Original Paper

Thermal performance study of traditional slate roofed mud houses in the sub-tropical sub montane and low hills of Himachal Pradesh

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Abstract. *The indoor environment of an area affects its overall functionality and sustainability. Vernacular architecture is noted for its use of sustainable solar passive strategies that result in improved thermal performance. The current study looks at the thermal performance of slate-roofed mud huts, which are common in Himachal Pradesh. The field study, which is based on the adaptive approach, entails both qualitative and quantitative components of thermal comfort via a questionnaire-based thermal comfort survey and onsite measurements of environmental attributes of 130 vernacular dwellings in the sub-tropical submontane and low hills of the north Indian state Himachal Pradesh. A thermal comfort survey about physical and psychological parameters of thermal comfort was done for July, and October of the year 2022 symbolizing the summer and autumn seasons in the region. The parameters were also correlated to the thermal sensation votes of the residents of vernacular houses in the area on the ASHRAE thermal sensation scale. The findings revealed that these traditional dwellings work admirably in the study area's comparably hotter summer season and that the majority of the inhabitants are content in a wider range of temperatures.*

1. Introduction

Vernacular architecture can be referred to as a captivating and culturally rich image of human society, which showcases the evolution of human society through the ages. It is an integral part of the built environment and has helped a lot to shape it in its current modern form. It comes out as a reflection of the local traditions, materials, and practices that have organically developed within specific geographical conditions and communities. It can be referred to as a need-based indigenous style of architecture, which effectively responds to the daily needs of the inhabitants (Oliver, 1997; Singh et al., 2010a). This particular architectural style has aged with human civilization and embodies the wisdom and knowledge of generations, adapting to the unique social, climatic, and cultural needs of its inhabitants. From the mud-brick houses of the African continents to the stilted houses in southeast Asia, vernacular architecture remarkably showcases the diversity of residential arrangements based on the culture and geography of a

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place. These houses are often seen as a harmonious part of the natural environment, well integrated with the local landscape.

By understanding the concepts and principles of vernacular architecture one can learn how communities have thrived while honouring their unique identities through their habitats.

1.2 Vernacular architecture of Himachal Pradesh

Himachal Pradesh is the northernmost state of India, nested in the Indian Himalayan region with a difficult terrain and breathtaking natural landscapes. Himachal Pradesh's traditional architecture, developed as a result of centuries of adaptation to the challenging mountainous terrain and climatic conditions reflects a profound understanding of the local environment, culture, and lifestyle.

The vernacular architecture in Himachal Pradesh is characterized by its distinct architectural features, construction techniques, and use of indigenous materials. The structures seamlessly integrate with the topography, benefitting from the natural resources available in the region to the fullest (R. Sharma & Sharma, 2023). Ranging from the mud houses in the ancient hilltop villages to the intricately designed wooden temples and monasteries, each architectural marvel tells a story of resilience, sustainability, and a deep connection to the land. Himachal witnesses a diverse type of climatic regions from the cold deserts in Kinnor and Spiti regions to the green valleys of the Kangra region and the flatter terrain of the Una region each area hosts a distinctive style of climate-responsive architecture (R. Sharma & Tanwar, 2018). Unique building styles like that of Kathkuni, Dhajji Dewari, adobe, and Taq construction showcase the local craftsmanship and the utilization of available resources like wood and stone (Gadi et al., 2019; Heritage Management Team, n.d.). The vernacular architecture of Himachal Pradesh replicates the region's response to the challenges posed by its varied climatic conditions, including heavy snowfall in winter and monsoon rains in the summer. The buildings often incorporate features like steep-sloped roofs to shed snow, and wide eaves to protect against the elements.

1.2 Thermal Performance

Thermal performance can be termed as a resultant of a building's energy exchange with its surrounding thermal environment. Many active and passive strategies are used to keep the internal environment in line with the desires of occupants and boosting the ability of the building exterior to fulfil inhabitants'

Figure 1: A typical vernacular house in the study area

thermal comfort needs (Joshima et al., 2021). The desired indoor circumstances, the prevalent outdoor climatic conditions, and the type of construction materials and techniques employed, as well as their insulation capabilities, all influence thermally efficient building design. Thermal performance of different building components results in the overall experience of an individual in the indoor surroundings in terms of comfort levels and thermal sensations. Thermal properties of the building components along with user's thermal preference majorly govern the overall performance of any building envelope (Joshima et al., 2021). Analysing both the thermal comfort and thermal properties of a building component is required to judge the overall thermal performance of that component.

Henson defines the concept of thermal comfort as "a situation in which the person lacks the impulses to alter the existing interior environment through behavioural changes" (Djongyang et al., 2010). The American society of heating, refrigerating and air-conditioning engineers (ASHRAE) delineates it as "the state of mind in which an individual expresses satisfaction with the existing thermal conditions"(Chaulagain et al., 2020). It can be seen in the above definitions that thermal comfort largely depends on ones frame of mind, philosophy and culture along with the prevailing environmental conditions (Du et al., 2014). Different individuals in a same indoor environment can have different thermal sensations and can give different opinions on thermal comfort (Kuchen & Scientific, 2018). Lifestyle changes such as change of clothing, position, heating, cooling mechanisms or windows also affect the thermal comfort of individuals in an area. Ecological factors such as outdoor and indoor temperatures and humidity combine with personal factors i.e., clothing or the physical nature of work of the individuals to impact the 'thermal comfort'. The most generally used indicator of thermal well-being is air temperature influenced by other climatic factors like humidity and wind velocity (Singh et al., 2010b). Thus two types of variables affecting thermal comfort were identified as physical parameters namely air temperature, wind velocity, relative humidity, mean radiant temperature, and personal parameters viz levels of clothing insulation and activity performed (metabolic rate) (Mamani et al., 2022).

Indoor thermal conditions of a place majorly govern the energy utilization in a building and therefore hampers the overall sustainability (Barrios et al., 2012; Toe & Kubota, 2015). Different authors have undertaken different approaches to study the concept of thermal comfort like establishing thermal comfort indices (Cardinale et al., 2013) and adaptive thermal comfort models (Dear et al., 1998; Indraganti et al., 2014; Mishra & Ramgopal, 2015; Singh et al., 2015), onsite field surveys (Fernandes et al., 2020; Madhumathi et al., 2014; Priya, 2019; Singh et al., 2010b). International comfort standards like ASHRAE are majorly based on theoretic investigations of heat exchange in the human body. Researches show that thermal comfort of a building is a resultant of the thermal performance and material properties of the building envelope (Cardinale et al., 2013).

1.3 Thermal comfort in vernacular houses

Vernacular houses are more climate responsive with better solar passive features as compared to modern style of construction. Studies have shown that vernacular structure has better indoor microclimate when compared to conventional houses in the areas with similar climatic conditions (Madhumathi et al., 2014; Priya, 2019; Sarkar & Bose, 2015; Soleymanpour et al., 2015). Different studies undertaken in Nepal, China and Tibet show that traditional architecture there is very well adapted to the local climate conditions (Bajracharya, 2014; Bodach et al., 2014;

Chaulagain et al., 2020; Gautam et al., 2019) (Borong et al., 2004; Du et al., 2014; Huang et al., 2016; Huang & Liu, 2010). Traditional residential buildings were relatively 1 to 2°c cooler in summer & 1 to 2°c warmer in winters when compared to current residential buildings. Further there are studies focused on adaptive model of thermal comfort showing the effect of quantitative studies along with those of qualitative data analysis. Researchers took onsite measurements of environmental factors like indoor- outdoor temperatures, relative humidity and wind velocity to account for indoor thermal conditions of the buildings. Their interrelationship was further studied to understand the overall behaviour of the area (Chandel & Sarkar, 2015; Jayasudha et al., 2014; Radhakrishnan et al., 2011; Shanthi Priya, Sundarraja, & Radhakrishnan, 2012c; Shanthi Priya, Sundarraja, Radhakrishnan, et al., 2012). Additional factors like clothing was also considered in certain cases (Indraganti et al., 2014).

Another study highlighted the role of solar passive architecture in achieving indoor thermal comfort for south Portugal which further affirms the climate responsive nature of vernacular architecture (Fernandes et al., 2020). The study involved the use of adaptive thermal comfort model, the case-study building showed good indoor thermal comfort conditions for the whole year except winter where heating systems were required. A lot of studies undertake the qualitative method of heat balance suggested by ASHRAE taking predicted mean vote of the residents into consideration (Dili, Naseer, & Varghese, 2010c; Dong et al., 2014; Nematchoua et al., 2014).

In India also similar studies were undertaken to understand the concept of thermal comfort in the local architecture styles of the country. Comparison of vernacular and modern architecture was drawn on the basis of various architectural factors in terms of the thermal comfort of their residents (CV et al., 2016; Madhumathi et al., 2014; Priya, 2019; Shanthi Priya, Sundarraja, & Radhakrishnan, 2012a; Shanthi Priya & Radhakrishnan, 2019). The studies involved use of linear regression analysis of thermal sensation vote (TSV) to acquire the neutral temperature and comfort range. Authors have evaluated the contribution of vernacular features like the presence of internal courtyard and optimum window openings resulting in a constant air movement, highly insulated building envelop, verandas to guard the external walls from solar radiation and the pitched roof to protect from heavy rain, in a passive environment control system resulting in better indoor conditions (Chandel et al., 2016; Dili, Naseer, & Zacharia Varghese, 2010c; Indraganti, 2010; Rajasekar et al., 2020; V. Sharma et al., 2014). More studies in similar context have evaluated the behavioural adaptation of people in the analysis & gave guidelines as per Mahoney's tables (Sarkar, 2013)(Shanthi Priya, Sundarraja, & Radhakrishnan, 2012b).

One similar study for Kerala involved the field measurements, qualitative and quantitative data analysis and use of predicted mean vote analysis based on Fanger's comfort theory for prediction of maximum and minimum indoor temperature in different seasons (Dili et al., 2011; Dili, Naseer, & Varghese, 2010a, 2010c). Mean radiant temperature of traditional house is very low due to the presence of effective air flow and cooler surfaces in the interiors providing evaporative cooling. Use of bioclimatic chart showed that the traditional building is more thermally comfortable. Summer discomfort is marked by both an increase in humidity and a rise in the minimum temperature. Presence of the internal courtyard, optimum number & size of windows on the external walls, walls made of thick laterite blocks and pitched timber roof covered with Mangalore pattern clay tiles prevents the conductive heat flow into the interiors (Dili et al., 2011; Dili, Naseer, & Varghese, 2010b, 2010a; Dili, Naseer, & Zacharia Varghese, 2010a, 2010b).

Yet another study regarding research on thermal performance of vernacular houses in north east India was done for winter, pre-summer, summer/monsoon, and pre-winter months for various climate zones (Singh et al., 2009, 2011b, 2011a). The study showed different styles of architecture practiced in three climate zones was studied specifically in relation to their individual climate responsive features. It was seen that temperature readings for warm - humid and cold - cloudy climates display permissible limits for indoor temperature swing. In cool - humid climates, the indoor temperature variation is much higher due to low insulation level and thermal inertia of walls. Based on the observations a new Assam type of house was introduced which was an amalgamation of both sustainable practices from the past and present. Solar passive measures were suggested for all the three climate zones ensuring better thermal comfort of the residents (Singh et al., 2009, 2010b, 2010a, 2011b).

2. Thermal comfort analysis of slate roof houses of Himachal Pradesh

The main objective of the study was to understand the concept of thermal comfort in the slate-roofed vernacular houses of the hill areas in the summer season through a qualitative and quantitative approach. From the census of India 2011, it was observed that houses with adobe-style wall construction and stone slate roofs are predominantly seen in the state. And most of them were seen in the Kangra region. amounting to a total of 1,28,160 residential units (*Census of*

India 2011, 2011; *District Census HandBook - Himachal Pradesh*, 2011). Further Kangra district has three major bio-climatic zones namely: 1) Sub Tropical sub montane and low hills. 2)Sub humid Mid hills, and 3) wet temperate high hills as shown in figure 2 (Department of Agriculture, n.d.). Most of the region lies in zone 1, subtropical sub-montane and low hills Sub humid Mid hills, henceforth the "study area", which covers areas of Jawali, Nurpur, Shahpur, etc., and has an elevation of 240-1000 meters above sea level, and a mean annual temperature of 15^{o}C to 21.9^{o}C. Zone 1 is further characterized by hotter summers as compared to zones 2 and 3 and therefore ideal for the study.

The thermal comfort study was undertaken in summers and a transition towards a cooler period of autumn season was considered. Data was collected in the month of July & October, 2022, representing the Summer and Autumn seasons of the year. A sample size of 385 houses was obtained from Yamane's formula (Yamane, 1967). However, due to certain constraints like unoccupancy and inaccessibility throughout the year a 30% of the total sample size was considered. A total of 130 slate roofed mud houses, were undertaken for further study.

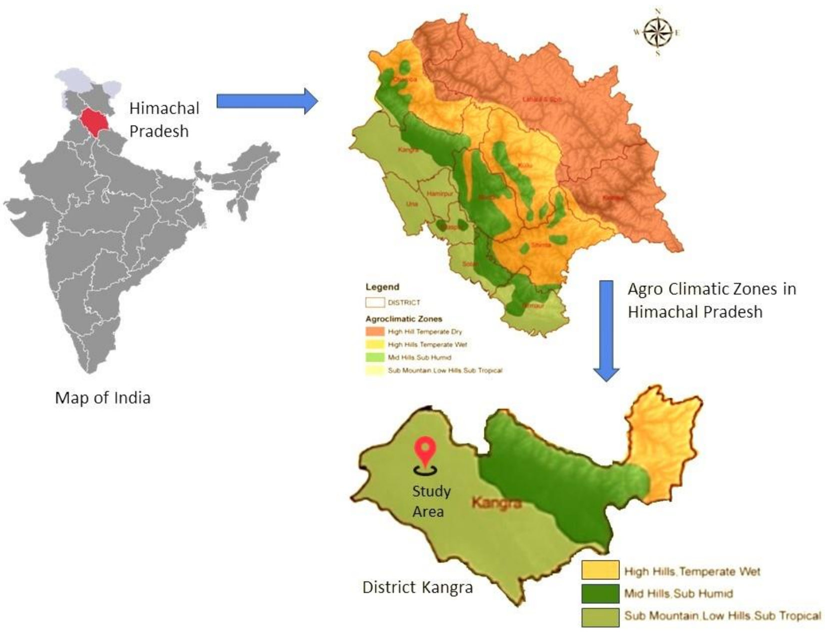

Figure 2: Overview of the study area

2.1 Architecture style of the studied area

Vernacular architecture mostly is characterised by locally available materials and construction techniques. In the study area vernacular houses are mostly two storied structures characterised by verandas as sun shades and smaller wooden doors and windows. Houses were mostly made up of thick mud wall built with the help of unbaked mud bricks or rammed earth mixed with grass and cow dung. Roofs were made up of bamboo layered on with overlapping slates. The roof structure consisted of wooden or bamboo rafters and purlins framework with an overlay of slate nailed together.

Figure 3: A typical vernacular house in the study area

The roof structure lacked any kind of ceiling or insulation below. Typical houses and living rooms on the ground floor with kitchen mostly on the first floor. Front yard or angan is normally present for day today gatherings and other activities. Staircases are generally narrow (2'6"- 3'wide) and straight flights & that is also made up of completely wood with treads plastered in mud or cow dung and husk. Additional bathing and toilet facility is given at a small distance outside the main house. The houses with hipped or gable type of roof were considered for the analysis. The roofs were mostly rectangular in shape with a few L and U-shaped structures. A ceiling height of 7'-8'6" with an attic space of 4'-5' was mostly observed.

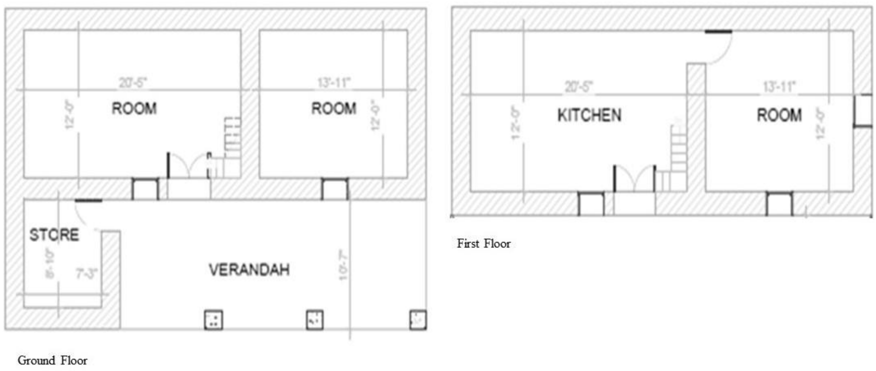

Figure 4: Typical planning layout of vernacular houses in the study area)

2.2 Thermal comfort survey

The lifestyle of a village is deeply rooted in the area's natural beauty, agricultural practices, and traditional values. It reflects a harmonious relationship between the residents and their environment. The residents of the vernacular houses in the study area are mostly farmers or retired government service personals, who opted for agriculture and cattle for their livelihood. The area reflects a strong sense of community, and the people mostly have close ties with their neighbors and extended families. Social interactions are a major part of their daily life. Most daytime activities are outdoor in the common angans (front yards), where the people spend most of the day. Indoor activities in these houses during morning and evening are mostly sedentary and no major metabolic activity was recorded thus, the value of metabolism was taken as 1 for the analysis (Gangrade & Sharma, 2022). Further because of the high thermal insulation of the mud walls the temperature indoors was slightly lower as compared to the outdoors in peak summer season. No active thermal cooling was seen in the area, however people opted for light colored cotton cloths along with opening of doors and windows in the summer season resulting in less clothing insulation levels. In peak winters warm woolen cloths, quilts and blankets were used along with fireplaces to keep the indoors comfortable. Four tangible parameters, namely indoor-outdoor temperature, relative humidity, and wind velocity were considered to quantify the attributes of thermal comfort. Two intangible parameters viz clothing pattern and body metabolism/activity were considered along with thermal sensation votes of the residents were used for an onsite evaluation of the existing thermal conditions and lifestyle of the people through a detailed questionnaire-based thermal comfort survey. The thermal sensation of the occupants was quantified through thermal sensation votes (TSV) based on a seven-point thermal sensation scale specified by ASHRAE (American Society of Heating, 2017; Priya, 2019). The thermal sensation scale ranged from -3 (very cold) to -1 (slightly cold), 0 being (neutral) and +1(slightly warm) to + 3 (very hot). Values of -2 and +2 symbolized cold and warm respectively. Clothing insulation levels were quantified in terms of Clo values along with metabolism as 1 because of the resting state of the occupants during the survey. A correlation analysis was undertaken between the tangible onsite measurements and the thermal sensation votes and clothing patterns to understand their interrelationship. Further multiple regressions were undertaken to quantify these relationships individually as equations. Lastly, thermal comfort range and neutral temperatures were established for two seasons.

3. Result and Discussion

3.1 Summer Season

Field measurements were done for physical attributes like indoor-outdoor temperature, humidity, wind velocity and psychological attributes like clothing pattern and body metabolism in the month of July 2022, for the summer season as shown in figure 5. The body metabolism can be considered constant as all the occupants were in sedentary state with no physical activity. An outdoor temperature variation of 25.3^{0}C -40.2^{0}C.

The indoor areas were comparatively colder, a temperature difference of 0.7-3.5^{o}C was seen. When compared to ground floor the first floor was comparatively warmer because of the heat gain through the slate roofs during the day. The relative humidity was observed between 20%-78% with a wind velocity ranging between 1-4v7m/s which helped in making the indoor environment comfortable. The occupants voted the thermal sensation in a range of slightly warm (+01) to very hot (+03) as shown in figure 6.

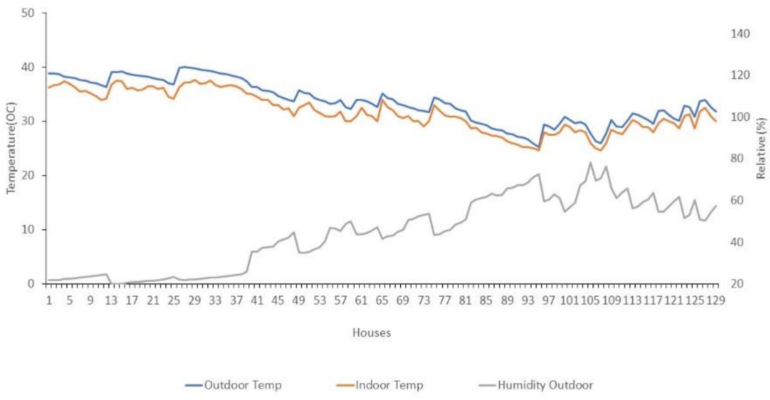

Figure 5: Physical attributes of thermal comfort in Summer

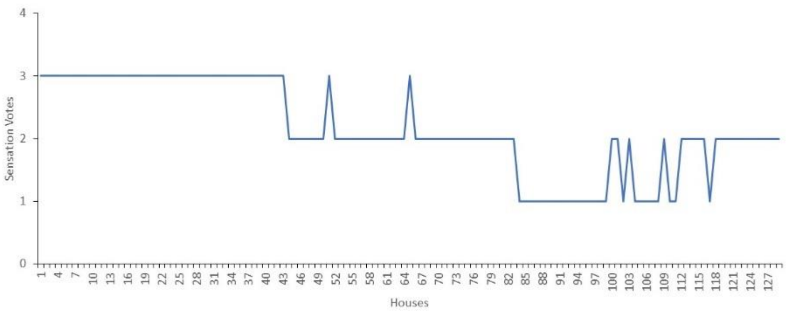

Figure 6: Thermal sensation votes in Summer

A correlation of the different factors was also analyzed as shown in table 1. It was seen that thermal sensation votes are very much related to the indoor and outdoor temperature, about 93%. A correlation of around 33% was seen between thermal sensation votes and relative humidity however their dependence on that of wind speed was negligible.

	Outdoor Temp	Indoor Temp	Humidity Outdoor	Wind Velocity	TSV
Outdoor Temp	1				
Indoor Temp	0.991713	1			
Humidity Outdoor	-0.977	-0.96962	1		
Wind Velocity	0.360203	0.368887	-0.36927	1	
TSV	0.931072	0.936542	-0.91201	0.360719	1

Table 1: Correlation between physical attributes of thermal comfort and TSV in Summer

A relation between outdoor- indoor temperature was established as shown in equation 01, achieving a R^2 value of 0.98 as seen in figure 7.

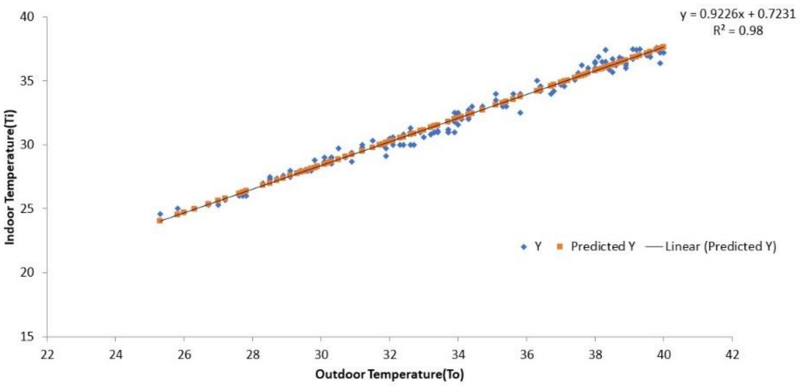

Figure 7: Relationship between indoor and outdoor temperature in Summer

T i = 0.9226T_o +0.7231……………………………………... (1)

Further dependance of thermal sensation votes on that of parameters of thermal comfort was also considered as seen in figure 8. The relation of thermal sensation votes to that of outdoor temperature, indoor temperature and relative humidity is as shown in equation 2-4 respectively. The R^2 value achieved is around 0.87, 0.87 and 0.84 in the three cases which shows a strong impact of the indoor, outdoor temperatures and humidity on the votes. The R^2 value for that of wind velocity is only 0.1, which shows a negligible impact of wind velocity on the thermal sensations.

TSV = 0.1724T_o – 3.6431……………………………………... (2)

TSV= 0.1864 T_i – 3.7636 ………….…………………………. (3)

TSV= -0.0389Rh – 3.8424 ………….…………………………. (4)

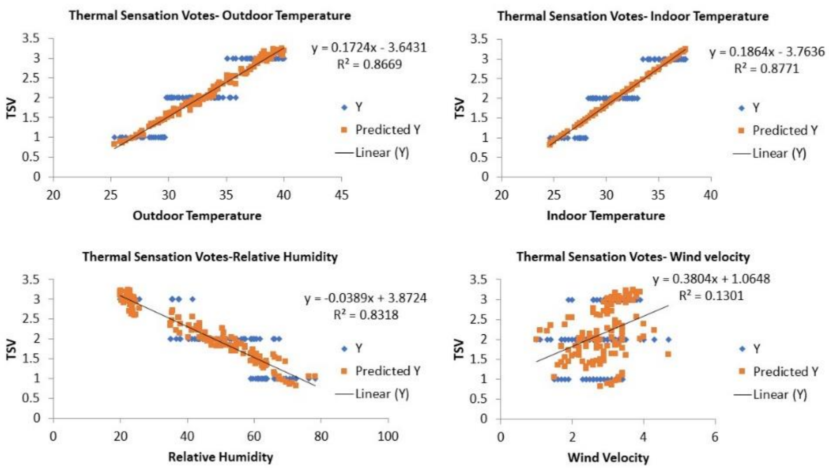

Figure 8: Relationship between thermal sensation votes and physical attributes of thermal comfort in Summer

On hotter days residents in some houses used cooling mechanism like fans, opening of windows etc. During the noon. Lighter cotton cloths were mostly donned in the region. The insulation levels (Clo Values) of clothing ranged between 0.5-0.57 (ASHRAE Standard, 2004; Gangrade & Sharma, 2022). It is seen in figure 9 that clothing levels majorly depend on the indoor-outdoor temperatures and relative humidity, with very less correlation with wind velocity. The relation of clothing insulation with that of indoor-outdoor temperature, relative humidity and wind velocity is as established in equation 05-08.

$$Clo = -0.0064T_o + 0.7473 \tag{5}$$

$$Clo = -0.0069T_i + 0.7505 \tag{6}$$

$$Clo = 0.0015Rh + 0.4666 \tag{7}$$

$$Clo = -0.0137v + 0.5706 \tag{8}$$

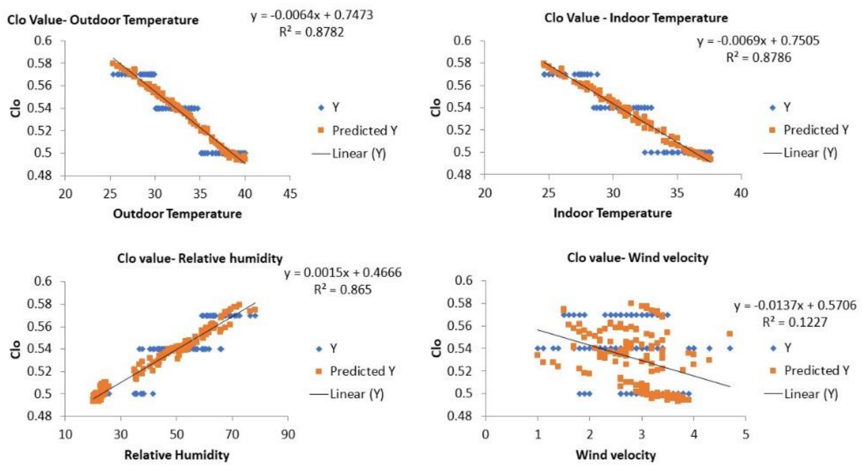

Figure 9: Relationship between clothing insulation levels and physical attributes of thermal comfort in Summer

3.2 Autumn season

An outdoor temperature variation of 22.2°C -37.8°C was seen in the area with a slightly varying range of indoor temperatures as shown in figure 10.

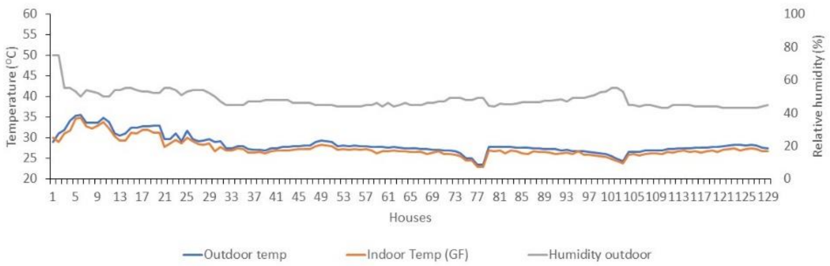

Figure 10: Physical attributes of thermal comfort in Autumn

Due to the insulation properties of thick walls and high thermal mass. The indoors were slightly colder on days when the outdoors are comparatively hotter and vice versa. When compared to ground floor a trivial variation in the temperature of the first floor was seen. The first floor was slightly hotter than the ground floor in higher outdoor temperatures, but slightly colder than the ground floor when the outdoors is colder because of the less thermal lag of the slate tiles in addition to the absence of a proper ceiling material. The relative humidity was observed between 34%-75% but the wind velocity ranged between 0-2m/s which was quite negligible in this scenario.

Thermal sensation votes were taken from the residents in the month of October, which ranged from 0 (neutral) to +3 (hot) in certain cases, but majority of the votes lied in the neutral zone showing that the respondents were very much comfortable in the given conditions.

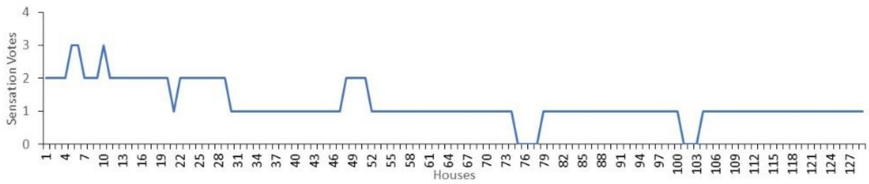

Figure 11: Thermal sensation votes in Autumn

A correlation of the different factors was also analyzed as shown in table 2. It was seen that thermal sensation votes are very much related to the indoor and outdoor temperature, about 90%. Their dependence on that of wind speed and relative humidity was negligible. The relative humidity measured was in a very comfortable range of that of 25-50%. No extremities were seen which could have led to a discomfort amongst the residents.

	Outdoor temp	Indoor Temp	Humidity outdoor	Wind Velocity	TSV
Out Door Temperature	1				
Indoor Temp	0.986484	1			
Humidity outdoor	-0.07922	-0.09954	1		
Wind Velocity	0.457899	0.466278	-0.29412	1	
TSV	0.897773	0.908092	-0.10212	0.464108	1

Table 2: Correlation between physical attributes of thermal comfort and TSV in Autumn

A linear regression was undertaken to analyze the dependence of indoor temperature to that of outdoor temperature. The relationship can be established through equation number 9 and figure 12, Where Ti = indoor temperature & To = outdoor temperature.

$T_i = 0.9212\ T_o + 1.3315$ ………………………………… (9)

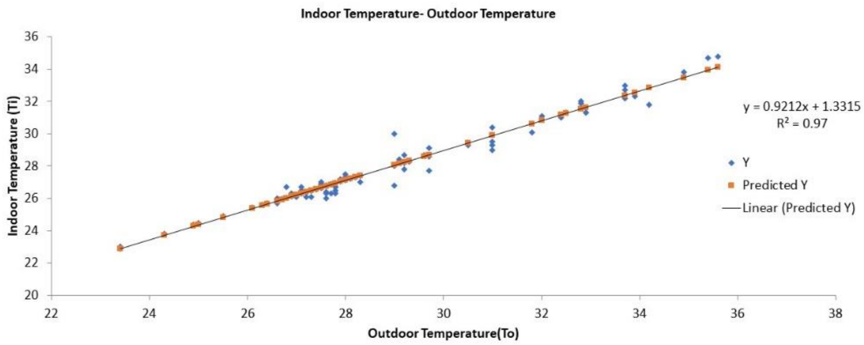

Figure 12: Relationship between indoor and outdoor temperature in Spring

Further dependance of thermal sensation votes on that of parameters of thermal comfort was also considered as seen in figure 13. The relation of thermal sensation votes to that of outdoor temperature and indoor temperature is as shown in equation 10 and 11 respectively. The R^2 value achieved is around 0.97 and 0.82 respectively which shows a strong impact of the indoor & outdoor temperatures on the votes.

$TSV = 0.222\ T_o - 5.0862$ ………………………………… (10)

$TSV = 0.2407\ Ti - 5.393$ ……….……………………… (11)

A R^2 value of 0.2 is scene in the relationship of thermal sensation votes to that of relative humidity which implies that a strong impact of the same is not clearly observed similarly a R^2 value of 0.01 shows a negligible impact of wind velocity on thermal sensation votes. The relation can be established as seen in figure 13

& equation 12 & 13. Where Ti = indoor temperature, To = outdoor temperature, v= wind velocity, Rh= relative humidity and TSV = thermal sensation vote

TSV = 0.0663Rh – 1.9602……………………………………….. (12)

TSV = -0.1099v + 1.259………………………………………. (13)

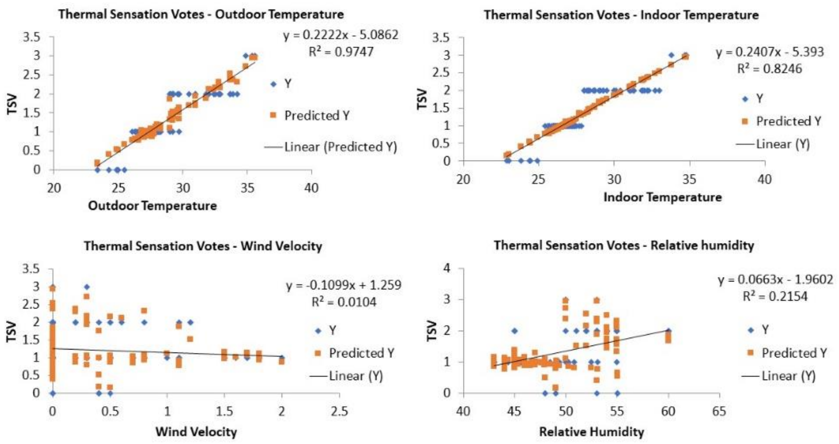

Figure 13: Relationship between thermal sensation votes and physical attributes of thermal comfort in Autumn

No artificial heating or cooling was undertaken as adaptive measures, only a shift towards slightly warmer cloths was seen in certain areas. The residents were majorly using full sleave flannel shirts, trousers, on normal days and light shirt with long sleeves on hotter days. Similarly, women were using thick fabric suits on slightly colder days, n normal full sleaves cotton ones in hotter conditions. The insulation levels of clothing ranged between 0.54-0.67. It is seen in figure 14 that clothing levels majorly depend on the indoor and outdoor temperatures, with very less correlation with the relative humidity and wind velocity.

The relation of clothing insulation with that of indoor-outdoor temperature, relative humidity and wind velocity is as established in equation 14 -17, where Clo = clothing insulation, Ti = indoor temperature, T_o = outdoor temperature, v= wind velocity and Rh= relative humidity

$$Clo = -0.0232T_o + 1.271 \quad (14)$$

$$Clo = -0.0242T_i + 1.2793 \quad (15)$$

$$Clo = -0.0067Rh + 0.9386 \quad (16)$$

$$Clo = 0.0499v + 0.5949 \quad (17)$$

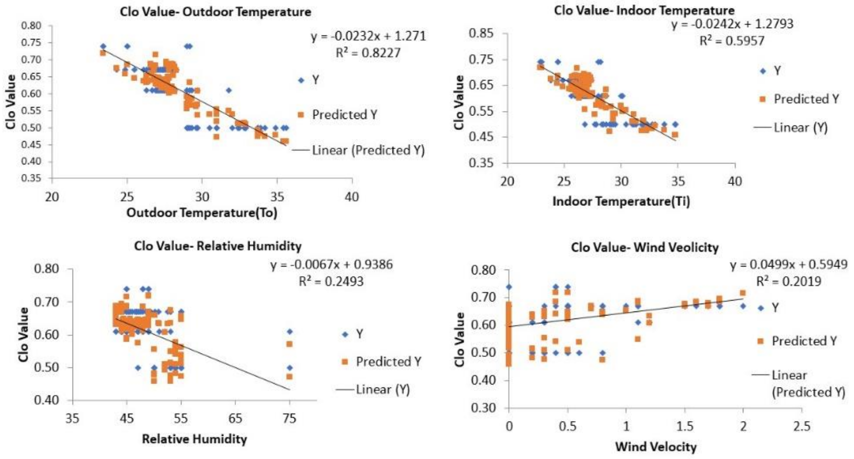

Figure 14: Relationship between clothing insulation levels and physical attributes of thermal comfort in Autumn

3.3 Thermal comfort range and neutral temperature

The field measurements were taken in the July and October months representing the peak of summer and autumn season. which resulted in comparatively hotter summers and colder winters as seen in table 3, based on the thermal sensation votes, a temperature range of was identified in which the residents were mostly comfortable throughout the year. A temperature range pertaining to -1(slightly cold) to 0 (neutral) to +1(slightly warm) were considered as comfortable. A temperature range of 22.9ºC – 28ºC with a neutral temperature of 23.7ºC was attained as thermal comfort range for the two seasons the year.

Season	Outdoor Temperature (°C)		Indoor Temperature (°C)		Relative Humidity (%)		Wind velocity (m/s)		TSV		Thermal Comfort Zone (°C)	Neutral Temperature (°C)
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max		
Summer	25.3	40	24.6	37.6	20	78	1	4.7	1	3	24.6-28	-
Autumn	23.4	35.6	22.9	34.8	43	60	0	2	0	3	22.9-27.8	23.7

Table 3: Physical attributes of the study area throughout the year

The majority of the indoor temperature was inside the thermal comfort zone, showing that the vernacular slate roof houses were much more climate responsive. If we take into consideration the overall satisfaction of the residents with respect to their vernacular style of house they are very much satisfied with the thermal behavior of the houses when compared to their modern counterparts. As seen in figure 15, satisfaction levels of 70-95% despite their maintenance and other materialistic issues were observed among the residents for the vernacular style of houses representing their livelihood and comfort.

Figure 15: Overall satisfaction levels of the residents

4. Conclusions

Vernacular architecture is decidedly sustainable when it comes to climate responsiveness and ease of construction. Previous studies in the field of thermal comfort were referred to and evaluated to identify the various thermal comfort settings and criteria. Studies have shown that vernacular architecture very efficiently responds to the harsh chilly winters of the hills. To evaluate their thermal performance in comparatively warmer summer season a study was carried out in the warmer areas of sub-tropical sub montane & low hills of Himachal Pradesh. A field survey was conducted in the months of July and October to understand the thermal perception of the individuals and the thermal efficiency of their houses. Based on the analysis following conclusions were drawn.

- Despite being a hill area sub-tropical sub montane & low hills of Himachal Pradesh witness a comparatively warmer summer. Thermal sensation of the individuals ranged from warm to very hot in the month of July. The residents were comfortable in the temperature range of 24.6°C to 28°C without using any active cooling technique.
- October month being the representative of autumn season was very comfortable compared to summer. a neutral temperature of 23.7°C was observed. an overall comfort range of 22.9°C to 28°C was seen for the two seasons.
- During peak summer season passive architecture features like thick walls, ventilated slate roofs without ceiling (with air gaps) and adaptive measures like change of clothing patterns help to enhance the thermal comfort of the individuals.
- A strong correlation of the thermal sensation of the individuals and the factors of thermal comfort like indoor outdoor temperature was seen. The study showed R^2 values of around 0.9 establishing the strong dependence of the thermal sensation votes and clothing patterns of the individuals on the indoor - outdoor temperature. R^2 values for TSV vs wind velocity and relative humidity were considerably lesser showing a lesser interdependence.
- People continued to lead highly contented, sustainable traditional lives. Residents' overall satisfaction levels ranged from 70% to 90%, demonstrating that it was in line with the climate, way of life, and culture of the area. Locals still consider that traditional mud homes are more climate-responsible and thermally viable than their contemporary counterparts.

Finally, it can be concluded that viable design interventions can therefore be done in the vernacular slate roof systems to make vernacular houses more sustainable and comfortable which later can be adopted in the modern houses to increase the quality of life and be thermally more responsive to the indoor conditions. further elaborate studies can be done considering all the 12 months of the year and using simulations etc. to look into the effects of passive design features on the thermal performance of vernacular architecture of the state.

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