese standard GB/T 50785-2012 (2) [13]		Severe cold and cold region	T_{op} = 0. 77 T_{rm} +12.04 (category I - 90% acceptability) T_{op} = 0. 73 T_{rm} + 15.28 (category II-75-90% acceptability)	T_{op} = 0. 87 T_{rm} + 2.76 (category I-90% acceptability) T_{op} = 0.91 T_{rm} -0.48 (category II-75-90% acceptability)	18 <= T_{rm} <=28°C (category I) 18 <= T_{rm} <=30°C (category II upper limit) 16 <= T_{rm} <=28°C (category II lower limit)
			Hot summer and cold winter region, hot summer and warm winter region and moderate area	T_{op} = 0. 77 T_{rm} + 9.34 (category I-90% acceptability) T_{op} = 0. 73 T_{rm} + 12.72 (category II-75-90% acceptability)	T_{op} = 0. 87 T_{rm} -0.31 (category I- 90% acceptability) T_{op} = 0. 91 T_{rm} -3.69 (Category II-75-90% acceptability)	18 <= T_{rm} <=28°C (category I) 18 <= T_{rm} <=30°C (category II upper limit) 16 <= T_{rm} <=28°C (category II lower limit)
5.	National Building Code of India - 2016[14]	This model is based on adaptive thermal comfort studies in 16 office buildings in three seasons in five cities (representative of five climatic zones of India).	This model is applicable for naturally conditioned, mixed mode and conditioned spaces.	T_{op} = 0. 54 T_{rm} +15.23 (naturally conditioned)	T_{op} = 0. 54 T_{rm} +10.43 (naturally conditioned)	12.5 <= T_{rm} <=31°C (naturally conditioned)

Note: T_c is the thermal neutral temperature (operating temperature), T_{rm} is the outdoor smoothing week average temperature, T_{m,out_av} is the outdoor monthly mean air temperature, and T_{out_av} is the continuous average outdoor air temperature.

Many studies have analyzed adaptive thermal comfort in various typologies of buildings in different climatic and technological contexts[17]. It is abundantly established that the occupants' thermal adaptation mechanism in non-residential buildings can differ from that in residential buildings due to different levels of adaptive opportunities afforded to the occupants. Thermal comfort investigation has been taken up in residential environments in diverse climate zones in India[18]. Thermal comfort standards (IMAC-R)[19] recommended for residential buildings adopted in India are based on the analysis of urban residences; thermal comfort in rural residential buildings has been largely overlooked. Given the contextual difference between rural and urban dwellings, this research questions whether the extant thermal comfort standards cannot be directly applied to rural contexts.

Research outcomes previously specified that climate and living conditions could affect occupants' thermal comfort levels. According to earlier research into the thermal comfort of dwellings in hot and humid climates, the likely reasons of specific thermal comfort conditions of rural dwellers are due to the local culture, occupants' thermal expectation and their environmental perceptions[20] [20]. Those non-climatic factors potentially influencing respondents' thermal comfort and associated behaviours are worthy of further study to facilitate comprehensive appraisal. Rural dwellings' occupants are supposed to make their behavioural adjustments to adapt to the surrounding environment to reduce thermal discomfort in summer. While India is a predominantly agricultural economy, approximately 68% of the population lives in rural contexts. It is well known that rural living and housing conditions are very different from urban areas; for example, mechanical cooling and heating are not provided in rural residences as per the Census of India-2011 [21].The flagship rural housing programme in India, "The Pradhan Mantri Awaas Yojana- Gramin (PMAY-G)", is being implemented w.e.f. 1st April 2016, Table 2 explains the present status and future targets of the scheme. It can be concluded that there is limited thermal comfort research accounted for from rural India, and there is a need to systematically investigate the thermal comfort conditions of rural dwellings in the composite climate.

The paper aims to assess the summer thermal comfort requirements of the occupants of rural dwellings in India. Since summer was warm and humid, relative humidity significantly affected comfort perception. The paper examines the objective indoor thermal condition, the participant's subjective responses (thermal preference and sensation), activity levels and clothing insulations. Rural residents in the composite zone preferred a warmer summer comfort temperature and exhibited higher acceptance of the thermal environment when compared to the National Building Code of India, probably due to the long history of inhabitation and acclimatization to the microclimate.

Table 2 Pradhan Mantri Awas Yojna- Gramin

	Key Parameter Indicators	Value
A	Total Target	2,92,96,775
B	Total Beneficiaries Registered	3,17,00,361
C	Total Geo-Tagged	3,10,54,670
D	Total House Sanctioned	2,85,15,352
E	Total House Completed	2,20,10,264

Source: https://dashboard.rural.nic.in/dashboardnew/pmayg.aspx (4.4.2023)

Methodology

The field study offers "first-hand" data which helps to comprehend the thermal comfort of occupants in their actual daily environment. Usually, this kind of study requires two types of data; subjective and objective field measurements. The standard thermal comfort questionnaire was used for the subjective measurement, and simultaneous physical measurement of indoor and outdoor environmental factors. Thus, a total of 315 sets of subjective and objective field measurements were gathered (105 participants thrice a day). Due to the limited availability of human resources and instruments in rural areas, field measurements were conducted in the summer from 24/06/2020 to 02/07/2020.

Locations and investigated villages

India has five climate zones according to the National Building Code[14] (Part 8, Section 1, Clause 3.2), including a composite zone, hot-dry zone, warm-humid zone, temperate zone and cold zone for the design of built environment (Fig. 2). The composite zone occupies 2/3 part of India and is densely populated. The composite zone is defined as a region that does not have any season for more than six months. Typical seasons in the composite climate zone are hot-dry summer, warm-humid monsoon, temperate spring/autumn and cold winter. The dwellers in this zone have the challenge of maintaining indoor comfort in different seasons-summer, winter and monsoon. Given the large area with high population density and seasonal variations in climate conditions, the composite zone will have to deal with enormous challenges in maintaining occupants' health and well-being and coping with increasing energy demand over the course of meeting the targets of the PMAY-G. Hence, the scope of the study is articulated to understand thermal comfort requirements in the naturally ventilated rural dwellings of composite climate zone.

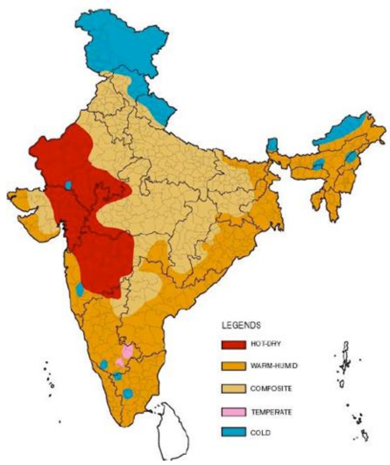

Fig. 2. Five climate zones in India[14]

Fig. 3. Bulandshahr district in Uttar Pradesh state

Source: open source
https://en.wikipedia.org/wiki/File:India_Uttar_Pradesh_districts_2012_Bulandshahr.svg#file

Bulandshahr district in Uttar Pradesh is a predominately rural area, Fig. 3; field measurements were conducted in eight typical villages (Fig. 4) with on-site measurements of environmental factors and simultaneous recording of subjective thermal comfort responses using questionnaire surveys. These villages fall within the composite climate zone and manifest predominately four seasons: summer, monsoon, temperate (autumn and spring) and winter. These locations are classified under humid subtropical climate (Cwa) as per Koppen climate classifications[22].

Fig. 4. Eight villages in Bulandshahr
Source: Google Earth image

The investigated rural dwellings represent conventionally designed separate dwellings without enforced building energy codes. The sample dwellings in rural areas were constructed between 1990 and 2015. The layout of the rural dwelling was open to the outdoor environment, with extensive surface areas (i. e. exterior roofs and walls) being directly exposed to the outdoor conditions. The orientations of dwellings varied North-South as well as East-West. Typical plans of dwellings are shown in Fig. 5. Rural dwellings are single or double-storey load-bearing structures generally constructed on a raised plinth. The walls are 0.25 m- 0.30 m and are built from traditional burnt bricks. The flat roofs are of two types; one consists of layers of mud and bricks over 20-25 mm thick red sandstone slabs (600 x 600 mm or 600 x 900 mm) laid over steel I section beams supported by brick walls, and the other consists of reinforced cement concrete slabs (100 or 150 mm) supported by brick walls, Fig. 6. The flooring in the invested dwellings was usually IPS, brick or tile. The sample dwellings were typically equipped with windows having wooden frames and single glass panes or wood shutters. The large front door is often made of wood in the investigated dwellings.

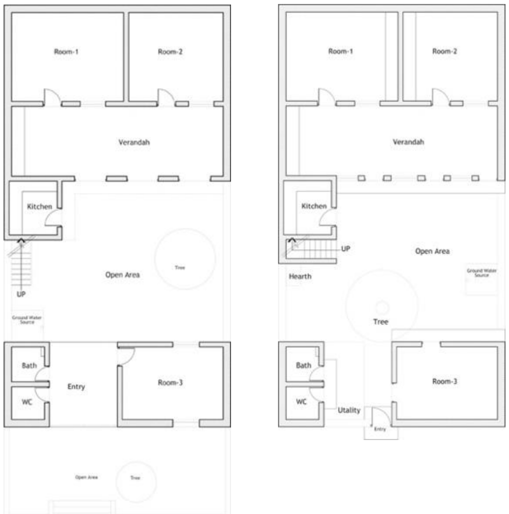

Fig. 5. Typical Floor plan of the dwellings

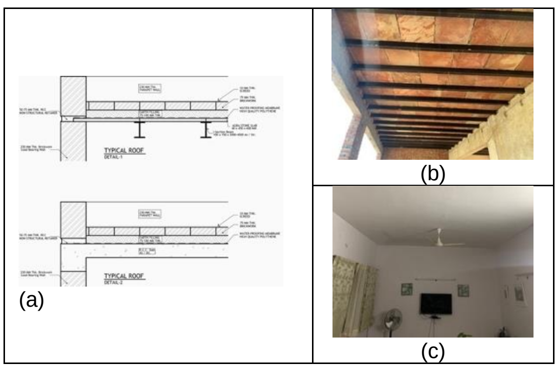

Fig. 6. Typical Roof details

All investigated dwellings were naturally ventilated during the field monitoring, as front doors always remained open regardless of the summer season. Most of the rural dwellings were equipped with ceiling fans. The data gathered from the field survey were analyzed to thoroughly understand the respondents' thermal comfort perceptions and the indoor thermal environment.

Subjective Questionnaire

The thermal comfort questionnaire used the standard "right-here-right now" type of questions, translated into Hindi. The questionnaire was designed to collect participants' demographic information (age, gender, and health condition) followed by thermal responses to ambient thermal stimulus, including thermal sensation vote (TSV), thermal preference vote (TPV), thermal acceptability vote (TAV), humidity sensation vote (*HSV*) and air movement sensation vote (AMS). The questionnaire items, rating scales and coding schemes are adapted from[23] and summarized in Table 3.

Table 3 Summary of questionnaire items and rating scale utilized in this research

No.	Questionnaire Item	Voting Scale				
1.	Thermal sensation vote (TSV)?	Hot +3.0, warm +2.0, slightly warm +1.0, neutral 0, slightly cool -1.0, cool -2.0, cold -3.0				
2.	Thermal preference vote (TPV) Would you like to be?	Needs warmer (1)	No change (0)		Needs cooler (-1)	
3.	Thermal Acceptability vote (McIntyre scale) TAV	Need cooler (-1)	Acceptable (0)		Need warmer (1)	
4.	Humidity sensation vote (HSV)	Too damp (2)	A little damp (1)	Just right (0)	A little dry (-1)	Too dry (-2)
5.	Air movement sensation (AMS)?	Too windy (-2)	A little windy (-1)	Just right (0)	A little still (1)	Too still (2)
6.	How much comfortable are you now?	very comfortable … very uncomfortable				
7.	How much is your satisfaction with respect to the indoor environment?	Unsatisfactory -6.0, -5.0, -4.0, -3.0, -2.0, -1.0, 0 Satisfactory				

Fig. 7. Subjects and surveyed environment

The participants answered each questionnaire item by choosing their options on the printed paper sheets. The researchers estimated each respondent's metabolic rate (MET, met) according to ISO 7730 and ASHRAE standard 55. The questionnaire included a checklist with clothing items for participants to choose from, and the researcher estimated clothing insulation (I_{cl}, clo) as explained in section 3.2.2. Two frequently used thermal indices, standard effective temperature (SET) and predicted mean vote (PMV), was calculated for each sample. Each household member was requested to complete the questionnaires at his or her convenience, provided that the respondent had resided in the given climate zone for more than four years and his/her age was in the range of 15 to 75.

Table 4. Details of villages surveyed during the summer

Village	**Number of Persons**	**Total responses**
Mohana	14	42
Kajmpur Devli	7	21
Fakana	12	36
Fatehpur Ladabas	11	33
Sanota	14	42
Aurangabad	14	42
Heralal Grhi	14	42
Bharana	19	57
Total	105	315

Table 5 Participants' characteristics

1	Total villages	EIGHT
2	Sample size	105
3	Date of Summer survey	24 June 2020 to 2 July 2020
4	Meeting time	8:30 to 11:00 AM- 12:30 to 2:30 PM- 3:30 to 5:30 PM
5	Gender Males Females	 65 40
6	Age (Years) Maximum Minimum	 75 yr 18 yr
	Mean Female (mean) Male (mean)	46.14 48.05 44.97
	Standard Deviation Female (SD) Male (SD)	16.78 16.79 16.81

The standard thermal comfort questionnaire was administered to participating householders to collect subjective responses (Table 3); Fig. 7 shows some participants. As per the standard operating procedures (SOP) prescribed by the institute ethics committee of IIT Delhi[24], which is based on Ethical guidelines for Biomedical research on human subjects by ICMR, the whole survey process was clearly explained to all the participants before taking their responses. The number of samples gathered for each village was big enough to adequately represent householders in the region studied,

Table 4. Table 5 presents the demographic information (age and gender) of the participants.

Environmental factor Measurements

The spot measurements of temperature, humidity and air movement were taken up while taking up the questionnaire responses. Each measurement lasted 6hr, and the thermal comfort questionnaires were administered a day thrice with a minimum of 3 hr. Apresys data logger, anemometer, globe thermometer and digital thermometer were positioned in the middle of the room in proximity to the respondent (N/M) and recorded the indoor environmental parameter, including air temperature (T_{in}, ºC), globe temperature (T_g, ºC), relative humidity (RH_{in}, %), and air velocity (V_a m/s). Table 6 summarizes the specification of the instruments (measurement range and accuracy) in compliance with ISO 7726[25].

The outdoor environmental factors, including air temperature (T_{out}, ºC) and relative humidity (RH_{out}, %), were recorded by setting an Apresys datalogger in the shade near the investigated building; the interval for measurement was set as 10 min. Further, the continuous daily outdoor air temperature of Bulandshahr during all monitoring days was also taken for reference from CBE Clima Tool[26].

Mean radiant temperature (*T_{mrt}*) is calculated by the following equation (Eq 1) ISO 7726:

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{h_g {V_a}^{0.6} \left(T_g - T_a\right)}{\in D^{0.4}} \right]^{\frac{1}{4}} - 273.15 \qquad (1)$$

Where,

h_g is the globe's mean convection coefficient.

For Black globe: $h_g = 1.1*10^8*V_a^{0.6}$

For Grey globe: $h_{cg} = 1.335*10^8*V_a^{0.71}$

V_a - wind velocity (m/s)

$\in$ - emissivity of globe (= 0.95)

D - diameter of the globe (mm)

T_g - globe temperature (°C)

Indoor operative temperature (T_{op}) was computed, accounting for the effects of air temperature, radiant temperature and air velocity, as given in equation 2 [5]

$$T_{op} = A\, T_{in} + (1-A)\, T_{mrt} \qquad (2)$$

Where,

A is the coefficient of the air temperature and radiant temperature based on air velocity.

A = 0.5 when V_a is below 0.2m/s,

A = 0.6 when V_a is between 0.2m/s and 0.6 m/s.

A = 0.7 if the value of V_a was above 0.6 m/s.

Table 6. The instrument used LCD Apresys Data Logger, DIEHL thermotron hygro, and Omega Multi-functional Environmental meter.

Instrument	Physical quality	Range	Accuracy
Apresys Datalogger	Air Temperature Humidity	-30 to +70◦C	+/-0.5 ◦C, +/- 3% RH
			
Anemometer GM816	Air velocity temperature	-10 ◦C ~+45 deg	+/- 2 deg C
			
Digital Thermometer Winner DTM 902	Global temperature	-40 T0 30 ◦C	1.5% +/- 2◦C Full Scale
			
6802 II Dual Channel Digital Thermometer With 2 K-Type Thermocouple Sensor	Global temperature	-50 ~ 1300 °C	±0.1 °C ± 0.4 Operating
			

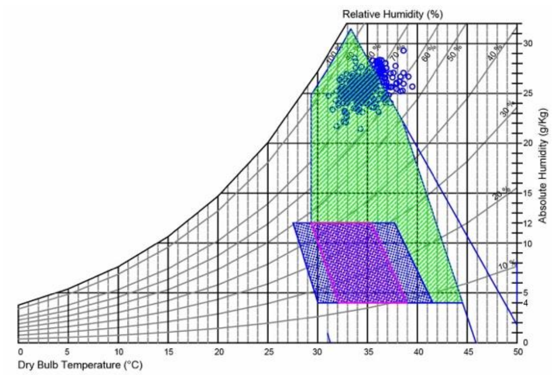

Fig. 8. Measured indoor thermal conditions mapped on the psychrometric chart and compared with the comfort zones (ASHRAE – pink and IMAC- blue

Data Cleaning and Analysis

It should be notable that data uncertainties from subjective votes are unavoidable in thermal comfort field research[27]. Hence, the data cleaning is essential to achieve a consistent data set, up to the data correlation that allows for certainty of the results. This study used standard thermal comfort questionnaires and field measurement instruments. The survey responses were meticulously examined to remove irrational or uncompleted 13 responses, and the remaining 302 responses were processed. The data was processed in three stages: a) outliers detection: Z-score b) Omission of non-representative thermal sensation categories, c) Omission of thermal sensation categories with the same value at physical variable.[28] The levels of significance for statistical analysis were set at $p < 0.05$ to ensure the precision of the results. Linear regression was employed to determine the correlation between TSV/T_{op} and PMV/T_{op}.

Results

Measured thermal environments and building thermal performance

Measured thermal environments

Table 7 presents descriptive statistics of the measured indoor and outdoor thermal environmental factors for the monitoring period. For temperature, the maximum T_{out} is 0.3 K higher than the T_{in}, and the minimum T_{out} is 0.5 K higher than the T_{in}. For Relative humidity, the maximum RH_{out} is 3.6% higher than the RH_{in}, and the minimum RH_{out} is 0.2% higher than the RH_{in}. Since low indoor air velocity and no significant effect of radiation were detected in the sample dwellings, the operative temperature is close to the indoor air temperature.

Table 7 Descriptive statistics of the measured indoor and outdoor environmental factors

Environmental factors	**Minimum**	**Maximum**	**Mean**	**SD**
T_{in} (°C)	31.1	39.5	34.83	1.53
T_{op} (°C)	31.06	39.34	34.89	1.53
RH_{in} (%)	54.1	85.2	70.82	5.77
V_a (m/s)	0.1	1.2	0.677	0.323
T_{out} (°C)	31.6	39.8	35.09	1.56
RH_{out} (%)	54.3	88.8	69.72	6.13

In order to broadly describe the monitored thermal environments, T_{out}, T_{in}, RH_{out} and RH_{in} are measured when each questionnaire has been completed. The samples are collected in naturally ventilated dwellings. Therefore, all the indoor data points are mapped on the psychrometric chart and compared against the adaptive thermal comfort zones (80% acceptability range) applicable for naturally ventilated residential buildings. All the observations fall outside the comfort zone generally recommended for adaptive thermal comfort in the context of India. In Fig. 8, pink and blue zones represent the comfort zones corresponding to June based on the adaptive comfort model recommended for naturally ventilated spaces by ASHRAE-55 [5] and IMAC-R [16]. It is shown again that the ventilation strategy is the most appropriate to provide thermal comfort in the summer green zone.

Thermal performance of the dwelling

The variations in outdoor environmental factors between the macro climate (the meteorological station) at Bulandshahr and the microclimate of eight villages are mainly due to moisture-ladened open agricultural fields surrounding the rural dwellings. In contrast, the difference in the outdoor and indoor thermal factors can result from the building configuration and thermophysical properties of building materials. As seen in Table 7, there are no significant differences between indoor and outdoor temperatures, which implies that rural dwellings have poorer thermal performance (in terms of dividing indoors and outdoors). It also means that these dwellings in summer do less work to improve indoor thermal environments by letting outside warm weather through indoor spaces. It is also noticeable good air movement is desired inside the dwellings to achieve thermal comfort.

Respondents' adjustments

Metabolic rate

The respondents' activity levels within an hour before responding to the questionnaire are considered in the estimation of metabolic rate in the current research. The high metabolic rate of 2.0 in the male and female samples in this study is primarily because of a high degree of activities like agricultural work or household work in which the rural dwellers are usually involved. The rural householders' mean metabolic rates are between 0.8 met and 2.0 met. The metabolic rates of respondents are statistically summarized in Table 8.

Clothing insulation

Table 9 statistically describes respondents' clothing insulation arranged by gender. In the summer, the maximum and minimum values of clothing levels significantly differ between the male and female groups. On average, females wear 0.099 *clo* more than male respondents in summer. It illustrates how male respondents are more active in adapting their clothing level than female respondents due to cultural inhibitions. Clothing insulation (*clo* value) was determined based on clothing worn by the respondents. The insulation of the traditional clothing ensembles was determined using ASHRAE 55 standard. Clothing insulation for the conventional Indian ensembles like *saree, odni and ghagra, dhoti, and Lungi* was estimated based on equation 2[29].

$$I_{cl} = 0.00103.W - 0.0253 \quad (3)$$

where, I_{cl} **-** clothing Insulation (clo) and W**-** the weight of the garment in grams (g), Fig. 9.

The clo values of *saree* (0.665), *odni and ghagra* (0.622), *dhoti* (0.5927), and *Lungi* (0.3352).

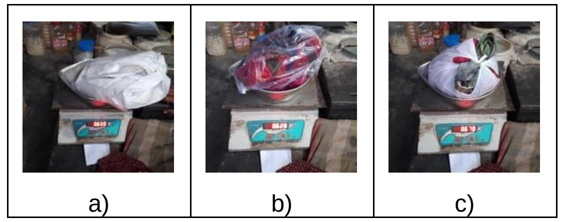

Fig. 9. Measurement of cloth weights

Table 9 Clothing insulation (I_{cl}) grouped by gender.

Clothing insulation	Minimum	Maximum	Mean	SD
Male	0.04	0.61	0.526	0.128
Female	0.44	0.665	0.625	0.038
All	0.04	0.6648	0.563	0.114

Adaptive Actions in Response to thermal discomfort

The total sample sizes are 105 respondents in eight villages, and all respondents participated in the "right-here-right now" thermal comfort survey. Figure 10 presents the percentage break-up of different behavioural adjustments commonly reported by the respondents to lessen thermal discomfort. The data shown in Fig. 10 only provides a complementary elucidation to the primary outcomes from the "right-here-right now" thermal comfort survey.

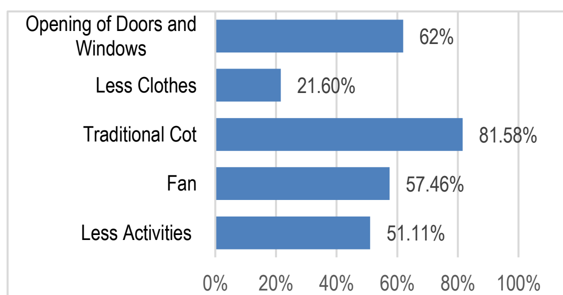

Fig. 10. Various behavioural adjustments in response to thermal discomfort in Summer.

The very high percentage (62%) of "opening doors and windows" in summer signifies that the occupants would wish to move freely between indoor and outdoor spaces, perhaps for ease of performing their day-to-day chores comprising different outdoor tasks. This can partly justify a high correlation between the indoor and outdoor temperatures (Table 7) and the high level of air movements (Table 7). In summer, space cooling using fans (57.46%) occurs more frequently in rural dwellings depending on the availability of electricity. In rural contexts, the traditional cot is used by 81.58% of people for sitting purposes. Thirdly, the lower percentage of "fewer clothes" (21.6%) reported in the rural respondents is consistent with the results shown in section 'clothing insulation.' Rural dwellers somewhat tend to dress heavily in summer out of inhibition.

Subjective Responses of the thermal environments

Predicted (PMV) vs Actual (TSV) thermal sensation

The sensation votes were recorded for all 105 subjects thrice daily in a regression analysis on operative temperature. The Fanger's predicted mean vote (PMV) for all 315 sets of data was determined using the CBE thermal comfort tool according to ASHRAE standards[30] [28]. The operative temperature was regressed with PMV (T_{op} vs PMV), R^2 is 0.3615, and the neutral temperature is 20.07 °C with the comfort zone (voting within -1 and +1) of 25.81 – 14.33°C during summer months. When the operative temperature was regressed with TSV (T_{op} vs TSV), R^2 was 0.2435, and the thermal neutrality was 26.8669 °C, with a comfort zone (sensation in the range of -1 to +1) of 22.09 - 31.49°C during summer months of 23.61 - 32.13°C.

Figure 11 displays the mean thermal sensation vote and predicted mean vote distributions against Top for the rural respondents. The linear regression models between TSV/T_{op} and PMV/T_{op} are plotted exclusively for summer in Figure 11. In summer, the rural dwellers are highly sensitive to *Top* variations with a regression coefficient of "0.2126" while the "0.1742" sensitivity of PMV. The slopes signify PMV model tends to overestimate the actual thermal sensation votes in naturally ventilated residential built environments. This can be ascribed to the occupants' long-spell acclimatization to these warm summer conditions without mechanical cooling systems in their dwellings.

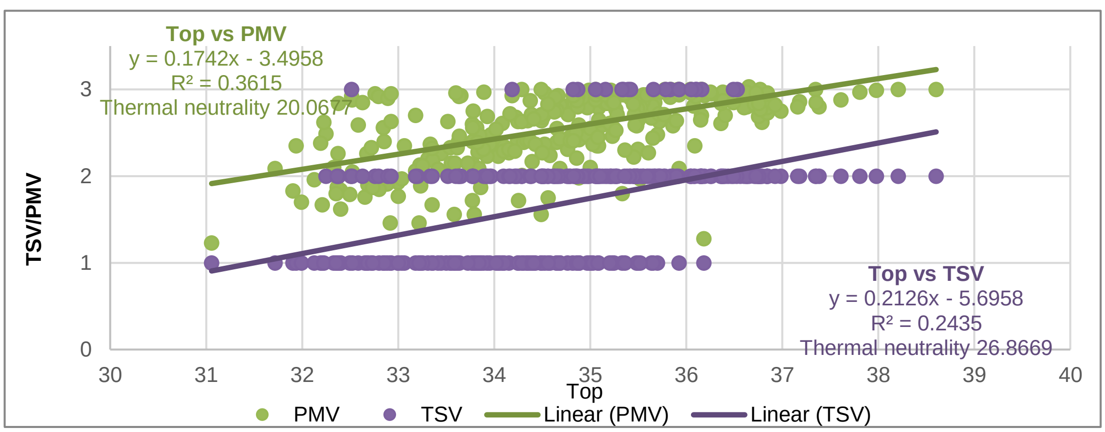

Fig. 11. The regression of Thermal sensation Vote and Predicted Mean Vote

Thermal Preference and Acceptability

The measured environmental conditions fall entirely outside the conventional comfort zone (Fig. 8), and a sample of rural dwellers corroborates the sensation of warm as TSVs falling within the two verbal anchors of the 7-point thermal sensation scale (i.e. "slightly warm-1" and "warm-2") Fig. 12(a). Thermal preference votes (TPV) histogram shows that a very high percentage of the respondents reported "needs cooler" in summer, Fig. 12(c). The direct acceptability scale (TAV) estimates the percentage of 'acceptable' votes. The rural residents report 76.83% acceptability in summer Fig. 12(d). The results based on the "TSV" and "TPV" scales exhibit that the rural residents voted sensation of warm in summer conditions.

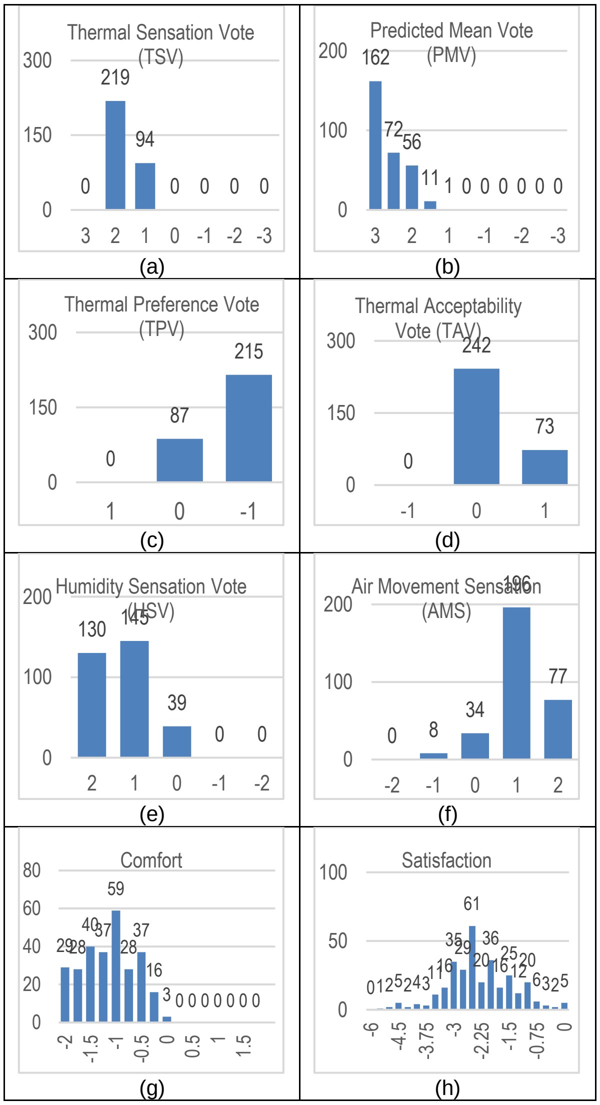

Fig. 12 Vote distribution for (a) TSV, (b) PMV, (c) TPV, (d) TAV, (e) HSV, (f) AMS, (g) Comfort, and (h) Satisfaction

Even though most of the surveyed occupants indicate a feeling of warmth in the given thermal conditions, their reactions on the "TAV" scale suggest that the rural respondents are tolerant of warm conditions in summer.

Discussion

Characteristics of Rural Dwellers

Behavioural characteristics of rural dwellers appear to affect their perceptions of indoor thermal comfort. They have high clothing insulation and metabolic rate in summer. Rural dwellers are often involved in outdoor agriculture work, requiring clothing that protects from direct solar radiation, even on warm summer days. The survey of adaptive actions shows that rural dwellers are less prone to adjust their clothing in response to climate variations due to social inhibitions. Rural dwellers often open doors or windows, even in summer. Such behaviour may have caused the rural dwellers' low expectations for indoor thermal comfort in summer.

The air movement sensation monitored in the majority of survey participants was "little still" (62%) and "too still" (24.44%) Fig. 12(f); resulting in their warm discomfort, fig. 12(a) and their preference to feel cooler in summer, figure 12(c). According to SP 41[31], a minimum wind speed of 2.26 m/s is desired for thermal comfort conditions inside (table 10), which can be explained by the potential ventilation comfort zone (for one m/s wind speed) mapped on the psychrometric chart in fig. 8[32].

Table 10 Minimum wind speeds for thermal comfort conditions

Dry Bulb Temperature (°C)	Relative humidity (%)						
	30	40	50	60	70	80	90
	Wind speed (m/s)						
28	*	*	*	*	*	*	*
29	*	*	*	*	*	*	*
30	*	*	*	*	*	*	*
31	*	*	*	*	*	0.06	0.23
32	*	*	*	0.09	0.29	0.60	0.94
33	*	0.04	0.24	0.60	1.04	1.85	2.10
34	0.15	0.46	0.94	1.60	2.26	3.05	+
35	0.68	1.36	2.10	3.05	+	+	+
36	1.72	2.70	+	+	+	+	+

* None, + higher than acceptable in practice
Source: SP 41 (S& T) -1987, page 80[29]

Prospective design strategies for summer

Notably, 76.83% of rural residents accepted indoor thermal environments that fall well beyond the recommended comfort zone, and about 71.2% of residents choose to feel cooler in summer, Fig. 12 (c) and (d). The concept of adaptive thermal comfort is based on the premise that occupants of naturally ventilated buildings can more closely map the outdoor climate patterns and adjust their thermal preferences and behaviour. Fluctuating and dynamic indoor thermal conditions synchronized with the outdoor climate conditions would ensure the health and wellbeing of the occupants as well as minimize energy use than maintaining. While maintaining completely static thermal comfort all year round would be highly energy-consuming, particularly in residential buildings.

The outcomes of this research have established that passive cooling design techniques should be encouraged in PMAY-G dwelling design to achieve adaptive thermal comfort in the composite climate zone of India. Firstly, natural ventilation should be maximized in dwelling design, specifically for summer. Since rural dwellings have few constraints in building configuration and ceiling height, techniques like the stack effect, cross ventilation, the venturi effect, and ceiling fans can enhance convective cooling effects from air movement inside a dwelling. Secondly, improvements in the flat roof and external wall insulations are beneficial to reduce heat gain in rural regions, where detached dwellings are conventional.

Conclusions

This study examined the indoor environment of naturally ventilated rural dwellings in the composite climate zone of India and its effects on thermal comfort perceptions and associated levels of adaptions of the occupants in summer conditions. This research involves collecting and analysing 315 field data sets comprising subjective thermal comfort responses and objective instrumental observations.

The significant outcomes of the present research are summarized as follows:

(a) In summer, the indoor air temperature in dwellings varies from 31.1 to 39.5 °C and the outdoor temperatures between 31.6 and 39.8 °C. The indoor relative humidity ranges from 54.1% to 85.2,% and the outdoor relative humidity ranges from 54.3% to 88.8%. The indoor air temperature and relative humidity were similar to the outdoor air temperature and relative humidity during the monitored period.

(b) The residents in rural India wear 0.563 clo and are involved in 1.098 met activities in summer.

(c) While objectively field-measured indoor environmental factors fall entirely outside the comfort zone delineated by ASHRAE 55 Standard and IMAC-R, the subjective thermal comfort survey outcomes denote that most occupants yet vote for such conditions as' acceptable'.

(d) The thermal neutral temperature (T_n), based on the TSV model determined by the subjective responses, was 6.8 K higher than the T_n determined by the PMV model. The thermal neutral temperature (T_n) determined by the PMV model was 6.8 K lower than the T_n observed based on the TSV model determined by the subjective responses. When TSV is equal to 0, the indoor thermal neutral temperature in summer was 26.8669 °C with a comfort zone range of 22.09 - 31.49°C (TSV within -1 and +1), which was higher than the predicted thermal neutral temperature of 20.07 °C with the comfort zone 14.33– 25.81 °C (PMV within -1 and +1) in this climate zone. A comparison of the results of the present study with previous other similar studies is presented in Table 11.

(e) Comparisons between PMV and TSV data signify PMV model overestimated the actual thermal sensations of the occupants in summer conditions. The rural residents are sensitive to T_{in} variations and incline to sense warmth in summer.

(f) Passive solar design techniques for rural dwellings seem vital to achieving adaptive thermal comfort in summer. Dwelling walls and roofs should be insulated to avoid heat gain in summer. Passive cooling techniques such as comfort and natural ventilation must be promoted in dwelling design in the composite climate zone. The dwelling occupants accept natural air movement in rural regions.

The results of this research can be directly applied to optimize rural dwelling design under PMAY-G in composite climate to improve indoor thermal conditions and have overarching implications for saving energy in India, Figure 13[33]. Further, extensive research is needed on the region's climate, materials, technology, and economic viability and applying those identified approaches to new and existing dwellings.

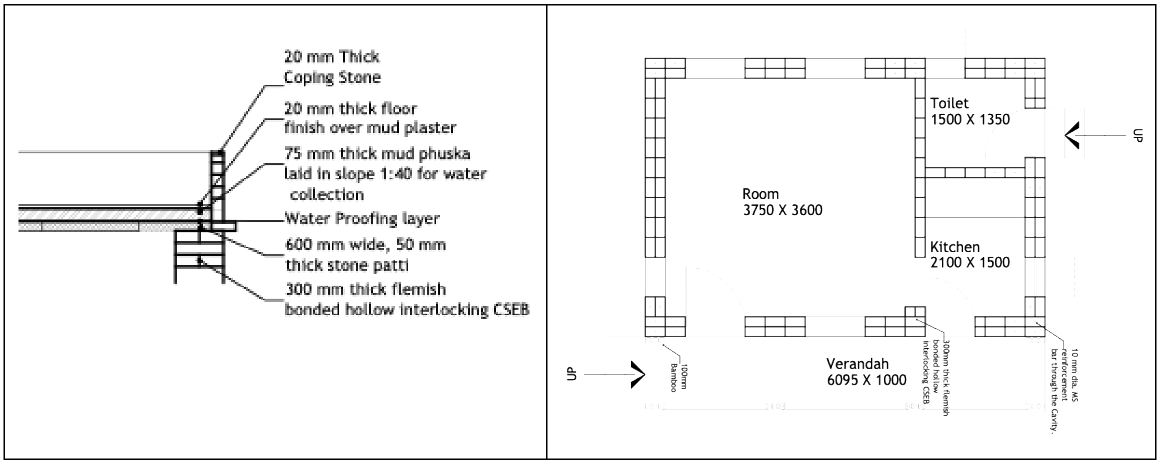

Fig. 13 Typical rural house under PMAYG for the region 'B' of Uttar Pradesh

Table 11 Regression correlation between thermal sensation and interior temperature in various research

Author	Location	Regression equation	Correlation coefficient (r)	Neutral temperature (T_n)
Present study (rural India)	Bulandshahr	y = 0.2126x - 5.6958	0.49	26.87
Mallick (1996)[34]	Dhaka	y = 0.18 Top - 5.11	0.50	28.39
Nicol and Roaf (1996)[35]	Pakistan	y = 0.154x + 0.09	0.74	25.45
de Dear and Brager (1998) [6]	NV buildings	y = 0.27x – 6.65	-	24.63
Karyono (2000)[36]	Jakarta	y = 0.31x – 8.33	0.63	26.87
Rijal et. al (2002)[37]	Nepal	y=0.058x-1.27	0.44	21.90
Ye et. al (2006)[38]	Shanghai	y = 0.13x-2.92	0.69	22.50
Indraganti (2010)[39]	India	y = 0.310x-9.060	0.65	29.23
Kumar, Mathur and Mathur (2016)[40]	India	y=0.6902x+0.1345 window use	0.68	
		y=0.9341+0.002 Fan use	0.9551	

Notes:

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