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Thermal comfort of traditional mud shelters with climate responsive strategies in Nepal

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Abstract

In Nepal, the vernacular architecture developed with available resources have resulted in traditional buildings being constructed from local materials such as mud, stones, and other organic substances in accordance with climate requirements, as directed by the knowledge and experience of regional builders. Over recent years, urban areas have been rapidly transitioning to modern construction techniques, primarily concrete, causing a reduction in the prevalence of traditional mud shelters, even in rural regions. While traditional mud homes are closely tied to socio-cultural values, tourism, finance, and infrastructure, their ability to deliver thermal comfort has been disregarded over past years due to modern construction practices. To improve the current fragmented studies on thermal comfort, performance, and climate strategies in earthen structures, an interdisciplinary investigation focused on mud structures and their passive strategies for maintaining comfort is conducted. The thermal comfort and thermal performance assessments of mud shelters in the region have shown superior thermal comfort compared to non-mud shelters, with comfort temperatures generally 1-1.5°C lower in mud shelters, also confirmed by local inhabitants' preference. Furthermore, the study proposes improved passive design strategies, including settlement patterns, form, orientation, wall types, openings, and roof and floor conditions, to enhance thermal comfort in mud shelters.

Keywords: Mud shelter; Thermal comfort; Thermal performance; Climate responsive design; Time lag, Passive design strategies.

1. Introduction

In Nepal, the geographical and climatic variations with elevations ranging from 60 meters to 8848 meters have resulted in a wide variety of lifestyles and housing types. The five climatic divisions have been categorized based on the temperature, altitude, and precipitation [1] as shown in Table 1, and mud-shelters can be found in all of them. Traditional mud shelters have been found in the form of rammed earth, mud masonry, adobe bricks, cob, straw bales [2]. Traditional mud shelters provide insights into how people used their practical knowledge and experience to construct from thermally stable nature-friendly materials with climate-responsive designs to fulfill their desired thermal comfort levels. The thermal environment investigations of mud shelters have been classified and analyzed accordingly for such climatic zones by different scholars [3]. However, studies of settlement regions between those distinct regions (e.g., between cool temperate and alpine regions with significant rainfall and snowfall in summer and winter, respectively) need further investigation.

Thermal comfort is an essential parameter for better human performance, which depends on physiological and psychological factors. Investigations have pointed out that the level of thermal comfort directly affects energy usage, and its future demand depends on future climatic changes [4]. Nepal lies within the top 50 countries in the ranks of poorest countries in the world [5]. However, the transition from rural to urban areas has silently occurred in various parts of Nepal due to tourism, local development projects, etc., but its spatial variability is high due to poverty. Due to a significant housing demand gap in urban and rural areas and limited resources, the housing solution must be as effective as possible, optimizing the use of available resources in land, energy, and construction materials. In these transition periods, many traditional mud shelters have been replaced by concrete structures with time and private requirements, with haphazard and sub-standard constructions. In these conditions, prioritizing thermally comfortable mud housings can save energy, material resources, and investments while preserving the identity-defining architecture of the country.

Even though traditional mud shelter has stood for an extended period, they are considered old and outdated and are gradually being replaced by modern ones as it is neither monumental nor ancient. Such traditional shelters have tremendous traditional, cultural, and identity values that separate us from the rest of the world. Losing identity for a country with great tourism potential can have ripple effects on the whole tourism sector. The goal is to prevent the traditional mud shelters from being completely replaced by modern concrete structures, which would become a huge loss to our traditional values, tourism, and sustainability if not corrected sooner. However, the scientific evidence that supports this argument to create awareness in both the research/and actual community is lacking.

By knowing the factors related to human preferences and the thermal behavior of the surroundings, determining the thermal comfort conditions of dwellings for similar regions can be possible. However, traditional designs and methods differ excessively in material, shape, and the surrounding climate, which can become a barrier to defining thermal comfort standards in traditional structures. Even in the same area, there have been accounts of different thermal comfort requirements due to different indoor temperatures [6]. Therefore, generalizing standards for each climatic region may require more thermal performance and comfort analysis

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Table 1: Climatic zones in Nepal [1].

Zone	Level(km)	T($°C$)	Precipitation(mm)
Sub-Tropical	0-1.2	15 - 30	100-200
Warm Temperate	1.2-2.1	10 - 30	100-200
Cool Temperate	2.1-3.3	5 - 20	150
Alpine	3.3-3.5	0 - 15	25 - 50
Tundra	Above 5	< 0	Snowfall

Table 2: Classification of investigated buildings.

House	Type	Description
A & B	I	SS-SMM with mud roof
C & D	II	DS-SMM with mud roof
E & F	III	SS-RCC
G	IV	DS-SMM with hybrid roof
H	V	TS-RCC

in many regions.

Studies worldwide have shown that vernacular architecture has higher thermal performance compared to modern structures [7, 8, 9]. In addition, traditional mud constructions, as well as modern ones, perform better in terms of thermal lag and periodic oscillation [10]. In Nepal, a study of the thermal performance of brick masonry concrete buildings in two different locations using energy simulation revealed that [11] they are under-heated in winter. However, passive heating and cooling strategies have effectively provided thermal comfort without using any external energy source [12, 13]. The typical reason is assumed to be the inherent passive design strategies (heating and cooling both) and thermally insulating materials, which are naturally climate responsive as well as sustainable. For better performance, selecting better architectural elements and designs to counter the prevalent environmental conditions for traditional mud shelters is essential. However, no such studies have been done that directly relate the thermal comfort, performance and the passive design strategies in the mud shelters in Nepal.

This study evaluates the thermal performance and comfort of traditional mud shelters with particular focus on stone masonry with mud mortar structures located in climatic grey zones that experience both rainfall and snowfall in Nepal. The investigation is focused on whether these traditional shelters perform better than modern constructions in the same region. In addition, the inherent passive design strategies, climate-responsive features and human practices that define the vernacular architectural elements of these shelters are also analyzed to clarify their role in sustaining thermal comfort. Also, this investigation provides recommendations for new passive techniques for improving thermal comfort in such vernacular shelters for the specific climate.

2. Methodology

2.1. Investigated area

The location was considered based on ease of accessibility, climatic conditions, and the type of structures required for studying mud shelters. The thermal comfort environment was assessed in Odar Village of Manang, one of Nepal's mountainous regions that experiences winter snowfall. According to the Koppen climate classification, Manang has climatic conditions of subtropical highland, Tundra, and little sub-arctic zones with an elevation of around 2100-2400 meters. Geographic and climatic variables have influenced local settlement and alignment of the structures in this region. The mud structures that are recently built look more scattered compared to the previous culture of house construction in clusters. The average temperature fluctuates from -1.5 to $24°C$ around the region during the winter months, making the winter very cold because there is no external heat energy supply besides firewood [14]. Hence, people in this location rely on clothing and a compact and cozy home environment during winter.

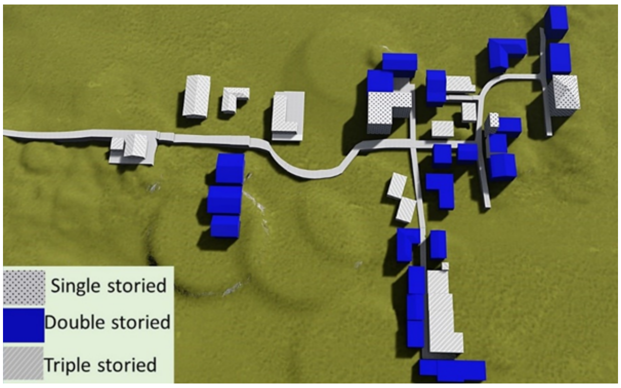

Figure 1: Unscaled model of shelter arrangement in studied area.

2.2. Investigated buildings

Most traditional houses are either single or double-storied stone masonry with mud mortar(SMM) houses, whereas non-mud structures are made up of reinforced cement concrete(RCC) with stories up to 3. The houses are named alphabetically from A-H in the mountainous region where houses A-D are mud shelters, and houses E-H are non-mud shelters. The investigated building types are as follows. Type I-IV described in Table 2 where SS, DS and TS are single double and tripled storied houses. Hybrid roof was considered, where both corrugated galvanized iron(CGI) sheets and mud were used in different areas of the house as roofs.

2.3. Inherent passive strategies in mud shelters

2.3.1. Settlement pattern

Economic, religious, social, and ethnic aspects have an impact on how settlements emerge and grow, and locals' wish to incorporate these influences into their settlements. The settlements were observed on either the slope of the hill or the valley due to preference of location and layout; these categories show great adaptation of local construction to a landform via continual trial and error over many years. The settlement of mud shelters faced the northeast, opposite the nearest mountain 'Lamjung Kailas' and lake 'Kajin Sara' on the southwest side. Mountain cold wind from different directions is possible in this region as mountains surround it. The settlement is on a large ledge between the mountainside and the' Marshyangdi' river gorge. The houses are densely packed but not attached in most places. The settlements are mostly road-oriented for ease of access. Some houses are attached to the east-west side in one direction, generally the wind direction, as shown in the unscaled 3D SketchUp model of shelter arrangement in Fig. 1.

2.3.2. Building form, orientation, stories, and internal space

The houses are mostly rectangular-shaped, with the longest side facing towards the south or southwest direction to obtain maximum solar radiation in the winter. The house has a compact floor plan where the internal spaces are used as a multi-purpose living area. The story height is generally 1.82-2.13m, much lower than the standard of around 2.8m. Two-storied buildings are more sig-

Table 3: Opening to wall ratio in SMM mud shelter.

Storey	Opening to wall ratio
Single	4.9% - 6.5%
Double	16.9% - 20%

nificant where the ground floor is mainly used as a cattle shed, contrary to the explanation by [13] Bodach et al. Traditional mud shelters are no more than two stories and the height of the lower and upper floors are the same. The mud shelter is internally open without partitions but enclosed by outer walls where cooking, eating, and sleeping are all done in one space, see Fig. 2. Since each room is a living area for a family, even if the rooms are partitioned, each room is used as a multi-purpose room. There is a porch-like area, semi-open space on the southern side of the shelters which is used for passive cooling in summer and heating in winter. In addition, the two-storied houses have a small veranda on the south face of the region. The open hearth is almost placed at the center of the building, which is used for cooking as well as internal heating.

2.3.3. Wall, opening and illumination

Walls are constructed with locally available materials like granite stone and mud where the thickness of the wall is around 0.5m with 75mm thick mud plaster on both sides of the structure. The mud plaster is believed to have excellent resistance features to harsh cold weather. The internal spaces are partitioned with SMM walls or wooden planks. The average U-value(thermal transmittance) of the wall is 0.55W$/(m^2°C)$ and 1.43W$/(m^2°C)$ for SMM mud and non-mud structures, respectively. Some houses have internal walls covered with timber lathes. There are very few small-sized windows facing south to light and heat the rooms during the winter, whereas in some houses, there are no windows at all. Unlike other traditional shelters found in Nepal, these structures did not have enough openings in any direction. The only opening is the doors, which are also very small in size with an opening-to-wall ratio as shown in Table 3. The illumination problems are compensated by electric illumination and holes made on the structure's roofs. The door shutters are used to close these openings entirely at night during cold seasons.

2.3.4. Roof, foundation, floor, ceiling

The roofs in Odar village for vernacular structures are somewhat mixed. The mud roofs have small holes which are used for light penetration during the daytime. However, since the effect of increasing temperature change has caused more rain than snow in these areas, this method is on the verge of vanishing. As flat roofs became heavier due to snow in winter, many residents have opted for CGI roofs. Although some older houses have composite mud roofs where mud is placed on top of wood purlins and branches, new shelters have pitched CGI roof supported by timber structure which is mainly focused on summer rainfall and winter snow. The overhangs of the pitched roof are two feet to save the structure from moisture due to monsoon rain. The locals say that people's movement on the roof has compressed the mud roof into a water-impermeable layer. The floors are made of wooden planks, a better thermal insulator tightly placed together. The foundation is mainly rammed earth surrounded by stone walls below the plinth level, with floor insulation using wooden planks.

2.4. Thermal measurement

A hygrometer, both dry and wet, is used to determine both the inside and outside temperatures as shown in Fig. 3. The digital hygrometer comes with a thermo-hygrometer that measures relative humidity as well as air temperature. This device can measure temperature in the range -34°C to 93°C with an accuracy of ±1% of the full-scale temperature while humidity in the range of 20% to 90% with an accuracy of ±3% of the relative humidity at 20°C. The device comes with a sensor affixed to the thermometer that is connected outside the building to measure the temperature from the outside, while the thermometer is situated within the building to measure the temperature from the inside. The inside and outside temperatures of all the houses were taken for 15 consecutive days three times a day at 7 AM, 2 PM, and 7 PM respectively during the transitional period between winter to summer months around late winter. The devices were kept at locations of the maximum duration of occupancy throughout the day which was generally the living room and bedroom area. For time lag measurement, the hourly temperature for a day in both the traditional and modern mud shelters was taken for a day. The temperature measurements were also done during the time of the survey of respondents. According to ISO 7726, the measuring equipment was situated near the respondents. From the ground, the measuring height was set at 0.6 m (sedentary) or 1.1 m (standing).

2.5. Thermal comfort survey

The questionnaire survey aimed to obtain residents' thermal sensation and include questions on the basic information about the buildings, residents' demographic information and habits. In addition, the time and temperature at which the thermal survey for each individual is recorded to know at which point the responses have been recorded. 36 people volunteered to take part in the survey. The demographic makeup of the sample is shown in Fig. 4. Respondents were assigned various tasks throughout the facility, with most of the sample (30.5 %) focusing on the 26-40 and 41-60 age range. The data was analyzed using the KOBO Toolbox and Statistical Package for Social Sciences (SPSS).

The 7-point scale recommended by ASHRAE Standard 55 was used to analyze the subjective thermal sensation vote (TSV) of the respondents. The comfort temperature is calculated by applying the following equation to the respondents' thermal sensation votes and the associated observed indoor globe temperature values [15]:

$$T_c = T_g + \frac{4 - mTSV}{a^*} \tag{1}$$

$$T_{per} = T_g + \frac{4 - TP}{a^{**}} \tag{2}$$

where; T_c, T_g, T_{per}, a^* are the comfort temperature, globe temperature, preferred temperature, increment of thermal sensation vote, assumed increment of preference vote corresponding to an increase of 3°C in global temperature respectively. Reference [15] provides further information regarding the equations Ojha & Panday, 2021 and A. Tamrakar, 2018.

3. Data preparation and analysis

3.1. Variation in recorded temperatures for 15 days

3.1.1. Mud shelters

While comparing the indoor and outdoor temperatures at different points in time for a day, it can be observed that the outdoor temperature fluctuations are more prominent than the indoor fluctuations. The mean indoor temperatures are more than the mean outdoor temperatures for all four houses. Even though houses A, B, C, and D were close to each other, the outdoor temperature difference exists due to airflow and solar conditions. The structure performs well as the average indoor temperatures are always greater than the average outdoor temperatures of non-mud shelters showing its resilience toward cold temperatures. In addition, it allows more

(a) Internal space (bedroom + kitchen)

(b) Outside.

(c) Mud roof.

(d) Kitchen area.

Figure 2: Indoor and outdoor environment of typical SMM shelter.

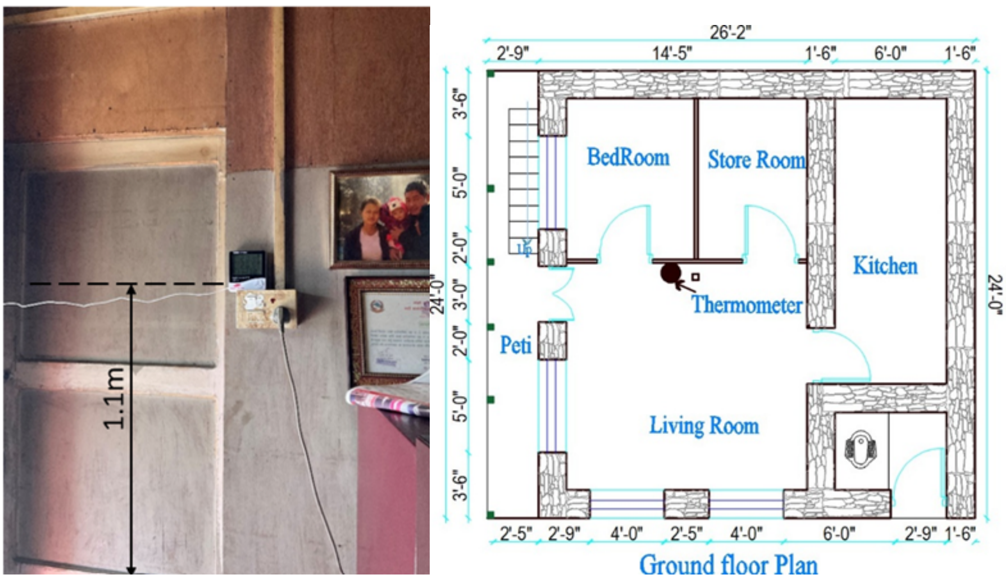

Figure 3: Position of hygrometer placed 1.1m high from floor level.

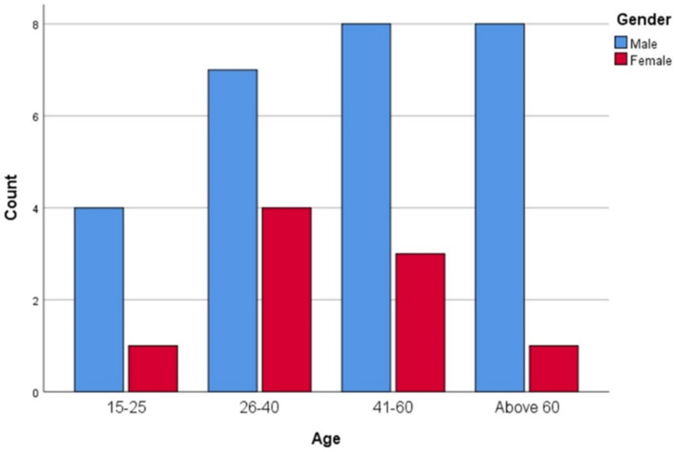

Figure 4: Age and gender distribution of participants.

Table 4: Temperature measurements in mountain region.

House type	T_{in} $(avg.)$	T_{out} $(avg.)$	ΔT $(avg.)$
I-A	16.48	16.0	0.48
I-B	16.6	16.3	0.46
II-C	16.43	16.0	0.43
II-D	17.34	16.9	0.44

fluctuations toward maximum temperatures, which can be problematic in summer if the temperatures rise too much. The overall mean indoor and outdoor temperatures for 15 days between 7 AM to 8 PM are shown in Table 4.

Besides house II-C, all other houses have longer faces facing the southern side which can help increase solar heat gains in the winter. Since the roofs are also made up of mud the house has a higher gain than other types of roofs. As the structure has internal heating during cooking, the heat radiated from the fireplace is radiated inside the room during the nighttime and stays inside the room as there are no windows for ventilation. Since the floor height is also less, the heat is distributed easily in the internal spaces but cannot escape due to the prevention of thermal leakage with 3-inch plaster from both inside and outside the house. These houses have a higher temperature than the non-mud shelters due to some passive design as well as some conventional strategies like not putting any windows in the house. Although it performs better thermally, the air quality for respiration becomes questionable due to the smoke trapped inside the building due to the lack of openings.

3.1.2. Non-mud shelters

The indoor and outdoor temperatures for 15 days show that the fluctuations are more prominent than the temperatures in the mud shelters; see Table 5. The mean outdoor temperatures are less than the mean indoor temperatures for all E, F, G, and H houses. The overall mean indoor and outdoor temperatures for 15 days between 7 AM to 8 PM are shown in the table below:

The overall temperature difference between indoors and outdoors shows that modern house performs worse than traditional mud shelters. The reasons may be due to their less compact design, thinner width of the wall, higher floor level, and overall thermal leakage. The concrete structures don't perform well as the average indoor temperature for the non-mud structures was always less than that for the mud shelters when compared to average outdoor temperatures. Similarly, the temperatures swing more along with the outdoor temperatures during the uprise of temperatures which shows that these structures have more fluctuations.

Table 5: Temperature measurements in hilly region.

House type	T_{in} (avg.)	T_{out} (avg.)	ΔT (avg.)
III-E	16.5	16.3	0.2
III-F	16.45	16.3	0.15
V-G	16.27	16.08	0.19
IV-H	16.5	16.38	0.12

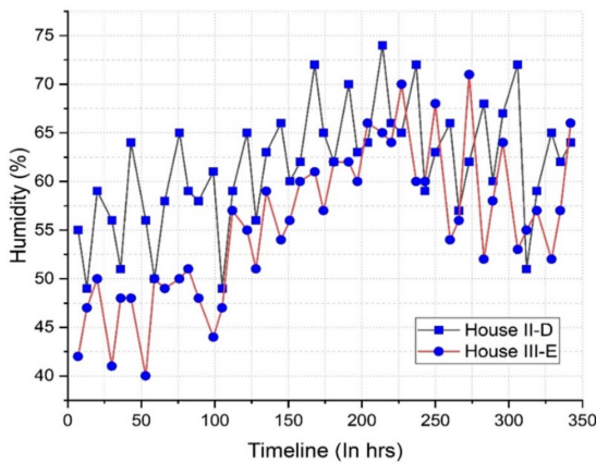

Figure 5: Humidity inside mud and concrete structures.

3.2. Humidity measurement

The humidity levels are related to not only the climatic conditions but also the size of the room, the size of the openings, and the internal arrangement of the spaces which control air movement. The ASHRAE guidelines recommend a relative humidity (RH) of 30 to 60 %. Low humidity causes static electricity, dry skin, and hair, increased susceptibility to colds and respiratory illness, and allows viruses and germs to thrive. As the humidity levels soar, people tend to sweat more. Since high humidity makes the temperature feel hotter than regular, our body responds differently. In worse cases, excess humidity hampers sweat evaporation, so the moisture remains on our skin.

In this study, the humidity is compared between the representative humidity of mud shelters and non-shelters in distinctive regions. In the mountainous regions, the humidity is higher inside the mud shelters than in the concrete structures, which may be caused by the lack of ventilation provided in the mud shelters than in modern shelters and cooking during morning and evening, as shown by Fig. 5. However, the humidity conditions are dry according to the respondent's survey.

3.3. PIT daily average temperatures differences

For the mud shelters, the temperature differences are much greater than in the non-mud shelters due to the lack of ventilation as well as the low thermal transmittance of the mud shelter, see diagram Fig. 6. The negative sign in the bars of the bar diagram indicates that outdoor temperatures were more than indoor temperatures at noon during thermal measurement. The extra layer of coating of local mud on the SMM walls, both on the inside and outside face, allowed a stable thermal environment in mud shelters. The difference is more prominent in the night than in the day due to heat stored, which was released from cooking dinner at night. All the temperature differences at different times are greater than those observed in the non-mud shelters. The differences are much more prominent in the morning and evening than in the daytime, implying that SMM mud shelters are not as good for increasing temperatures as for decreasing temperatures during the near-winter season.

The non-mud shelters in mountainous regions are more vulnerable to temperature changes, and the temperature differences are less than the mud shelters. Therefore, these structures are more susceptible to temperature changes in colder climates, possibly due to the construction materials and process. The construction materials mainly used are concrete and cement plaster, whereas the construction process may have caused some air leakages, leading to strong fluctuations along with the outside temperatures. The results of the temperature differences during the noon time between mud and non-mud structures indicate that overall the non-mud structures doesn't gain heat energy from the cooking activities during the morning. Hence, the resulting temperature difference is more in non-mud structures.

3.3.1. Comfort and preferred temperature

The relationship between the temperature of the internal and outdoor air in mud and non-mud-built structures in a mountainous environment is shown in Fig. 7. The indoor temperatures are higher in mud shelters compared to the non-mud shelters. The indoor-outdoor temperature relation is calculated using the regression analysis which is shown by the equation below.

$$Mud : T_i = 0.47T_o + 9 \tag{3}$$

$$Non - Mud : T_i = 0.48T_o + 8.16 \tag{4}$$

360 data-plots were available from both types mud and non-mud residences. Generally speaking, the inside air temperature increased as the outdoor air temperature was raised. In equations (3) and (4), the mud house regression coefficient (the intercept) is slightly larger than that of the non-mud house. This is most likely caused by the materials utilized in the homes' ability to retain heat. There are data points for both mud and non-mud buildings in the 12°C to 23°C range of outdoor air temperature. When assuming an outdoor air temperature of 22°C, the regression lines in the plot reveal that the indoor air temperature (T_i) becomes 19.34°C for mud buildings and 18.72°C for non-mud houses; this represents a difference of 0.62°C in the indoor air temperature. This indicates that in a chilly place, the traditional house is 0.62°C warmer than the modern house. This might be because the kitchen cum. bedroom, burns firewood twice or three times daily but in non-mud houses, the kitchen and bedroom are different rooms.

The comfort temperature and preferred temperature are calculated using the equation provided in equation (1) and (2). Since there was no measurement of globe temperature, it was calculated using the regression equation for the temperate and cold regions provided in the reference [15].

$$(Cold - region) : T_g = 0.54T_o + 7.7 \tag{5}$$

The comfort and preferred temperature distribution are shown in Fig. 8. The comfort temperature result shows that the mean comfort temperature is around 18.5°C as most of the votes are counted in this range whereas the mean preferred temperature is 19.7°C, which shows that most respondents desired a higher temperature. Similarly, the comfort temperature is higher for non-mud shelters than mud shelters, as the average comfort temperature is 19.5°C. The preferred temperature of a non-mud shelter is 20.1°C, greater than the comfort temperature for a non-mud shelter by 0.5°C. In the same location (a mountainous region of Manang), the comfort temperature of a mud shelter is lower than the comfort temperature of a non-mud shelter, which indicates that the thermal performance of a mud shelter is better than that of a non-mud shelter and shows the adapting nature of people toward lower temperature in traditional mud houses. However, the preference for thermal conditions is higher in mud shelters compared to non-mud, which shows that residents of mud shelters may require more energy to achieve a preferred level of comfort in mud shelters.

The use of mud as a plaster on the SMM structures is also very effective in controlling the changes in the outdoor environment as seen by the results of hourly thermal lag as shown in Fig. 9. SMM mud shelters have a time lag of at least 1.5 hours. Therefore, a thicker mud plaster could be used for better thermal performance.

3.4. Influence of clothing on thermal comfort

The ideal temperature drops as garment insulation rise as shown by the regression analysis of clothing factors and preferred temperature.

$$Mud : T_{per} = -4.23I_{cl} + 23.5 \tag{6}$$

$$Non - Mud : T_g = -4.30I_{cl} + 24.64 \tag{7}$$

The preferred temperature is inversely associated with apparel insulation, as seen in Fig. 10. The ideal temperature has a propensity to decrease as clothing insulation rises. The mud construction has a higher slope than non-mud structures. As the amount of clothing reduces, the desired temperature tends to rise. The results indicate that the lower clothing insulation value causes a higher preferred value in mud and non-mud constructions. Nevertheless, the preferred temperature of mud constructions is lower than that of non-mud structures. Therefore, people must dress more as the indoor temperature is lower in non-mud constructions than in mud structures.

4. Conclusion and recommendations

To study and compare traditional mud shelters' thermal comfort and performance and their passive design strategies, thermal environment measurements, and a thermal comfort survey were conducted. Additionally, their inherent architectural strategies were also studied. These studies provide evidence that support the argument that mud shelters with traditional passive strategies can perform better than the modern construction available in climate gray regions, as mentioned below.

- In the cool temperature region with snowfall and rainfall, the thermal measurement during the initial months of winter to summer transition shows that traditional SMM mud shelters are 0.5°C warmer daily than non-mud shelters. The thermal comfort results agree with the measurements as comfort temperatures were generally 1-1.5°C lower in mud shelters compared to non-mud shelters in this region. This decreased comfort temperature indicates that people are more comfortable in mud shelters in such regions.
- The studied mud structures achieved better thermal performance due to their architectural features, including thermal mass with time lag, compact arrangement, and smaller room sizes. Additionally, the fireplace, typically used in the morning and evening, significantly contributes to thermal comfort, particularly during early morning and night. This demonstrates that mud shelters can provide thermal comfort when combined with central heating practices and passive design strategies.
- Regarding thermal preference, the residents prefer 0.5°C higher temperatures in mud than 1°C higher temperatures in non-mud shelters. This result indicates that people prefer mud shelters for better thermal comfort. In addition, res-

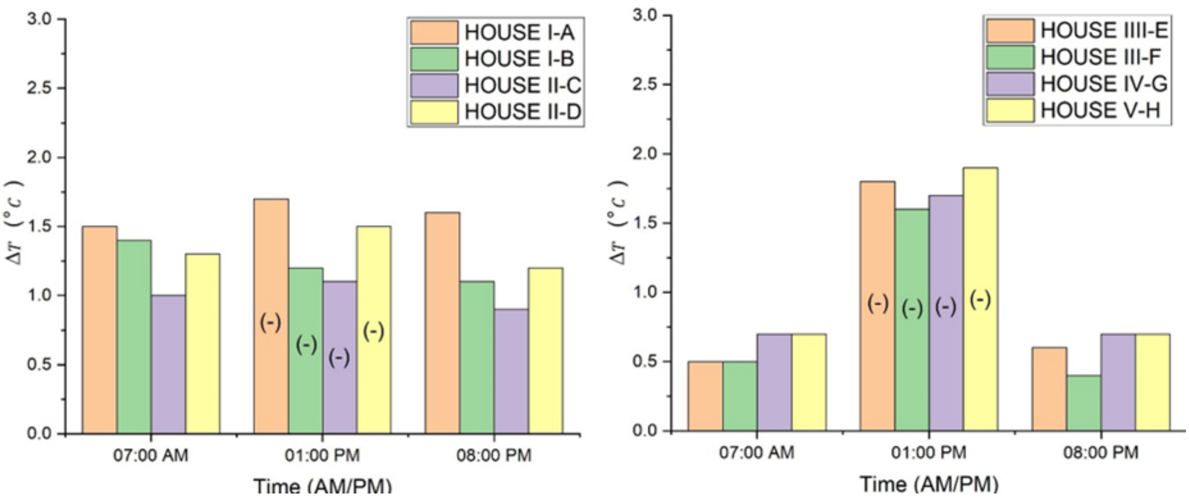

Figure 6: 15 PIT daily average temperature differences of mud and non-mud shelters.
Note: $(-)$ indicates that the ΔT between outdoor and indoor is negative.

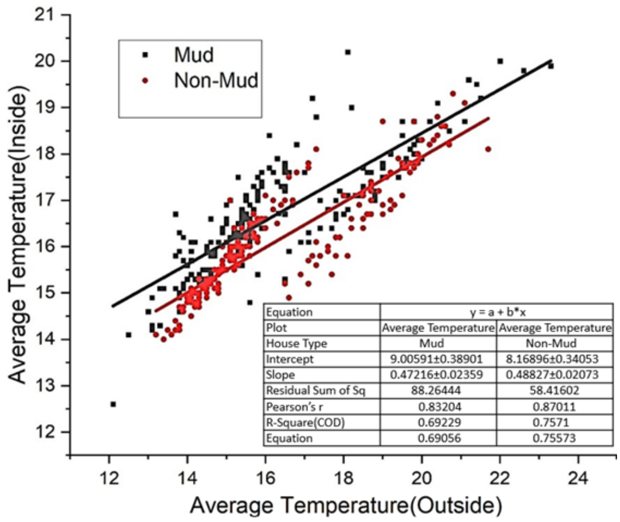

Figure 7: Relation between indoor-outdoor temperature in shelters.

idents of non-mud shelters need to put on more clothes to achieve their preferred temperature.

- Using the vernacular passive design strategies applied in various other countries as well as some of the modern concepts of passive design, the suggestions of thermal improvement on settlement pattern, form, orientation, wall types, openings, and roof and floor conditions are addressed in the next section as a recommendation.

4.1. Improved architectural design of traditional shelters

4.1.1. Walls

Since rammed earth can perform better in providing thermal comfort, [16] the proposed composite wall structure is made up of rammed earth (73%) and SMM (23%) and mud plaster which can be argued to have a better thermal performance without compromising the visual aesthetics of the vernacular architecture located in the cool temperate climate of Nepal, see Fig. 11. The width of the rammed earth is considered the highest as it provides higher thermal stability than the SMM walls. The U-values of the proposed wall vary significantly depending on whether the wooden planks are present or not. Without the wooden planks(height-2.5ft.), the wall has a U-value of 0.37W/$(m^2 {\circ} C)$, however, with the addition, it drops to 0.31W/$(m^2 {\circ} C)$, which is 0.23 W/$(m^2 {\circ} C)$ and 0.29 W/$(m^2 {\circ} C)$ less than the U-values of the mud shelters. Therefore, this type of wall is suggested so that it can store heat during the day and slowly release it during the night time.

4.1.2. Floors

During the colder season when snow falls, the ground temperature becomes around 0°C as well as the overall temperature of the surrounding falls way below the comfort level. To maintain better thermal comfort inside the structure, an air gap between the ground and floor level is proposed to create thermal insulation, as air is a bad conductor of heat, as shown in Fig. 12. The air gap is around 1 foot to 1.5 feet from the ground. The ground floor is also made up of rammed mud which provides better thermal comfort condition from the ground as well. Therefore, the floor is supported by 5" wooden logs forming horizontal and vertical pegs, covered by 4 inches of rammed mud below the 1 inch of wooden planks and dry branches on the top. According to the calculations, the intended floor's U-value is 0.18 W/$(m^2 {\circ} C)$, which is lower than the U-values of the walls. Even when there is heavy snowfall, this keeps the minimal amount of heat exchange with the earth.

4.1.3. Roofs

The proposed roof in Fig. 13 consists of rammed earth placed over the small wooden planks which are naturally compressed by the residents walking over the roof. Our design considers two additional layers of branches and gravel so that rammed earth is used less in the roof. The roofs are slanted slightly so that any water melted through snow gets drained from the roof easily. These roofs are made up of multi-layer constructions made of different materials with low heat transmission coefficients. Therefore, the mud roofs are designed with 5-inch wooden pegs, and 1-inch dried branches which are covered by 8-inch of sand/gravel followed by 8-inch of rammed earth on the top. According to calculations, the planned roof has a U-value of 0.43 W/$(m^2 {\circ} C)$, which is lower than the U-values of the existing mud huts in the mountainous area.

4.1.4. Orientation, opening, and location of heat source

Fig. 14 shows that the arrangement of the house is compact with no spaces between such that heat conduction towards the outer environment can be minimized. The design of the buildings was considered on either side of the road along the east-west direction, such that the façade of the houses always faces the south direction. Since the terrain is moderately sloped, the structures are stacked in such a way that they won't block the sun against each other. The form of the structure is cuboidal which is stacked linearly along

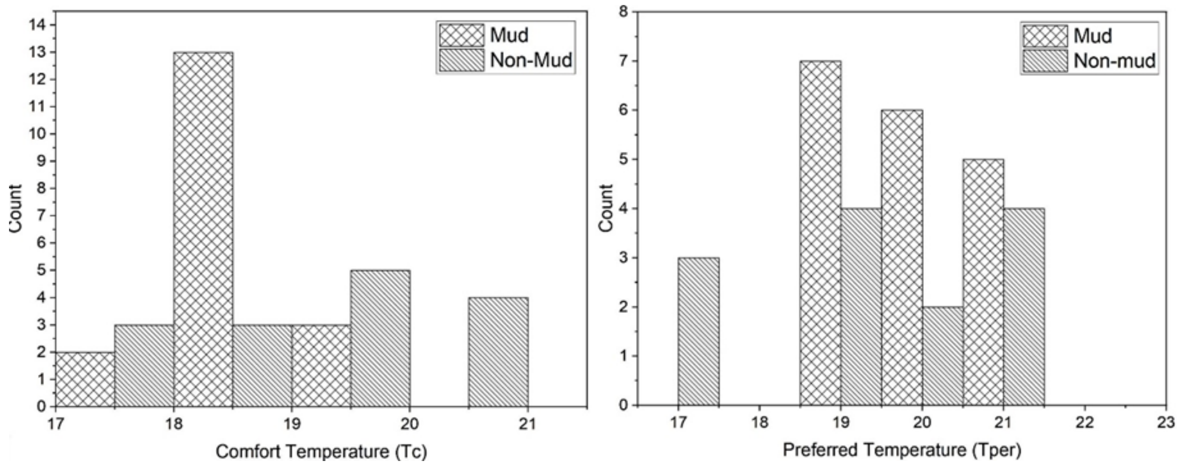

Figure 8: Comfort and preferred temperature in mud and non-mud structures.

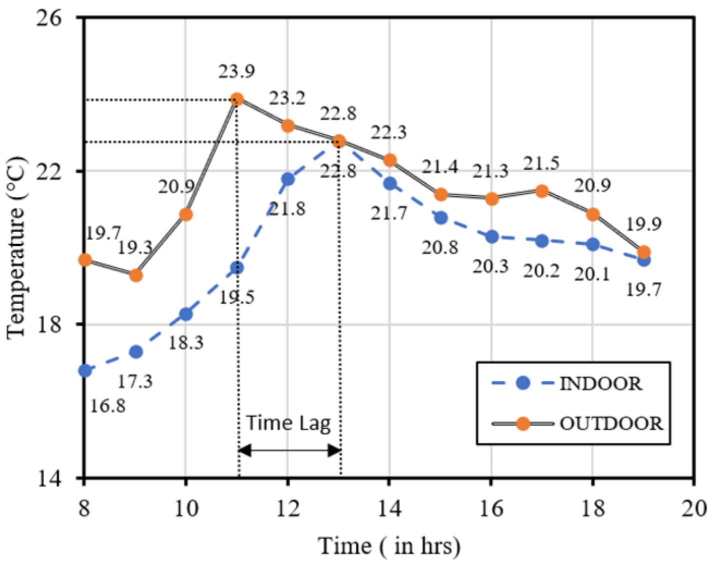

Figure 9: Influence of mud as an insulating material

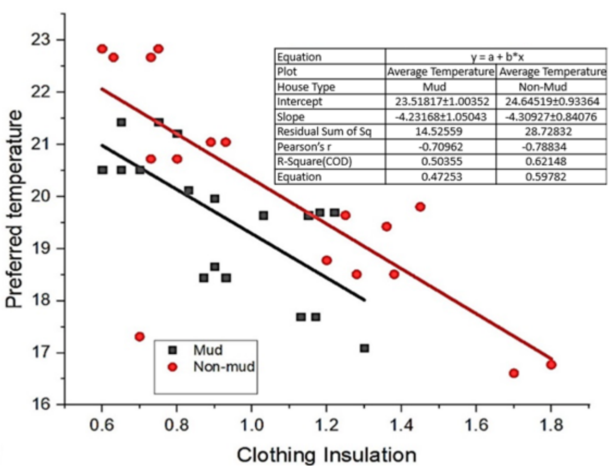

Figure 10: Influence of clothing in the mountain region.

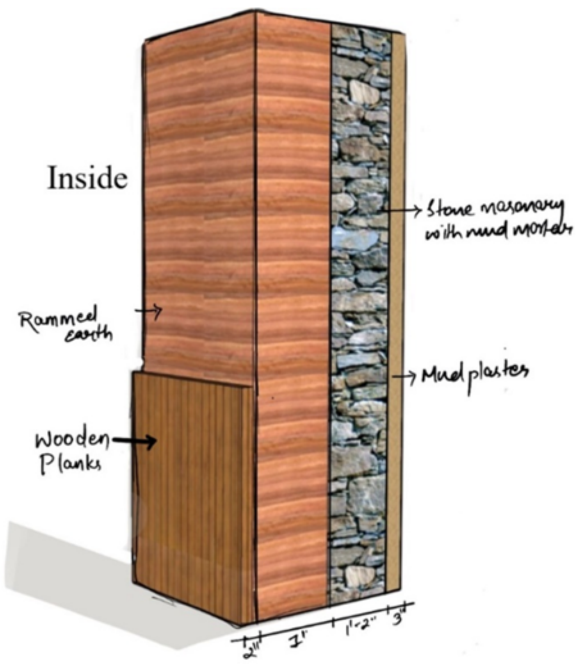

Figure 11: Composite wall with a wooden plank.

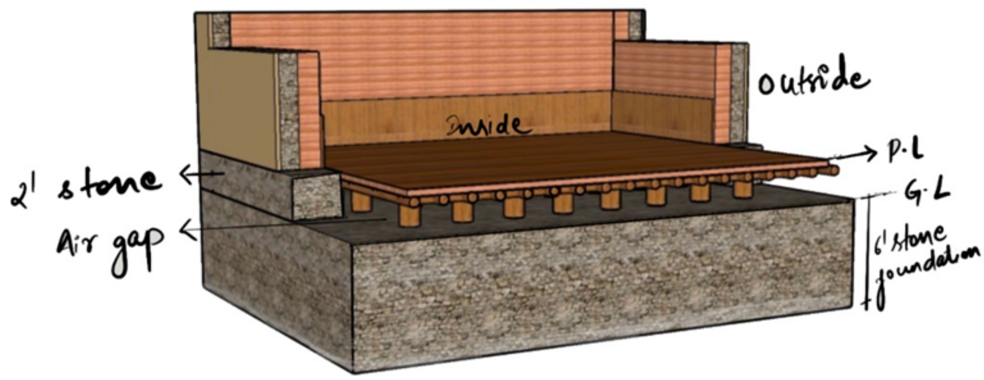

Figure 12: Proposed floor design.

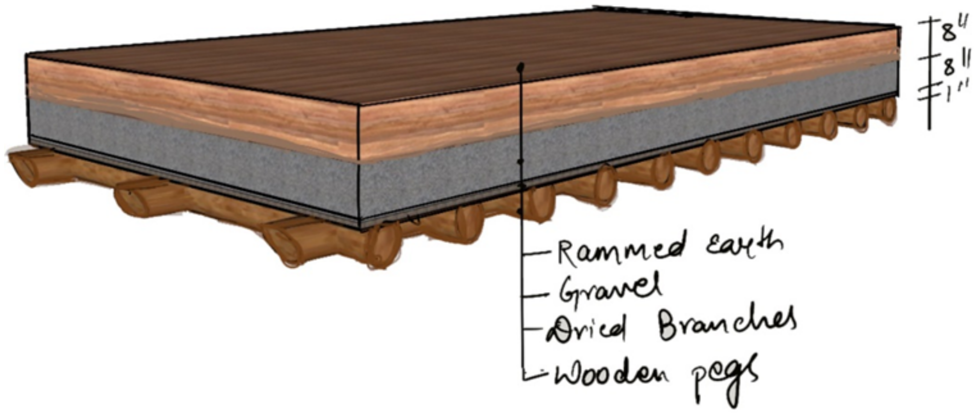

Figure 13: Proposed roof design.

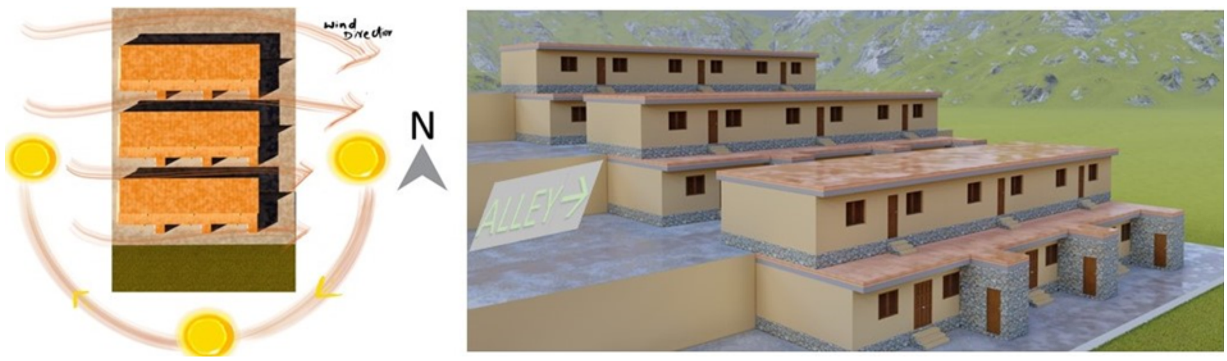

Figure 14: Proposed settlement pattern and perspective view.

the road/street. For simplicity and protection of cultural significance, the structures are designed as single-storied buildings. The structures are designed with semi-double blanked walls where the opening is only provided in the south direction to avoid cool air breeze from the north as well cross-ventilation.

The room is actively heated with a fireplace which is also used for cooking. The location of the fireplace is kept such that heat loss can be minimized to keep the living area as warm as possible in the winter seasons in the cool temperate climate. Individual latrines are attached to each house to provide ample use of the latrines. In addition, a home-stay like environment is developed which can improve the ambiance of the house.

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