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Thermal Comfort Environment of Mud Shelters in Nepal

(A case in Hilly and Mountain Region)

by

ANKITA YONZAN

A THESIS

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DECLARATION

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ABSTRACT

Nepal, a country with high geographic variation due to tectonic plate movements, has different climatic conditions in different regions. Due to the climatic variations, it consists of locations with hot and cold locations where the surrounding is not suitable for human habitation. However, the adaptation of people to the surrounding environmental condition in terms of the people's habit and their housing architecture has helped a lot in creating settlements in beautiful but remote locations of Nepal. Many houses are made up of mud which can be found in all the regions, namely, the terai, mountainous and hilly regions of Nepal. Nevertheless, the form, type of material, and its use vary according to the need of the people in their respective regions. Studies have shown that traditional mud architecture, as well as modern ones, are better in thermal performance as mud has a high thermal mass. In the context of Nepal, there have been studies of thermal comfort and thermal adaptations of people in different types of houses. However, there is a lack of research on mud architecture and its effect on the thermal performance of residential dwellings and the thermal comfort of the people. In addition, people are opting for modern concrete buildings wiping out the traditional methods of construction that show both cultural tourism values. This study reveals the thermal performance and comfort of traditional mud shelters in comparison to modern concrete structures located in the cool temperate and warm temperate climatic regions of Nepal. Moreover, the architectural elements of both traditional and modern mud shelters were studied which consists of different types of passive design strategies for climate responsive designs. In both regions, mud shelters performed better than the modern concrete structures, modern mud shelters have overall better performance than both traditional mud and modern concrete structures. But there may be other reasons influencing the results like cooking habits and clothing as well. Designing changes are suggested for traditional mud shelters for better performance for better utilization of available direct and passive solar energy around the region.

Keywords: Mud Shelter, Rammed Earth, Thermal Comfort, Passive Design Strategies

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LIST OF SYMBOLS

Rsi	Thermal Resistance of Inner Surface Material
R1	Thermal Resistance of Inner Surface
Ra	Thermal Resistance of Air Gap
Rso	Thermal Resistance of Outer Surface Material
Rt	Total Thermal Resistance
Φ	Time Lag
T_{in} , T_i	Indoor Temperature
T_{out} , T_o	Outdoor Temperature
T_{om}	Outdoor Mean Temperature
DF	Decrement Factor
T_c, T_{comf}	Comfort Temperature
T_g	Globe Temperature
a^*	Increment Coefficient for Comfort Temperature
a^{**}	Increment Coefficient for Preferred Temperature
f_i	Internal Surface Conductance
f_o	External Surface Conductance

LIST OF ABBREVIATIONS

CBS	Central Bureau of Statistics
PIT	Point In Time
SMM	Stone with Mud Masonry
PMV	Predicted Mean Vote
TSV	Thermal Sensation Vote
CWB	Subtropical Climatic Zone
RCC	Reinforced Cement Concrete
CGI	Corrugated Galvanized Iron
SMC	Stone Masonry with Cement Mortar
SPSS	Statistical Package for Social Sciences
HRRP	House Recovery and Reconstruction Platform
EEFIT	Earthquake Engineering Field Investigation Team
GoN	Government of Nepal
LCD	Liquid Crystal Display

CHAPTER 1: INTRODUCTION

1.1 Background

Mud shelters and their architecture is the study of mud as a construction material, form, and functionality that has been tried and refined for thousands of years(ASC, 2022). Because the properties of this material are considerably different from those utilized in the current building, the manner of application is also highly different(Architect, 2011). Since Neolithic times, mud has been extensively utilized as a building material. These mud buildings are an outcome of humanitarian efforts and a reflection of the natural environment in which they emerged; it was this environment that provided the primary source of materials for architecture and urbanism in various climatic zones across the world(Suliman, 2016). Mud has its inherent benefits such as its malleability, low cost, abundance, insulation, etc., and also indirect advantages like usage of less fuel and energy in transportation, and construction which is beneficial for the environment's protection. In addition, even a simple modification or process can turn the mud into a high-performing construction material(Depth, 2022). Mud has the potential to form thermal insulation between humans and the surrounding while providing adequate functions to sustain the modern residential lifestyle. The plentiful supply of soil in wide areas enables the economically disadvantaged to finance mud construction. Hence, the historic significance and adaptive learnings of these mud shelters can provide renovated ideas for today's trend of sustainable structures.

As the necessity of life changed from hunting to agriculture, the need for permanent settlement brought the use of stones followed by mud progressively. There has not been an exactly known transition period from stone to mud houses but archeological evidence shows the use of mud for the construction of shelters dating back to 8,000-10,000B.C. Such examples can be considered from Catalhoyuk, Turkey which is one of the first villages formed by humankind when nomads first settled and began to farm(Ciancio et al., 2015). Another similar earliest town was Jericho, Arabia(currently Palestine) (Kenyon, 2022). These houses were made up of mud bricks that were topped with dome roofs. According to Niroumanda et al., the first known shelters were outgrowths of temporary, seasonal shelters built of wood and brush, which were typically waterproofed with mud. The term

"Facal" refers to this form of building(Niroumand et al., 2013). Another building type that used mud was partly underground mud dwellings called pit-houses. Almost all ancient civilizations from Egyptian to Jiahu(Chinese) civilizations used mud in various ways like rammed earth, compressed mud-straw bricks, etc. During the early centuries, houses were built on a natural stone footing with hand-made mud bricks as wood was costly(JS, 2022). Just a little amount of it was utilized in the roof framework. Nazareth's dwellings were most likely single-story, basic, and modest. In the medieval period, panels that did not bear loads were filled with wattle and daub in dwellings, which had a timber structure(Simkin, 2020). The wattle was then daubed with a combination of mud, straw, cow manure, and lamb oil once it had been created. After it had dried, the surface was covered and the crevices were sealed with a combination of lime plaster and cow hair. Both cob and wattle/daub structures were popular in Europe during the middle ages(Susanna & Viljanen, 2019). Both houses and monumental structures were found in the early ages and the medieval period in Syria which showed massive use of mud bricks during both periods(Genequand, 2005). Hence, it can be said that mud shelters have been a part of human civilization throughout the ages, the only difference is their application to form different composite materials.

Figure 1.1 Catalhoyuk (8000 BC)
Source: (Plantware, 2022)

Figure 1.2 Mud house in Jericho (8000BC)
Source: (Pinterest, 2022)

Figure 1.3 Cob house, England(1532A.D)
Source: (Insteading, 2020)

Figure 1.4 Wattle and Daub, France
Source: (WordPress, 2016)

Mud construction has been previously seen in various parts of Asia like India, Bhutan, and China. In present-day Bangladesh, a village exists where they prefer traditional mud houses instead of modern concrete houses even though they have more access to modern technology(Pabna, 2021). Among 118million houses in India, 65 million dwellings are still made up of mud as it has better performance in hot summer. In Nepal, mud shelters have been found in the form of rammed earth, mud masonry, adobe bricks, cob, straw bale, etc. (Tamrakar, 2020). The traditional buildings in Nepal are usually made up of mud, stone, and wood which represents the unique and vernacular architecture of the specific location. In Nepal there are distinct geographical variations with elevations ranging from 60 meters to 8848 meters, resulting in a wide variety of lifestyles among the people and a wide range of housing types. Housing types in Nepal have been inspired by traditionally valued construction techniques according to geographic and climatic variation. Altered multiple times since the ancient ages, they have been passed from generation to generation with almost many modifications, but they are slowly being replaced by modern construction techniques, modern design, and the use of artificial material. Modern housing technology must be restrained from encroaching on traditional houses. Sub-tropical, warm temperate, cold temperate, alpine, and tundra climates are the five climatic divisions Shrestha uses to categorize Nepal(Ojha & Panday, 2021).

Table 1.1 Climatic Zones in Nepal

Climate Zone	Altitude(m)	Temperature (℃)		Precipitation(mm)
Sub-Tropical	0-1200	15	>30	100-200
Warm Temperate	1200-2100	10	24-30	100-200
Cool Temperate	2100-3300	<5	20	150
Alpine	3300-3500	<0	10-15	25-50
Tundra	Above 5000	0 <		Snowfall

However, some regions of settlement lie in between those distinctive regions, e.g. cool temperate and alpine regions where there is a significant amount of rainfall and snowfall in the summer and winter respectively. The house architecture is different for different climatic regions. Mud is a popular construction material in all regions in one form or the other. There are both permanent and semi-permanent houses involving mud as a building material among which most are traditionally built; some people usually migrate to warmer locations during winter. The traditionally built houses in each locality show their unique identity and enhance the ambiance, culture, and architecture related to the particular society. This exceptionality along with the natural beauty of the Himalayas and rivers behind this settlement has brought an income source directly to the local people in terms of tourism. The income source is generated from homestays, tea houses, trekking routes, etc.

In Nepal, Gandaki province has 47,447 people employed, respectively in the tourism sector. These traditionally built houses are a result of the acquisition of vast experience by our ancestors which is surprisingly sustainable and has the potential to fulfill our present needs for comfort(Tiwari et al., 2004). Currently, people still stay in their respective settlements to earn income and sustain themselves even with hard living conditions and low overall comfort. This situation can be improved using the current knowledge and technologies while preserving the architecture of traditional houses.

Mud shelters are considered to perform better in terms of thermal performance compared to other building materials. Studies conducted by Udawattha shows that mud concrete block has better structural cooling ability and thermal performance than other wall materials. MacDougall et al. pointed out that insulated earth-rammed construction has a significant reduction (70%) in heating energy requirements compared to construction using conventional methods of earth-rammed construction(mactps.). Giuffrida et al. used passive design strategies and reduced 20% in discomfort hours with optimized insulated constructions to achieve indoor thermal comfort and energy needs in rammed earth dwellings to be used in Mediterranean climates with optimal thermal insulation for rammed earth walls in hot temperate climates(Giuffrida et al., 2021). More studies have been conducted on traditional mud shelters in various parts of the world which have been covered in the literature review section, and it shows that traditional mud shelters with their inherent passive designs can perform better to provide adaptive comfort for the residents.

Nepalese settlement with traditional mud shelters as well as modern concrete structures without proper planning and development has been a challenge throughout history. Although it is among the least developed countries, the rate of urbanization is among the highest with notable indications like the increased number of municipalities and their expanding areas(Bakrania, 2015). Due to a significant housing demand gap in both urban and rural areas, as well as limited resources on all fronts, the housing solution must be as effective as possible, optimizing the use of available resources of land and construction materials. Nepal lies within the top 50 countries in the ranks of poorest countries in the world(Ventura, 2021). The transition from rural to urban area has been silently occurring in various parts of Nepal due to reasons like tourism, local development projects, etc., but its spatial variability is high due to poverty. In these transition periods, many mud shelters have been replaced by concrete structures with time and private requirements, with haphazard and sub-standard constructions. The local bodies previously applied low interference with the uncontrolled development and now have an enormous task with the situation to manage the resources for both the present and the future generations. In this condition, studying and prioritizing sustainable mud housing and settlement options can provide an alternative for both the rural and urban areas in terms of energy, material resources, and finances. Villagers choose to live in small, filthy, conventional concrete containers instead of following building codes to boost their income, which is completely at odds with the way of life in the countryside(Bodach, 2014). Tradition is being destroyed in the hasty pursuit of progress. The most unexplored source of architectural inspiration, in terms of shelters, is the philosophy and wisdom of the nameless architects and their architecture. In addition, as many ancient homes provide intelligent solutions to the architectural issues of enduring extremely cold as well as hot climates, modern architecture has been criticized for failing to respond to the local environment. Utilizing both traditional architecture and new technologies is necessary for a healthy future civilization.

1.2 Problem Statement

Traditional mud shelter provides insights into how people used their practical knowledge to obtain climate-responsive designs to fulfill their desired levels of thermal comfort. The energy-efficient and sustainable nature just came with these vernacular designs. From the viewpoint of durability, these structures have stood for a long period even surpassing the lifetimes of structures made using modern technology. The most fascinating aspect of these traditional structures is their blend with the local nature even when seen in clusters and different arrangements from an architectural viewpoint. These structures are created from the enormous accounts of failures and learnings throughout history by our ancestors which can still outperform modern structures if conditioned with modern technology. Compared to traditional structures, modern structures look out of place, are ill-designed, and destroy the ambiance of the surroundings if placed together in groups. On contrary, traditional vernacular structures are considered old and outdated, which are gradually being replaced by modern ones as it is neither monumental nor ancient. Such traditional shelters have huge 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 thermal comfort conditions, an important parameter for better human performance, are governed by both physiological and psychological factors of the local people which have generally been adapted to the local surroundings. After considering all the factors from human, physical properties, and form, it is still hard to generalize the thermal comfort conditions for similar regions because both the construction material as well as the traditional designs differ in material, shape, and the surrounding climate. Even in the same area, there have been accounts of different thermal comfort requirements due to different indoor temperatures(Rijal, 2021). In Nepal, traditional structures are mostly related to mud whereas modern structures are related to concrete. As an exception, there are also a few new mud shelters designed according to climate. As evident from the background of the study, Nepal has 5 distinctive climatic regions where there exists considerable settlement of people from subtropical to the tundra. Besides mud shelters being sustainable, the main argument is that the thermal performance of traditional mud shelters is superior to the modern concrete structures built in the same climatic surrounding. This argument, even if researched in many other countries, may or may not be true for Nepal as there has been a lack of comparative study on the thermal performance of mud and non-mud shelters located in the same climatic region which has different construction materials, traditional designs, shape, etc compared to other countries. 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/actual community is lacking. Furthermore, this study helps to understand whether our argument is positive, and with a certain degree of positivity, it further establishes that using traditional mud shelters instead of modern concrete shelters in different climatic regions can be thermally comfortable in addition to its sustainable nature and unique architecture. Therefore, from the literature, it can also be argued that the generalization for each climatic region may require more thermal performance and comfort analysis in those regions. In an ideal world, a country like Nepal with its limited resources can set an example to create large mud shelter communities which are both sustainable and thermally comfortable for the residents of that climatic region. Modern architecture can benefit from the principles of vernacular architecture for better climatic adaption.

Studies in recent years have shown that vernacular architecture has higher thermal performance compared to modern structures in many parts of the world(Elias-Ozkan et al., 2006); some studies have also been done in India and Nepal (Akella, 2005) (Bajracharya, 2014). For vernacular mud architecture, some researches show that traditional constructions(adobe), as well as modern ones (rammed earth) built with mud, perform better in terms of thermal lag and periodic oscillation (case 1). The better thermal performance is due to the selection of better architectural elements and designs to counter the prevalent environmental conditions as shown by the research on traditional mud shelters. Also known as the thermal flywheel effect, the most typical passive solar building design uses thick walls to stabilize the interior temperature, which is also common in many older, traditional mud buildings(Nie et al., 2019). In China, there have been accounts of using the flat roof of the lower house as the terrace of the upper house, for better distribution of sunlight around each house. These are some of the architectural examples that have been implemented in traditional mud houses which have helped them to perform better thermally. In the context of Nepal, the thermal performance studies of traditional mud architecture based on its architectural elements have been lacking despite a number of studies in modern mud architecture, especially modern rammed earth. Another important aspect is the mud architecture of the traditional structures which has distinct characteristics which play a significant role in better thermal performance, energy efficiency and sustainability. However, the sensitivity of thermal comfort from the different architectural elements have not been considered before. This separation of positive and negative influences of architectural elements helps in finding the weak areas that inhibits the maintenance of thermal comfort which can be fulfilled using modern technology, little energy resources and better designs. Such kind of study of architectural elements are related to climate responsive design and their passive design strategies. A study similar to our intent has been done by Chaulagain et.al for concrete buildings in two different locations in Nepal using energy simulation(Chaulagain et al., 2020). As the vernacular architecture has acquired some advanced strategies of passive design inherently from various learning of the past, a detail study of such strategies is also necessary as different shelters have different strategies located in different places. The typical reason for its better performance 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. Bodach et.al have extensively studied the climate responsive passive design strategies found in various parts of Nepal. However, no such studies that directly relates the thermal performance and the passive design strategies in the mud shelters in Nepal have been done. Thermal comfort and thermal performance are both necessary for human as one is related to human performance and another is related to the surrounding that encloses the humans as a shelter. The broader problem is that to maintain thermal comfort, the developed nations as well as the developing nations, one rapidly whereas the other slowly, moving towards higher energy consumption to maintain the thermal standards of heating and cooling by using HVAC and other equipment that are depleting the energy resources. The usual modern architecture, on the other hand, does not focus on using passive systems and strategies for improving indoor surroundings. Unsatisfactory interior thermal comfort is a result of residential structures' disregard for environmental design standards. Lack of regard for the thermal efficiency of contemporary materials in terms of internal thermal comfort is a tendency that results in several environmental issues (Alzoubi,2019). Additionally, the energy consumption of buildings increases as a result of their non-climatical design obligations. Thermal performance studies for traditional structures are rising which shows the immense possibility of it being used in small-scale housing construction and replacing the concrete jungle that we live in in the name of urbanization. Understanding the beneficial aspects of passive solar designs that have been implemented in certain traditional vernacular architecture in the context of Nepal has been lacking in the study. The gained knowledge from this study can be implemented both in new vernacular and modern structures in the future.

Hence, this study compares the thermal performance of traditional and modern mud shelters with modern concrete structures in different locations in Nepal. In addition, its focus is on understanding the role of architectural elements in providing passive design strategies in different regions for both traditional and modern mud structures and finding out the good and bad practices. Furthermore, the research is focused on fulfilling the gaps in understanding the relationship between thermal comfort, thermal performance, and the inherent climate-responsive designs of the traditional mud shelters. Also, recommendation of different new passive techniques for improving the thermal comfort in both vernacular and modern shelters according to the climate is done in detail.

1.3 The rationale of the Research

1.3.1 Need of research

Nepal is a country with existing climatic extremities without adequate natural and sustainable resources to maintain a proper thermal comfort environment. In high-altitude regions, environmental problems like wind, snow, and extreme temperatures create problems whereas the terai region is very hot and highly humid due to its low altitude and flat lands. In both cases, it requires a considerable amount of renewable/non-renewable energy consumption to maintain a thermally comfortable environment where humans can function at their optimum level. In the world, buildings are commonly considered to be responsible for almost 30% of global final energy and for 35–40% of that in industrialized nations, of which 30–60% is used to enhance the indoor thermal climate of buildings(Pokharel, 2021). In Nepal, 80 percent of rural residents still use traditional fuels including firewood, agricultural waste, and animal dung for cooking and space heating because they are relatively expensive and in short supply. From the world data web, it has been found that as of 2020, Nepal imports 2.18 bn kWh energy in terms of electricity which is a deficit annually(WorldData, 2020). Studies in the residential sector of Kathmandu Valley showed that biomass provided 50% of the energy needed for space heating, with electricity and LPG coming in at 25% and 16%, respectively which shows that people are still dependent on non-renewable resources for survival (Rajbhandari & Nakarmi, 2014). For space heating, people in three locations predominantly rely on firewood; in cold, temperate, and sub-tropical climates, respectively, per-capita total energy use was determined to be 37, 30, and 20 MJ/(capita. day)(Shahi et al., 2020). While doing so, a substantial quantity of hot gas gathers at the top of the ceiling which is inefficient in terms of heat energy usage and poses both a health risk and thermal discomfort indoors(Rijal, 2021). Assuming the urbanization pattern in rural areas similar to Kathmandu Valley, it can be said that there will be an unsurmountable energy gap shortly as the population and their energy demand increase. In one way, the available energy could be used efficiently as there is a lack of such resources in the rural regions while still maintaining thermal comfort while the other positive aspect is that thermal comfort through passive design can help reduce energy consumption. Energy consumption is also related to pollution as almost 5% of the energy used in Nepal is directly produced from fossil fuels imported from other countries (word data.). In addition, according to standards established by Nepal's Energy Efficiency Center, the ideal energy consumption for the cement production process alone is 105 kWh/ton of cement and 750 kCal/kg (3.138 MJ/kg) of clinker in enterprises using limestone(A. Shrestha et al., 2016). The production and transportation of cement which is used to build concrete structures consumes a lot of energy and is unsustainable in nature. Hence, this research studies whether thermal comfort conditions in Nepal have been fulfilled from passive design strategies in mud shelters so that they can be built for a sustainable future without being replaced by the modern structures.

Since the dwellings are constructed with thick walls in such regions, there is a presence of a passive thermal heating effect that slowly diffuses and dissipates from the internal environment throughout the day/night time. However, the architectural forms and elements that best suit such dissipation are still unknown in the context of traditional architectural styles for high-altitude cold regions. In addition, the thermal comfort condition is different for the same area(Rijal, 2021). This investigation can help maintain thermal comfort by understanding what is the relationship between the architectural elements and thermal comfort which helps to stabilize and organize the energy-efficient features to improve the indoor thermal comfort conditions of the traditional buildings. Therefore, there is an urgent need for the study of thermal comfort efficiency of such traditionally built structures based on the different architectural elements that were constructed in light of the knowledge of heat and comfort by the local people.

Concrete and composite structures have overtaken our traditional materials, style, and method of construction which has plummeted our uniqueness in traditional architecture. In addition, it is also one of the main sources of CO_2 emissions as well as energy consumption. Buildings have an active role in environmental degradation, it is essential for finding housing systems that meet the principles and standards of sustainability, longevity, and stability. To match the present requirements (control quality, strength, mix proportion, etc.) for structurally stable sustainable housing, nations like China, India, New Zealand, Australia, Zimbabwe, etc. have included guidelines for stone and earthen construction in their building codes and references, for eg, Australia 2002, NZS 4297:1998, NZS 4298:1998, NZS 4299:1998, SAZS 724:2001, 2001, etc. Thermal comfort is also needed in every aspect of our life and especially in the indoor household environment. The works of Tanabe and Nishihara(2004) stated that subjects worked harder to maintain their work performance when IEQ (moderately high temperature and lighting condition under 3 lux) was suboptimal(Lan et al., 2011). Hence, it is evident that thermal comfort is necessary for the survival of the people living in traditional houses, not only for psychological satisfaction and work performance but for survival as well. Lastly, the research on thermal comfort has broader implications for health, performance, economy as well as the sustainability of the environment in the coming years.

1.3.2 Importance of research

In the vernacular construction practices, more social bonding and interactions are fostered as villagers pitch in to help build the houses. The helping hands are either paid or bartered with goods and in the end appreciated with feasting ceremonies(E. Shrestha, 2019). Hence, vernacular architecture is worth saving and its performance enhancement is necessary. The maintenance of thermal comfort by decreasing the hours of thermally uncomfortable periods is necessary for human performance which can be achieved by optimizing the energy-efficient features already available in traditional houses. Such sustainable houses protect the environment, provide economical gains, and effective risk management toward health hazards. By managing thermal comfort, you are likely to improve morale and productivity as well as improve health and safety. People working in uncomfortably hot and cold environments are more likely to behave unsafely because their ability to make decisions and/or perform manual tasks deteriorates(Hou, 2016). A safe range of temperature not only supports human life; coolness and warmth but also provides a symbol of protection, community, and even sacredness in different cultures. In recent times, thermal comfort studies have been done by many scholars to advance technologies for low thermal energy consumption, sustainability, and carbon efficiency(Hou, 2016). If thermal comfort conditions are provided, then the increased confidence along with good health conditions helps to improve the output efficiency in both physical as well as intellectual tasks. This fact has been proven in many studies related to office buildings and research facilities(Kaushik et al., 2020). After the correct prediction of the comfort temperature for a particular surrounding, a reasonable neutral temperature can be determined which can be used as a guideline for similar places of research. Different thermal comfort models have been developed for people of different races, ages, and locations (Zhao et al., 2021).In building science studies, thermal comfort has been related to productivity and health. Office workers who are satisfied with their thermal environment are more productive. The combination of high temperature and high relative humidity reduces thermal comfort and indoor air quality. The study of thermal performance is very important to understand how thermal comfort is influenced by the physical properties of architectural elements used in traditional houses.

This study will help to compare the results obtained from the study with other related studies to develop the thermal performance and comfort standard for cold climate areas in Nepal. Hence, thermal comfort becomes important when it comes to the survival of the people in higher settlement regions. The thermal performance requirements of structural changes with the changing climate, hence it is important to study the thermal performance in the cold region also which is reasonable in Nepal as a rural community has hard living conditions in the cold region. Using mud architecture as energy-efficient material, environmental degradation and economic challenges can be alleviated.

1.4 Research Questions

The scope and limitation of our research are limited to the following question:

- What is the thermal performance/comfort of traditional mud shelters in Nepal?
- What is the thermal performance/comfort of modern mud shelters in Nepal?
- What are the architectural elements involved in the thermal performance of mud shelters for maintaining energy efficiency?

1.5 Validity

The validity of a research study refers to how well the results among the study participants represent true findings among similar individuals outside the study (NCBI). For the validity of the research question, it is evident from the literature that no such study has been conducted before that considers the thermal performance study of both traditional and modern mud shelters and their architectural influences in the context of different climatic conditions found in Nepal. The main agenda of this study is to find the thermal performance differences of mud shelters, both traditional and modern in Nepal. In addition, this research compares and contrasts the thermal performance with the common concrete structure, which is a dominant material in the field of construction. For internal validity, more than one house type of the same region has been considered. The external validity of the results is assured by an adequate number of samples concerning the population residing in the respective region whether it be hilly or mountainous. For such reasons, mathematical relations are used to justify the number of participants for the survey. Besides, the results are compared with previous studies, and the parameters like U-value, time lag, and so on are also measured which helps to know whether the thermal performance has changed over time.

1.6 Scope and Limitations

This project has many limitations in terms of understanding the thermal performance and thermal comfort of the residents living in different residential mud shelters in Nepal. The main drawback of this thermal environment analysis is that it is specific to a short period. Hence, it is not easy to justify those results for both summer and winter. Another shortcoming is that the number of measurements may be inserting biases in our study throughout the day because the study is being done in only three periods of the day. It is difficult to choose the time that represents the temperature for a specific period of the day. The instruments used are hygrometers that are generally used for daily household measurements and their accuracy is limited as it is not specifically made for scientific measurements.

The research was focused on taking temperatures in the colder period, however, due to the scheduling of exams and initiation of the survey, it could be done as early as desired. The influence of a single resident is very high on the result of the questionnaire survey. Therefore, the conclusion of obtained results indicates incomplete data which needs further research and survey in the future.

1.7 Organization of Report

The first chapter covers the background, statement of the inherent problems in the research content where thermal comfort issues persist. The importance and need of conducting the thermal comfort research in Nepal for different mud and non-mud shelters are carried out. The main objectives of research are figured out for fulfilling the research gaps in the field of thermal comfort. The scope and validity of the research content are discussed as it it difficult to fulfill all the aspects of thermal comfort research due to different technical difficulties.

The second chapter covers the thermal performance, thermal comfort and mud shelter scenario of Nepal. In addition, the climate responsive strategies that are inherent in the mud shelters of Nepal in both modern and traditional mud shelters are mentioned and compared with different other countries. Moreover, case studies of different mud shelters with respect to thermal comfort and performance is done in various parts of the world having both hot and cold climates.

The third chapter includes the conceptual framework that fulfills the objective of the research and the followed methodology which provides the research direction. The methodology of thermal environment measurements and the thermal comfort survey are mentioned in detail. Furthermore, the detailed information of the studied area, studied shelters and their inherent passive design strategies are compared with each other as well as other non-mud structures.

The fourth chapter covers the results of thermal measurement as well as thermal survey records which were analyzed according to the obtained data with respect to comfort and preferred temperatures, humidity ad thermal transmittance. The data of the houses were divided into mud and non-mud shelters as well as hilly and mountainous region which helped to segregate the results for analysis. The results and their analysis show the positive responses of mud-shelters in terms of thermal comfort during near summer and near winter seasons.

Finally, the final chapter provides the key research findings in bullets and also gives the guideline as well as recommendation for the mud-shelters so that it can perform better than the inherently designed mud structures. A detailed designs suggestion in graphical form are provided for clear representation. In addition, the annex portion consists of detailed properties of studied houses, location of thermal equipment, average temperatures of individual houses and other additional information that helps to understand the research methods that have been followed.

CHAPTER 2: LITERATURE REVIEW

2.1 Thermal performance

The phrase 'thermal performance' refers to how well something maintains or stops heat from passing through it(Construct, 2022). This is usually about the heat conductivity of materials or materials assemblies. Therefore, it deals with how well a structure reacts to heat flow from inside to outside the structure or vice versa. Thermal performance is measured in heat loss/transfer, governed by convection, conduction, and radiation. The main factors determining thermal performance are heat gains or losses through various structural elements, such as walls, windows, and floors, internal heat loads, and ventilation rate (Aye et al., 2006).

2.1.1 Thermal transmittance and envelope

The transfer rate of all the layers of a constructed building element (wall, floor, base) from the inside to the outside is called thermal transmittance, also known as U-value (W/m2K). U-values are used to know the thermal performance of constructions, i.e., assemblies of materials such as cavity wall constructions. The lower U-value means better performance of the structure. Building components with good insulation have a low thermal transmittance, whereas those with inadequate insulation have a high thermal transmittance. The U-value accounts for losses brought on by thermal radiation, thermal convection, and thermal conduction. The reciprocal of a structure's thermal transmittance is the structure's thermal resistance. The thickness of the material and the Thermal Conductivity (K) value must be determined to compute thermal resistance. The Metric Handbook and the Architects Pocket Book both contain these values(Mishra & Rai, 2018).

$$\text{Total Resistance } (R_t) = R_{si} + R_1 + R_2 + R_a + R_3 + R_{so} \quad [2.1]$$

$$\text{U-value} = 1/R_t \quad [2.2]$$

Where; Rsi, R1, R2, and R3, Rso are the thermal resistance values of the inner surface, inner material, air gap, and outer surface material. A building envelope requires physical isolation of the building from the outer environment. The performance of the thermal envelope relies on (Allouhi et al., 2018):

- Insulation levels in the walls, ceiling, and ground

- Thermal properties of windows, doors, and walls
- Airtightness to prevent wind and indoor/outdoor temperature, pressures differences

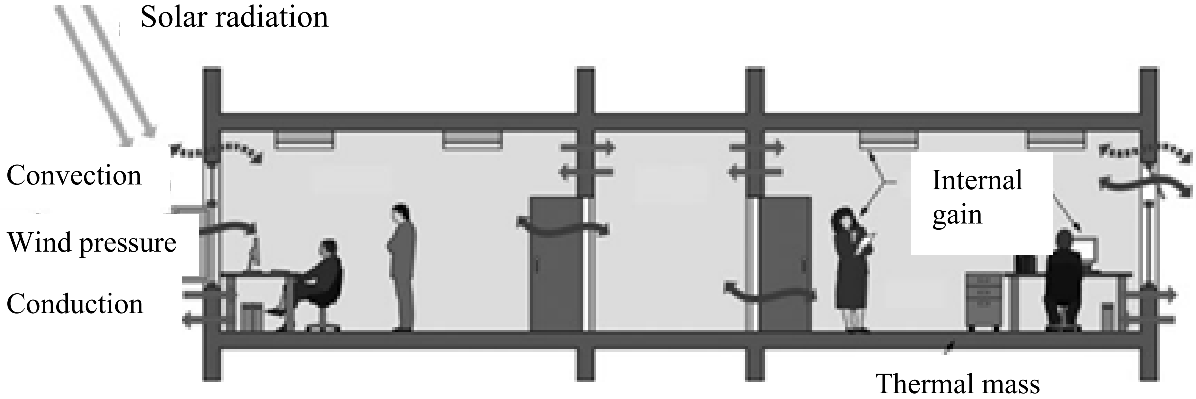


Figure 2.1 Building Envelope between inside and outside (CIBSE,2013)

The architecture of the building has a huge impact on the thermal envelope as the selection of the material, their sizes, and the overall airtightness depends on the architectural design for both traditional and modern structures. In addition, the design strategies like suspended ceilings or floor area reduction can also influence thermal performance. A recent study shows that suspended ceilings which are an architectural addition, can cause unnecessary heating for more hours and also don't provide enough compensation in saving the heating energy in the colder period as it alters the thermal mass considerably(Høseggen et al., 2009).

2.1.2 Time Lag and Decrement Factor

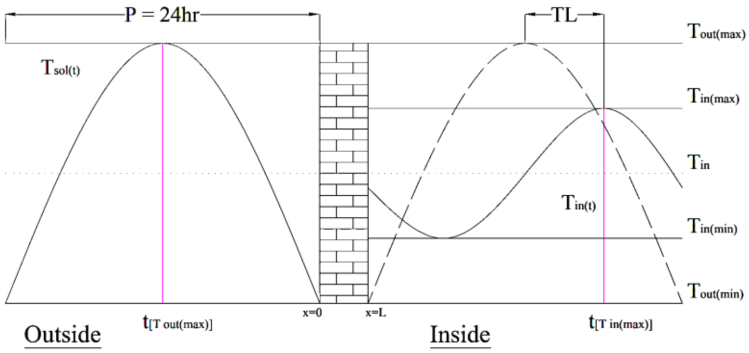


Figure 2.2: The schematic representation of time lag and decrement factor

$$\Phi = t_{[T_{in}(max)]} - t_{[T_{out}(max)]}$$

[2.3]

$$DF = \frac{T_{in}(max) - T_{in}(min)}{T_{out}(max) - T_{out}(min)}$$

[2.4]

Time lag (Φ) is the time difference between the maximum temperature on the outside and inside when subjected to periodic heat flow conditions (IS 3792-1978). A decrement factor (D.F.) is defined as the ratio of the amplitude of the temporal evolution of the temperature on the inner surface of the multi-layer material to that of the sol-air temperature or the outer surface temperature(Luo et al., 2007). The schematic of time lag and decrement factor is shown in Figure 2.6

2.1.3 Thermal mass and inertia

The primary thermal properties are conductivity, density, and specific heat capacity, whereas the derived properties are thermal inertia & thermal mass(Balaji et al., 2013). Thermal inertia is the degree of slowness with which the temperature of a body changes concerning its surroundings; it depends on thermal conductivity, absorptivity, specific heat, dimensions, etc. Thermal mass is the ability of a material to absorb, store and release heat. Materials such as concrete, bricks, and tiles absorb and store heat and have high thermal mass. In considering thermal mass, it also needs to consider thermal lag, which is the rate at which heat is absorbed and released by a material. Materials with long thermal lag times (for example, brick and concrete) will absorb and release heat slowly(Reardon, 2021) Mathematically,

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}\right)$$

[2.5]

Where t is time, ρ is the material density and C_p is the specific heat capacity. When calculated for the total volume of material present, ρC_p becomes mC_p Where m is the mass of the material and which is more commonly referred to as "thermal mass"(Beckett & Ciancio, 2012). Materials having high thermal mass can help increase thermal comfort and save the extra energy required to heat or cool the home system. In addition, thermal mass eases the slow regulation of internal temperatures by averaging out extreme temperatures during the daytime and nighttime for both hot and cold climates.

Therefore, it helps in both summer and winter. However, thermal inertia is more effective in summer than in winter because it can only store the heat energy that is absorbed due to sunlight or other external sources of heat. Therefore, materials with high thermal mass have difficulty maintaining the temperature required for thermal comfort if there is no external source of heat energy.

2.1.4 Thermal performance of mud shelters in other countries

Different methods have been employed to understand the thermal performance of the building. Chaulagain et al. used simulation modeling software (Energy Plus) which showed the potential heat gain and heat loss zones that are playing a role in thermal discomfort(Nicol et al., 2020). In a different approach, Bajracharya et al. compared the indoor-outdoor temperature and used the Nicol graph to find the comfort temperature in traditional residential buildings of Kathmandu revealing the adaptation of people to these houses. Danielski et al employed a nondestructive steady-state heat flux thermography technique for finding the building envelope's thermal condition with higher accuracy than previous thermography methods(Danielski & Froling, 2015). Another method that has been used is an AES(architectural evaluation system) to measure environmental parameters like temperature and humidity at the same time for different locations(Shanthi Priya et al., 2012).

Many studies have been conducted on traditional mud structures similar to the ones found in Nepal. In Saudi Arabia, Mohamed et al. conducted subjective and objective evaluations of connected concrete and mud dwellings, finding that the temperatures were more or less all within thermal comfort norms(Mohamed et al., 2019). Martin et al. examined the thermal environment of three distinct buildings, two of which are traditional stone and mud constructions in Spain. Their findings found that no energy was required to maintain thermal comfort in the summer and that the internal thermal climate was more stable in traditional dwellings than in contemporary ones(Martín et al., 2010).On the contrary, Heathcote compared the thermal performance of adobe walls to composite walls and showed that adobe walls still require huge improvement to match the modern composite wall structures even though their performance is better when the wall thickness is improved(Heathcote, 2011) Azad and Fooladi compared the vernacular houses made up of mud and stone of different eras and found that the 1st and 2nd eras were much better for thermal comfort than the 3rd era because the 3rd era changed the previous practices of thick walls, low height of the house, low wall to opening ratios in Cold and Mountainous Region of Iran(Azad & Fooladi, 2022). Chandel et al. showed that the main parameters affecting energy efficiency and thermal comfort in vernacular architecture are identified as: the use of earth, stones, wood, and bamboo as a building material, built mass design, orientation concerning the sun, space planning, openings, sunspaces, construction techniques, and roof materials(Chandel et al., 2016). Meir, in their study, pointed out that even though traditional structures which involve mud have high thermal mass due to a lack of openings, it has the drawback of not being able to absorb solar radiation during the winter. In addition, the dwellings could not provide cooling at night with a lack of cross ventilation during the summertime (Meir & Roaf, 2003). Researchers in India studied the thermal behavior of mud structures under complex climate conditions and discovered thermal time lag helped in winter comfort by keeping nighttime temperatures higher than outside temperatures. Summer temperatures, on the other hand, remained high at night, with fewer ventilation apertures(J. Gupta et al., 2020). Gupta et al. studied the thermal performance of three mud structures with courtyards and concluded that these structures, as well as their orientations, should be properly designed, clustered, and oriented to reduce thermal discomfort in the summer and lower summer season temperatures through air circulation(J. Gupta et al., 2017). The thermal properties of materials used in the construction of traditional rammed earth structures in Bhutan were studied which showed that traditional construction types are the worst-performing structures due to massive air leakages. (Jentsch et al., 2017). A study conducted in North-east India showed that houses in cold and cloudy climatic zone provided better comfortable time in comparison to the house in other climatic zone and occupants have enhanced control over indoor environments in the vernacular houses because they have the flexibility to control their personal and environmental conditions in the form of different adaptations(Singh et al., 2010).

Overall, traditional mud shelters in other countries with varying climatic conditions also show satisfactory thermal performance which is beneficial as it is cheap and sustainable. Most of the mud shelters belong to vernacular architecture which has been optimized through the experience of weather in a certain part of the country.

2.2 Thermal comfort

Thermal comfort is the condition of the mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation(ANSI/ASHRAE Standard, 1979). Thermal comfort varies from person to person depending on their physiological and psychological conditions. Since it varies from person to person, satisfying every individual is almost impossible. Therefore, a plausible approach that has been considered in recent designs is to satisfy the high majority of the people towards an acceptable thermal environment. Factors determining the thermal comfort of human beings can be categorized into 6; among them, air temperature, the mean radiant temperature, air velocity, and air humidity are environmental factors, whereas metabolic rate and clothing insulation are personal factors(Dong et al., 2014). Parsons suggests the inclusion of outdoor adaptation and those 6 factors(Parsons, 2019). The metabolic rate is defined by food and drink, acclimatization, body shape, subcutaneous fat, age and sex, and state of health(Hamzah et al., 2018). Recent studies have highlighted that thermal comfort has a higher impact on dwellers than other forms of comfort(Frontczak & Wargocki, 2011). Thermal comfort investigations have pointed out that the level of thermal comfort is mainly concerned with energy usage and its future projection depends on future climatic changes(Sangita Thapa et al., 2020). Thermal comfort can be evaluated with both objective and subjective approaches.

2.2.1 Objective approach

Objective methods involve physical measurements of thermal comfort parameters. The ASHRAE standard uses Fanger's heat balance model to calculate the Predicted Mean Vote(PMV), which is ranged in terms of the thermal sensation vote scale(TSV) (Gilani et al., 2015). PMV is an index that intends to quantify thermal comfort as the mean value of votes of a group of occupants on a seven-point thermal sensation scale. In the PMV range, +3 is considered too hot, while -3 is considered too cold, while 0 shows thermal neutrality. Both the PMV and the thermal environment survey are equally important in their perspectives as one includes most aspects related to thermal comfort.

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

2.2.2 Subjective approach

In contrast, subjective methods require the building users to evaluate their thermal environment in terms of thermal sensation, acceptability, preference for change, and more through occupant surveys (objective and subjective evaluation). In contrast, the other provides insight into the residents' thermal comfort provided by the surroundings. There are usually two types of surveys: right-now and satisfaction surveys. This objective, as well as subjective methodologies, assists in determining the thermal comfort of the house that we live in.

2.2.3 Thermal comfort condition in Nepal

The thermal comfort conditions vary significantly in Nepal as it has drastic changes in climatic conditions at different places due to the geographical form of the country.

Unfortunately, there is still a lack of definitions of thermal comfort policy in the building codes provided by the responsible governing authority in Nepal. Therefore, Nepal uses biomass burning or complicated HVAC systems to maintain thermal comfort and adjust clothing conditions and eating routines to fulfill the remaining energy gap(Chaulagain et al., 2020). There have been many thermal comfort surveys in the various regions of Nepal, which have given a brief perception of thermal comfort in the high-altitude cold region, hilly region with a moderate climate, and flatlands with a tropical climate. Pokharel et al. suggest that significant advancements are required in maintaining the indoor thermal environment by improving the thermal insulation of building envelopes (Pokharel et al., 2020). Point in Time Thermal comfort surveys have shown that research indicates people who live there have adapted well to extremely cold climates; however, longitudinal surveys are needed to be done in the future(Rijal, 2021). Some studies have also shown that it is more difficult for migrant people to maintain thermal comfort than those the local people(Gautam, 2021). In addition, the thermal environment measurement and analysis of the dwellings have shown that people are living far lower than the accepted comfort standards due to the poor thermal performance of sun-dried bricks in high-altitude regions of Nepal(Rijal & Yoshida, 2006)

Since the rural areas of Nepal are mostly populated by ancient settlements, research related to thermal comfort is related to vernacular architecture which has been constructed using mud, stone, wood, etc. Pokhrel et al. showed that the indoor temperatures in a cold region of Nepal were below ASHRAE standards, and people depend on firewood and require massive improvements in maintaining thermal envelopes (Pokharel et al., 2020). However, people were highly satisfied due to adaptation which can help lower the indoor heating temperature settings(Rijal, 2021). Rijal emphasized the preservation of traditional buildings and simulated different insulation techniques to improve their thermal conditions of them(B.Rijal, 2012). The simulation based on the Japanese heat/loading code showed that a significant reduction(20-50%) in firewood consumption was observed in the present research with optimization of the building's window-to-wall opening ratio(Rijal & Yoshida, 2005). Bodach et al carried out a qualitative analysis of the architectural elements that provided climate-responsive characteristics which helped to provide thermal comfort conditions. Their analysis revealed that alpine traditional mud houses have many features to protect from the coldness than houses in the other climates of Nepal.

2.3 Mud shelter in Nepal

2.3.1 According to Building Material Use

Earth has been used in different ways to create shelters since ancient times. The classification of mud shelters has been divided into many categories according to constructive techniques, water content, and load-bearing systems(Carrobé et al., 2021). Materials that are considered to have strong thermal performance are also good insulators, implying that they do not readily convey heat. Materials with poor thermal performance, on the other hand, tend to be stronger heat conductors and hence allow heat to transfer more quickly resulting in massive heat energy loss in a short time. Seasonal and diurnal temperature fluctuations, the amount of solar gain and shading, incoming and outgoing heat radiation, water and moisture absorption, air movement, infiltration, pressure differences, and so on all impact the thermal behavior of a building's material composition. There are different types of building materials used in various parts of Nepal based on the availability of materials, choice from the constructor, and the form of the structure.

- Adobe

The most common and well-known application of adobe is for the building of walls made of sun-dried bricks (adobe), with the two wall leaves being bonded together using the same clay soil. These sun-dried bricks have been used since 8000 B.C(Blondet & Garcia, 2003). Most nations have comparable architectural elements, such as a single door and rectangle design. Foundations are composed of intermediate sizes of stones having mud as mortar to form walls. The soil used to construct the blocks and mortar is often supplemented with straw or wheat husk. The dimensions of adobe blocks vary by the area where the thickness of a wall in a traditional structure is usually determined by the region's climate. However, it is particularly frequent in agricultural and rural settings. Bricks are often sun-dried and produced from mud near the construction site. The mud is allowed to season for a few days before being blended and poured into wooden brick-shaped molds to dry outside. The mortar is made from the same soil.

In Nepal, adobe structures are more common in rural areas. Adobe bricks are normally put on a foundation of stones gathered in neighboring fields or along riverbeds rather than directly on the ground. The construction is made up of two wall leaves: the visible outer leaf is generally made of high-quality bricks or has a unique finish, while the inside leaf is simply rendered(Bonpace & Sestini, 2003). The mud used to construct the bricks and mortar is utilized to fill the hollow between the leaves. Never less than 50 cm in overall thickness. Due to the bad economic situation, people used natural building resources such as sand, clay, water, and organic materials (sticks, straw, and/or dung) to construct their homes. Wooden frames are frequently used to keep things in shape. The structural walls of these structures are similarly made of sun-dried bricks (earthen) and mud mortar. In most cases, the wall thickness exceeds 350 mm.

Figure 2.3 Adobe House in Israel

Source:(Pinterest, 2017)

Figure 2.4 Adobe to rebuild the house, Lele village

Source:(offset, 2018)

There is another modern structure called the Super adobe structure that has been built in recent years with the help of the international organization. Superadobe is a stabilized earthbag made composed of woven polypropylene bags that are filled with a cement-stabilized soil mix on-site, then sealed, piled, and strengthened with steel barbed wire between courses to construct domes and walls (Cement & Earthbags, 2022). The local people have rejected these kinds of modern adobe structures because of their dome shape resembling holy stupas, their high requirement of labor and cost, and the local people's will to retain the traditional architecture (Khalili, 2015)

- Wattle and Daub

Wattle and daub is a traditionally used composite construction material made out of a woven lattice (the wattle) constructed from twigs, wood, or bamboo that's been daubed with a sticky infill substance like mud. It is one of the ancient weather-resistant houses that highlighted the medieval European era(Tikkanen, 2022). Composed of moist earth, straw, clay, sand, and animal dung, Daub is often produced for mud plaster. It is mostly found in the southern parts of Nepal and many parts of India. Wattle and daub is a western term, however, it has several regional meanings in Indian vernacular traditions, notably mat and mud(Varanashi, 2020). Split bamboo spacing varies depending on the kind of wall, and must not exceed 6 inches. The thermal insulation is maintained in part by the mud wall and thatch roof. The thatches and soil are regarded as thermal insulators(Shree Thapa, 2019)These kinds of structures are mostly found in the Terai region where the temperatures are above 38°C. The outer walls are whitewashed and painted. The thickness of the wattle and daub wall is typically 50cm. A modern and proper construction method has been defined by Gupta which consists of the following steps (J. Gupta et al., 2020):

- Bamboo culms are treated by using hot bitumen.
- Vertical and horizontal stripes are woven by wire at intersections
- Mud blended with rice husk, cinder, lime, and liquid is applied
- After drying, the extra mud is cut off from the surface and then plastered with a mud-lime mortar of 2cm thickness
- 1mm of gypsum is coated for smoothness of the wall followed by whitewashing.

Figure 2.5 Details of wattle and daub

Source: (WIKIPEDIA, 2022)

Figure 2.6 Daub and Wattle house

Source: (WIKIPEDIA, 2022)

- Rammed earth

Figure 2.7: Kag Chode Thupten Samphel Ling Monastery, Kagbeni (Vernacular Architecture)

Source: (Pandey, 2017)

In Nepal, the Annapurna region, Mustang, rammed earth structure can be seen in both monumental and vernacular architecture of the high-altitude dry region of the Mustang Kingdom(Jaquin, 2011). For vernacular structures, vertical poles are fixed to the ground and tied at the top by ropes. These timbers are tightened against the wall using wedges, and the earth is rammed into place(Jaquin, 2012). In Jharkot, two rammed earth buildings, one heavily damaged and another heavily repaired using masonry were observed(Richard Hughes, 2008). In the context of Nepal, they have been used even in the highest altitude regions like Lomanthang (3700m) to construct monasteries bigger than the normal dwellings with traditional knowledge which is now being combined with modern construction techniques for rammed earth(Rawal et al., n.d.).

Figure 2.8 Modern Rammed earth structure -Matoghar

Source: (Thapa, 2020)

Concerning thermal performance and thermal comfort analysis, only a few pieces of literature are available on rammed earth structures. Both the theoretical heat transfer analysis, as well as the in-situ site experiments, have shown that rammed earth provides good thermal performance due to its low thermal conductivity, and high heat capacity allowing thermal control(Lamsal & Bajracharya, 2016). The study of energy-efficient buildings in terms of rammed earth has been restricted to the study of "Mato-Ghar" of Buddhanilkantha which was built around 2011 and designed with passive solar techniques. It also has a solar photovoltaic panel and solar water heater installed for heating through solar water heating. Mud or "Mato" in the Nepalese local language is the main ingredient for construction. The building form is rectangular and its form and utility have been described in previous studies(Shakya & Bajracharya, 2015).

- Stone masonry with mud mortar (SMM)

According to Nepal Census 2011 statistics, brick/stone masonry with mud mortar (BM/SM) which is one of Nepal's oldest construction methods accounts for 44.2 percent of total structures. Stone masonry structures are typically found in Nepal's northern highland area. The stones are frequently mined along riverbanks or from boulders removed from mountain stone quarries. It is popular because construction supplies are readily available and locals are not bound to pay for the stone, but they must pay for the labor involved in mining and transport. It is one of the most cost-effective and cheap constructions. This style of structure is distinguished by its large bulk, poor strength, and fragile failure behavior (Kasajoo & Hongwang, 2018). These structures are usually constructed by the owners or local contractors. In some rural adobe buildings, not only the foundations but also the walls up to the first level are composed of stone. The entry approaches to the dwellings in urban areas are also fashioned of stone(Bonpace & Sestini, 2003). For masonry work, dressed, semi-dressed, or random rubble stones may be used, depending on the region.

Figure 2.9 2-story SMM shelter
Source : (HRRP, 2018)

Figure 2.10 SMM with mud plaster – Solukhumbu
Source : (EFIT,2019)

Traditional SMM structures are rectangular in design with an openings area of 35% of the span of the wall. and have two floors including an attic(L. Shrestha et al., n.d.). The short floor height and thick walls of these constructions compensate for the masonry's lack of strength. The mud floors in these structures are supported by a central wood beam that runs through the middle of the floor and holds the wooden joists, which in turn support the mud floor. The size of the stones changes from structure to structure (Adhikari & D'Ayala, 2020). Likewise, the stones are flat in some structures and tend to form horizontal courses throughout the height, but the shape is random in others and no identifiable horizontal courses can be seen. The quantity of mortar used in the walls is affected by these imperfections; for example, if there are bigger voids in the case of irregularly shaped units, the mortar layers are thick, but if the stone is reasonably flat and forms horizontal courses, the mortar thickness is modest. Therefore, these kinds of structures have variable properties and thermal performance according to their material, design, and surrounding.

2.3.2 According to geographic location

Till now, different types of mud have been used as construction materials such as cob, adobe, wattle, daub, pressed earth blocks, rammed earth blocks, etc. The vernacular mud architecture of traditional houses in Nepal is unique according to its locality which has been gradually optimized for better performance throughout the years by the local people. Surprisingly, these types of architecture have been maintaining the thermal requirements of the people to some extent as a sustainable option without the need for external energy consumption. The design, form, and material used in a certain locality for residential purposes are usually affected by climatic conditions, culture, and urbanization. In addition, the same locality also has different types of traditional mud houses in Nepal. Nepal is geographically diverse; the climatic conditions are completely different that can be distinguished according to the altitude. Nepal can be divided into 3 different climatic regions: plain(sub-tropical), mountainous(temperate), and Himalayan(cool)(Rijal, 2018). The figures below show the different typical mud architectures found in different parts of the region.

In plain regions, traditional buildings consist of wattle and daub walls with bamboo striped outer walls with gaps in between, which are tied up by a timber frame. Roofing is done with thatch. Openings are very few except for the low windows below the roof, which help to maintain indoor comfort by allowing air circulation in and out of the building. Usually, rammed earth is used on floors however clay tiles and stones are visible in some cases. The houses are mostly single-storied with internal medium-height partitions for rooms so that the airflow is maintained inside the house(Pandey, 2017).

Similarly, for the hilly region, n, the buildings are south-oriented to inlet solar gain, to prevent overheating in the summer, a shading roof and openings are provided in the houses. Houses are arranged in a courtyard system so that passive heating and cooling are done in the winter and summer, respectively. The form of construction is usually done with stones, slate, timber, thatch, clay for brick making, sand, gravel, mud, cow dung, wood, and clay as the traditional building materials of Nepalese architecture. In the hilly region, residential buildings are mostly rectangular with sloping roofs. The form is identical in all buildings though the size may be small or big, maybe two stories or three stories based upon the hierarchy of economic status(Bhatt, 2017).

In the Himalayan region, denser building settlement is prioritized since the main target is to maintain warmth and prevent heat loss. No or very few windows are seen in the houses. Roofs, walls, and partitions are made from materials with high thermal mass with longer lag. Flat roofs with inverted pots or timber on top are sometimes seen to preserve the heat gained by the sun. (Adhikary & Johnson, 2016) The space pre-arrangement is vertical where the ground floor and top floor of the houses are allocated to secondary use and have the effect of a thermal buffer to keep the main living area on the first floor as warm as possible(Gautam et al., 2019).

Figure 2.11 Mustang (Mud of Lo Manthang)

Source : (Stocksy, 2015)

Figure 2.12 Manang (mud as binding material)

Source : (Dreamstime, 2020)

Figure 2.13 Central hilly area-Sundried brick

Source: (Abari,2011)

Figure 2.14 Gorkhar - Mud House

Source: (Savagemind,2015)

Figure 2.15 Mahendranagar - thatched roof

Source: (Downtheroad,2013)

Figure 2.16 Banke Thatched Roof Mud House

Source: (Rijal, 2018)

In addition, the roofs are typically made of mud and stone laid on a timber post and beam structure has been developed with different techniques to counter water leakage. In addition, made of stone (sometimes cut into more rectangular shapes, sometimes not), timber and mud, these houses typically follow the same layouts and can be additive, with duplexes and triplexes common and levels built up for expanding families(Kurtz, 2019)

It can be said that the traditional mud architecture of Nepal is not only monumental but also sustainable which has been obtained after the adaptations in design, form, and use of locally available materials. In addition, these vernacular architectures are worth saving because they inherit the traditional knowledge of our ancestors in maintaining thermal requirements with minimum use of energy from the surrounding. Some of the traditional building architectures are unique in material use as well as functionality that requires detailed analysis, which can also be used in conjunction with today's technology to improve thermal conditions efficiently.

2.3.3 According to form, size, and space utilization

Among many famous architects, influential quotes from two famous architects are recalled where said, "Architecture should speak of its time and place, but yearn for timelessness" – Frank Gehry and "We should attempt to bring nature, houses, and human beings together in a higher unity."- Ludwig Mies van der Rohe. Combining these two ideas, it can be implied that houses should be close to nature while serving the needs of human beings in their specific era with their unique local identity which can last for years. Mud architecture in Nepal has its legacy as it has been built for thousands of years and gradually optimized throughout the years with each mistake as a lesson. Some have been discontinued and some are still in existence passing the tests of time. Comparing the mud architecture's spatial and visual features with the two famous architect's sayings, the mud architecture fits closely to their ideas in terms of the building being close to nature through serving the functional needs of the human beings without losing the identity of the social-cultural values and the history of the place.

2.4 Climate Responsive Strategies

There are many vernacular passive heating and cooling strategies adopted around the world that have been studied in detail. The climate-responsive strategies implemented in the vernacular houses of the neighboring countries have been studied in detail in the following research. Nie et.al and Huang et.al have studied these strategies in detail for China(Du et al., 2016; Nie et al., 2019)(Huang et al., 2016). Similarly, for India, climate-responsive strategies implemented in traditional and modern houses have been also researched recently(Indraganti et al., 2014; Sarkar, 2013; Singh et al., 2011). For Nepal, Bodach et.al has listed out these implemented strategies according to the climatic condition of

Nepal(Bodach, 2014). Rijal et.al has mentioned some of the strategies used in cold regions of Nepal. Similarly, Bajracharya et.al has commented on the traditional newar houses on their thermal performance. For India, there have been different articles on climate responsive strategies used for heating purposes in the north-eastern region of India.

2.4.1 Vernacular Passive Heating Strategies

The referenced articles mentioned in the above articles are analyzed to see the common passive heating strategies among the three neighboring countries. There were other unique vernacular passive heating techniques in other countries which have also been listed in the table. The high-altitude location of Iran and Turkey have unique features of vernacular architecture that help in passive design strategies which are also mentioned below

Adopted Strategies	**Location**		
	Nepal	China	India
Internal Courtyard	✓	✓	
Outer Courtyard	✓	✓	
One-sided opening to avoid cross ventilation		✓	
compact arrangement	✓	✓	✓
Wooden shutters/Glazing used on the south side	✓	✓	
Combining rammed earth and log wall construction		✓	
Large windows of south-facing primary rooms	✓	✓	
compact forms and a rectangular plan-low surface to volume	✓	✓	✓
houses in terrace form without overshadowing each other	✓	✓	
settlement starts at the center and radiates outward		✓	
rammed earth, adobe clay, mud plaster– thermal mass	✓	✓	✓
Attached houses	✓	✓	
Balcony connected to the courtyard to obtain maximum solar		✓	
Use of shutters to reduce cold air during the night		✓	
Houses placed on the southern side for solar gain	✓	✓	✓
Mud roofs if low rainfall	✓	✓	
No opening in the backside with north face	✓		
Use of timber as interior/floors	✓	✓	✓
Opening - medium to small	✓	✓	✓
Dense/Denser settlement pattern	✓		
0.5-1 m thick sundried/mud brick walls as thermal mass	✓		✓
0.08-0.3m thick wall			✓
Living and bedroom in the buffer zone	✓		✓
Compact floor plan, low floor height	✓		✓

Adopted Strategies	Location		
Large windows placed on longer façades	✓		
Uplifted floor level (up to 1m)	✓		✓
Minimum area exposure to the prevailing wind	✓	✓	✓
Location of fireplace – open, centered	✓		✓
Shaded Verandah			✓
Ground Floor is used as Tandoor floor (Varolgüneş, 2020)	Turkey		
Avoid portion of the veranda in the wind direction(Bahramifar	Iran		

2.5 Vernacular Passive Cooling Strategies

Similar to the passive heating strategies, many common passive cooling strategies could be found in the regions of Nepal, China, and India which are shown in the table below. Some of the interesting studies can be found in the following references (N. Gupta, 2017; Sonowal, 2009).

Adopted Strategies	Location		
	Nepal	China	India
Dense clustering of large houses			✓
the building has been surrounded by water body			✓
Courtyards or yards	✓	✓	✓
Solar shading devices - horizontal, vertical, and shading	✓		✓
Ventilation pair-near floor and roof level			✓
False wooden ceiling	✓	✓	✓
use of local materials like mud, laterite, granite stone blocks			✓
Loose Building Arrangement	✓		✓
Sided open courtyard			
North-south oriented rectangular Longhouse	✓		✓
High ceiling		✓	✓
Undivided internal space for ventilation			
Veranda	✓		✓
Compacted composite mud floor	✓	✓	✓
Light wall and roofing materials	✓	✓	
End and Low window openings	✓		
East-west orientation			✓
Painted with light colors		✓	✓
Wide window openings	✓		✓
Surface to volume ratio- less			✓

Adopted Strategies	Location		
The traditional window is latticed into small cells by small	✓	✓	✓
bamboo-mud wall	✓	✓	✓
semi-enclosed rooms.			✓
Raised floors(Zune et al., 2020)	Myanmar		

2.5.1 Modern passive heating and cooling strategies

The existing and new concepts of passive strategies have been explained well in the research done by Gupta and Tiwari(N. Gupta & Tiwari, 2016). Great concepts like a combination of evaporative cooling and wind tower as well as a Trombe wall for both heating and cooling are proposed. Nocturnal radiation cooling, solar dehumidification, outgoing longwave radiation cooling, 'Sky Thermal' etc. are suggested by Agarwal for heating and cooling purposes as a passive strategy(Agrawal, 1992). According to Balcomb et al., a single-glazed south-oriented system without storage mass is rather ineffective, but a double-glazed system with night insulation and solidly stored mass heat capacity shows to be effective in satisfying the needs for heating. Another novel idea is "Solarium," which combines the ideas of direct gain and thermal storage. The solarium is divided into three sections: the sunspace, which has a thick mass wall on the south side (for the Northern Hemisphere), the linking space, and the living space. In the extremely cold regions of northern China, Wang et al. presented an On-top Sunspace (OS) solution to the problem of rural heating. By building several roofs, these heat surfaces may be magnified, increasing the quantity of heat gathered (Wang,2019). This is a very efficient way to lessen the need for artificial lighting and boost daylight. Sun et al. demonstrated how numerical simulation may help to enhance the almost ideal integrated control approach and natural ventilation in order to save energy expenditures and guarantee occupant comfort(Sun et al., 2013). The passive design strategies that can be implemented in the three different climatic conditions of Nepal have been suggested in different kinds of literature (Lamsal & Bajracharya, 2016). In addition, Lamsal et al. suggested a guideline by taking into account the vernacular architecture, Mahoney tables, and the bioclimatic map (control potential zone).

Many modern passive design methods can be integrated into the vernacular architecture as well for better thermal performance which can save them from being replaced by modern structures. In addition, active and passive heating systems can be used for better thermal performance of mud shelters in all types of regions with technology.

2.6 Case Studies

The case studies below show the relation between thermal comfort, vernacular architecture, and climatic condition as well as the passive control features that were implemented to neutralize extreme environmental conditions in various parts of the world. A detailed study has also been conducted by Singh et al. which is mainly focused on the mathematical and adaptive models which relate these two terms. However, our approach is to understand their relationship from the different cases of thermal problems and their coping mechanisms around the world. Some of the case studies at international, regional, and national levels are shown below:

2.6.1 International

- Case I

Thermal Performance of Traditional and New Concept Houses in the Ancient Village of San Pedro De Atacama and Surroundings (Palme et al., 2014)

This village is situated in the hot deserted Andes mountains of northeast Chile, on a high, arid plateau. The situation of the locality is changing from ancient civilization to modernization which has brought new construction materials and methods replacing the old ones. The identity of the community is lost with these types of new structures which are haphazardly growing. The ancient construction methods and materials which were difficult to study before can now be studied at different levels using experiments and simulations. The thermal performance of four different cases of houses was studied among which the adobe and tapial houses were designed by architect Magdalena Gutierrez. The adaptive comfort concept has been used along with Ecotect software as a comparison tool to assess the thermal performance of these individual houses with the following physical and thermal properties of the material. The applied values of infiltration and ventilation in adobe rammed earth and concrete houses are 0.4 air changes per hour while for the wooden houses it is 50 air circulations.

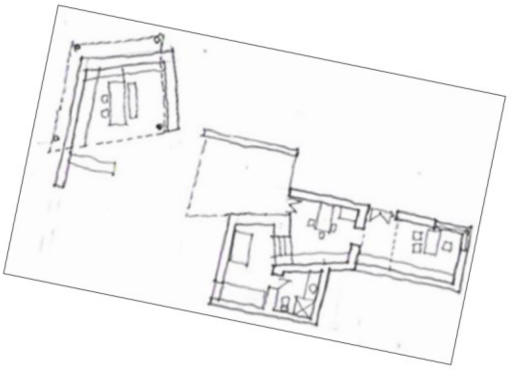


Figure 2.17 Adobe structure and orientation

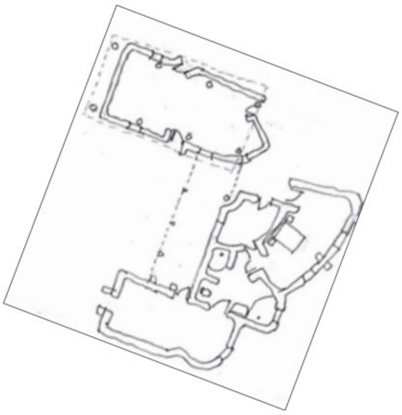


Figure 2.18 Rammed earth structure and orientation

Table 2.1: Physical and Thermal Properties

Material Type	Thickness(cm)	Transmittance (W/m2K)	Time Lag(h)	Solar Absorption(%)
Adobe wall	30	1.7	8	0.4
Earth roof	15	2.3	3	0.5
Concrete wall	20	3.5	5	0.7
Cement Roof	0.2	5.0	0	0.8
Zinc roof	0.2	7.0	0	0.9
Rammed earth	50	1.3	14	0.4
Wood	1.2	1.6	2	0.6

The results in table 5 show that the adobe and rammed earth buildings have better thermal performance than the concrete block house as the hours of discomfort are lower compared to the latter. Especially for adobe's performance in overheating and rammed earth's performance in undercooling is exceptional. A 24-hr evaluation of the temperatures for the 4 houses shows better performance of the rammed earth structure and considering the hot climate, the adobe houses provide better performance during the daytime which is important in this location.

Table 2.2 Thermal discomfort degree hours

House Type	Overheating(deg-hr.)	Undercooling(deg-hr.)	Total discomfort
Concrete	22538	144	22682
Wood	10387	2703	13090
Adobe	4040	1460	5500
Rammed earth	6475	539	7015

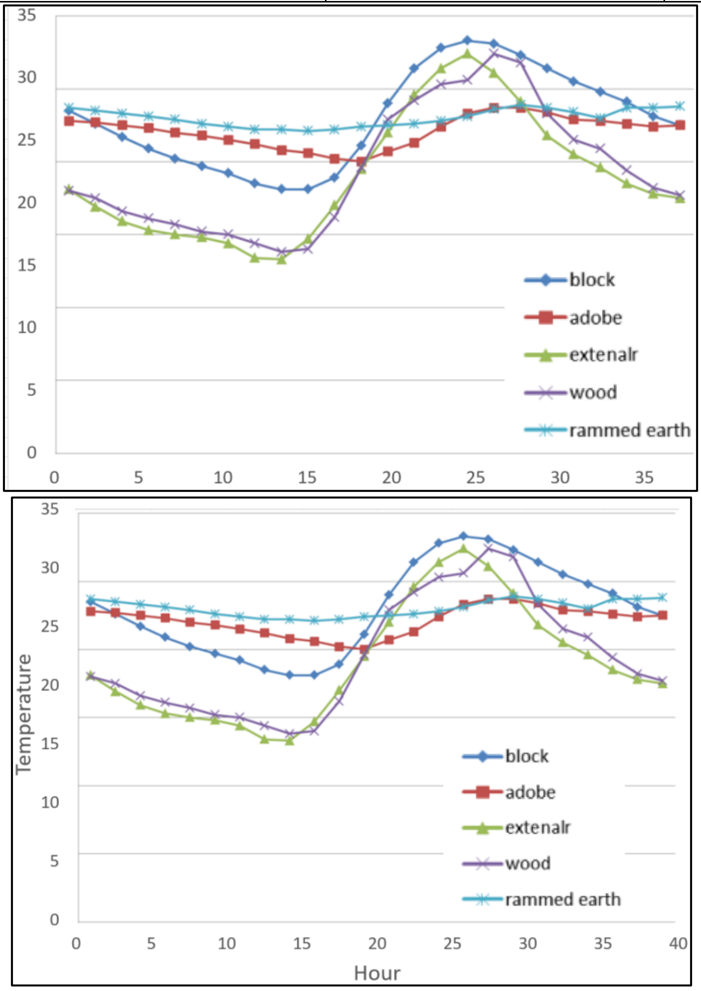


Figure 2.19 Summer and winter temperature fluctuation in 4 structures

The authors have concluded that traditional structures made with mud as materials are more successful in thermal lag and oscillation performance. Hence, the problem with traditional mud structures is rather concerned with mechanical performance in earthquakes rather than thermal performance. Because adobe and tapial have such durable behavior in the face of day-night and seasonal external fluctuations, it seems only natural that ancient techniques should employ earth as the primary building material.

- <u>Case II</u>

Thermal Performance and Comfort Condition Analysis in a Vernacular Building with a Glazed Balcony (Fernandes et al., 2020)

The main concept of this article revolves around achieving passive strategies and techniques to avoid using active systems in buildings to maintain sustainability. A part of this study analyzes the thermal performance of a northern Portuguese vernacular architecture located in Granja do Tedo. The average range of temperature in winter and summer is between 12-15°C and 22.5-25°C. It is exposed to a high amount of solar radiation from the south with low wind conditions. The primary building material is granitoid. The typical houses in this location are 2 storied where the ground floor is used for goods storage and the other floors are for the living. The selected case is a semi-detached home belonging to a nuclear family. To reduce heat dissipation, only two windows are present (facing west and southeast). The calculated floor area is around 50m2.

Figure 2.20 Southwest and Southeast elevation

Source: (Fernandes et al., 2020)

Both short-term and long-term thermal measurements were done; the short-term assessment was used to find the operative temperature whereas long-term measurements were done to find the relationship between indoor parameters with outdoor parameters. In addition, subjective opinions were quantified using the "Thermal environment survey" to find the perception of two residents about indoor thermal conditions. For thermal comfort analysis, an adaptive approach that calculates the comfort temperature as a function of outdoor temperature throughout the last seven days was used to define the thermal comfort considered as the building is naturally ventilated.

$$\Theta_{rm} = (T_{n-1} + 0.8T_{n-2} + 0.6T_{n-3} + 0.5T_{n-4} + 0.4T_{n-5} + 0.3T_{n-6} + 0.2T_{n-7})/3.8$$

$$(\Theta_o = 0.30\Theta rm + 17.9)$$

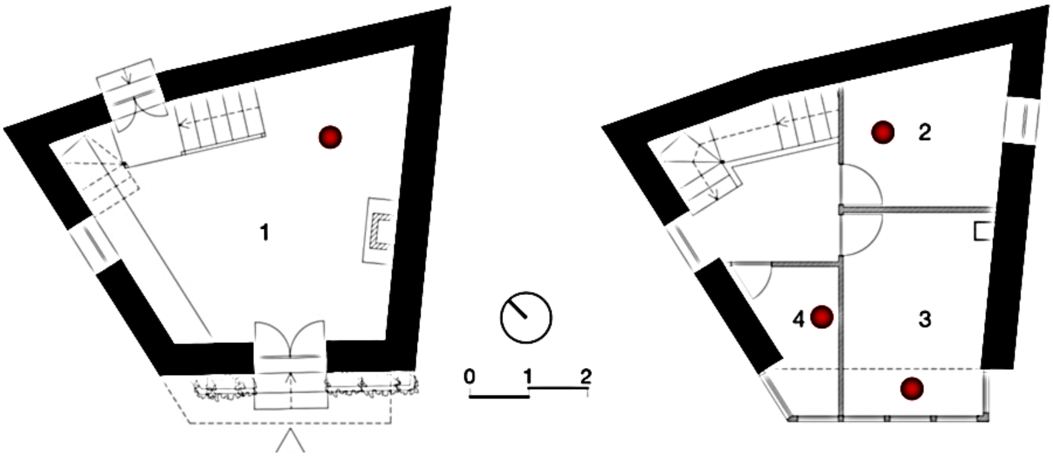


Figure 2.21 Ground floor(left) and upper floor(right)

Source: (Fernandes et al., 2020)

Figure 2.22) From Left to Right picture description

(a) Kitchen view; (b) bathroom view; (c) bedroom with balcony; (d) closed wood-burning fireplace; (e) removable ventilation net; (f) smoke exhaust by the roof.

Source: (Fernandes et al., 2020)

The figure of winter monitoring of indoor and outdoor temperatures and humidity is provided in Annex 1.The influence on the thermal comfort of using the closed wood-burning fireplace is quite evident since when the heating system was in operation, the living room/kitchen had a comfortable thermal environment. The impact on the thermal environment when utilizing the closed lumber furnace is clear since the living room/kitchen had pleasant thermal conditions while the heating system was on, according to both temperature measurements and survey findings.

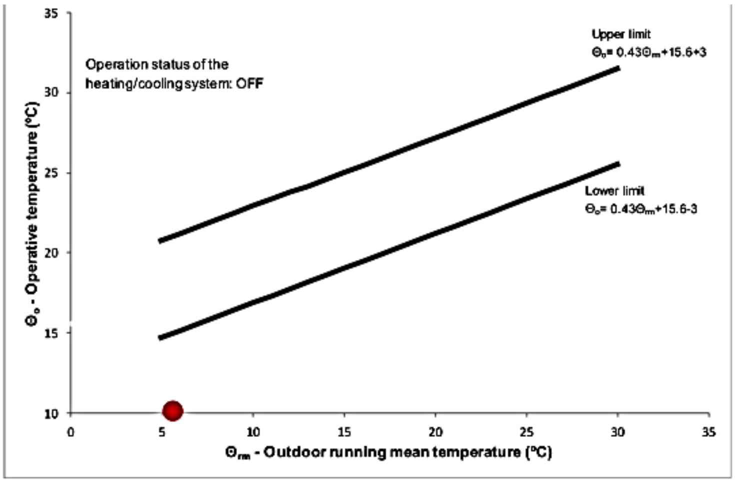


Figure 2.23Adaptive comfort chart with the heating off

Source: (Fernandes et al., 2020)

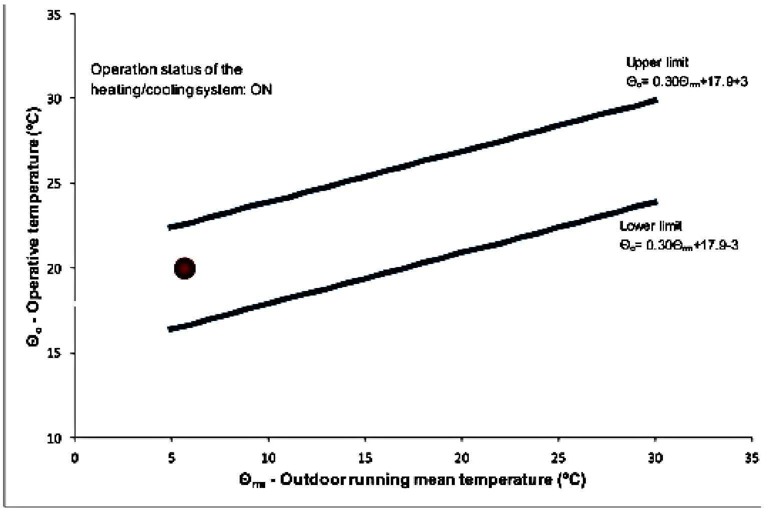


Figure 2.24 Adaptive comfort chart with the heating on

Source: (Fernandes et al., 2020)

- Case III

Evaluation of summer thermal comfort in arid desert areas. Case study: Old adobe building in Adrar (South of Algeria) (Bassoud et al., 2021)

Introduction

This article emphasizes that a larger part of the energy consumption is being used to maintain thermal comfort in the hot and long summers in Algeria. The traditional architecture, with local materials with passive solar design techniques and nearly zero-energy consumption, has also been replaced by modern cementitious structures which have high maintenance costs with low sustainability. Many kinds of literature have shown that thermal comfort for these traditional structures can be achieved by themselves without an external energy supply. This study also points out that the standards like ASHRAE which is based on the enormous amount of data on comfortable environments also fail in addressing the thermal comfort limits in different parts of the world. Therefore, adaptive and hybrid adaptive and static methods for thermal comfort are currently being used. Since the once-a-month average temperature exceeds the 38℃, ASHRAE-55 standards could not be used and therefore a new adaptive model is developed. They have considered the ancient earth and clay-based architecture of Ksar Tamentit in the Adrar area (southwest) as a case that is dry according to Köppen's classification. Residents of areas having 400 adobe Ksar homes are considered for thermal comfort analysis which is mostly covered, with inside, a mosque surrounding courtyards, and passageways 1.5 to 2.0 m wide. The walls are 45cm thick with a density of 1640kg/m^3.

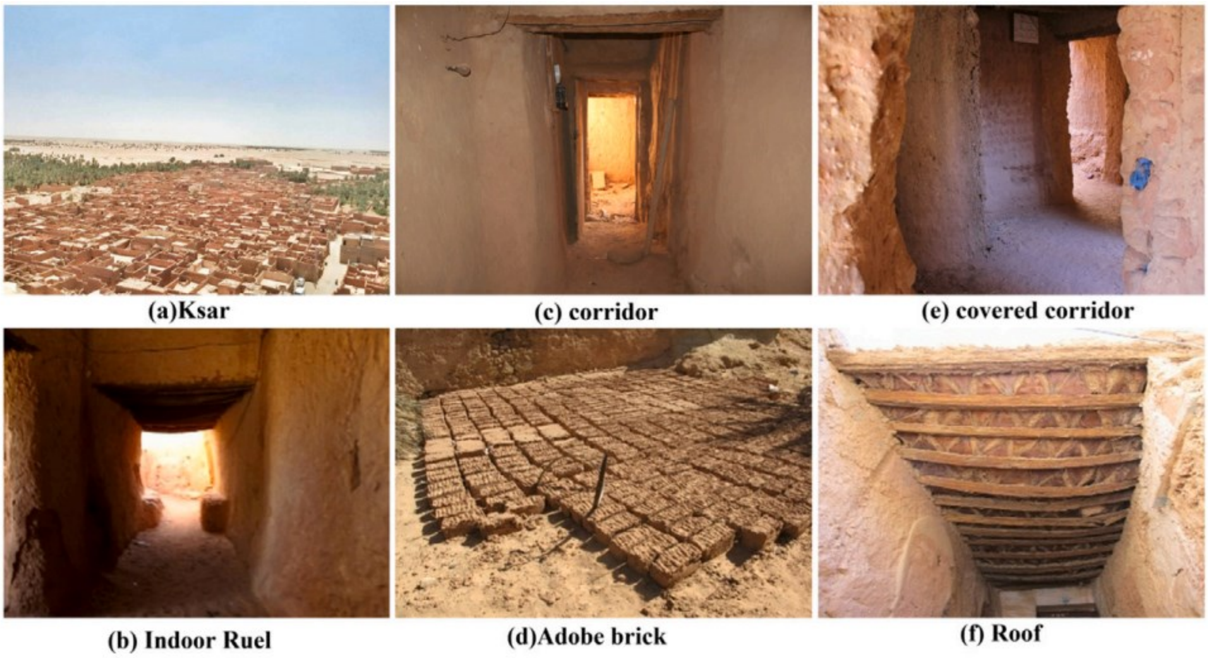


Figure 2.25 Housing details of Ksar Adobe houses

Source: (Bassoud et al., 2021)

Both thermal comfort surveys and temperature measurements are done. They compared the measurements with those provided by URERMS Adrar -CDER to improve their reliability. The thermal comfort survey was done in 3 different periods 6-10 a.m., 10-12 p.m., 12-5 pm, and 5-9 pm. The main limitation of this survey is that it was conducted in the summertime from May to August.

The scaled sample size according to population was considered with 251 men and 191 women ages between 20 to 70. They have considered a different division for the summer and winter periods in which summer is from mid-March to May whereas winter is from January to mid-March. The temperature analysis showed that temperatures were in the range of 25-50°C through night and day outside. Whereas, the indoor climate is up to 47°C with low humidity levels (25%). The low humidity level is due to the rapid movement of warm air. The time lag is 4 hours for indoor and outdoor temperatures.

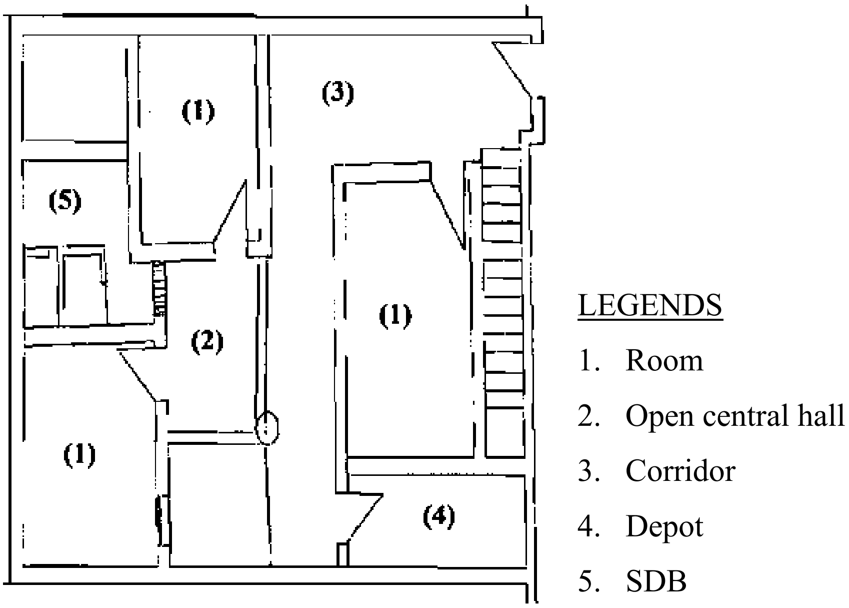


Figure 2.26 Distribution plan of a house (Ksar)

Source: (Bassoud et al., 2021)

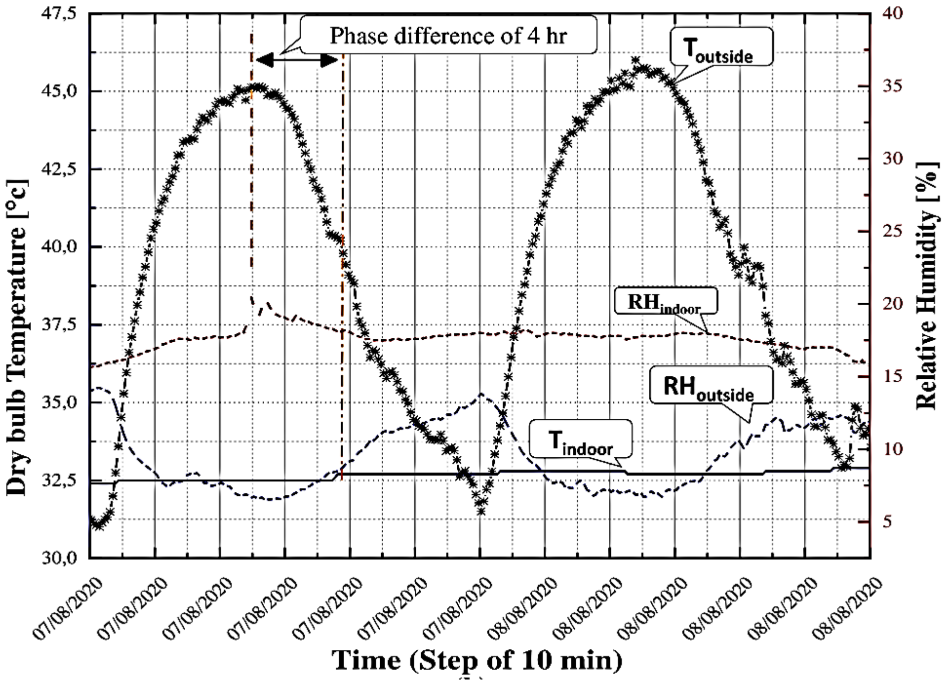


Figure 2.27 Indoor and Outdoor dry-bulb temperature timeline

Source: (Bassoud et al., 2021)

The major thermal sensation, humidity sensation, and satisfaction votes are 44%(neutral), 65%(neutral), and 54%(satisfied for neutral) meaning that they are neutral or somewhat satisfied with the indoor environment and consider the air to be acceptable despite their high heat vote. The correlation between thermal sensation and indoor temperature showed a positive significance. The linear regression shows neutral temperature and neutral relative humidity to be 32 ℃ and 20.7% respectively. Using Griffith's model, the comfort temperature of the study area is determined as

$T_{tamentit} = 0.33t_0 + 20.15$ where, t_0 = outdoor temperature

They have also provided thermal comfort models for 80 and 90% acceptability which shows that ASHRAE standards cannot correctly represent the thermal comfort situation of this area. This study has shown that although the thermal performance of adobe structures in hot areas is relatively good there is room for improvement and also shown some areas like the window-to-wall ratio, shading area, etc, that need to be considered while doing architectural designs

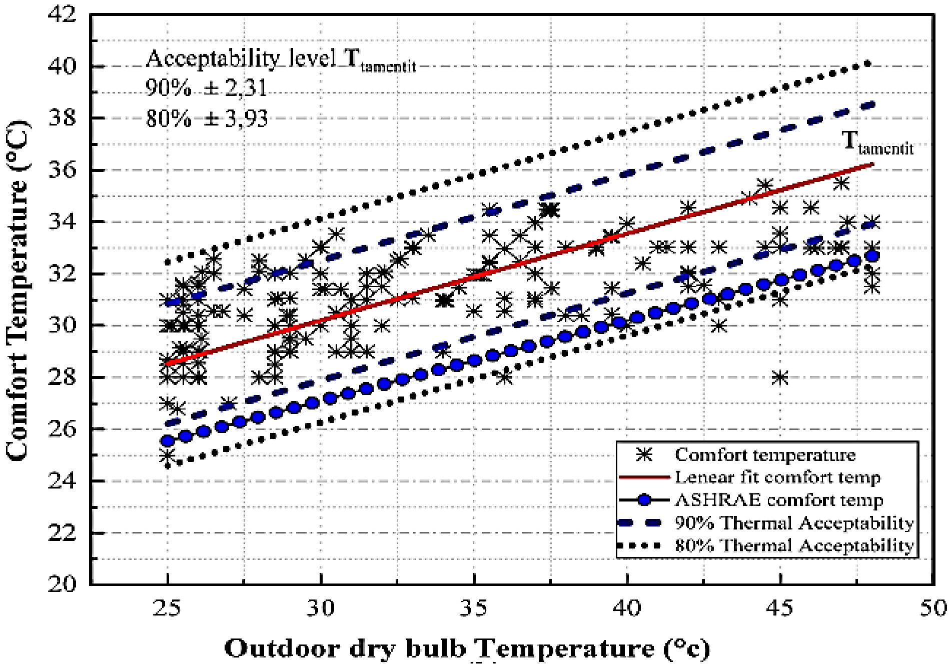


Figure 2.28 Comparison of acceptability and ASHRAE STANDARD

Source: (Bassoud et al., 2021)

- <u>Case IV</u>

Evaluation of vernacular and new housing indoor comfort conditions in a cold climate – a field survey in eastern Turkey (Varolgüneş, 2020)

This article outlines that different factor like culture, finance, material, climate, etc., play a role in the thermal performance and comfort of the structure which is a result of its architecture. In addition, it emphasizes that psychological factors also play a significant role in shaping the perception of thermal comfort. The case study site is located in eastern Turkey, which is a seismically active zone. Therefore, the structures are slowly being replaced by modern structures. The territory around the site is hilly and mountainous, with an altitude of over 1,250 meters. Adobe, stone, wooden planks, brick, and briquette are the most common building materials used in Bingol structures. The walls are made up of stones that have been joined with mud as a binding material(mortar). The courtyard is closed due to the chilly temperature in eastern Anatolia, and it serves as a central place for the other portions on the ground. The dwellings' windows are tiny, and the walls are rather thick. The buildings are relatively congested, constructed on the mountain's southern slopes and aligned east–to the west to catch the most sunshine. Wooden flooring may be found in almost every home. Wood, being a poor heat transmitter, increases interior thermal comfort. The inside of the home has an extremely low ceiling height. These homes feature a low surface-to-volume ratio, which enhances heat build-up in daylight areas while minimizing heat loss in the evening. Neither home has an impact on the other's sun, light, wind, or privacy. In general, stoves are used to generate energy, and the fuels consumed are wood, coal, and dried animal waste which saves the need to put the extra sources of insulation.

Figure 2.29 Description of pictures from basement to outdoors

a) Residents who cook in a tandoor house; (b) Interior view (transforming the trees into natural furniture); (c) Laundry in the bathroom (d) Housing directly connected to street

Source: (Varolgüneş, 2020)

Table 2.3 Methods used for heating in vernacular Bingol houses

Methods for heating	**Vernacular houses**	
	N	%
Window opening and closing	5	10
Traditional Heating	41	82
Stationary Heating	4	8
Natural Gas	0	0
None	0	8

In the summer(June, July, and August) of 2017 and the winter(December, January, and February). of 2017-2018, the research was done in two locations in Bingöl: the rural area and the new housing area among which the results are discussed for the rural area only here. The sample size was 50 people from the traditional housing area. The questionnaire included demographic details, preferences, and satisfaction levels. Only comfort characteristics (thermal and visual satisfaction) that influence energy usage and associated problems were considered in this study.

The results of the thermal comfort survey analyzed using the Rikert range indicate that the average satisfaction is higher for traditional structures than the modern structure by 1.94 times during winter and 1.74 times during the summer. The main source of heat for the vernacular houses were stoves and wood and the main source of ventilation is opening and shutting windows. In traditional buildings, the mean window open and shutting period is 6 hours per day. When the warming, conditioning, and ventilation behaviors in summer and winter are compared, it is clear that residents of traditional and modern houses in the same temperature zone have different comfort perceptions, as well as different satisfaction perceptions and occupant behavior. In traditional houses, for example, windows are opened and ventilation is performed for a longer length of time than in modern residences.

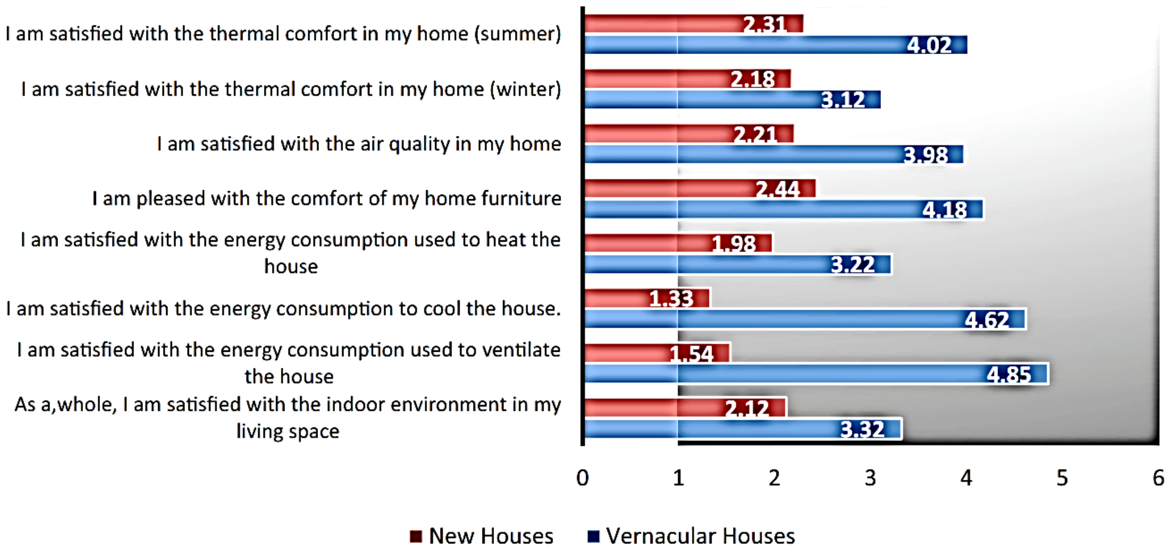


Figure 2.30 Thermal comfort satisfaction of occupants

Source: (Varolgüneş, 2020)

In addition, demographic data indicates that more women stay in the home and is also known that thermal comfort and its perception also depends on sex. In comparison to vernacular dwellings, the number of people living in modern houses was greater. Civil servants made up the majority of tenants and homeowners, and they were an essential component of the city.

Table 2.4 Demographic Data

Demographics	Frequency(n)	Percentage
Male	28	56
Female	22	44
Users<3	18	36
Users<7	22	44
Users<8	10	20

Civil servants made up the majority of tenants and homeowners, and they were an essential component of the city.

2.6.2 Regional

- <u>Case I</u>

The Thermal Performance of Chinese Vernacular Skywell Dwellings(Yao et al., 2021)

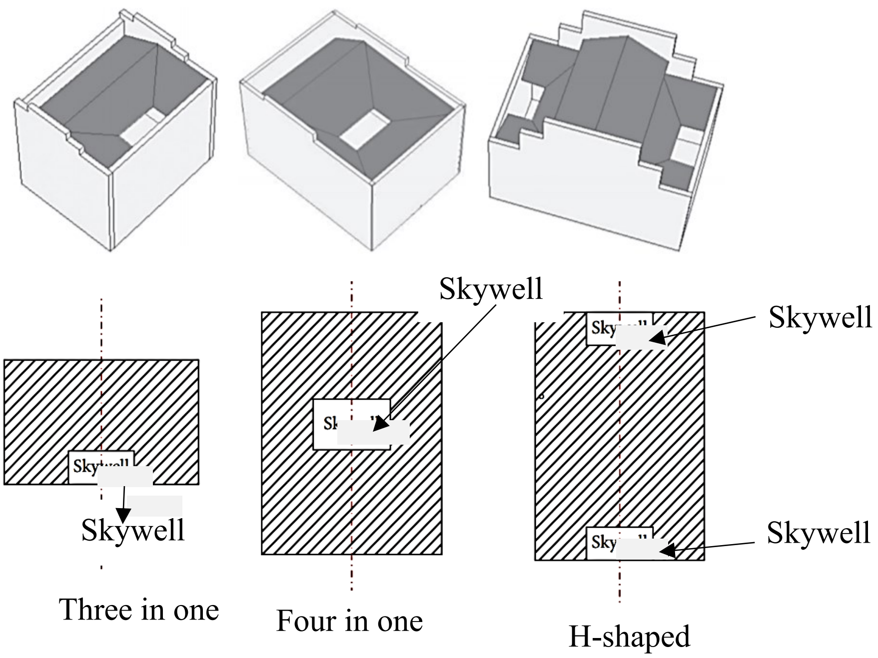


Figure 2.31 Main dwelling types in three villages studied

Source: (Yao et al., 2021)

The main location of the studied Chinese vernacular dwellings in this case study is in the hilly region. The main architectural feature is the sky well whose purpose is to gather water while also catching the wind as water represents prosperity in Chinese culture. The main occupancy areas are located on three sides of the sky well having usually two-storied levels. The houses nearby provide shading to one another. There were 8 houses considered for analysis that have H-form, three in one form, and four in one form. The primary materials are wood, brick, mud, stone, white lime, fired clay, etc. The outer walls are typically 300 mm wide with two 2 cm strata of brick containing a 26 cm broad vacuum packed with mud as well as stones of varying sizes.

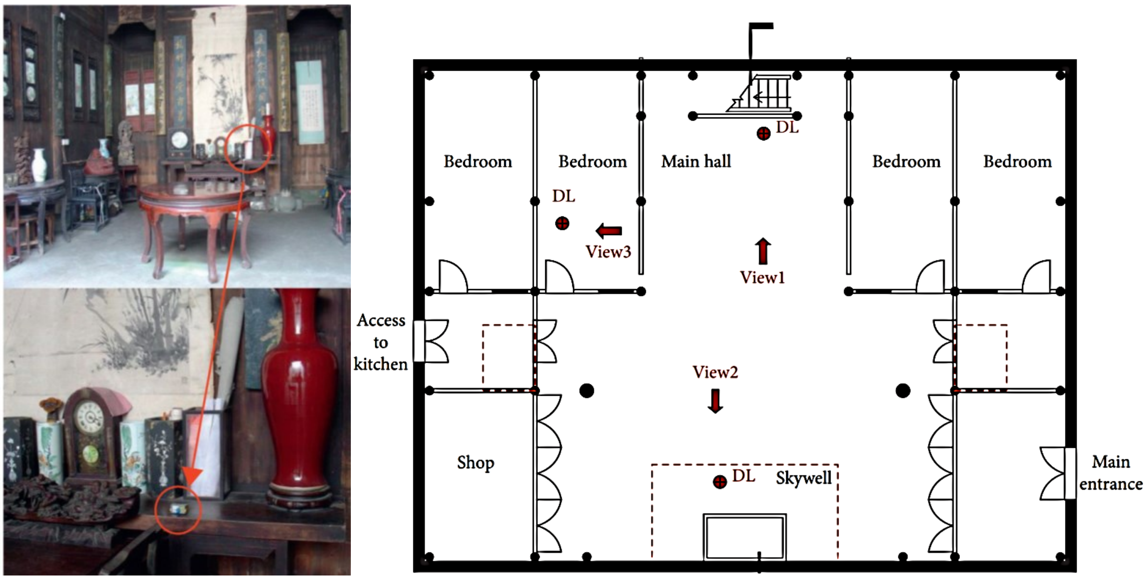


Figure 2.32 Typical Skywell Rooms and their plans

Source: (Yao et al., 2021)

To perform thermal performance assessment, air temperature and relative humidity measurements were done. The data loggers were used to record the temperatures and relative humidity for 7 continuous days for all the houses, but 2 were skipped as these two days were comparatively higher than the other houses. To figure out the amount of direct solar effects during the daytime, the Ecotect simulation tool was used by utilizing weather data from EnergPlus software between the period covering the summer and modeling the building zones and dimensions into the Ecotect. The simulation in this case has helped to apply the data for a longer period than the real measurement done on the site. The analysis of winter performance was mainly considered in this study among both the summer and winter studies at different houses. The experimental data indicated very cold temperatures and less humidity with mean diurnal changes of temperatures around 11 to 18°C while the inside temperature fluctuation difference was 3.2 to 7.6°C indicating that the thermal environment was steady.

Traditional building construction materials have low thermal conductivity and a good thermal mass, which combined lower peak heat flow and overall heat absorption by retaining a large amount of heat and prolonging heat entry into the room. According to the measured thermal characteristics of the materials, the traditional building materials used in China have high specific heat which helps to absorb heat and prevents high fluctuations.

The calculated thermal specific mass belongs to the high category. In conclusion, it can be said that sky-well houses have fewer temperature fluctuations compared to regular houses in general.

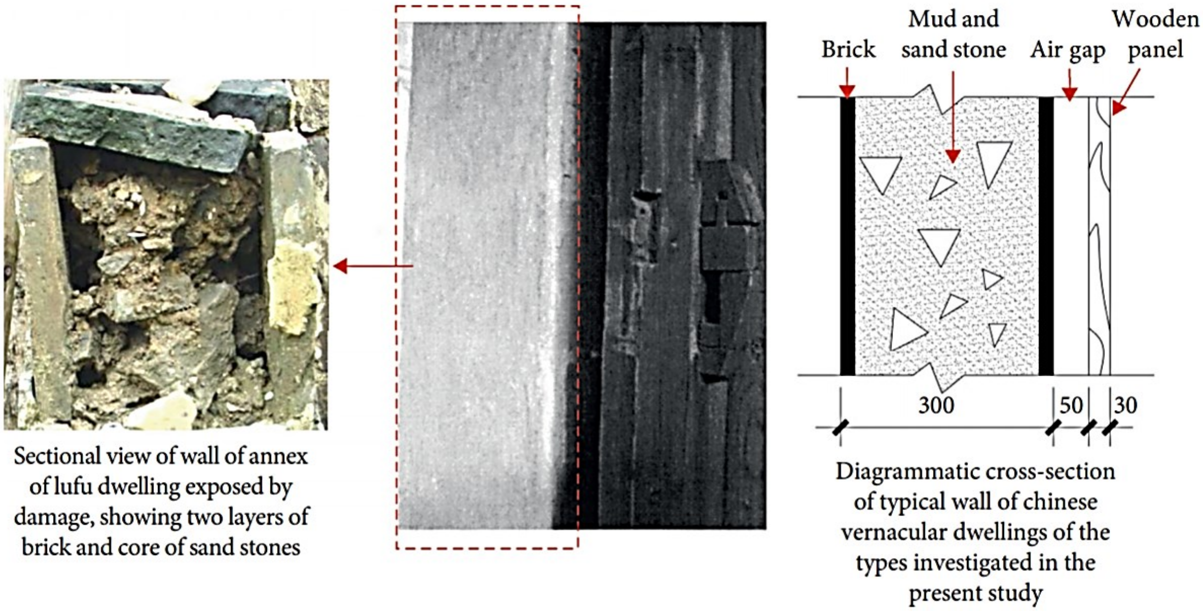


Figure 2.33 Composition of Traditional Chinses house

Source: (Yao et al., 2021)

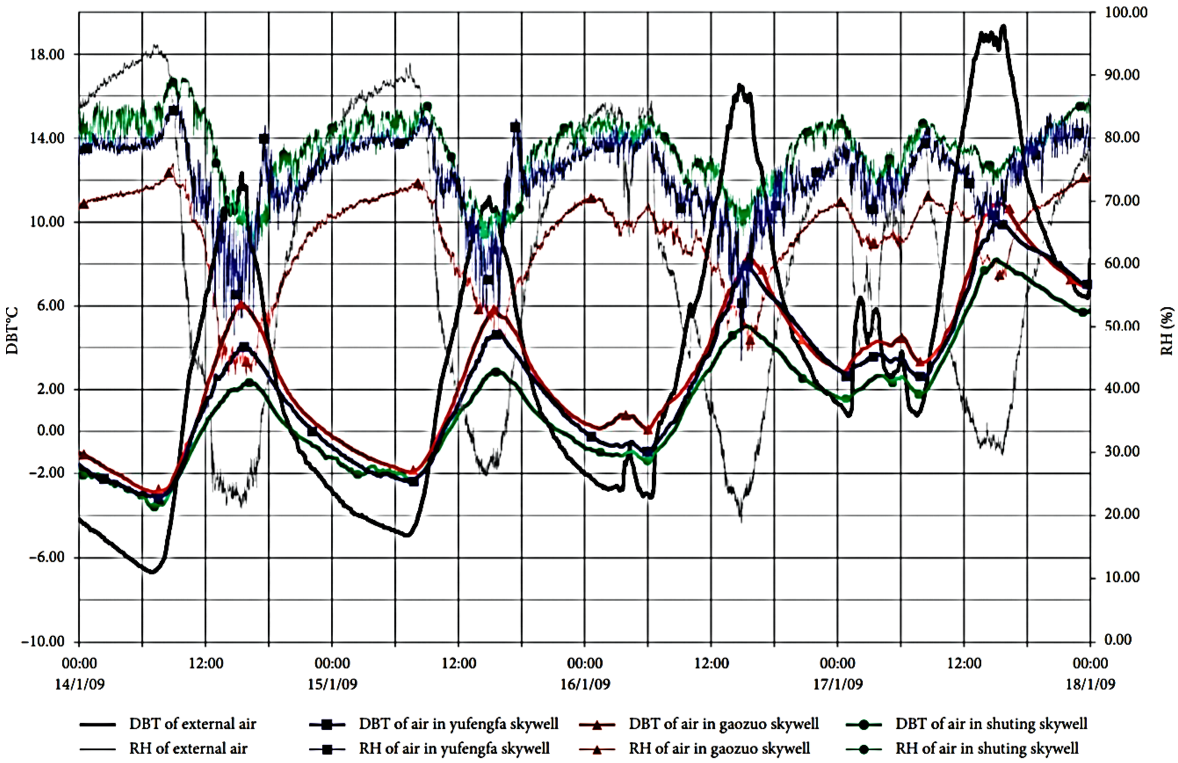


Figure 2.34 Temperature and Humidity of external environment and 3-sky well houses

Source: (Yao et al., 2021)

• <u>Case II</u>

Assessing Thermal Performance of Mud House Using ECOTECT Analysis - A Case of Vernacular Architecture in Northern Bangladesh (Sadat, 2021)

This case analyzes the traditional oblong-shaped adobe-earth building on the north side of rural Bangladesh. There are two villages taken into consideration, named, Bagura and Rajshahi. The general climate is warm and humid with excruciating heat in summer and light winter. The author points out the importance of adobe buildings as a sustainable asset as it dissolves in the ground if abandoned by the users. The huts, arranged in a line along the streets in an east-west direction around agricultural areas and rocks, are near the main road in the community. Their orientation allows high solar gain as well as ventilation. The average temperatures are highest in August for Bagura and June for Rajshahi. The length of the structure is around 4-6m. One family has 5-8 minimum. The total floor size is 173.8m2. The construction materials are mud, cob, and paste made with rice husk.

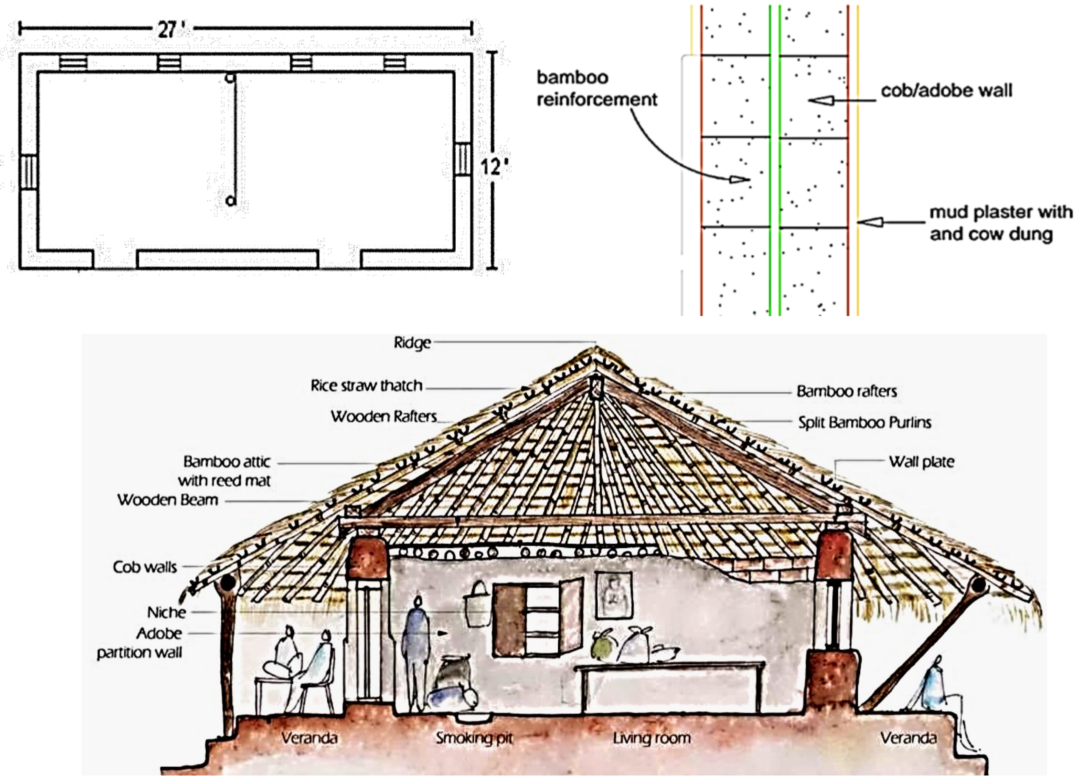


Figure 2.35 Plan, section, and detailed cross-section of a mud house

Source: (Sadat, 2021)

The 24 hourly temperature data shows that the adobe buildings absorb heat slowly and take more time to release which is due to the less thermal conductivity of the material compared to modern materials. Especially, this aspect can be beneficial in the winter to keep the interior warm with a stable thermal environment for the residents who cannot use an external supply of energy. The thermal performance during both the summer and winter is shown in the figure below. The winter performance is much better as the temperature difference between inside and outside is around 11℃ warmer. Hence, it is evident that traditional buildings made with mud as a construction material perform better in stabilizing the thermal environment around the building without any external sources of energy which is beneficial both for the environment, saving the traditional culture as well as the energy cost for maintaining the thermal comfort as inferred by the simulation and in situ results.

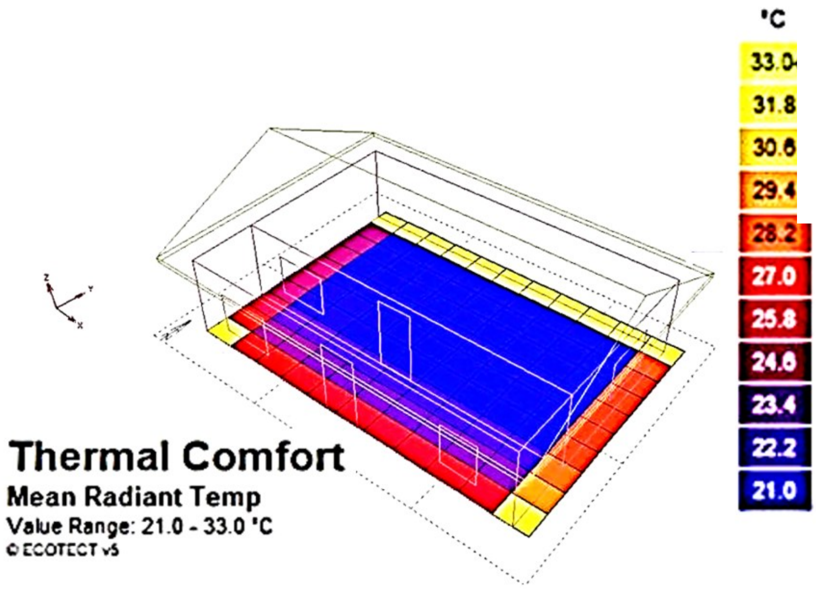


Figure 2.36 Mean Radiant Temperature of the house

Source: (Sadat, 2021)

- Case III

Evaluating thermal comfort and building climatic response in warm-humid climates for vernacular dwellings in Suggenhalli (India) (Shastry et al., 2016)

This case study points out that vernacular buildings made up of traditionally used materials have not been thoroughly explored and are treated as an outcast among modern concept dwellings. The location, Suggenhalli of the case is located in the rural agricultural Bengaluru of India with temperatures around 36 in summer and 14 in winter. People are more sensitive to changing winter temperatures which can be observed in their clothing. The building materials include mud, timber, clay roofs, stones, a mixture of cob and cow feces, etc. Roofs are generally flat with openings to provide ventilation supported by wooden frames. It has a central courtyard providing natural ventilation. The main entrance faces the road located on the northern side. The building is surrounded by other buildings as well. The external walls were rubble masonry joined using mud mortar and the internal walls were made out of cob. The summer and winter clothing are lungi, nightgown, and sweaters respectively. To adapt to the hot weather, people often sleep outside the house or in the courtyards.

Figure 2.37 Materials used inside and outside the building

Source: (Shastry et al., 2016)

Both real-time thermal environment factor measurements and thermal comfort survey were conducted to find the thermal performance of the dwellings. In addition, a dynamic simulation was also performed in Design-Builder. A thorough TSV for the entire village population included reactions from 20 individuals or more than 20% of the total public. Along with environmental parameters, wet bulb globe temperatures were also taken periodically. In the model, various factors like heat gain, openings of the walls, resident occupancy as well as other construction variables were introduced as input in the simulation model.

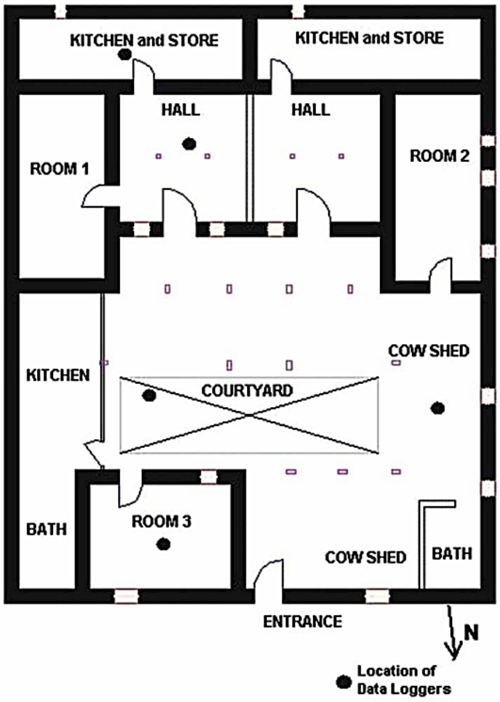
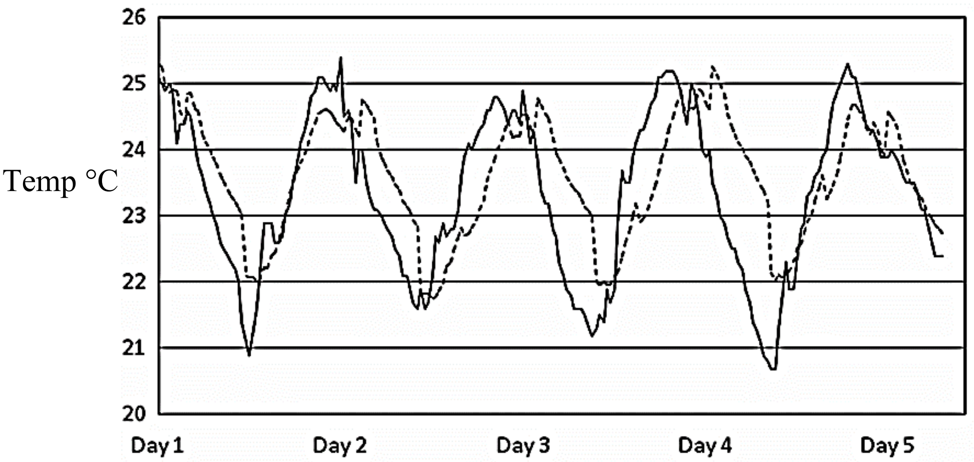


Figure 2.38 Forms of the building

The measured and simulated indoor temperatures show that daily maximum and minimum temperatures were relatively similar. From July through December, the community reported (good) comfort. Figure 11 shows an examination of observed mean indoor temperature vs. neutral temperature over time (every monthly quarter). The neutral temperature, like with the PMV evaluation, implies a strong resemblance to 2°C than the mean interior temperature, especially during the winter periods. The interior temperature is substantially outside Humphreys' non-adaptive bottom limit for 70% of the time. However, the thermal comfort survey indicates a different scenario as they are perceived to be bearable by the local people. Therefore, a new modified Humphrey’s model is defined for this region for thermal comfort modeling in this region.



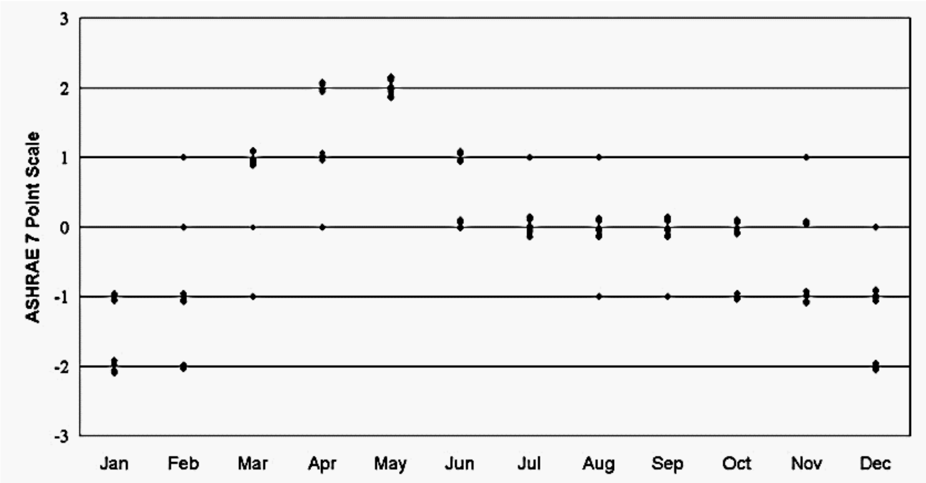


Figure 2.39Measured/Simulated indoor temperatures and TSV

Source: (Shastry et al., 2016)

Case IV

Influences of vernacular building spaces on human thermal comfort in China's arid climate areas(Chang et al., 2021)

The paper's key discovery is that there are changes in thermal conditions between indoor and semi-open spaces that provide thermal comfort at different times of the year due to their unique architectural spaces. The site is located in the arid northwest region of China, Turpan with annual precipitation of 16.4mm and high evaporation. Therefore, the location is mostly dry throughout the season. The Uyghur houses can be separated into three parts: open, semi-open, and closed areas. Small windows are installed to combat overheating difficulties with the help of densely enclosed regions. Asymmetrical structures include U-shaped, L-shaped, I-shaped, and U-shaped structures. These houses feature flat roofs covered with mud and have walls built of adobe and mud that are roughly 600mm wide. The interior weight-bearing system, on the other hand, is made of wood.

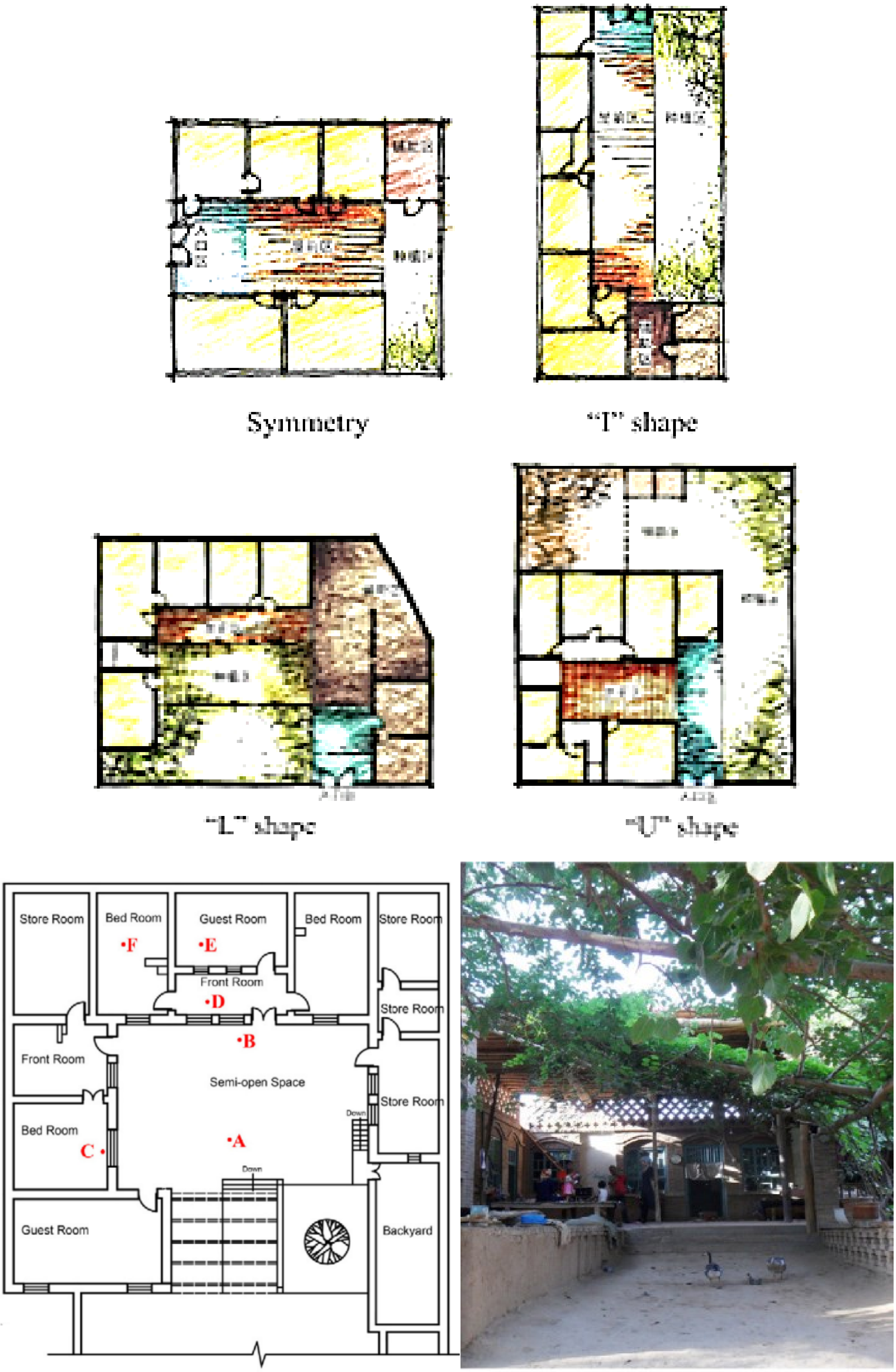


Figure 2.40 Plans and Pictures of Tested Vernacular Building

Source: (Chang et al., 2021)

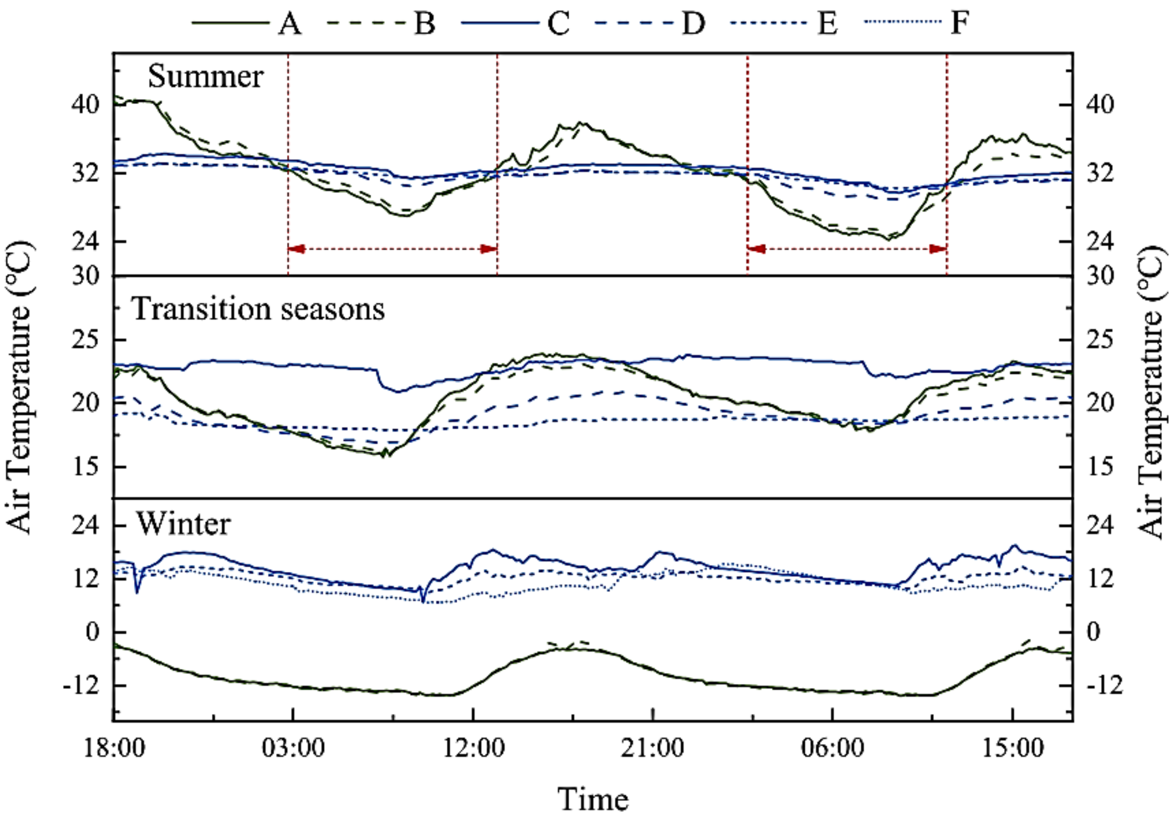


Figure 2.41 Temperature measurements

Source: (Chang et al., 2021)

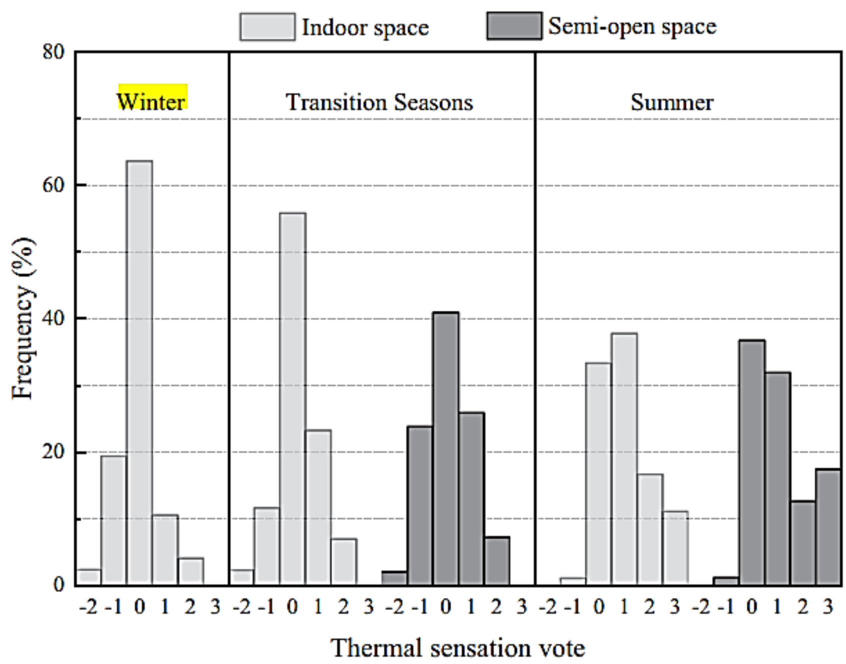


Figure 2.42 TSV

Source: (Chang et al., 2021)

Table 2.5 Behavior of respondents in different seasons

Thermal adaptation behaviors	Active behaviors	Special behaviors		Common behaviors					
	Heating and Electric fans	Space selection behavior	Water sprinkling	Changing clothes	Drinking hot/cold drinks	Taking shower	handheld fans	Closing/opening doors and windows	Changing activities
Winter	96.4%	0.9%	-	10.9%	3.6%	-	-	12.7%	0.9%
Transition Season	68.9%	25.2%	5.9%	3.0%	0.7%	11.1%	4.4%	11.1%	2.2%
Summer	74.7%	74.4%	18.3%	61.9%	60.8%	56.9%	53.1%	51.8%	1.1%

In conclusion, the vernacular architecture of Turpan provides better thermal comfort between indoor and semi-spaces for a longer duration in the winter. While comparing the thermal comfort range with the international standards of adaptive thermal comfort, neutral temperature, and outdoor temperature, it can be said that locals adapt to climatic conditions very well in the Turpan region. In addition, the thermal comfort requirement is somewhat fulfilled by the physical increment of temperatures due to physical activities like household work and kitchen work. The durable and low-energy development of vernacular architecture, as well as the environment, can be achieved by properly using the different kinds of spaces in the household region.

2.6.3 National

- Case I

Regional differences in the wintry indoor thermal environment of traditional houses in Nepal l (Basudev et al., 2019)

This study examined how indoor and outdoor temperatures differ as well as how indoor air temperatures vary among Nepal's three climate regions during the winter months. In the future, the findings may serve to improve traditional houses in three climatic regions. Many houses in this area are quite compact and are connected by narrow passages to keep outwinds, snow, and rain. To attain optimal solar heat gains, the houses are positioned on the southern slopes of hills or in flat valleys and stand close to each other, sharing one or more exterior walls constructed from stones and mud. The external walls are built up to 60 cm thick. Because the animals are enclosed on the ground floor, the temperature indoors rises due to the heat generated by the animals. Stone and mud roofs are affixed to a timber frame with columns and beams. A house usually built in an area of temperate climate usually has a detached pattern, a rectangular floor plan, or an L-shape plan, and is two or three stories high. With a thickness of 50 cm, the walls are built with local stone and mud while hatch, tiles, and zinc sheets are used for the roofing.

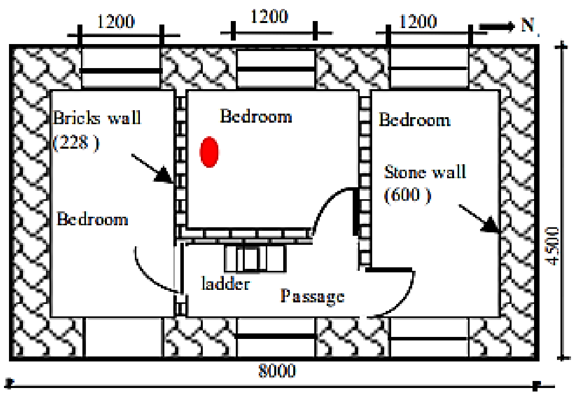


Figure 2.43 Floor plan of the cold climate

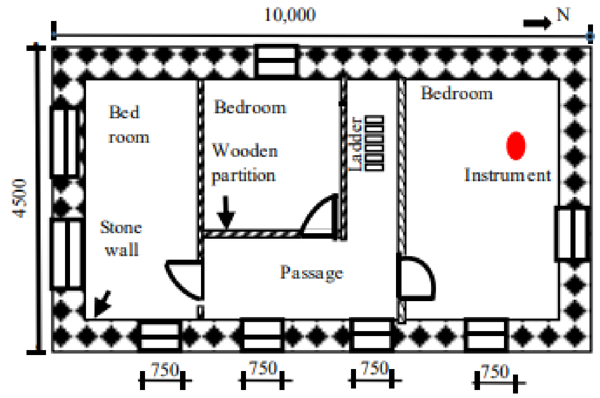


Figure 2.44 Floor plan of temperate climate

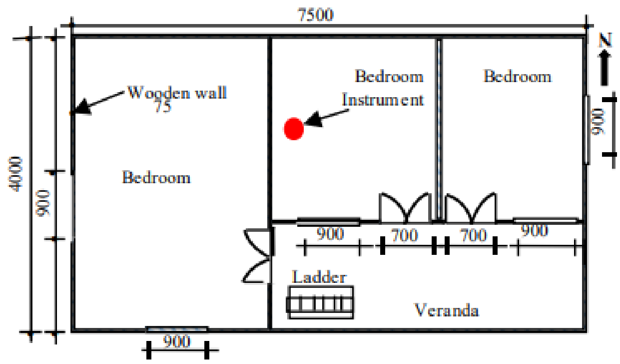


Figure 2.45 Floor plan of the Sub-tropical climate

Source: (Basudev et al., 2019)

This region's diverse cultures are reflected in the houses built by different castes. Low-walled rectangular buildings have long sides that face north and south and rectangular floor plans. Because of this, houses with one to two stories and high ceilings are designed for greater ventilation, which is needed in hot and humid climates. Wood and bamboo make up the walls of the houses, while thatch and tiles cover the roofs. During the winter of 2016-2017 from December 3rd to January 2nd, field measurements took place in three climatic regions using digital instrument: Mustang in the cold Himalayan region (altitude 3000m>8848m); Kavrepalanchok in the temperate Himalayan region (altitude

600m>3000m); and Sarlahi in the sub-tropical Terai region (60m>600m); and 9 traditional houses were measured in each region.

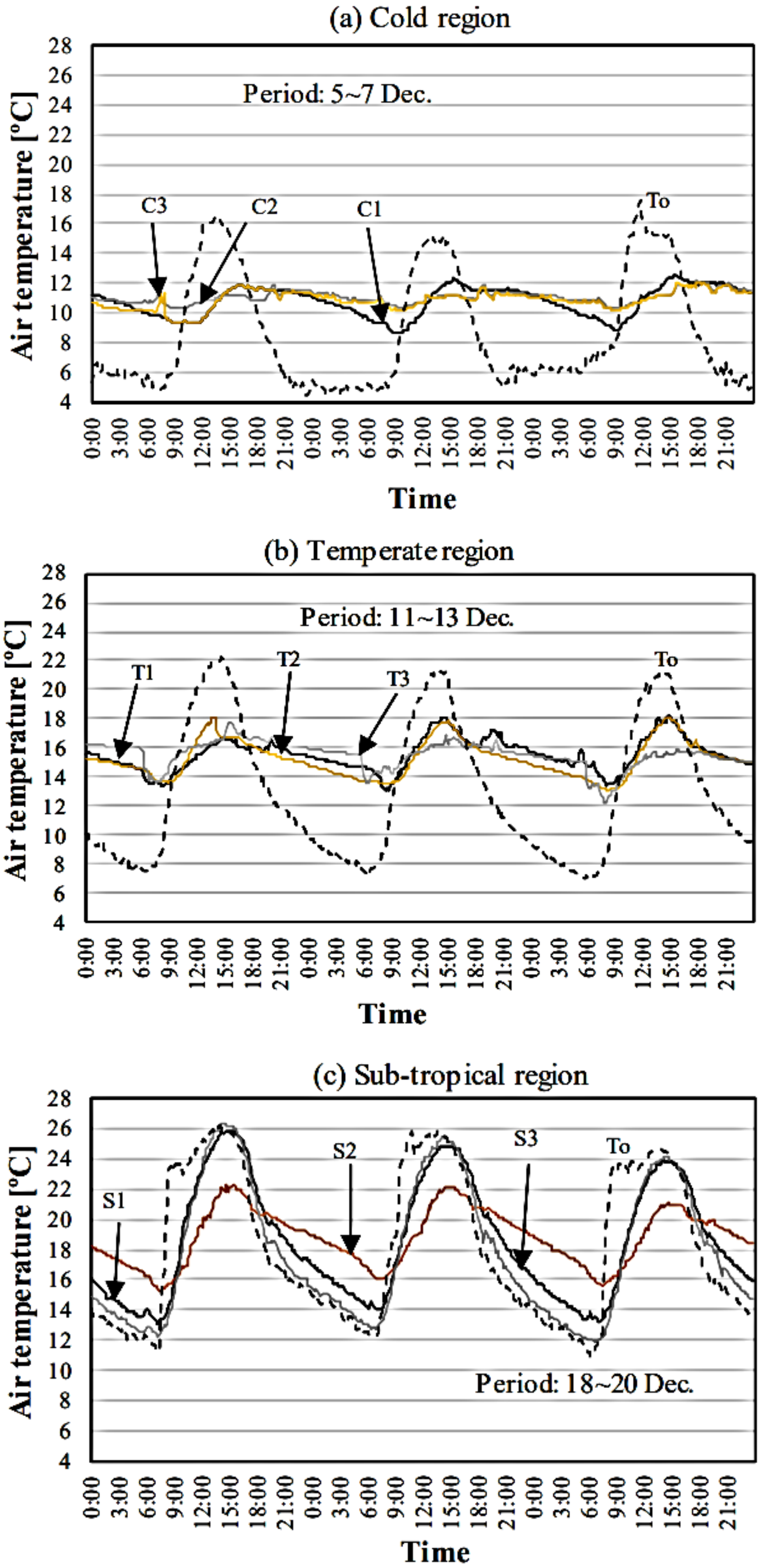


Figure 2.46 Variation of indoor to outdoor temperature in 3 days

On average, indoor air temperatures were lower in the cold region, middle in the temperate region, and highest in the sub-tropical region, where 80% of the data points were below 11°C, but house C1 data points were below 11.5°C, despite being located in a cold region. Eighty percent of the data in temperate regions are below 16°C. Additionally, the temperature data for houses S1 and S2 are below 22°C on average, but for house S3, the temperature data are below 20°C on average which may be the reason for the difference in house materials being used, heat generation, and the thickness of the wall.

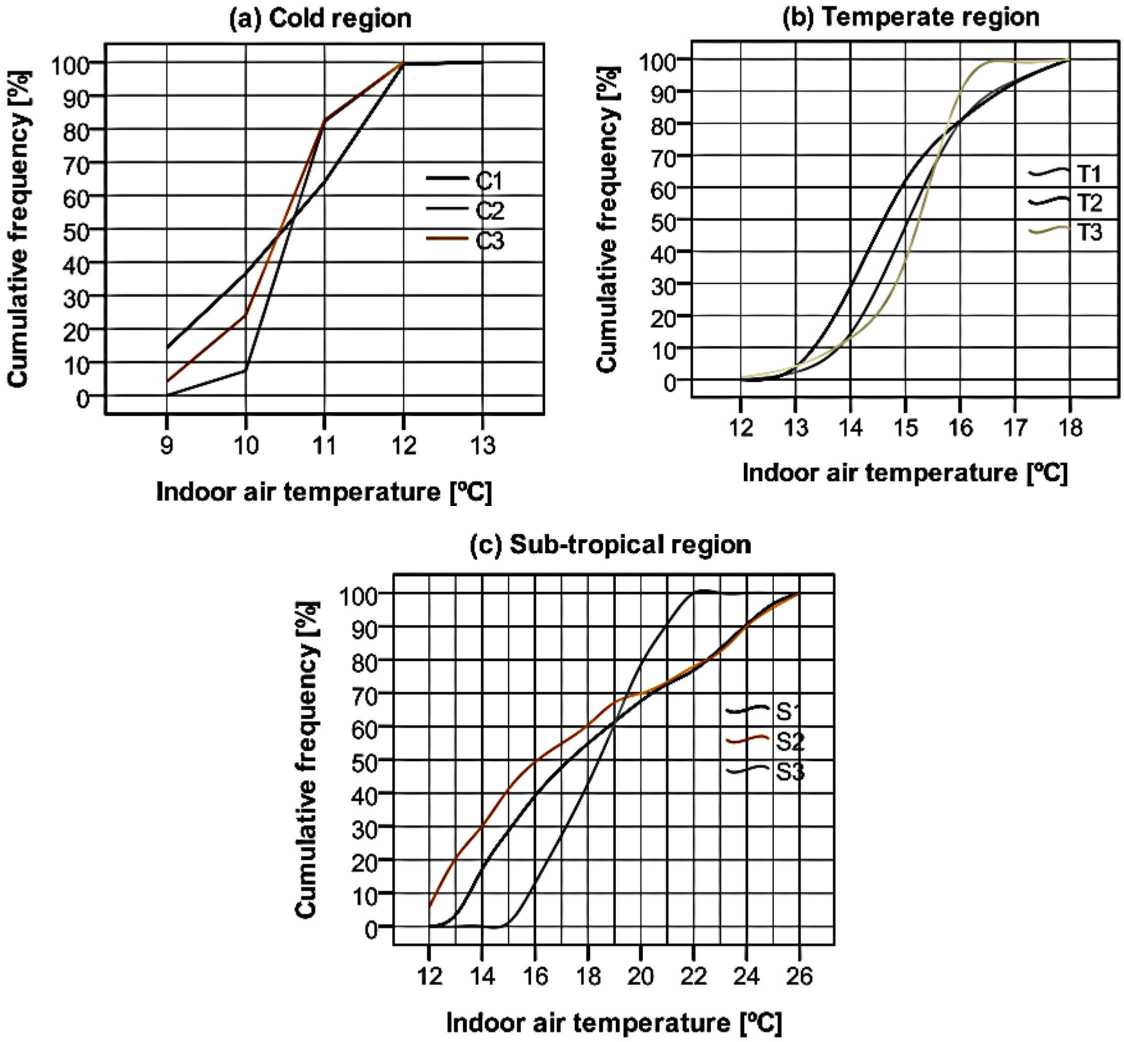


Figure 2.47 Frequency of indoor temperature in three different climatic conditions

Source: (Basudev et al., 2019)

Due to the effect of the thermal mass of the materials used in the buildings, the regression coefficient for cold locations was found to be relatively tiny, while temperate regions were found to be smaller than sub-tropical regions. For both the temperate region and sub-tropical region, there are data plots between 10°C and 22°C. Indoor air temperature, Ti =

16.6°C for temperate regions and Ti = 19.9°C for sub-tropical regions, according to the regression lines above, using an assumption of 21.0°C for outside air temperature. The difference in interior air temperature between regions Ti =3.3°C.

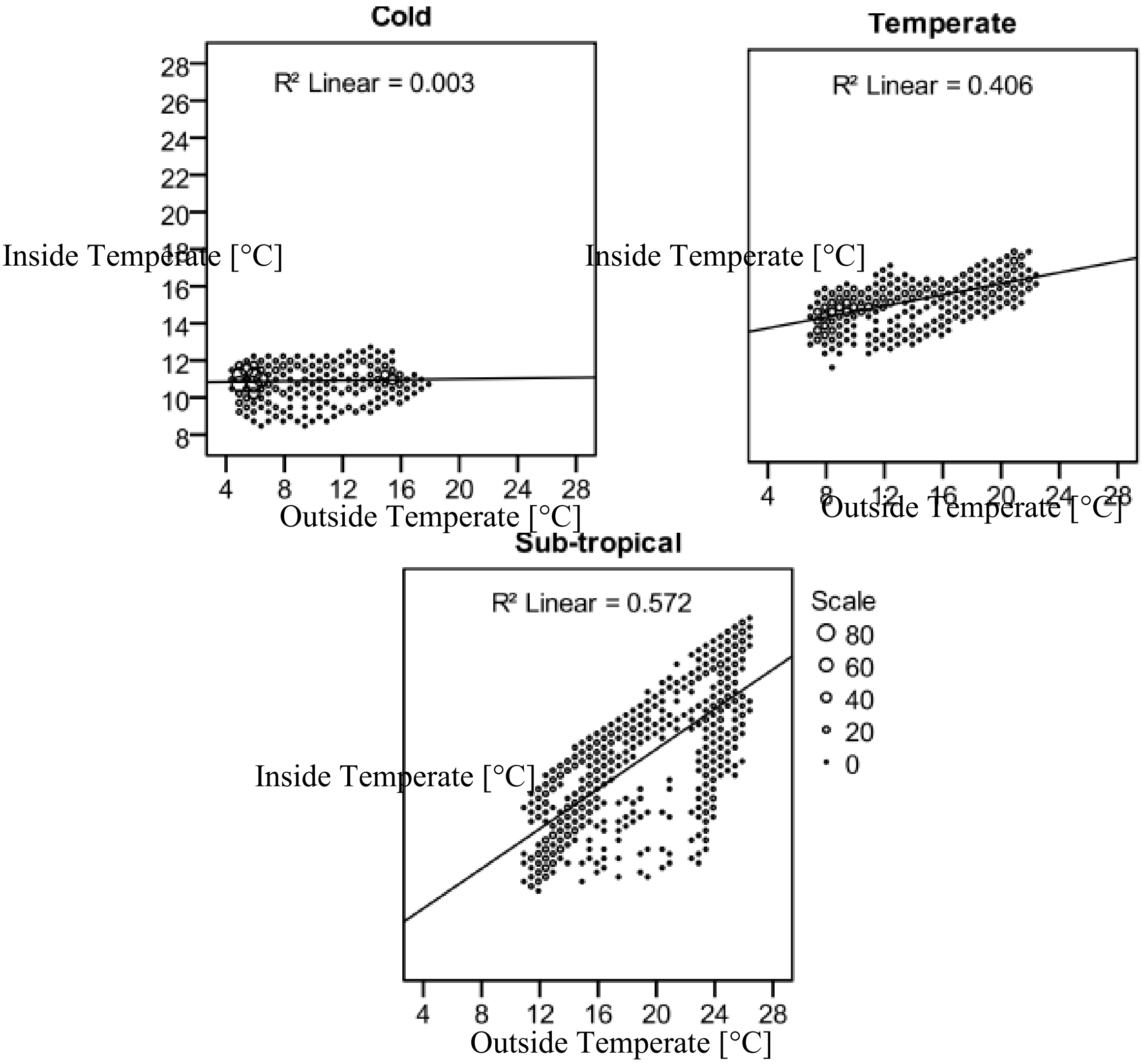


Figure 2.48 Indoor and Outdoor temperature relationships

Source: (Basudev et al., 2019)

The average indoor and outdoor air temperatures in the cold region are lower than in temperate and subtropical regions, according to this study. In comparison to temperate and subtropical regions, the cold region's mean outdoor air temperature is 4.4°C and 9.5°C lower, at 8.6°C. Extreme cold has an impact on human health, increasing mortality rates as a result of increased cold stress.

- <u>Case II</u>

The Thermal Performance of Traditional Residential Buildings in Kathmandu Valley(Bajracharya, 2014)

Traditional Residential Buildings' Thermal Performance in Kathmandu Valley aims to investigate how traditional Kathmandu houses can inform future thermal comfort using the same materials, building forms, and construction technology, as well as help, preserve traditional architecture from the cityscape. The study's main focus is a field study with thermal performance monitoring that took place in Patan and Kirtipur in the Kathmandu valley. Field data, sample analysis, regression analysis, and discussion are used to draw results and conclusions about a building's thermal environment. All data acquired from the field were statistically evaluated using SPSS software.

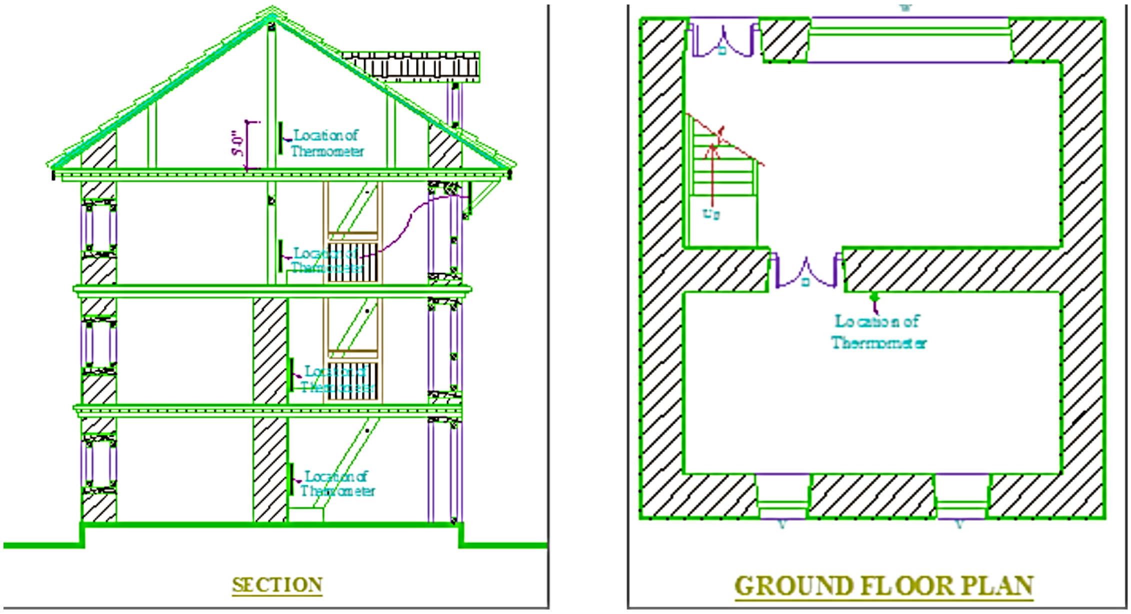


Figure 2.49 Plan and section of walls with the location of thermometers

Source:(Bajracharya, 2014)

Traditional mud architecture developed in the valley, with the main construction materials being sundried brick, burnt brick, mud mortar, mud plaster, clay tile, timber, and stone. External walls have a multilayer of Burnt Redbrick (pakki apa), Sun-dried brick (kachi apa), and mud plaster applied from the outside to the inside, with a thickness of 450 to 600 mm. For weather resilience, one layer of burnt bricks is visible, while sun-dried bricks make up 34% of the inside side of the wall. The load-bearing center wall is typically 450 mm thick and constructed completely of sun-dried brick (kachi apa) and mud plaster.

Two modern households are randomly selected for detailed study with temperature data to compare with traditional buildings, as well as fourteen various historic residences suggested as research samples for evaluation of thermal environment with temperature data.

Table 2.6 Adaptive indoor comfort zone and temperatures

S.No.	Thermal Sensation	Thermal Scale	Nicol Summer	Tc (oC) Winter	Rijal Summer	Tc (oC) Winter	Comfort Category	Remarks
1	Hot	3	32	*	32	*	Very Uncomfortable	
2	Warm	2	30	*	30	*	Uncomfortable	
3	Slightly Warm	1	28	*	28	*	Comfortable	Comfort Zone
4	Neutral	0	26	19	26	15	Very Comfortable	
5	Slightly Cool	-1	*	17	*	13	Comfortable	
6	Cool	-2	*	15	*	11	Uncomfortable	
7	Cold	-3	*	13	*	9	Very Uncomfortable	

Air temperatures were recorded for thirty days in each season at five different locations in each building: four inside, from the ground to the top level, and one outside, below the roof overhang, in the living room on the third story. All data was gathered above 150cm above each floor level for interior measurements and 30 cm below the roof level for outdoor measurements every day at 7:00 a.m., 2:00 p.m., and 10:00 p.m.

Mean comfort temperature

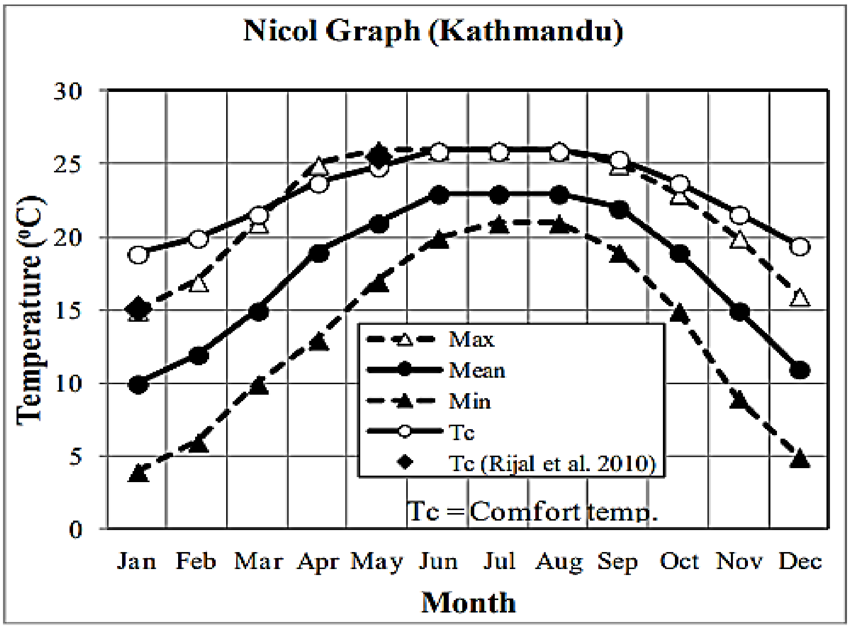


Figure 2.50 Monthly comfort temperature from Nicol graph

Source:(Bajracharya, 2014)

The following graph compares Kathmandu's monthly mean temperature to the Nicol graph's indoor comfort temperature. According to the Nicol graph, the lowest comfortable temperature in winter is around 18°C, and the highest temperature in summer is 26°C. The lowest temperature deemed acceptable in winter is roughly 15°C, and the highest temperature in summer is 26°C, according to Rijal et al. The table depicts the Kathmandu valley's indoor comfort zone temperature throughout the winter. The table depicts the Kathmandu valley's indoor comfort zone temperature throughout the winter.

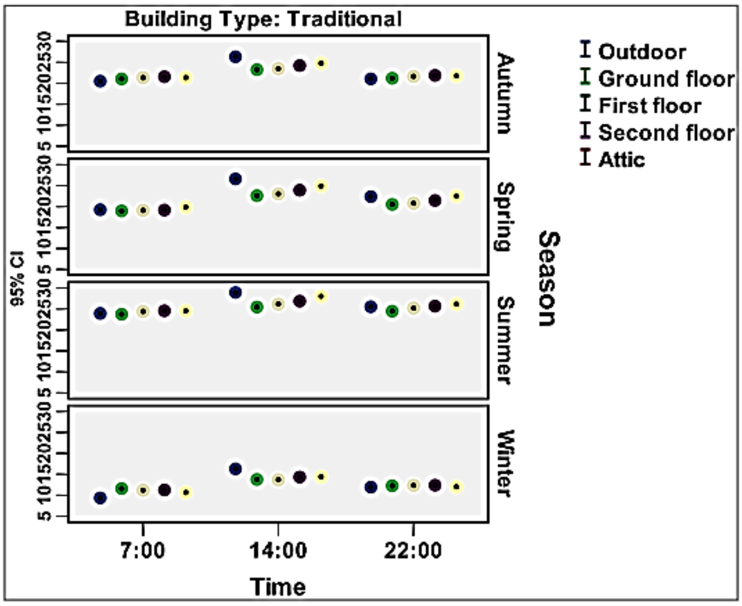


Figure 2.51 Indoor and outdoor temperatures for traditional house

Source:(Bajracharya, 2014)

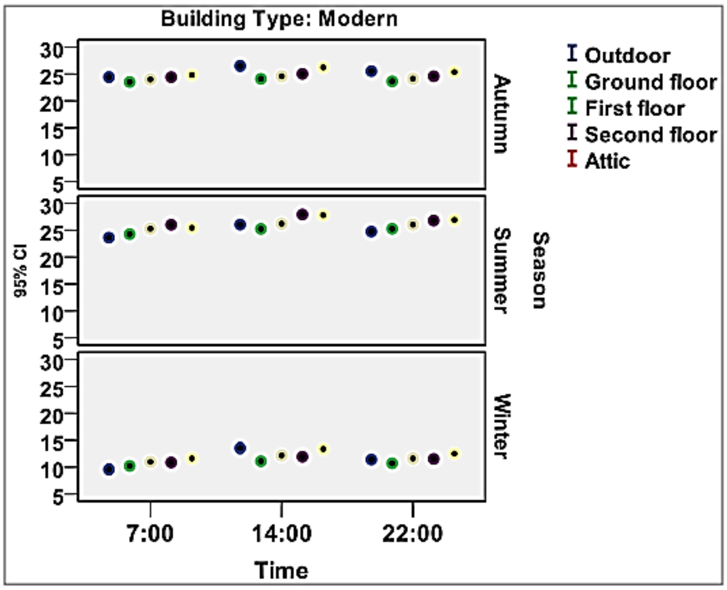


Figure 2.52 Indoor and outdoor temperatures for modern house

Source:(Bajracharya, 2014)

The thermal behavior of ancient and modern Kathmandu buildings, as well as air temperature, was investigated in winter and summer. During the summer, ancient buildings' mean inside air temperature was lower than the mean outdoor air temperature, whereas modern structures' mean indoor air temperature was greater. When the outside temperature is nearly 26°C, traditional buildings' indoor mean air temperatures range from 24 to 26°C, while modern buildings' indoor mean air temperatures range from 25 to 27°C, indicating that traditional residential buildings were 1 to 2°C cooler than modern residential buildings in the summer.

Table 2.7 Individual and overall relation between indoor and outdoor temperatures

Type	Floor	n	Equation	R^2	S.E.	p	Tp Max °C	Tp Min °C
	Ground	1292	T_i=0.714T_o+4.829	0.82	0.009	<0.001	24.8	12.0
Traditional	First	1295	T_i=0.758T_o+4.211	0.82	0.010	<0.001	25.4	11.8
	Second	1276	T_i=0.806T_o+3.610	0.86	0.009	<0.001	26.2	11.7
	Attic	1295	T_i=0.885T_o+2.301	0.90	0.008	<0.001	27.1	11.2
	Ground	325	T_i=0.922T_o+0.655	0.93	0.014	<0.001	26.5	9.9
Modern	First	325	T_i=0.904T_o+1.802	0.92	0.015	<0.001	27.1	10.8
	Second	325	T_i=0.975T_o+0.805	0.92	0.016	<0.001	28.1	10.6
	Attic	325	T_i=0.937T_o+2.165	0.95	0.012	<0.001	28.4	11.5
Traditional	All	5158	T_i=0.890T_o+1.612	0.92		<0.001	26.5	10.5
Modern	All	1300	T_i=0.939T_o+1.338	0.95		<0.001	27.6	10.7

Similarly, the average indoor air temperature in most typical dwellings was about equal to or somewhat warmer than the average temperature of the outside air (12.5°C) throughout the winter. Traditional residential structures were 1 to 2°C warmer than modern residential buildings throughout the winter, with indoor air temperatures generally equal to or 1°C lower than the mean outdoor air temperature. (11.5°C). The regression analysis of the indoor and exterior air temperatures was used with SPSS software to forecast the inside air temperature of a residential building. Table 4 displays the results of a linear regression study of each floor of Traditional and contemporary residential structures.

When the outside air temperature is 10°C, the indoor air temperature in a conventional residential building's ground floor is 12°C, while the indoor air temperature in a modern residential building's ground floor is almost the same at 10°C following the regression equation.

Traditional: $Ti = 0.8905To + 1.6125$ ....(1)

Modern: $Ti = 0.9392To + 1.3379$ ....(2)

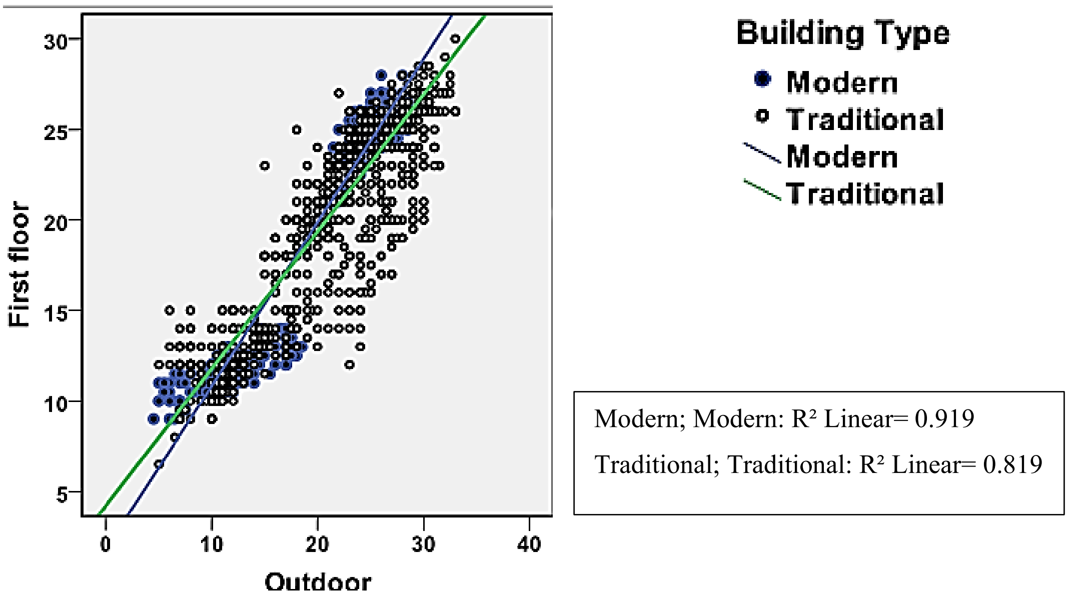


Figure 2.53 Indoor and outdoor temperatures for modern house

Source:(Bajracharya, 2014)

Traditional buildings are not antiquated, according to the research, but they do have advantages over modern structures. Traditional structures save at least 1-2°C in temperature in both hot and cool seasons when compared to modern buildings, and they also save a significant amount of energy, saving at least 10-20% in energy for either heating or cooling in both summer and winter when compared to Kathmandu's modern buildings. Enacting a bye-law with conservation goals will also help to preserve Kathmandu's historic residential buildings in the future. Among the five municipalities in the valley, the bye-laws of the typical cultural neighborhood are better for the preservation of traditional residential buildings. The lower the room height, the better the thermal performance, because the volume of air in any area immediately demands energy to generate a suitable thermal condition, especially during extreme cold and hot seasons when additional energy is required to control thermal conditions.

- <u>Case III</u>

Comparative Performance Assessment of eco-friendly Buildings and Conventional Buildings of Kathmandu Valley (Mishra & Rai, 2017)

Rapid development inside the valley has undoubtedly increased the number of concrete buildings, resulting in large volumes of carbon emissions and embodied energy during the manufacturing of the building materials used in their construction. As a result, the carbon footprint left by the construction of these concrete structures is causing environmental damage, which is one of Kathmandu Valley's most pressing issues. Growing urbanization in the city is a major concern, and alternative building construction technologies should be thoroughly researched. Eco-friendly buildings are created using proper construction processes and materials with the primary purpose of improving environmental resources. Only a few Eco-Friendly constructions exist in the city, which are designed and constructed using natural building materials and other green construction features in an energy-efficient manner. When people compare the performance of existing environmentally friendly and conventional buildings, they may be able to better grasp the outcomes of environmentally friendly buildings. The main goal of this research is to compare the performance of environmentally friendly and traditional structures in the Kathmandu Valley. Other research goals include determining the building materials utilized in present eco-friendly structures in the Kathmandu Valley, as well as evaluating the environmental, economic, and social performance of eco-friendly versus conventional buildings.

Because of its high population and quickly developing urbanization, the Kathmandu Valley was chosen as the research region. Ama Ghar, Godawari, and Mato Ghar, Budanilakantha in Kathmandu Valley, as well as two similar conventional houses, Happy Home, Godawari, and Mrs. Paudel's Residence Building, were selected for this study. The case study "Hama Steel," which is currently pursuing LEED certification, is used to better illustrate the facility and its qualities. The major data came from case selection and two focus group discussions with locals.

The data acquired to compare the performance assessment of the structures with theoretical validation includes calculations of U-value, embodied energy, and CO2 emission during construction. Cost estimates for eco-friendly features in green construction, as well as operational and maintenance costs for both types of structures, were also prepared. The performance of their constructions in terms of thermal comfort and satisfaction was discussed by owners and two focus groups with other house occupants. This goal's conclusions were reached via a focused group discussion with the inhabitants of the case study buildings. The first Case Study of an environmentally friendly structure, Ama Ghar, had ten participants in the focus group. During a case study visit to Happy Home, a traditional building, ten people participated in a focus group discussion.

The outcomes of this aim were based on the Performance Assessment of Buildings for environmental, economic, and social factors. The total estimated embodied energy, emitted carbon of the structure and superstructure of the buildings during construction, and U-Value of different surfaces of the buildings during construction were calculated and compared for the environment parameter. Mato Ghar has a total built-up area of 2500 square feet, whereas the Paudel house has a total floor space of 3683.33 square feet. While building the structure and substructure of Mato Ghar in Paudel's residence, a total of 371,473.55 MJ embodied energy was collected; 508,240 MJ embodied energy was produced.

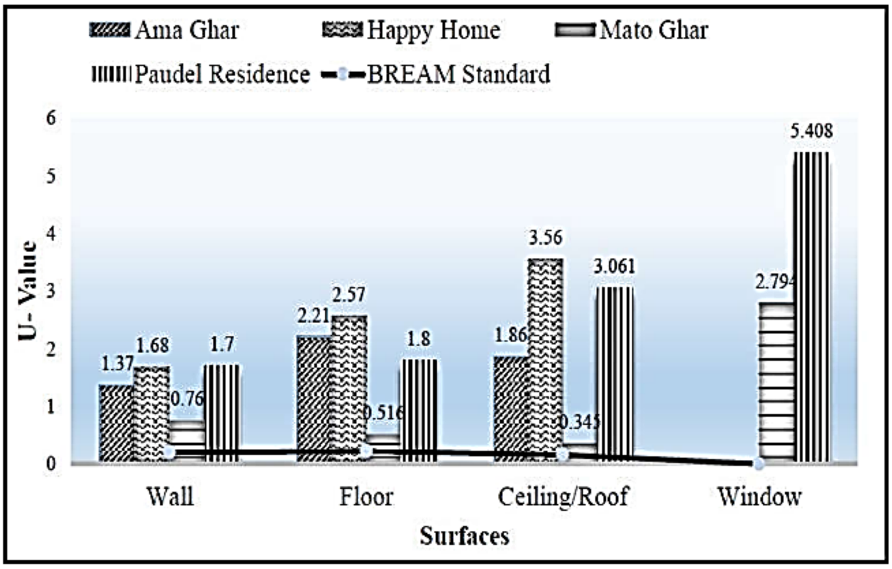


Figure 2.54 U value of studied houses

Source: (Mishra & Rai, 2017)

Mato Ghar emitted 49,062.51 kg of CO_2, while Paudel Home emitted 53609.3 kg. The obtained statistics and comparison reveal that Mato Ghar, an eco-friendly home, emitted less carbon and created less embodied energy during construction when compared to Mrs. Paudel's traditional house. Mato Ghar's embodied energy per unit space is 143.828 MJ, while Paudel residences are 187.06 MJ, suggesting that Paudel Residence produced 40.885 MJ more per unit area than Mato Ghar. Mato Ghar produces 17.89 kg of carbon per square foot, while Paudel House produces 20.11 kg. In comparison to Mato Ghar, Paudel Residence produces 2.227 kg more carbon emissions per unit area. Existing greenhouses have a favorable influence on the environment as a consequence of our analysis, with decreased embodied energy and carbon footprint during construction.

As a result, the insulating properties of both homes are the same. Roofs at Ama Ghar and Happy Home had U-Values of 1.86 and 3.56, respectively. The roof of the Ama Ghar is made of clay tiles, but the Happy House has a reinforced concrete ceiling. The results show that Ama Ghar's roof insulation is superior to Happy home's since its U-value is lower. The obtained U- Values of Mato Ghar and Paudel dwelling walls were 0.76 and 1.73, respectively, indicating that Mato Ghar's thermal insulation is superior to Paudel residence's.The Matoghar home also features double-paned windows, however, the Paudel house only has single-paned windows. Even though a double pane window has a lower value, the math shows that a double pane window provides significantly more insulation than a single pane window. U-Values of 2.79 and 5.6 were calculated for Mato Ghar and Paudel houses, respectively. The U-Values of Mato Ghar and Paudel Residence floors were 0.5 and 1.8, indicating that Mato Ghar floors are better insulated than Paudel Residence floors. Mato Ghar's roofs were also found to have a lower U-Value than Paudel Residence's, which had a value of 0.3 and a U-Value of 3.06. The resultant figure clearly illustrates that Mato Ghar roofs provide much better thermal insulation than Paudel homes.

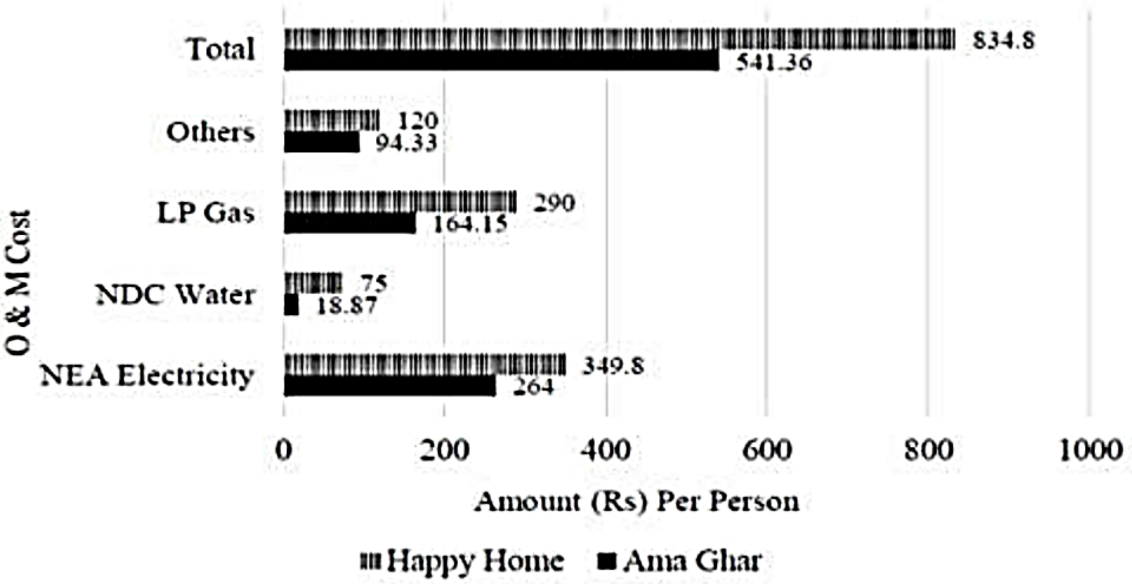


Figure 2.55 Embodied energy of studied houses

Based on economic, environmental, and social parameters, the information gathered and analyzed revealed that current eco-friendly buildings in Kathmandu Valley outperform conventional ones. However, many eco-friendly houses continue to employ the same traditional construction materials, even though other eco-friendly characteristics are being explored more in those projects. The conclusion also encourages people to design and develop environmentally friendly buildings since they meet today's energy needs without harming the environment and contribute to a brighter and healthier tomorrow by establishing a balanced relationship with nature.

- Case IV

Improving indoor thermal comfort in residential buildings in Nepal using Energy Efficient Building Techniques (Borgkvist, 2016)

Nepal is facing a lot of development challenges. A major problem in Nepal is the power cuts. The development in the country must find smart and affordable solutions to this problem shortly. The objectives of this research are to give examples of how energy-efficient building techniques, such as the use of insulation and passive solar heating, can contribute to improving indoor thermal comfort in Nepalese houses and long-term sustainable development in Nepal. In this research. Two locations, Ghorepani and Dhulikhel on different altitudes are chosen to represent the cold and warm temperate climates in the country. Eight interviews are performed with people living in similar houses in the chosen areas and one house of the interviewees is chosen for the indoor climate simulations. The indoor temperature and air quality are simulated for the warmest and coldest days of the year.

Table 2.8 Building properties taken for simulation

Elements of construction	Material	Thickness [m]	U-value [W/m^{2}K]
External walls	Stone	0.4	3.30
Internal walls	Stone	0.4	3.30
Roof	Slate	0.015	5.71
Ground floor and foundation	Stones and soil	0.9	1.86
Windows	Wooden shutters	0.025	2.87
Door construction	Wooden door	0.035	2.38

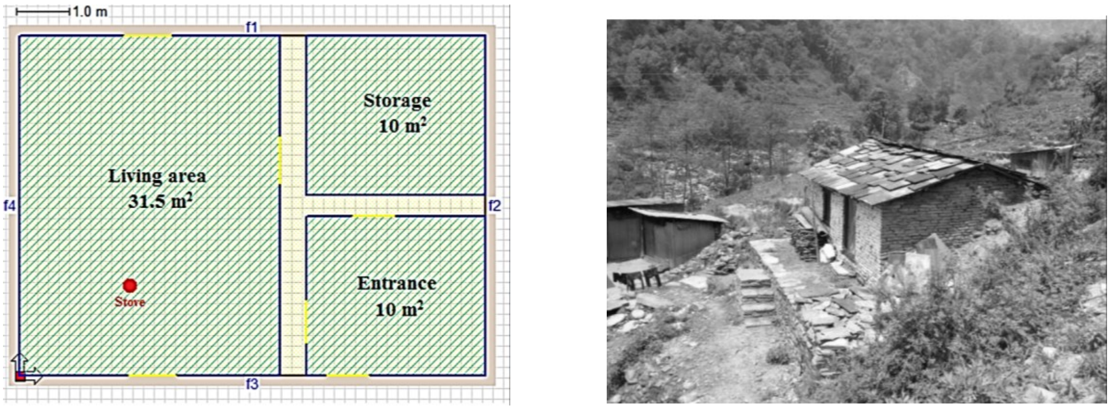


Figure 2.56 Plan and picture of chosen house for simulation

Source: (Borgkvist, 2016)

The house for the case study taken in the traditional house of Dhulikhel in the central hills is made of dried bricks and mud for walls while the foundation is of stones and rammed earth. The floors are constructed of tree piles or/ and bamboo covered with mud on walls. The roof is usually the maid of tiles but steel sheets are also common these days. Similarly, In the mountain areas, the houses are mainly made out of mud-bonded stones with tile roofs. Villages in cool temperate climates usually have a denser settlement pattern (Bodach, Lang & Hamhaber 2014).The primary methodology related to this research is to find the research the related parameter that governs the thermal comfort and improvise it to optimize the building model using simulations. In addition, the climate data study, as well as the comfort survey, was performed. The building is made from stone with mud mortar with walls, roofs, and foundations. The doors and windows are made from wood and there are also air leakage problems. The building materials and element properties are shown in the table

During certain times of the day, the windows must be open to maintain a suitable level of indoor air quality. When the parameter research simulations employ the basic scenario with closed windows and doors, the carbon dioxide level is 6000 ppm per m3, which is excessively high and unacceptable. Different schedules of open windows are tested to attain an average carbon dioxide level below 1000 ppm per m3. When the western window is open 25% of the time and the eastern window is open 25% of the time while cooking, and the average throughout the night. Improving interior thermal comfort in residential buildings in Nepal utilizing energy-efficient building approaches. The carbon dioxide level in residential buildings in Nepal is 796 ppm per m3, with a modest daily variance.

The findings show that using passive solar heating and insulation in the roof and walls may raise the average temperature on the coldest winter day from 0.8 to 11.1 degrees Celsius. In the basic scenario, the coldest winter day was defined as the day with the lowest interior temperature. This indicates that the coldest day after the building adjustments might be different because direct solar radiation has a considerable impact on the findings when the orientation and windows are modified in the final simulation. If nothing more is specified, the parameters will be utilized in all subsequent simulations. These amounts of ventilation will be insufficient as long as people utilize open firewood burners.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Conceptual Framework

The theoretical features are based on past kinds of literature. Kinds of literature were considered to understand the ideas of vernacular architecture and the active paradigms in the global background. The topic that has been taken as research, *"Thermal Performance of Mud Shelters in Hilly and Mountain Region in Nepal"*, leans towards a quantitative paradigm for understanding the thermal performance of mud shelters in hilly and mountainous regions of Nepal. The post-positivist paradigm involves the study of reality from a probabilistic viewpoint. (Groat & Wang, 2004). Therefore, the ontological claim is that mud shelters are better in thermal comfort/performance than concrete structures in the context of Nepal. Our epistemological position is to understand this subjective nature of thermal comfort of the individual through collective generalization using partially objective study. The source of obtaining the thermal comfort conditions is through quantification of the thermal comfort conditions of an individual concerning their surrounding environment's physical parameters like temperature, humidity, and wind velocity. This quantitative study considers the statistical side of the study which involves questionnaires as a response of the participants who reside in the cold regions of Nepal. Along with the survey, field measurements of the physical parameters like temperature, humidity, etc. are also conducted. From past works of literature, thermal comfort is known as a subjective topic by itself. However, it has been studied briefly and codified such that quantitative studies can be made for indoor scenarios for generalization. The code includes both the measurable variables and personal factors involved in finding out the thermal conditions and their satisfaction in the majority of human occupancy.

There is no subjective interaction between the researcher and the occupants and external influence is assumed as non-existent. Therefore, the ontology of this research is largely objective, quantitative, and primarily focused on fulfilling the requirement of objective satisfaction among the occupants. Initially, thermal comfort case studies of traditional structures are done for international, regional, and national locations. The strategies are selected to determine the thermal performance defined by the human perspective and the physical properties of the structure and surroundings. To determine the effect of architectural elements on thermal performance, thermal measurements of different forms of buildings are compared for understanding the changes in the performance of respective mud and non-mud shelters. A special factor of the climatic condition is kept in mind while pursuing the research forward as the climatic condition changes throughout the year. Since the aim is to find whether the traditional structures can fulfill the requirements of thermal comfort, data of mostly colder months are very essential for this research. Therefore, it is essential for proper planning for efficient data collection in both the physical and psychological aspects of the research. ((See Annex 3:))

3.2 Methodology

The main objective of the research is a quantitative evaluation of the thermal environment of the mud shelters in the hilly and mountainous regions of Nepal. To achieve the goal, the analysis of the structure, as well as the experience of the residents inside the buildings, was done based on different research indicators. The research was conducted in two different locations, one in the hilly region and one in the mountainous region. There was a total of 8 different houses surveyed and monitored in the mountainous region, whereas in the hilly region there were 3 houses in total. The investigation was conducted between 26th April-10th May and 15th June-30th June in the mountainous area and hilly areas respectively. A total of 50 residents were surveyed from all of the houses among which 36 belonged to the mountainous area and 14 belonged to the hilly area.

3.2.1 Investigation of features of different shelters

After reaching the investigation site, we visited different traditional and modern houses and tried to cover most of the locality as permitted by time and logistics. The sample size for the survey was determined on the convenience of the people in the community for the survey. The physical properties of materials, air temperature, form, and structure of the house used were figured out using existing works of literature for simulation purposes. In addition, the number of floors, the sizes of these houses, the finishing of the walls, and the size of each opening to a wall is checked thoroughly for each floor. Special attention was given to the architectural spaces and their utilization in plan and elevations, orientations, and floor height of the dwellings. The resources, tools, and equipment used for heating and cooling purposes by the residents of the house were distinguished.

3.2.2 Thermal environment

The main data comprised field measurements of air temperature, while minor data included weather data of the location from the Department of Hydrology and Metrology (GoN), Nepal. A hygrometer, both dry and wet, is used to determine both the inside and outside temperatures. The Digital Hygrometer comes with a thermo-hygrometer that measures relative humidity as well as air temperature. Pre-calibration and ready-to-use tools are included with the Digital Hygrometer. It features a large LCD to allow users to view both time and humidity. 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.

Figure 3.1 Hygrometer used in the measurement by Omsons

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. 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).

3.2.3 Thermal comfort survey

Most of the survey was conducted in the daytime as per convenience and free time of the residents both in hilly and mountainous regions. The thermal comfort survey that determines the sensation, preference and acceptance of the traditional and modern structure was used to keep an account of the demographic data and the parameters for thermal comfort evaluation. To consider a demonstrative and justifiable sample, the sample selection was done using the Steven-Thompson method:

$$n = \frac{Np(1-p)}{(N-1)\left(\frac{d^2}{z^2}\right)+p(1-p)} \qquad ....(1)$$

Where,

n: Sample size

N: Population size

Z: Confidence level at 95% (1.96)

D: Error proportion (0.05)

P: Probability 50%

The questionnaire survey aimed to obtain residents' thermal sensation and include questions on the basic information about the buildings, residents' demographic information such as gender, age, regional location, occupancy time, living habits, and the present measures regarding the regulation of the indoor thermal environment. It was divided into demographic data, date, time, building information, building environment, activity and clothing, thermal responses, and building responses. Once all the thermal responses were obtained from residents of different dwellings, there were binned through KOBO Toolbox software and analyzed through SPSS software which is usually used as a social science statistical tool. In addition, the time and temperature(T) at which the thermal survey for each individual is recorded to know at which point in time have the responses been recorded. The data from both the traditional and modern mud shelters found in the hilly and mountainous regions are compared using frequency distribution histograms and box charts.

Respondents' subjective thermal sensation vote (TSV) was evaluated using the 7-point scale suggested by ASHRAE Standard 55. The questions are included in Appendix A. To evaluate the overall thermal responses, the 'thermal comfort zone of this research is classified as ± 1 for thermal sensation (on a 7- point scale), ±1 for thermal preference (5-point scale), and ±1 for overall comfort (6-point scale). The comfort temperature (CT) and preferred temperature (PT) are calculated using the equations below. It is considered useful when linear regression is unreliable to estimate the comfort temperature. Based on the respondents' votes of thermal sensation and the corresponding values of measured indoor globe temperature, we estimated the comfort temperature by using the following equation:

$$T_c = T_g + \frac{(4-mTSV)}{a^*} \qquad ....(1)$$

$$T_{per} = T_g + \frac{(4-TP)}{a^{**}} \quad ....(1)$$

Where; T_c , T_g , T_{per} a^* are the comfort temperature, globe temperature, preferred temperature, increment of thermal sensation vote, and assumed increment of preference vote corresponding to an increase of 3 ºC in global temperature. Number "4" indicates "Neutral (neither cold nor hot)" in the mTSV seven-point scale, which is assumed as linear from 1 to 7, mTSV denotes the modified thermal sensation vote obtained from the survey, and a* denotes the increment of thermal sensation vote with indoor globe temperature. Thus, a* replaces the regression coefficient assumed as 0.50, which is equivalent to assuming that an interval of two adjacent votes corresponded to an increase in global temperature by 2°C. The value of a** was assumed as 0.33 (= 4/6 × 0.50), due to which the range of the seven-point thermal sensation scale and that of the five-point scale of preference corresponded to each other(Nicol et al., 2020)(Pokharel et al., 2020). For comparison with the questionnaire survey, a qualitative assessment was also performed with a semi-structured interview to indicate how participants felt about their clothing and thermal comfort conditions.

3.3 Location and shelter information

3.3.1 Information on Studied Area

The study and analysis have been done in the hilly and mountainous regions of Nepal, namely, Kathmandu and Manang. These locations have been chosen based on the ease of accessibility, climatic conditions, and the type of structures required for studies on mud shelters. The Köppen Climate Classification System is the most generally utilized method for categorizing climates across the world. Its methods rely on monthly and yearly temperature and rainfall averages(Pidwirny, 2006). The mud shelters in the southern region of Nepal have been excluded as the study was essentially focused on warm-temperate rather than humid-subtropical climates. According to the Koppen Climate classification, Manang has subtropical highland, Tundra and little sub-arctic zones due to altitude and Kathmandu Valley lie in humid subtropical. In Nepal, the climate is mostly humid subtropical in the flat lands and some parts of the hills.

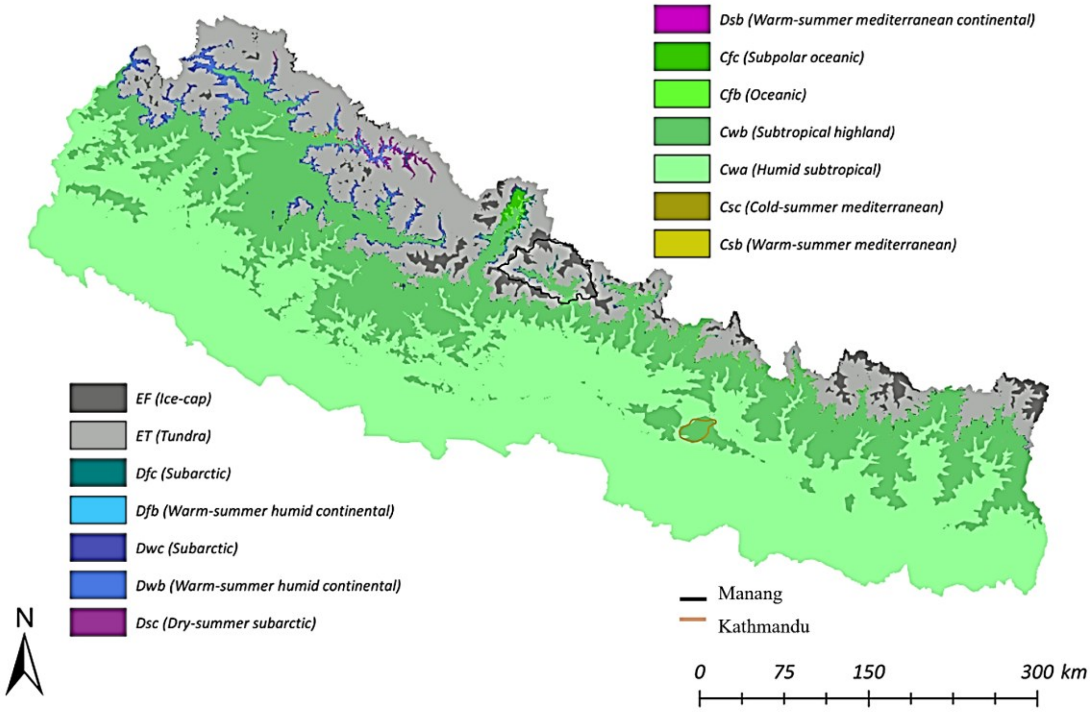


Figure 3.2 Koppen Climate in Nepal

Source: (Peterson, 2018)

- Mountainous Region-Manang

The major population settlements in Manang District according to the census 2011 are in the following locations:

Table 3.1: Population and Altitude of settlements in Manang District

Source: (Central Bureau of Statistics, 2012)

VDC/ Municipality	Population	Altitude
Bhraka or Braga	306	3472m
Chame	1129	2650m
Dharapani	1012	1860m
Fu	176	4080m
Ghyaru	71	3730m
Khangsar	257	3765m
Manang	630	3519m
Nar	362	4180m
Ngawal	274	4573m
Pisang	307	3250m
Tachai Bagarchhap	544	2176m
Tanki Manang	377	3519m

VDC/ Municipality	Population	Altitude
Thoche	382	4078m

Figure 3.3 Manang District trekking route and settlements

Source: (Nepal, 2019)

Pradhan describes Manang as breathtaking beauty where a play of cosmic energy along with simple awareness of the human habitat has given rise to unique culture and architecture that is humble, strong yet devoid of monumental or iconic architecture that we witness in urban cities(Pradhan, 2021). Manang village is the main settlement of the valley, both from tourism and historical points of view. Manang is a town in the Manang District of Nepal. It is located at 28°40'0N 84°1'0E in the broad valley of the Marshyangdi River to the north of the Annapurna mountain range. The village is situated on the northern slope, which gets the most sunlight and the least snow cover in the winter. The cultivation fields are on the north slope with terraces. There are now motorable roads as well as trails where goods are transported on jeep or mule trains or carried by porters. A small airport, located 2.5 km (1.6 mi) east of the town, serves the whole valley. Besides catering to trekkers, there is some agriculture and herding of yaks.

Manang village is the epicenter of all social, political, cultural, and administrative activities

Figure 3.4 Braga Valley(Mud Roof)

Source: (Travelers, 2017)

Figure 3.5 Mud Used as Mortar

Source: (Art, 2020)

Figure 3.6 Narphu Village

Source: (Ghumante, 2019)

Figure 3.7Mud used as outer protection

Source: (Ghumante, 2019)

Figure 3.8 Interior of House in Ngawal

Source: (Art, 2019)

Figure 3.9 Ngawal stone mud school

Source: (Art, 2019)

in the valley(IFC, 2021). Manang village also has a cultural museum, movie theater, restaurants, and other recreational facilities. A typical house is made up of stone walls and mud roofs as shown in the figure. In general, the architecture of Manang includes stone masonry with mud mortar houses with or without thick mud plasters and mud roofs. The interiors are usually plastered with mud. Even the temples are constructed in this same style but the walls are thicker than the residential houses. With increasing altitude, the houses seem closer to each other with narrow passageways and a thicker layer of mud protection.

<u>*Odar Village:*</u>

In Manang, Odhar village is a quaint little village that is getting very popular for its amazingly serene location and well-run homestays. The name of this village derives from a rock overhang in the central part of the village which is almost a cave and well 'odar' is a Nepali word for 'cave'. This village has an elevation of around 2100-2400 meters. Odar village is situated nearby to Thonje, and close to Bagarchhap and needs half an hour to reach Dharapani. The Gurung people, also called Tamu, are an ethnic group in this village of Gandaki Province. Geographic and climatic variables have influenced local settlement and alignment of the structures in this region. The structures which are recently built look more scattered than in the previous culture of house construction in clusters.

Figure 3.10 Odar gau location

Figure 3.11 Sloped roof in the snow(2022)

Figure 3.12 Flat and Sloped roof in snow

Source: (Art, 2019), (Local Resident- Dil Gurung Lama, 2022)

There are many mud-stone walled structures with a wall thickness of around 18 inches which have also been insulated both inside and outside the structure by 3 inches of mud. The traditional roofs are usually flat and made up of mud whereas the modern ones are sloped CGI(corrugated galvanized iron) sheets. This type of structure is especially found in this locality where the temperature fluctuates from -1.5 to 24$°C$ near Dharapani. As there is no provision of external heat energy supply besides firewood, people here rely on clothing and compactness in the home. The odar village is showered by winter snowfalls and ice pellets(Sherpana, n.d.). According to the local information, the snow usually falls at the same time as the snowfall in Manang village.

- Hilly Region-Kathmandu Valley

Two mud shelters located in different areas around the hilly region were studied. The double-storied rammed earth structure is located in Godawari whereas the single-storied rammed earth structure is located in Budanilkantha. The information about the location of these existing structures is given below. The location from where the mud shelters are considered is studied in detail whereas the location of concrete shelters is studied generally in terms of Kathmandu valley.

- Tarkeshwor

Tarakeshwor Municipality is located in the Kathmandu District's northwestern corner. The municipality is dubbed after the Tarakeshwar temple, which is located in the same area. Former VDCs, Dharmasthali, Futung, Goldhunga, Jitpurphedi, Kavresthali, Manmaiju, and Sangla merged to form the municipality. The area's latitude and longitude are 270 N and 850E, respectively. The municipality that covers the region is around 10 kilometers from the city center. Shivapuri Nagarjun National Park borders Tarakeshwar on the northwestern side. The elevation of this area is 1405m. In 2011, the municipality had an area of 34.9 square kilometers and a population of 81,443. Agriculture products and services are the primary vocations of the residents. Despite its proximity to Kathmandu, the majority of the people in rural regions still lack necessities. Due to its historical, cultural, and natural heritages, such as Taruka's Bullfighting, Dhiki-Jato Chulo, and other sites to establish a name for itself in the national and international arena, it also has a high probability of tourism potential.

In Kathmandu, the capital city, there is a lack of land accessible for housing construction. As a result, individuals are buying land on the periphery and building houses quickly. As a result, the region becomes urbanized. There is no direct climate data available for this location.

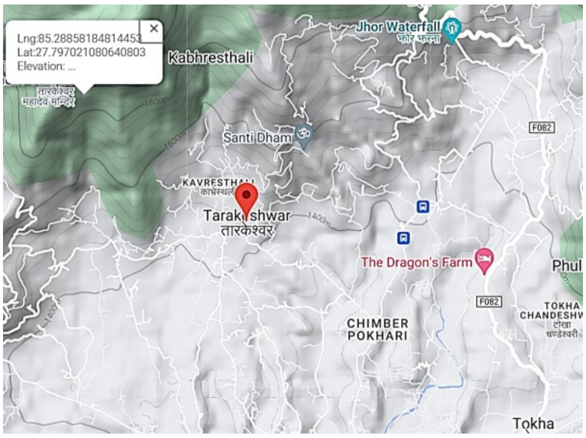


Figure 3.13 Tarkeshwor area- Location and picture

Source: (Wikipedia, 2022)

- Godawari

Godawari is a municipality in the Lalitpur District in Bagmati Province of Nepal. It is one of the popular hiking destinations for its rich wildlife and splendid environment. Godawari is also famous for its botanical garden and Godawari temple. Phulchoki is located in Godawari which is the highest peak in Kathmandu valley(Silwal, 2014). The climate here is mild and generally warm and temperate. In winter, there is much less rainfall in Godawari than in summer. The average annual temperature in the Godawari is 15.9 °C | 60.7 °F. In a year, the rainfall is 2595 mm | 102.2 inches. (Climate-Data, 2022). Precipitation is the lowest in November, with an average of 14 mm | 0.6 inches. With an average of 699mm, the most precipitation falls in July. At an average temperature of 20.3 °C, June is the hottest month of the year. January has the lowest higher average temperature of the year. It is 9.1 °C. The month with the highest relative humidity is July (91.67 %). The month with the lowest relative humidity is April (55.41 %). Godawari lies in the northern hemisphere. Summer starts here at the end of June and ends in September. There are the months of summer: June, July, August, and September. The best time to visit is May, June, and September.

There are a handful of rammed earth houses in the Godawari area as informed by Mr. Narayan Acharya, one of which is his own home. The modern rammed earth buildings have been equipped with manufactured and processed materials like steel, timber, etc. Among the many mud structures, double-storied rammed earth is considered for the detailed study. With modern tools and technologies, modern rammed earth structures which are also a part of mud architecture have adapted well to the locality similar to their traditional counterparts.

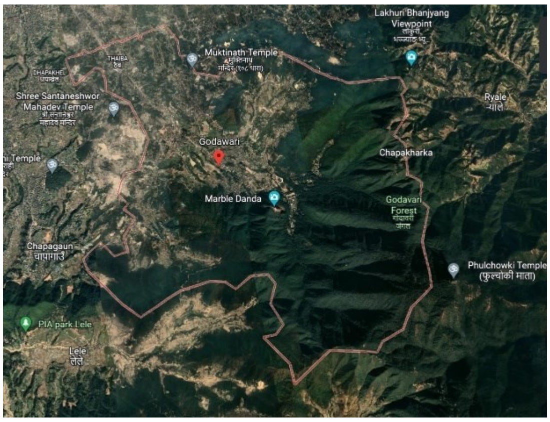


Figure 3.14 Godawari -Location and picture

Source: (Argoul, 2022)

- Budanilkantha

The latitude and longitude of Budanilkantha are 27.7654382 and 85.3652959 respectively and the elevation is 1371m. Budhanilkantha is a city in Nepal's Bagmati region, located in the Kathmandu district. After Kathmandu and Lalitpur, it is the Valley's third biggest city. According to the Nepal census of 2021, the city has a population of 179,688 people and 26,678 households. Budanilkantha was formed on December 2, 2014, by combining the old VDCs Hattigauda, Khadka Bhadrakali, Chapali Bhadrakali, Mahankal, Bishnu, Chunikhel, and Kapan. At the foot of Shivapuri hill, the city is located with a population of 15,421. The climate in this area is generally relatively mild, warm, and temperate. There is significantly less rainfall in the wintertime than in the summertime. Köppen and Geiger classify this location as Cwb. The average annual temperature of Budhanilkantha is 16.2 °C | 61.2 °F. The annual precipitation is approximately 2812 mm | 110.7 inches. From this location, single-storied rammed earth constructed by Prabal Thapa architects called Matoghar is selected.

Figure 3.15 Budanilkantha -Location and picture

Source: (Wikipedia, 2022)

3.3.2 Comfort temperature from climatic data

Utilizing the 5 or 10 years of climatic data, a Nicol graph is generated which is based on the works of Humphrey(ref). Humphreys revealed a consistent, nearly linear correlation between the temperatures that free-running (unheated or cooled) building occupants considered suitable and the existing mean outdoor temperature. The straight line's equation is given by

$$T_{comf} = 0.54\, T_{om} + 12.9 \qquad ....(1)$$

- <u>Manang and Tarkeshwor</u>

Unfortunately, the monthly temperatures in Manang and Tarkeshwor are unavailable from the climatological department due to technical reasons. However, data for other locations have been observed which is used in the next section.

- <u>Godawari</u>

Table 3.2 Climatic data from the Meteorological department

Max monthly Temperature	Min monthly Temperature	Humidity(%)	Precipitation(mm)	Tcomf
16.72	2.11	72.73	0.56	17.9

19.49	4.62	71.5	1.29	19.3
22.73	7.83	66.02	0.87	21.0
25.47	10.96	65.9	2.75	22.6
26.6	14.65	73	3.92	23.8
27.28	17.18	83.71	9.38	24.7
26.19	17.95	88.08	14.7	24.6
26.36	17.57	86.14	9.89	24.5
26.21	16.06	84.22	5.07	24.1
24.67	10.91	80.79	0.73	22.3
21.18	6.06	80.44	0	20.1
18	2.88	75.89	0.41	18.4

For Godawari, the climatic data shows that the region lies in the Cwb(Subtropical Climatic zone) where the average monthly temperature varies from 16.7°C to 27.3°C in maximum and 2.1°C to 17.9°C in minimum. The geographical features include valleys as well as hills. The ambient temperatures during summer (Jun-Aug) in the day at noon and night times at 3 a.m. are 21.6 whereas in the winter(Dec-Feb) it is 10.6. The relative humidity during summer (Jun-Aug) is comparatively high (%) than the winter (Dec-Feb) (%). The annual precipitation is nearly 49.6mm in terms of rain or snow. The mean monthly minimum and maximum temperatures with comfort temperatures are as follows with the Nicol graph.

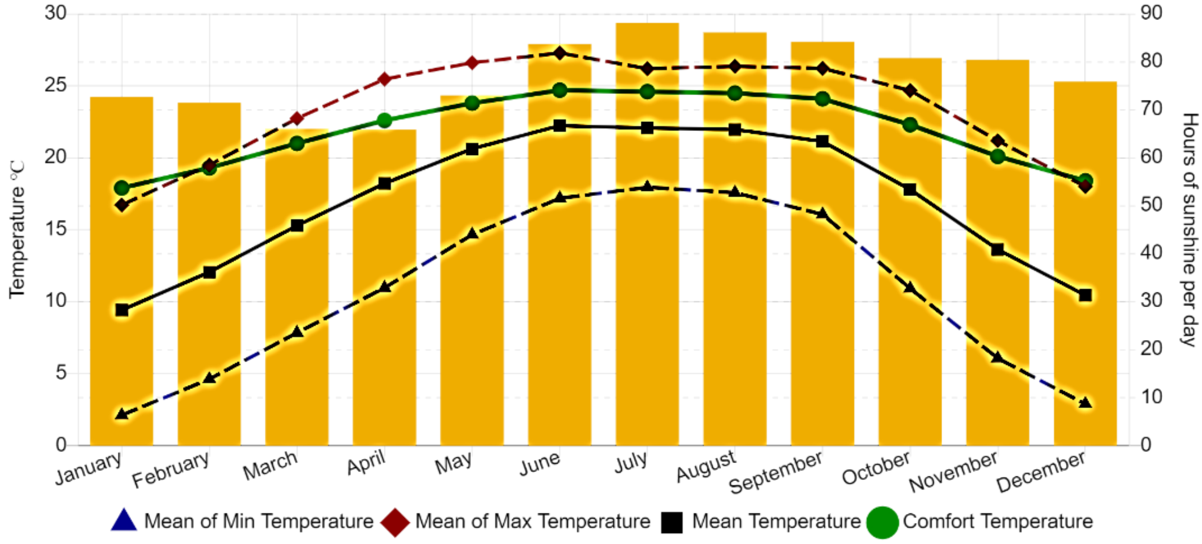


Figure 3.16 Nicol graph and comfort temperature for Godawari

- <u>Budanilkantha:</u>

For Budanilkantha also, the climatic data shows that the region lies in the Cwb(Subtropical Climatic zone) where the average monthly temperature varies from 17.6°C to 28.5°C in maximum and 4°C to 19.4°C in minimum. The geographical features include valleys as well as hills. The ambient temperatures during summer (Jun-Aug) in the day at noon and night times at 3 a.m. are 28.39 whereas in the winter (Dec-Feb) it is 4.6. The relative humidity during summer (Jun-Aug) is comparatively high (%) than the winter (Dec-Feb). The annual precipitation is nearly 66 mm in terms of rain or snow. The mean monthly minimum and maximum temperatures with comfort temperatures are as follows with the Nicol graph.

Table 3.3 Climatic data from the Meteorological department

Max Monthly Temperature	Min monthly Temperature	Humidity(%)	Precipitation(mm)	Tcomf
17.6	2.9	76.8	0.4	18.1
21.1	6.2	76.7	1.1	19.7
25.5	9.6	70.1	0.9	21.5
28.1	11.5	68.8	3.4	22.7
27.2	15.3	75.3	5.6	24.0
28.6	17.1	79.6	9.7	24.7
28.4	19.8	86.7	18.3	25.1
28.3	19.7	88.4	15.2	25.1
28.0	18.5	88.0	10.4	24.7
26.5	14.4	86.2	1.3	23.3
22.2	9.4	83.1	0.0	21.0
19.7	4.8	80.4	0.3	18.9

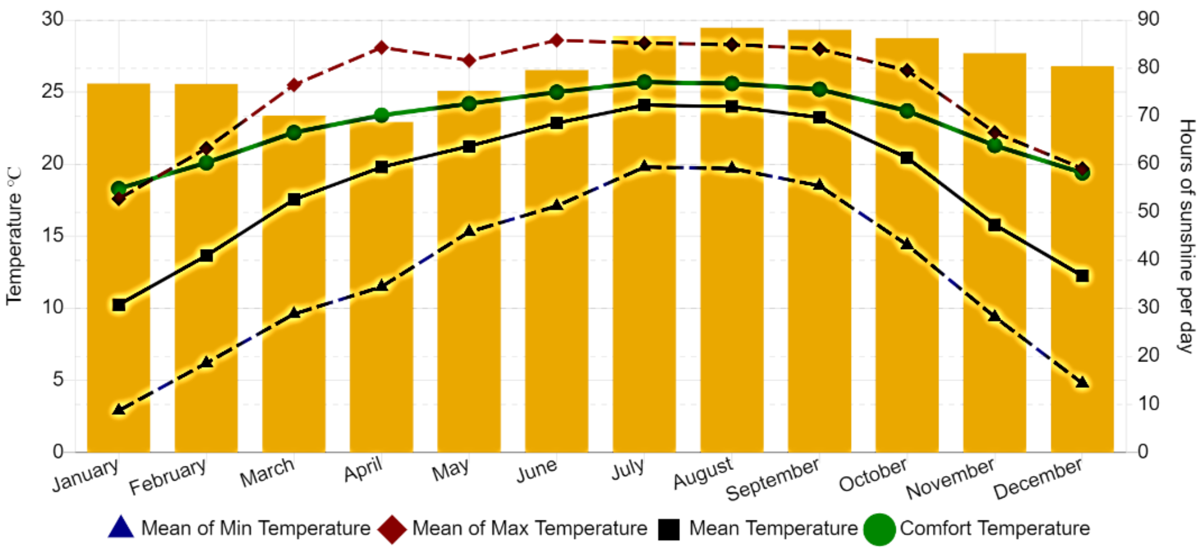


Figure 3.17 Nicol graph and comfort temperature for Budanilkantha

3.3.3 Information on Studied Shelters

The data and information of the houses obtained from the study of the site are segregated based on parameters such as location, roof type, story, temperature, orientation, opening sizes, and materials used. Most of the traditional mud shelters found in the research area were stone masonry in mud mortar (SMM) as both of the materials were available in the site location for construction. The modern houses were made up of RCC frame structures. All the houses in the mountainous region have 6 feet-deep stone masonry foundations to provide support from the ground. The houses are named alphabetically from A-H in the mountainous region and I-K in the hilly region.

- Type I

Single storied SMM with mud roof

Two houses of this category were fully investigated. The single-storied houses were very old structures which one has constructed around 100 years ago while another 400 years ago. The wall thickness was 16"-18" inch with the outer and inner surface plastered by 3" of mud. The floor heights were around 6'. The house has a wooden beam post supporting system with 6.5"wooden beams and 5"x5" of columns. The floors are made up of flooring woods while the roofs are covered by a 5"-8" thick mud layer. The locals say that people's movement on the roof has compressed the mud roof into a water-impermeable layer. The height of the doors is very small and there are no windows. The houses are different in sizes and number of rooms as one is a single kitchen cum bedroom while another consists of a kitchen, bedroom, and storeroom. Both the houses have only one door for access from the outdoors and there are no windows for light and ventilation. The locals prefer the enclosed rooms to prevent cold wind drifts throughout the year which can cause deprivation of natural lighting. Some of the illumination problems are compensated by holes that are made on the roofs of the structure. In addition, the lack of natural lighting is fulfilled by artificial electric illumination. The only opening/door is also very small in size around 2'-4"x5'.

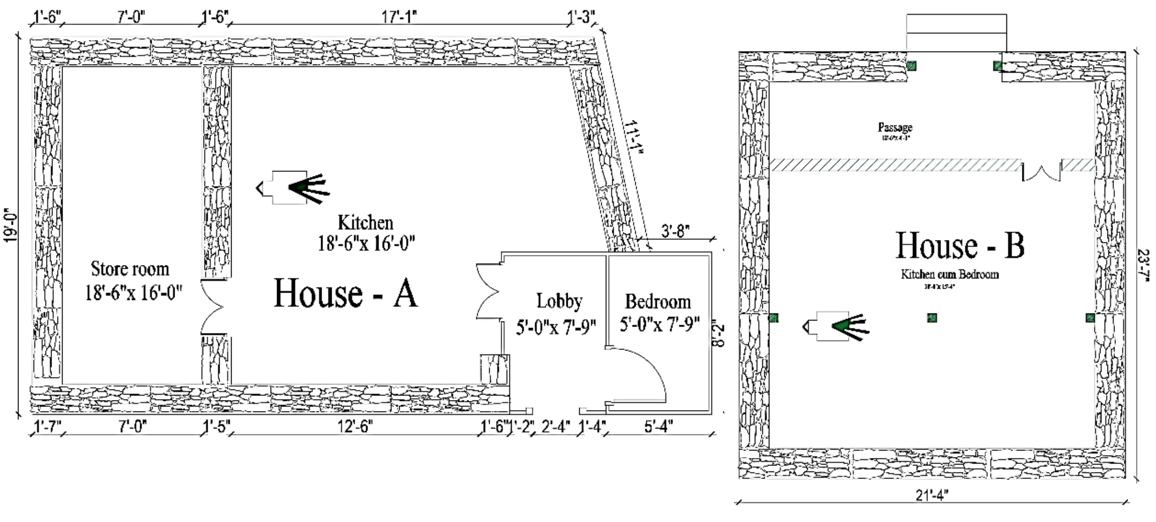


Figure 3.18 Plans of single-storied SMM with mud roof

Figure 3.19 House A- inside

Figure 3.20 House B- Outside

Source: (Case-study)

- <u>Type II</u>

Double-storied SMM with mud roof

Two of the investigated mud shelters were double-storied with the ground floor as a store room/cattle shed and the first floor used as a living area (kitchen and bedroom). As the plinth area is bigger, they have separated the rooms with SMM walls and wooden planks. The first-floor rooms consist of different flooring materials of which one has wooden planks and the other one has partitions inside the house. The internal partitions are also separated with wooden planks. In addition, the mud roof slabs are bigger than the single-storied houses with a 10" thickness. Similar to the single-storied traditional mud dwellings, the house is also supported by wooden beam post where the beams are of the sizes 8"x8" and the column sizes are 6"x6". The floor height is around 6-7'. Among the two structures C and D, house D has windows at sill height 2'10" from the floor level at east and west sides for lighting and ventilation whereas house C doesn't have a single window. House D has verandahs on the first floor which are covered by CGI sheets for shading from sunlight and rain. This mud slab is supported by 5" wooden beams and they consist of voids/holes(size) to allow the daylight entrance. The height of the doors is 1’-5’’ feet bigger than the single-storied houses.

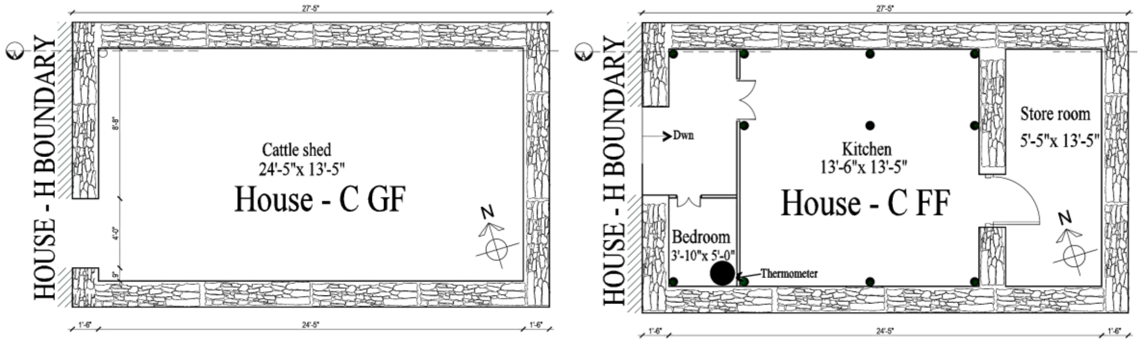


Figure 3.21 Plans of single-storied SMM with mud roof

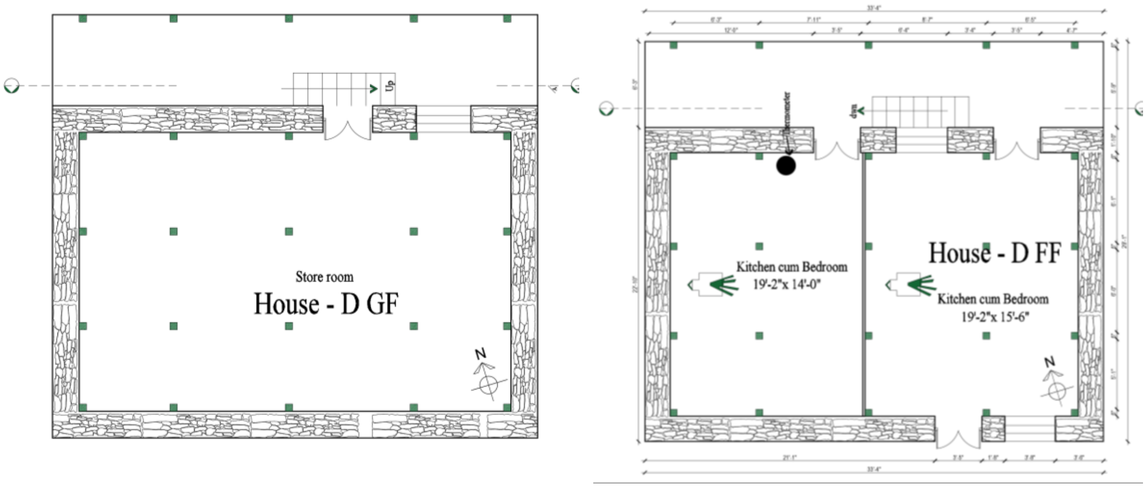


Figure 3.22 Double-Storied SMM structures

Figure 3.23 House C- roof

Figure 3.24 House D - Verandah

Figure 3.25 House C - Inside

Figure 3.26 House D - Roof

Source: (Case-study)

- <u>Type III</u>

Single Storied RCC

Among the two modern houses found in the hilly region, both are RCC structures with varying wall types. House E consists of stone masonry with 16" cement mortared stone walls; House F has a composite wall consisting of a shear wall of 4” thickness with the finishing of 2” plaster from both sides. The wooden planks of height 2’7” for insulation from the outside environment are attached on the internal walls. The sill height for windows is around 2.5' and the total building height is around 8.5'. House E has wooden planks used for flooring compared to the other which has concrete slabs used instead. Both RCC structure has around 1'x1' column supporting 9" beams which supports the roofs. The roofs are different in that house E consists of CGI sheets while another is a typical slab roof. Both of these structures are designed and constructed to reflect modern society and have no influence on traditional architecture on them.

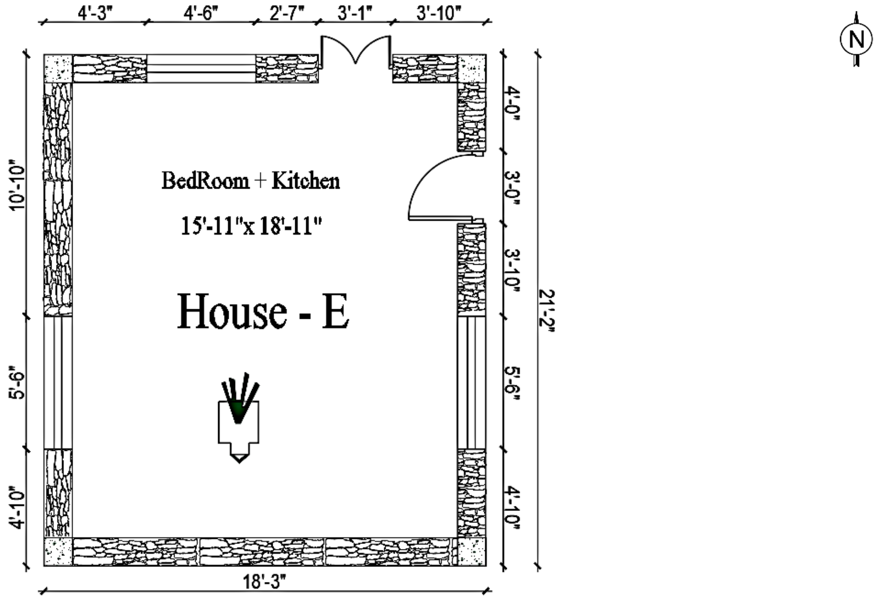


Figure 3.27 Single-storied RCC structure

Source: (Case-study)

Figure 3.28 House E-Inside

Figure 3.29 House E-Outside

Source: (Case-study)

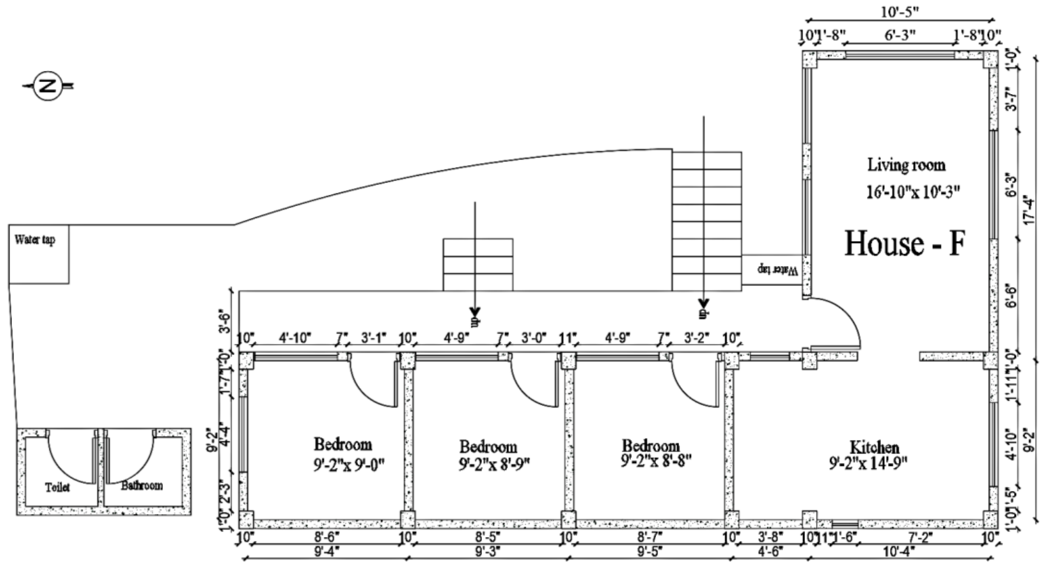


Figure 3.30 Single-storied RCC structures

Figure 3.31 House F- Outside

Figure 3.32 House F-Inside

Source: (Case-study)

- <u>Type IV</u>

Triple storied RCC

A 3-storied modern house investigated in the hilly region is an RCC structure with column sizes 10"x10" and beam 11"x9". It is attached to house C on the west side respectively. The house has access from the west side and the house consists of opening on every floor on the west side with different opening sizes. The ground floor is used as a bathroom/toilet whereas the 1st and 2nd floors are used as bedrooms. The staircase which creates an opening between the lower and upper floors also plays a role in air movement in the dwellings. Hence, the size of such vertical openings is also equally important in the thermal performance of the structure. This structure has a 2'-6"x6' vertical open area which functions as a staircase and regulates the internal air movements between floors. The floor slabs are 5" thick with a floor height of 7'-8". The structure is west oriented and it is expected with low wind velocity on the lower floor areas due to its surrounding covered by other houses. The sizes of window(5'x2'-6") and doors(3'x6') are also modern; hence the structure has larger openings than the traditional structures.

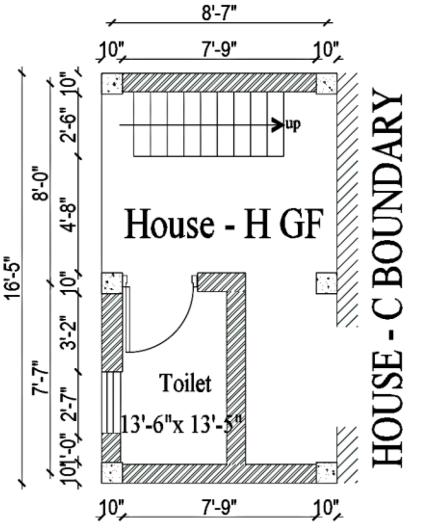


Figure 3.33 Ground floor Plan

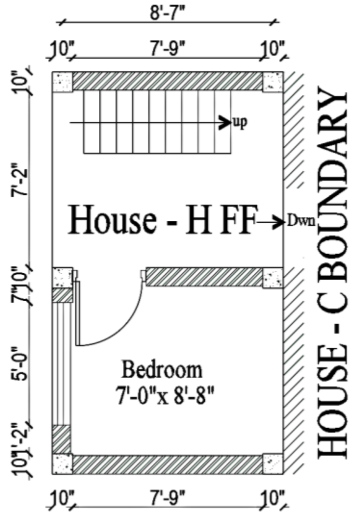


Figure 3.34 First floor Plan

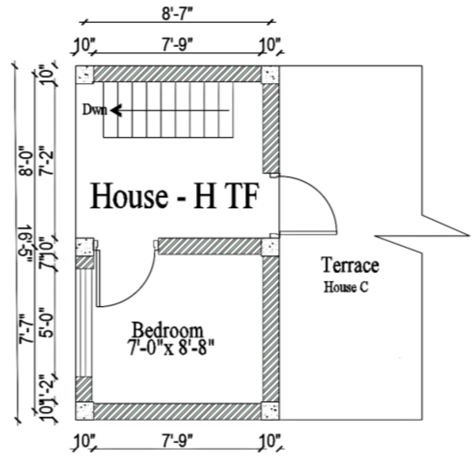


Figure 3.35 Top floor Plan

- Type V

Double-storied SMM with hybrid roof

There are two types of roofs on the top, on the west, it is a CGI roof whereas on the east side it is a mud roof. These houses are made up of stone with mud mortar which was covered by internal cement finishing. It has a west orientation. The floor heights are relatively more than the traditional SMM structures. The floor is separated by 4” thick slabs with wooden planks. The windows are located at the sill height of 2’ and are 5’ in height. The riser of the staircase is 9” of wood. The walls are 18” thick. All the internal partitions are plywood. The storeroom, bedroom, and living room come under the CGI roof whereas the kitchen and bathroom come under the mud roof. The main focus of this house is the mud-roofed area.

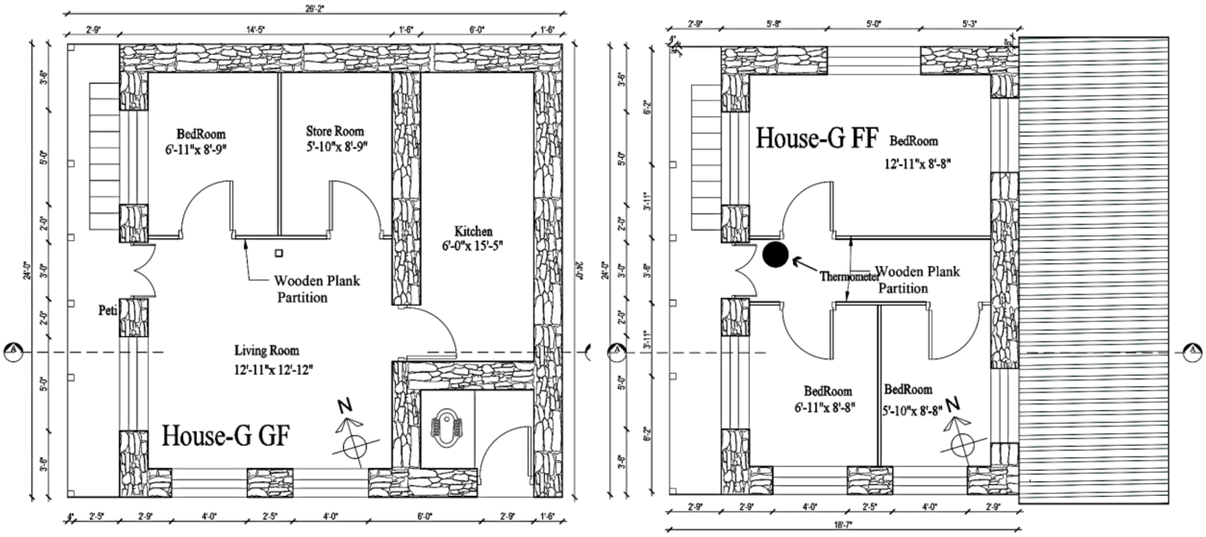


Figure 3.36 House G floor plans

Figure 3.37 Kitchen area SMM with mud plaster

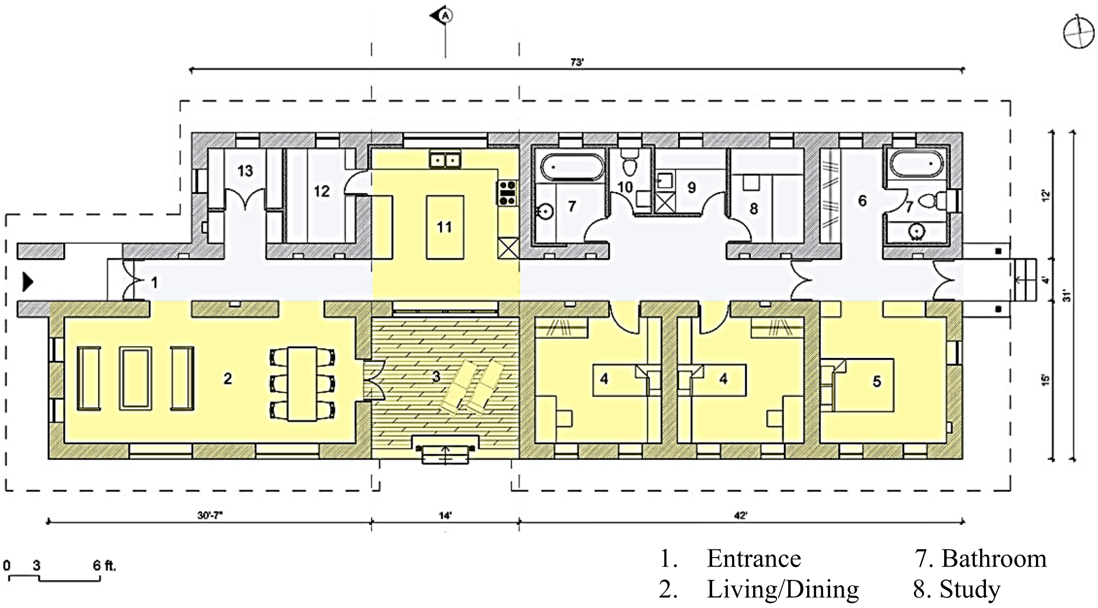
Figure 3.38 SMM with Cement Finishing

Source: (Case-study)

- Type VI

Single storied Rammed earth - MATOGHAR

The study of rammed earth has been restricted to the study of "Matoghar" of Buddhanilkantha, built around 2011 and designed with passive solar techniques. It also has a solar photovoltaic panel and solar water heater installed through solar water heating. Mud or "Mato" in the local Nepalese language is the main ingredient for construction. The building form is rectangular, and its form and utility have been described in previous studies(Shakya & Bajracharya, 2015). For the construction of the building, no land change has been done. Aside from focusing on environmentally friendly building materials, Matoghar's main feature following the completion of the project was rammed earth. The aesthetic purpose was also a consideration. The structure has also been referred to be an autonomous structure because no problems were encountered throughout the blockad. The structure was created using passive design methods. The living room bedrooms are placed in the south, and the kitchen, toilets, laundry, and study room have been kept towards the north. Between April and mid -September, the overhang on the southern side helps to keep the summer direct sunlight at bay. Cross ventilation is made possible by the structure. Because the groundwater table is high, there is no concern with recharge.(See Annex 4 for site plan)



Expansion joint

Expansion joint

1. Entrance
2. Living/Dining
3. Terrace
4. Bedroom
5. Master bedroom
6. Walk in closet
7. Bathroom
8. Study
9. Laundry
10. W.C
11. Kitchen
12. Store
13. Utility

Figure 3.39 Plan of Matoghar

Table 3.4 Description of Matoghar

House Owner	:	Mr. Hemendra Bohra
Area	:	2500 Sq.ft
Cost	:	Rs 1,00,00,000.00
% Cost of green building features	:	19.89%
Building Type	:	Residential
Building Shape	:	Rectangular
Number of Rooms	:	13
Embodied Energy	:	371,473.55 MJ
Carbon Emission	:	49,062.51 kg
Sustainable Building Rating (SBR)	:	127(Ranked first)

The primary building materials used during the construction of the Matoghar were rammed earth, sun-dried brick, stone, bamboo, Styrofoam, glass wool, linseed oil, etc. The project took 1.5 years to complete in all, with a lot of trial and error along the way. The foundation was built of stone with a maximum depth of 2' and a 6' coat of bitumen to avoid the cold. Then, for reinforcement, vertical rebars were used. To avoid the effects of the water, 15% of the cement was mixed with mud. As a result, following completion, the building required minimal interior maintenance. To prevent water damage on the north side of the structure, the wall was covered with linseed oil. The structure is made up of 85 percent local mud, 8% red mud, and 7-8 percent aggregates. The outer walls are 18" thick, while the internal walls are only 4". Linseed oil is used to finish the flooring in the structure. A total of 10% of the floor space is covered by double panel windows. Silicon is used to keep the air gap between the walls and the window as small as possible. The south-facing walls have big windows to allow sun inside the building for lighting and heating, while the north-facing walls have small windows to resist cold wind. An aluminum sheet and a 2"x2" pinewood purlin supported the gable roof. The roof was designed with a reflecting surface to prevent heat from CGI from entering the structure. Bamboo truss is made of bamboo truss that has been treated to prevent termite damage. The energy-saving equipment includes solar photovoltaic panels and solar water heaters. The structure has 2kw solar panels and a 3000L water tank. The use of passive design principles in the structure allows it to receive an abundance of natural light and the use of double-glazed window help to insulate the external noise to some extent. During the night, though, led lights are employed. Furthermore, grey water is recycled.

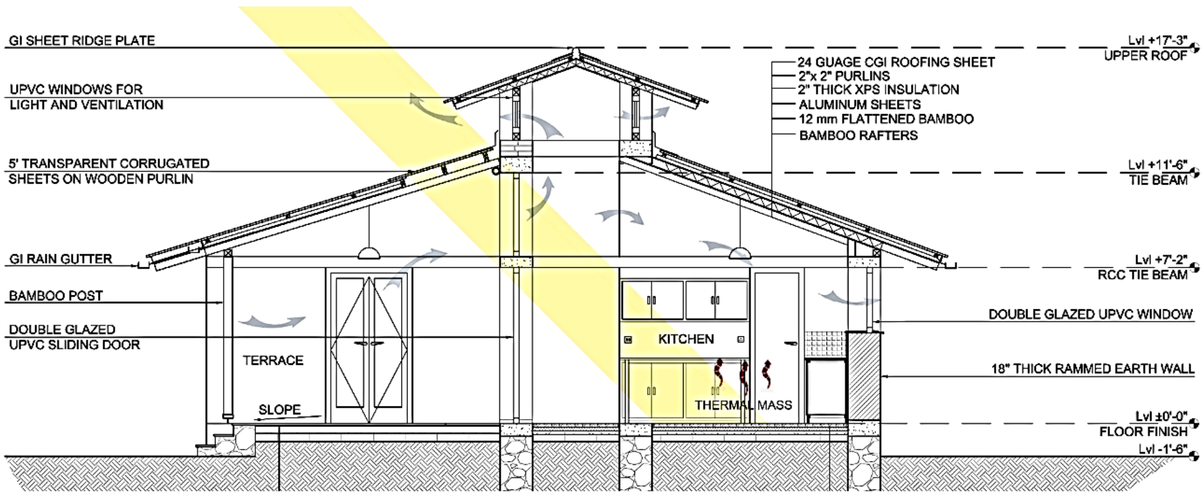


Figure 3.40 Section of Matoghar

Source:(Thapa, 2020)

The section details provide more insight into the thickness of the materials used for construction, as shown in the figure. The obtained data and comparison illustrate that Matoghar is an eco-friendly home with less carbon emission and embodied energy.

- Type VII

Double storied Rammed earth

A family's desire for a beautiful, environmentally conscious, and environmentally sustainable home inspired this initiative. After years of planning, the current occupants are very satisfied with the results. This project, like all others undertaken by Rammed Earth Solutions, is intended to be as environmentally benign as possible. This house's foundation was dug on-site, avoiding soil displacement and shipping expenses. Pollution-producing machinery is eliminated when the ground is hammered by hand. Bamboo is recognized as a highly sustainable (and strong, and beautiful material due to its quick development.

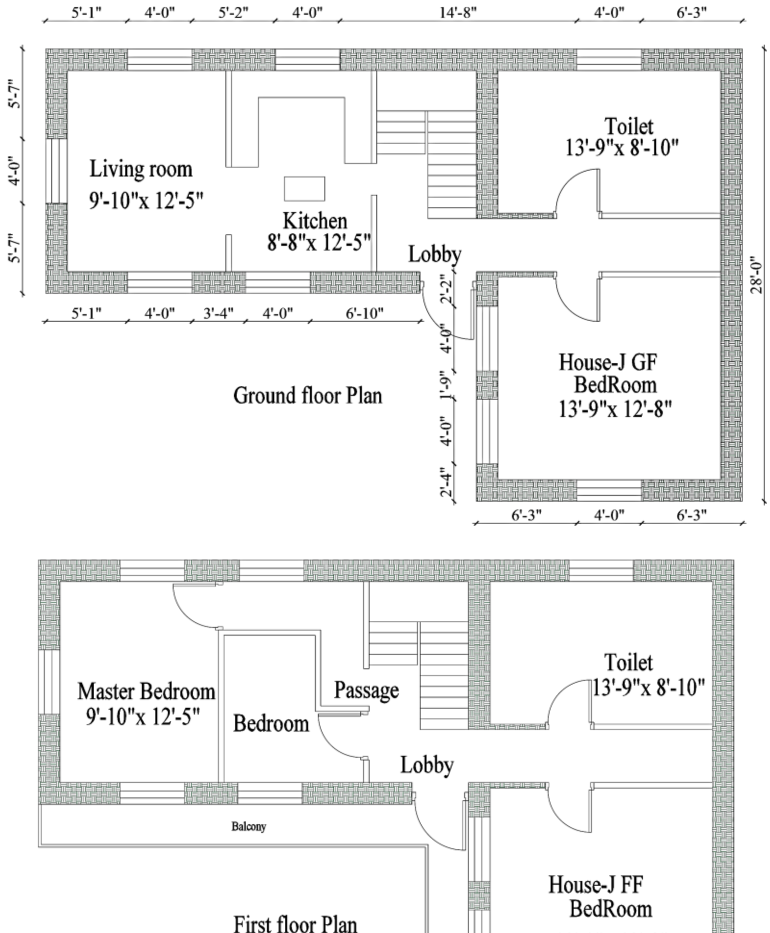


Figure 3.41 House J floor plans

Many aspects of this property are in accord with the spirit of environmental sensitivity: Solar panels and biogas provide an alternative, sustainable energy. Water collection and purification systems guarantee effective water use. The house's design (together with the inherent properties of rammed earth walls) keeps it warm in the winter and cool in the summer, reducing heating and cooling costs. This house also contains earthquake-resistant features. This project employed many people from a disadvantaged region of Nepal, and many of them have continued to work, creating a brighter future for themselves and their families. The building approach is sustainable and accessible to underprivileged communities because of its low costs and relative simplicity of construction. It's a technique that's been established and revitalized in this country, but it's mostly gone undetected, unappreciated, and unappreciated. Hundreds of people who had previously struggled to find meaningful work were employed as part of this effort, and the resulting company continues this tradition. Many of these workers were from tiny towns in the country. They believed that by providing jobs to people of different castes and economic backgrounds, these variables foster human solidarity and non-discrimination, therefore benefiting not just these individuals but also their communities. They have a better chance of becoming self-sufficient as a result of the skills they have learned. They are inherently integrating with the culture in a sustainable and useful way by bringing back skills that have been employed in this country. This project was groundbreaking at the time, not just in terms of construction technology, but also in terms of thinking. In terms of labor, dozens of people who would otherwise be jobless were hired, and the skills these workers acquired are culturally valuable.

The most appropriate technology in every given context is the most environmentally responsible one, according to this initiative. As a result, manual labor was preferred over machines whenever possible, such as when slamming the dirt. This results in more jobs, a broader skillset to learn, and less pollution. Wherever possible, the materials for this project were recycled (wood) or sustainable (bamboo). The earth used to build the walls was removed from the site, eliminating the necessity for (and expenses and pollutants associated with) bringing earth to the site, and thereby avoiding environmental damage. We believe that by demonstrating and debating these advantages, these objectives and the methods used to achieve them will become more widely accepted.

The house was built entirely by hand, using 60 percent local sand-mixed soil, 20 percent clay, 15 percent building aggregates, and 5% cement. House foundations are composed of stone, which provides a stable foundation on which to build the structure. Except for the transportation of a few raw materials that must be brought in from outside the local area, the construction process uses no energy or fuel. The structure's walls are 18 inches thick, ensuring the residence's structural integrity.

3.5m deep and 36” width size foundation is constructed of stone which provides a stable foundation on which to build the structure. Except for the transportation of a few raw materials that must be brought in from outside the local area, the construction process uses no energy or fuel. The structure's walls are 18 inches thick, ensuring the residence's structural integrity. The size of the tie beam is 1’x1’-8”. The walls of the ground floor of the building are constructed of rammed earth while the first floor walls consist of bamboo, wood dust, etc. At every interval of 2’, a single reinforcement of size 16mm is placed. A bamboo truss is constructed which holds the insulation material-XLP of 18mm thickness. Above the insulation material space for ventilation is left for removing the moisture content inside the building. UPVC is placed for the final covering of the roof. The building uses 50%

- <u>TYPE VIII</u>

Double storied RCC

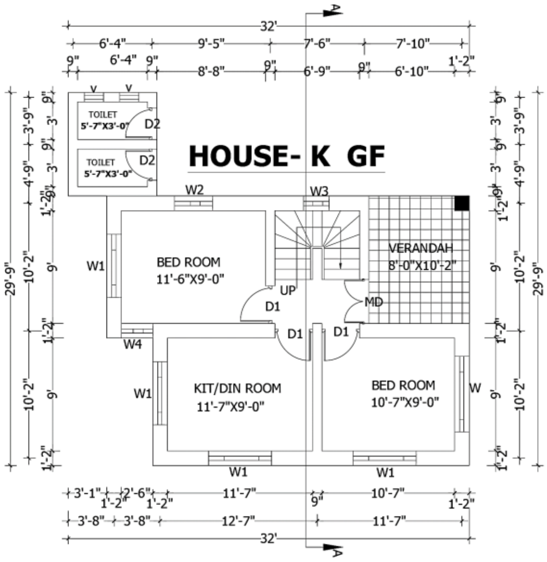


Figure 3.42 Ground floor Plan

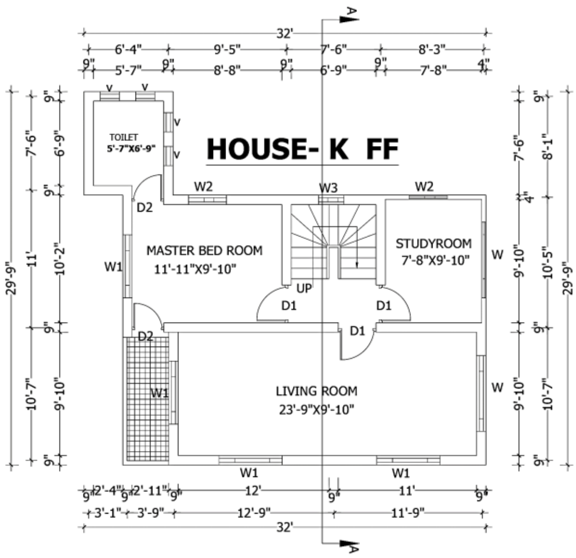


Figure 3.43 First floor Plan

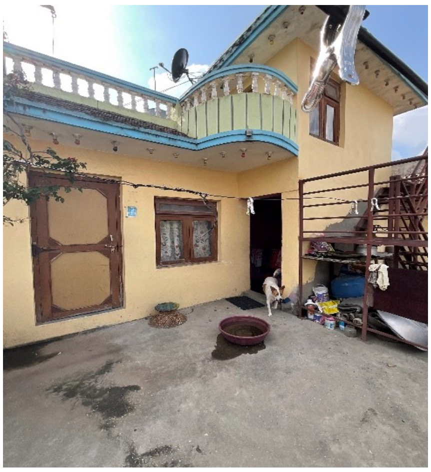
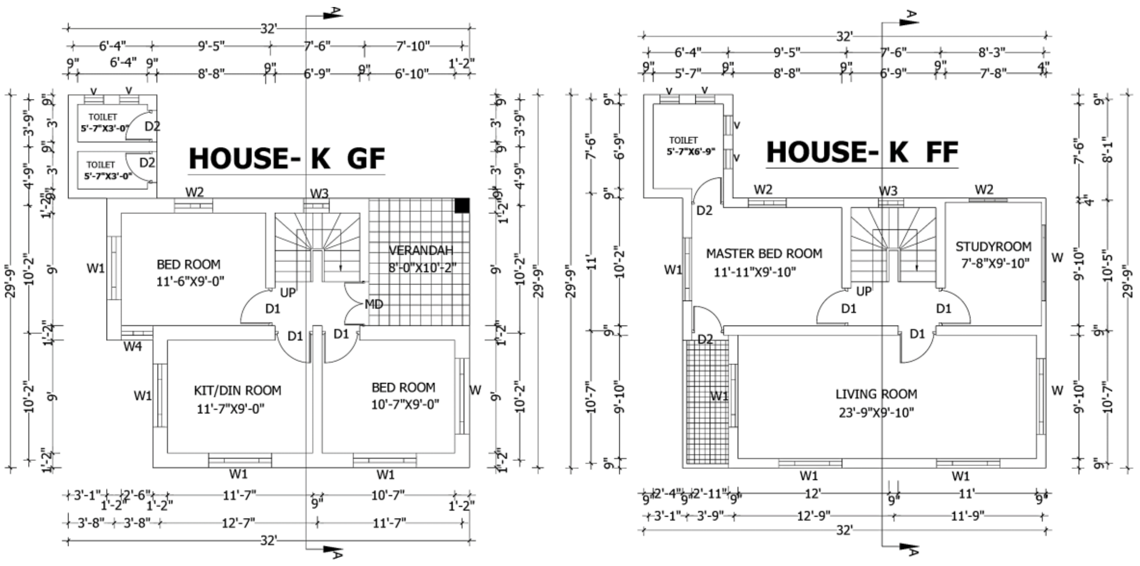


Figure 3.44 House-k outside

Figure 3.45 House-k living room



Source: (Case-study)

The chosen building for thermal performance evaluation is located in Tarakeshwor-8, Kathmandu. Eight people live in the building. It's a two-and-a-half-story load-bearing structure. The building's ground floor is made of brick and mud mortar, while the upper floors are made of Rcc and brick and cement mortar. There are nine rooms in the building, omitting the toilet and bathroom. The building's entire height, including the height of the parapet, is 32'-4". The ground and first floors are 8'-0" tall, while the second floor is 9'-0" tall.

3.3.4 Inherent Passive design of studied shelters

The study of architectural elements of individual houses is tabulated in annex A where different factors related to thermal performance like wall properties, form, orientation, roof, opening, etc are mentioned in detail. A brief summarization of mud and non-mud shelters according to their passive design in the hilly and mountainous region is shown below:

- <u>Mud-shelters</u>
  - Mountainous region
    - *Settlement pattern*

Basic factors that affect a region's architectural uniqueness include topography and climate. Settlements can be categorized into the slope of a hill and the valley due to variations in geographic position and layout; these categories show great adaptation to a landform via continual trial and error over thousands of years. Economic, religious, social, and ethnic aspects have an impact on how settlements emerge and grow, and Tibetans wish to incorporate these influences into their settlements.

The settlement of mud shelter considered in this study faces the Northeast direction which is opposite the nearest mountain 'Lamjung Kailas' and lake 'Kajin Sara' on the southwest side. The possibility of mountain cold wind from different directions is possible in this region as it is surrounded by mountains. The settlement exists on a large ledge between the mountainside and river gorge 'Marshyangdi'. 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 which is generally the wind direction.

- *Building form, orientation, stories, and internal space*

The houses are mostly rectangular shaped in which the longest side faces towards the south or south-west direction to obtain maximum solar radiation in the winter. The house itself has a compact floor plan where the internal spaces are used as a multi-purpose living area. The story height is generally 6-7' which is much lower than the standards around 2.8m.

Two storied buildings are larger where the ground floor is mostly used as cattle shed contrary to the explanation by Bodach et al. for Tamang houses. Traditional mud shelters are no more than 2 stories. The height of the lower and upper floors is the same. The interior of the Tamang house is almost an open space that is designated for cooking and eating as well as a living space. 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.

- *Wall and Opening*

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 resistant features to harsh cold weather. The internal spaces are partitioned with SMM walls or wooden planks. Some houses have internal walls covered with timber lathes.

There are very few small-sized windows facing the south to light and heat the rooms during the winter whereas in some houses there are no windows at all. Unlike other Tamang shelters found in Nepal, these structures don't have enough openings in any direction. The only opening is the doors which are also very small in size. The door shutters are used to close these openings entirely at night during cold seasons.

- *Roof, foundation, floor, ceiling*

The roofs in Odar village for vernacular structures are somewhat mixed. Some shelters have pitched CGI roof supported by timber structure which is mainly focused on summer rainfall and winter snow. Since flat roofs become heavier due to snow in winter, many residents are opting for CGI roofs. The overhangs of the pitched roof are 2 feet to save the structure from moisture due to monsoon rain. Some older houses have composite mud roofs where mud is placed on top of wood purlins and branches. These 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, the application of this method is on the verge of getting vanished. The floors are made up of wooden planks which is a better thermal insulator as timber is a bad conductor of heat and they are tightly placed with no gaps which indicates less thermal leakage. The foundation is mostly made up of stone and the plinth level is higher than the ground with floor insulation using wooden planks.

- Hilly region

The mud shelter which is considered for this study is all rammed earth shelters. They are designed on the advanced knowledge of passive design strategies to make the mud shelters resist the climatic conditions to achieve thermal comfort in the house.

- *Settlement pattern*

The studied mud shelters in the hilly regions are all isolated modern mud structures. These structures are situated where there is almost no influence of the neighboring structures on the ventilation and air movement. The settlement is distributed and beneficial for proper air movement as it is located in the warm temperate region. Both the rammed earth structures are located at the edge of the valley where there is the possibility of a cool breeze from the mountains located near the region. The structures are well designed such that it blocks the hot sunlight in summer and provides the sunlight to warm the internal areas in winter. The use of a water body in front of the house helps to reduce high heat extremities as it has its micro-climate.

- *Building form, orientation, stories, and internal space*

The building form is either rectangular or L-shaped which has its larger side facing towards the south to achieve better sunlight and heat in the winter. The house is in east to west direction. These modern mud shelters are either one or two storied buildings. The typical story height of these rammed earth structures is 2-2.5m which is still smaller than the standard height. The house has been separated into different rooms according to the requirements. However, they have been placed according to the passive design strategies. All the living rooms and bedrooms are placed on the southern face which can receive solar energy. In one of the studied buildings, the porch is used as a semi-open space whereas in another a balcony is provided in the southwest direction to achieve thermal comfort in the winter.

- *Wall and Opening*

Rammed soil is used to build the wall. At the external and internal partitions of the home, the walls are 18" thick. To withstand seismic shocks, the walls are strengthened at various levels. Mud plaster is used to give the walls an inside and outside smooth texture. While the north-facing walls have modest windows to fend off frigid winds, the south-facing sides have large windows to let sunlight into the structure for lighting and warmth. In some homes, there are no windows at all, while in others, there are very few little windows towards the south to light and heat the rooms during the winter. In one of the studied mud shelters, a lighter-weight bamboo construction with a second story that uses the Colombian Baharaque technology is also used.

- *Roof, foundation, floor, ceiling*

Both the studied mud shelters in the hilly region have sloped pitched roofs for proper channeling of rainwater to the drains. Use of modern passive heating designs using photovoltaic cells as solar water heating devices for the overhead tank but the natural passive designs are so effective that this feature has not been used. The roofing materials are insulated using natural products like bamboo strips or CGI insulated with Styrofoam. The exterior layer and purlin are separated by a gap, allowing hot air to move above. The foundation is made up of either SMM walls or reinforced concrete. The two-storied buildings are separated by floors made up of wooden planks and purlins.

- Non-mud shelters

- Mountainous region

- *Settlement pattern*

Most of the non-mud structures are isolated even in the mountainous region. Modern structures are considered modern in terms of material and form mostly. Even these structures have adopted some passive design strategies. These types of structures are also located around the same location as mud shelters in this study, however, the precise reason for making a separate house is only signified as a process of change in the house types in the locality. The so-called modern structures in the mountainous region of Nepal have a separate small pavement made up of concrete to reach their location.

- *Building form, orientation, stories, and internal space*

Common to the previous practices of mud shelters, the house is rectangular but longer is not face the southern side to attain passive heating in winter. Their orientation is haphazard. The modern houses have a generally higher number of stories than the mud shelters which creates a thermal buffer zone in the middle floors. The internal spaces are divided with wooden planks or partition walls but the passive design techniques have not been followed and service rooms like the kitchen have also been placed on the southern side. The structures with pitched roofs have separate attic space which separates the room from the CGI roof.

- *Wall and Opening*

The walls are either stone masonry with cement mortar or concrete shear walls. The number and size of the opening in the modern structures are more than the traditional mud structures. The houses are placed such that cross-ventilation can be made from the east-west direction. The external walls are 6"(shear wall)-18"(SMC) thick, whereas internal walls are thinner than the external walls. The walls on the lower levels are protected with wooden planks for better thermal performance. In addition, the walls are cement plastered on both sides for protecting the wall from the weather effects. The wall colors are white which reflects light and keeps the structures cool in summer whereas this same feature is a drawback in the winter. There are a greater number of windows and of bigger sizes which allows easy movement of air during summer. However, for cold regions, the windows are closed all the time and covered with thick blankets in the winter for better thermal performance as a passive strategy. This may be due to higher temperatures in the summer season in the non-mud shelters.

- *Roof, foundation, floor, ceiling*

The roofs are mostly pitched CGI sheets for SMC structures whereas, for shear wall structures, the roofs are concrete flat roofs. Both types of roofs are provided with sun shading using longer slabs(2') or longer eaves for protection from the sun during the summer season. Some roofs have long eaves in all directions. Since the summer season has had more rainfall in recent years as narrated by the residents, the height of the pitched roof is higher for proper channeling of water to the drains. The foundation is mostly SMC walls which are 1-2 feet higher than the ground level, the structures are safe from moisture damping. The houses are constructed with one side supported by a shorter foundation whereas a retaining wall is used to support the structure on the slope. For modern non-mud shelters also, the floors have wooden planks which is a good thermal insulator. The floors are supported by timber purlins.

- Hilly region
  - *Settlement pattern*

Most of the settlements in the hilly region of Nepal are located in the valley as it is easier to construct the structure in the flat lands of the valley. The urban areas are mostly dense with small roads and gaps between the shelters which is due to the lack of available land owned by individuals compared to the demands of the housing. Since the hilly region of Nepal has a warm temperate climate, the urban areas are mostly dense where there is a lack of sunlight on the lower floor areas whereas in sub-urban areas the houses have more space between each other.

  - *Building form, orientation, stories, and internal space*

The building form is according to the shape of the land owned by the owner of the land area is very small. If the land area is big enough, the form is usually rectangular. The orientation and internal spaces are kept concerning the recommendations of the culture, e.g. VaastuShastra. Since the requirement for living space is high, the number of stories is high, more than 2 floors. In the hilly region, the internal space arrangement is such that living and bedrooms are kept on the southern side and service rooms like kitchen, dining, and staircase are placed on the other side. The floor height is standard around 2.8m which is necessary for proper air circulation in the war temperate climate regions.

  - *Wall and Opening*

The walls are made up of burnt clay mortared bricks which are cement plastered on both sides. Typically, the outer walls of a home are 9 inches thick, while the inside partitions are 5 inches thick. There are more openings and ventilations provided in the modern structures in the hilly region than in the modern structures of the mountain region for proper movement of air during the summer. The opening sizes are medium to large and uniform for most of the rooms. The windows are closed and covered with clothes for better thermal performance in winter. The windows cover nearly 7% of the total floor area. Some houses use wall putty which is a fine powder made of white cement which is mixed with water & other additives to create a solution that is applied to the wall.

  - *Roof, foundation, floor, ceiling*

The roof is usually flat which is generally used as a terrace that can be used for sunbathing in winter whereas many houses have temporary shades for protection from the sun in summer. The foundation is also RCC and the floor is concrete slabs. General houses do not have floor insulation but carpets are used to increase thermal comfort on the floor. Some houses have false ceilings which are used with ventilation for better thermal performance and air circulation. In general, the houses do not have many implemented passive design strategies in modern non-mud shelters.

CHAPTER 4: RESULT AND ANALYSIS

4.1 Thermal measurements

The temperatures were taken 3 times at 7 AM, 1 PM, and 8 PM every day for 15 days consecutively during the field experiment. As the number of equipment was limited, the measurements of the mountainous region were done before measurements in the hilly region to obtain the temperatures close to the winter period. The temperatures of the houses in the mountain were measured in the transition period which was closer to winter than summer, whereas the temperatures of houses in the hilly region were taken in the period closer to the summer. The naming of the houses, for example, shelter I-A indicates mud house A which is a single-storied SMM structure with a mud roof.

4.1.1 Variation in recorded temperatures for 15 days

- <u>Mud shelters in the mountainous region</u>

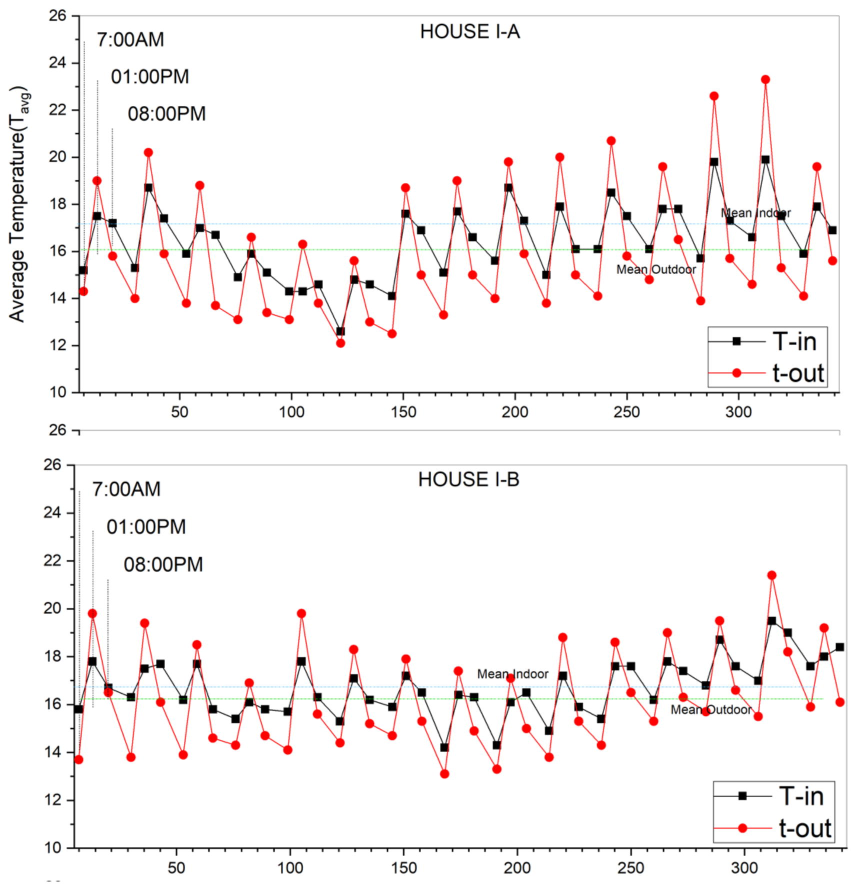


Figure 4.1 15-day temperature record for shelter A and B in mountain

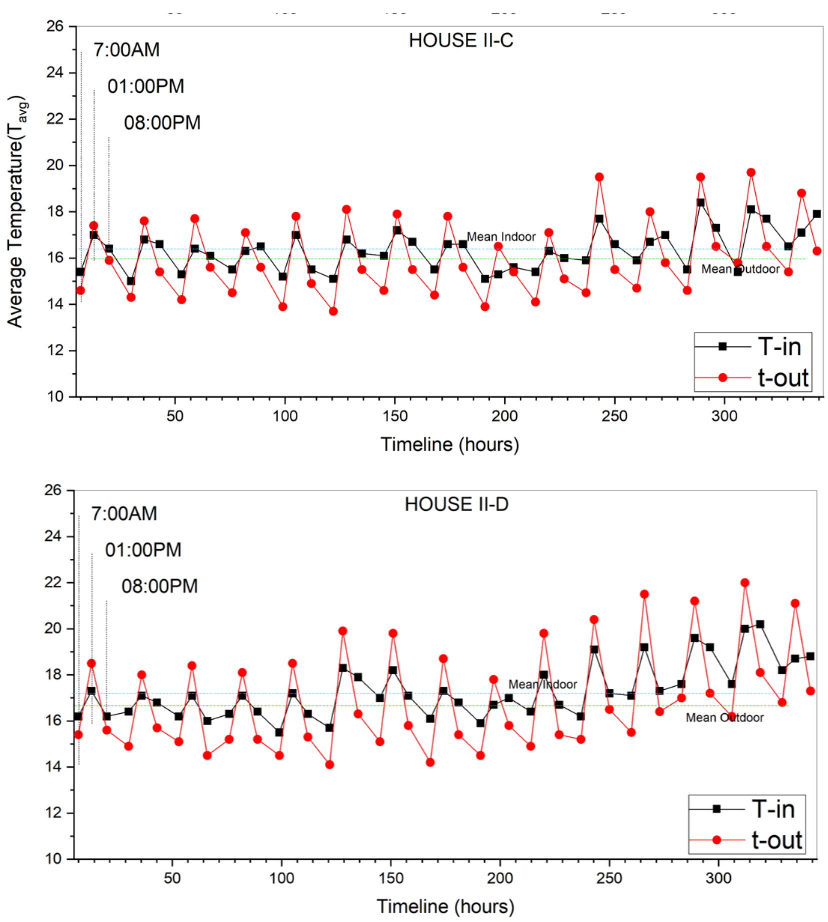


Figure 4.2 15-day temperature record for shelter C and D in mountain

The variation in temperature for 15 days is shown for mud houses of types I and II. Therefore, the considered houses for 15-day temperature analysis are I-A, I-B, II-C, and II-D respectively. 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.

House Type	Avg. In. Temp.	Avg. Out. Temp.	Avg. Difference
I-A	16.48	16.0	0.48
I-B	16.76	16.3	0.46
II-C	16.43	16	0.43
II-D	17.34	16.9	0.44

The structure performs well as the average indoor temperatures are always greater than the average outdoor temperatures of non-mud shelters which show its resilience toward cold temperatures. In addition, it allows more 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 the table below: 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 of 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.

- Non-mud shelters in Mountainous Region

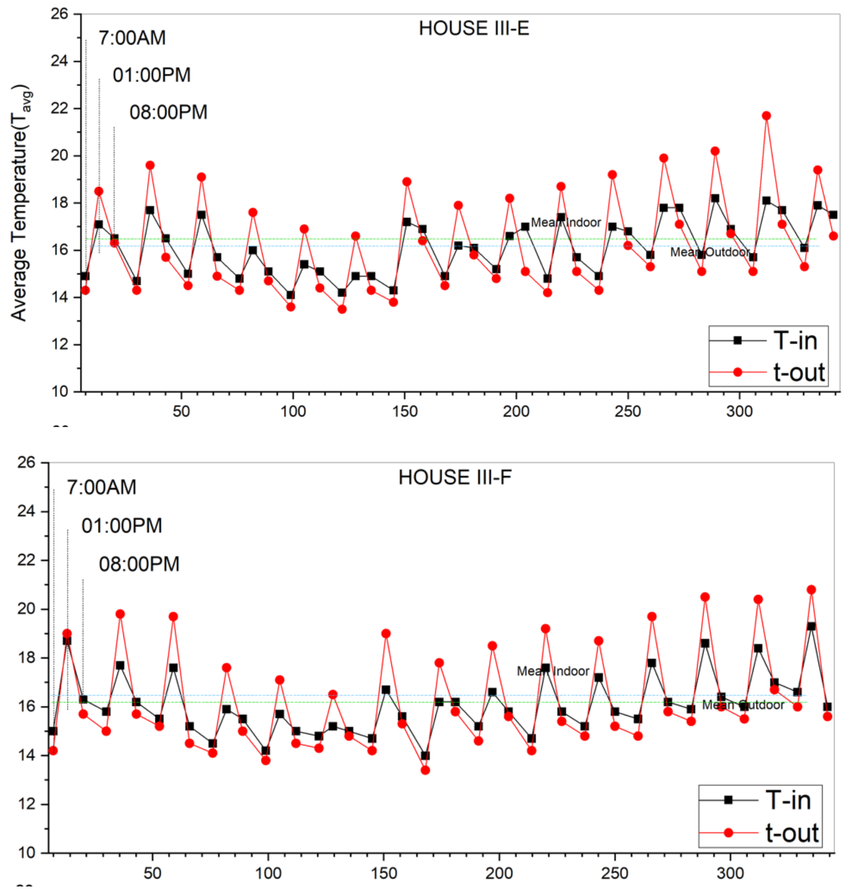
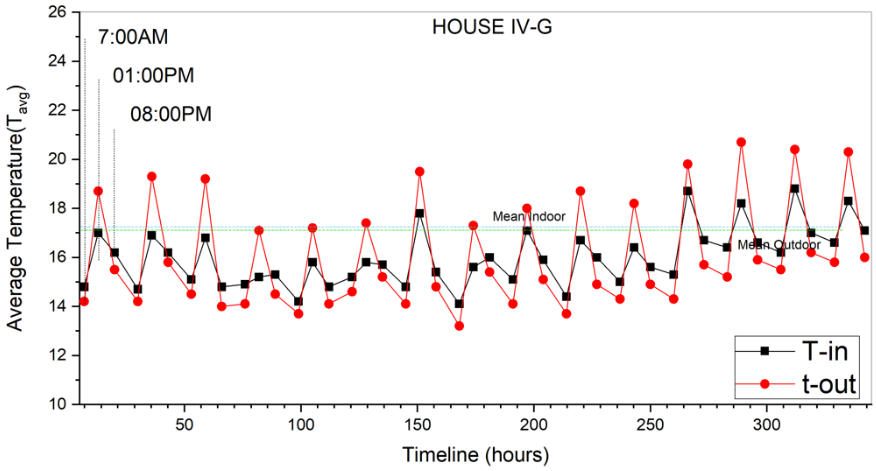


Figure 4.3 15-day temperature record for shelter E and F in moutain



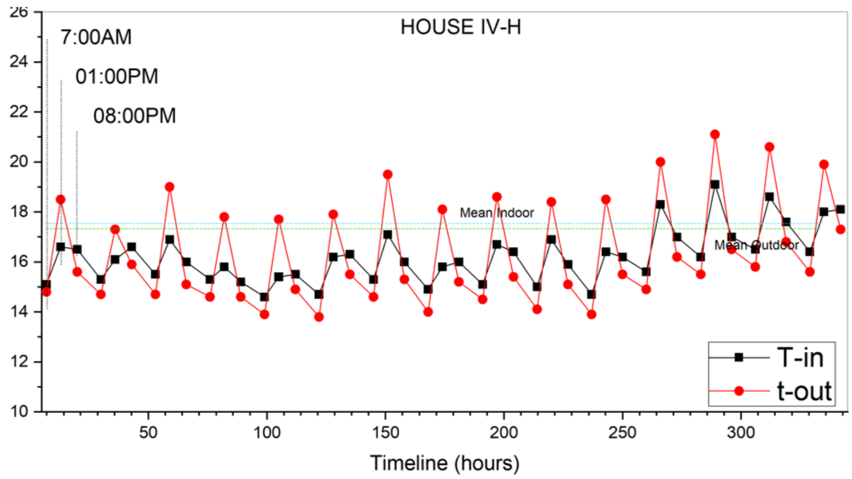


Figure 4.4 15-day temperature record for shelter G and H in mountain

The indoor and outdoor temperatures for 15 days show that the fluctuations are more prominent than the temperatures in the mud shelters. 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:

House Type	Avg. In. Temp.	Avg. Out. Temp.	Avg. Difference
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

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.

- <u>Mud Shelters in the Hilly Regn</u>

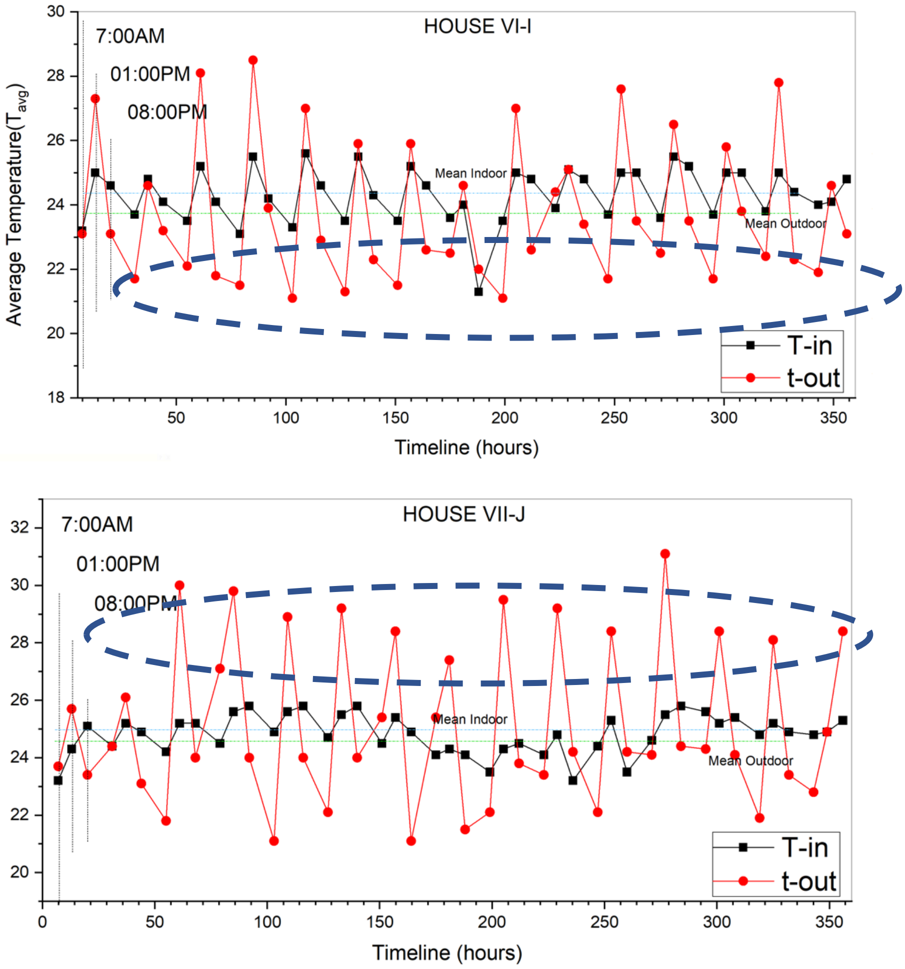


Figure 4.5 15-day temperature record for shelter I and J in hilly

The mud shelters considered in this study are house I (single-storied) and house J (double-storied) modern rammed earth structures built with passive design strategies for decreasing the external use of direct energy in harsh climates. Both house I and house J have better thermal performance. The measurement shows that the thermal performance of House J is better than house I. However, the measurement of house J which is a 2-storied building was conducted on the eastern side of the ground floor while the measurement of house I which is a single-storied shelter was conducted on the southern side. The overall mean indoor and outdoor temperatures for 15 days between 7 AM to 8 PM are shown in the table below:

House Type	Avg. In. Temp.	Avg. Out. Temp.	Avg. Difference
VI-I	24.3	23.7	0.7
VII-J	24.8	25.6	- 0.8

The comparison between the two rammed earth houses shows that the temperature difference between single and double-storied rammed earth houses is reversed as one is hotter and another one is cooler than the outside temperature. While comparing the extreme temperature fluctuations, house I(Mato Ghar) has more temperature fluctuation in the minimum region whereas house J(Madan Acharya) has more fluctuation in the maximum region. Therefore, it can be said that modern rammed earth performs well in both cases as it doesn't allow the temperature to rise or fall quickly to extreme temperatures. The primary reason for this better thermal performance is the passive design strategy where thermally superior walls with large widths are used. Other passive designs that have been included in these common houses are houses facing the south, the use of parallel windows for cross-ventilation, etc.

- Non-mud shelter in the Hilly Region

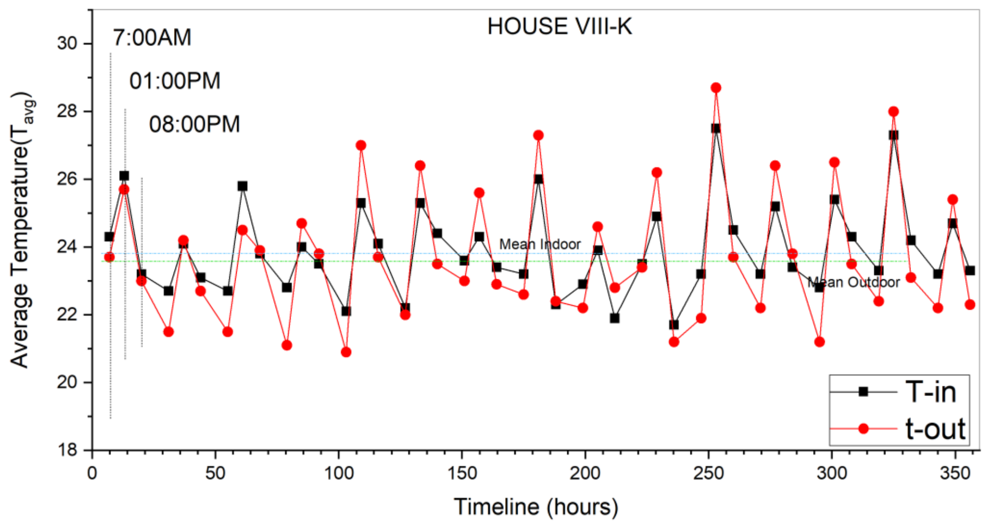


Figure 4.6 15-day temperature record for non- mud shelter in hilly

House Type	Avg. In. Temp.	Avg. Out. Temp.	Avg. Difference
VIII-k	24	23.7	0.3

The obtained 15-day indoor and outdoor temperature difference shows that non-mud shelter in the hilly region is better than the non-mud shelters found in the mountain region. The reasons may be due to the architectural design of structures as these types of modern structures are well suited for warm temperate rather than cold temperature climates. Even with the high thickness of external walls which is also one of the passive design methods for climate responsive design, the modern structures in the hilly region performed better which may be due to thermal leakage between the CGI roof and the external walls in a mountainous region. However, the non-mud shelters perform worse than both the modern rammed earth structures as well as the traditional SMM mud shelters.

After comparing all the results of 15-day average temperatures the thermal performance is such that the performance is in the order of rammed earth> Traditional SMM>Modern RCC in hilly > Modern RCC in Himalayan. This shows that such modern structures are unsuitable for providing thermal comfort in mountainous regions.

4.1.2 Humidity

- <u>Humidity in the mountainous region</u>

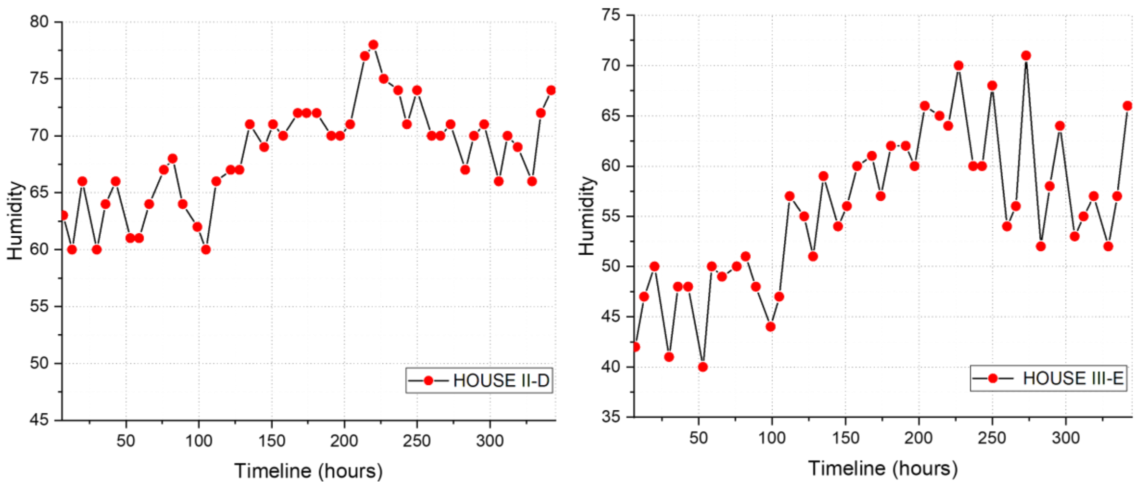


Figure 4.7 Humidity inside mud and concrete structures in a mountainous region

The ASHRAE guidelines recommend a relative humidity (RH) of 30 to 60 percent. Low humidity causes static electricity, dry skin and hair, increased susceptibility to colds and respiratory illness, and allows viruses and germs to thrive. We sweat more when humidity levels soar. 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 modern shelters in distinctive regions. In the mountainous regions, the humidity is more inside the mud shelters than in the concrete structures which may be caused due to the lack of ventilation provided in the mud shelters than in modern shelters. However, the humidity conditions are dry according to the respondent's survey which is shown in the survey section of this study.

- <u>Humidity in the Hilly region</u>

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. While comparing the humidity of the respective shelters, the humidity is more in rammed earth mud shelters in both conditions where the indoor temperature was higher or lower than the outdoor temperature. As all the houses are located in different parts of Kathmandu valley, the climatic conditions are more or less the same in these parts, hence the most plausible reason for the increase in humidity is the presence of a large water body near the house-in-house VI-I(Matoghar), whereas, for house VII-J(Narayan acharya's home), the measurements were taken at the ground floor which had compact internal spaces which can be seen on the plan of the structure.

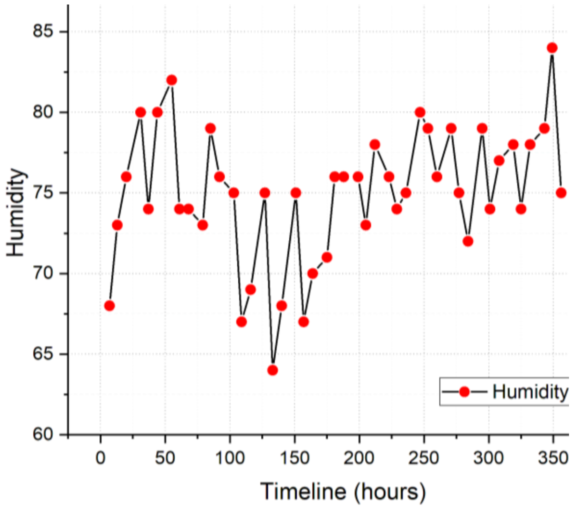


Figure 4.8 House VI-I

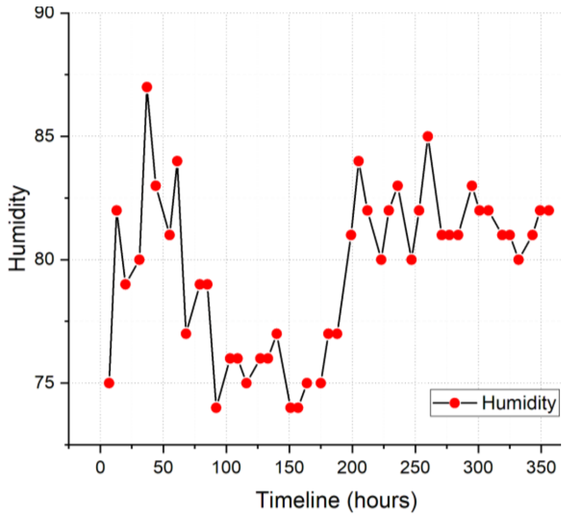


Figure 4.9 House VII-J

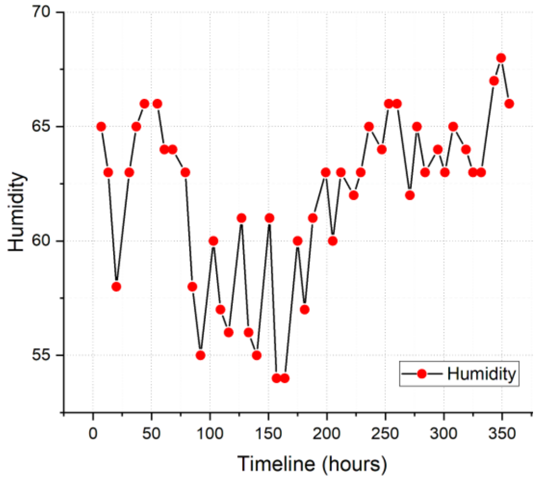


Figure 4.10 House VIII-K

4.1.3 PIT daily average temperatures

- Mud shelters in the mountainous region

PIT(point in time) daily average temperature is concerned with the mean of the point in time temperatures. Since all the graphical results could not be included in this section. Other graphical representations are included in Appendix A. These results indicate that the temperatures for single-storied and double-storied buildings are significantly different due to the direct contact with the ground which is usually cooler due to the moisture dampness from the ground. The temperature is higher in-house A due to the lack of ventilation while cooking in the morning and evening. Similar to the house A results, the house B results also have the same effect due to cooking in the enclosed environment which has altered the thermal conditions in the room where the temperatures were taken. Maximum temperature differences can be seen during the daytime when the inside temperatures are more stable than the outside temperature which fluctuates more than 2.5 degrees. While comparing the indoor to outdoor point-in-time measurements for mud shelters, it seems that SMM with mud plasters absorbs a considerable amount of energy from the environment during the afternoon period. Meanwhile, the decreasing temperature gradient in the afternoon is less inside the mud structures than the outside due to the high thermal mass of mud. The structures seem to be more intact than expected from the initial observations.

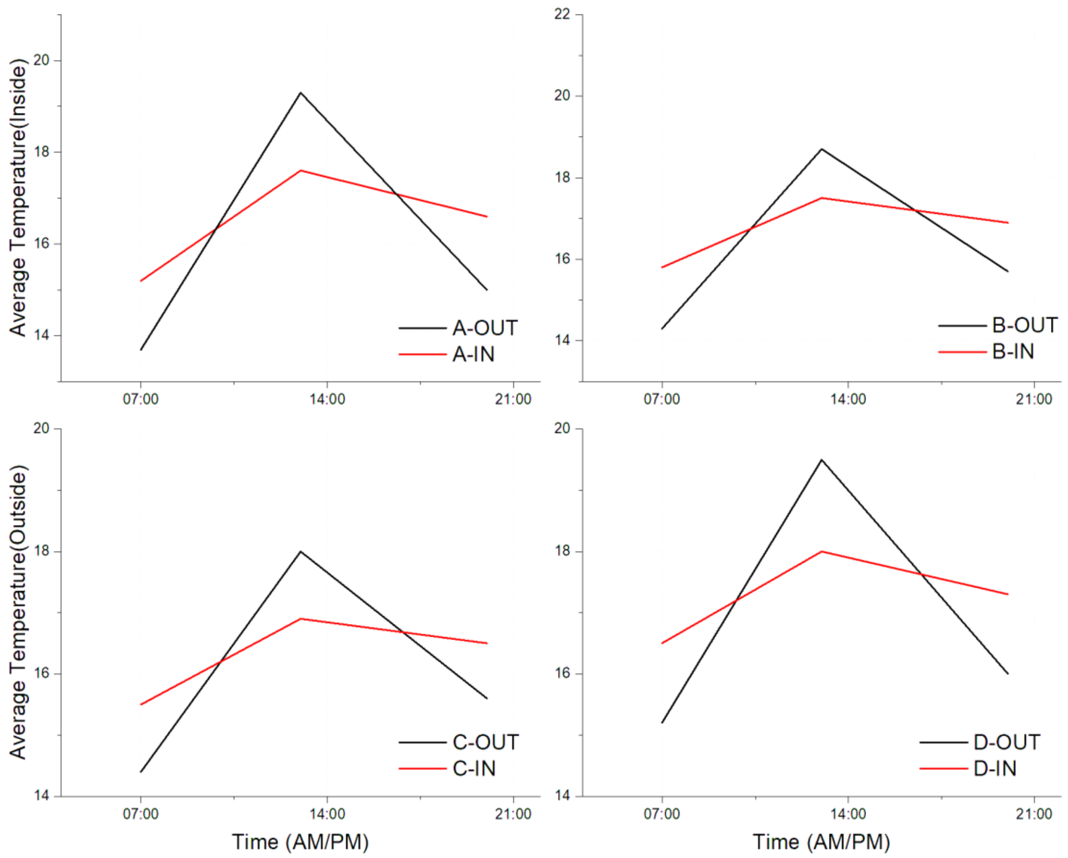


Figure 4.11 PIT average temperature of mud shelter in mountain

Since the temperatures were taken on the 1st floor in the double-storied mud shelter, the temperatures are larger in the double-storied structure. This also indicates that the floor level and its contact with the ground affect the thermal environment of the structure significantly. In addition, the influence of mud roofs is also seen as the temperatures are much higher on the 2nd floor which may also be due to the lack of frequency in which the ventilations are opened.

- <u>Non-mud shelters in the mountainous region</u>

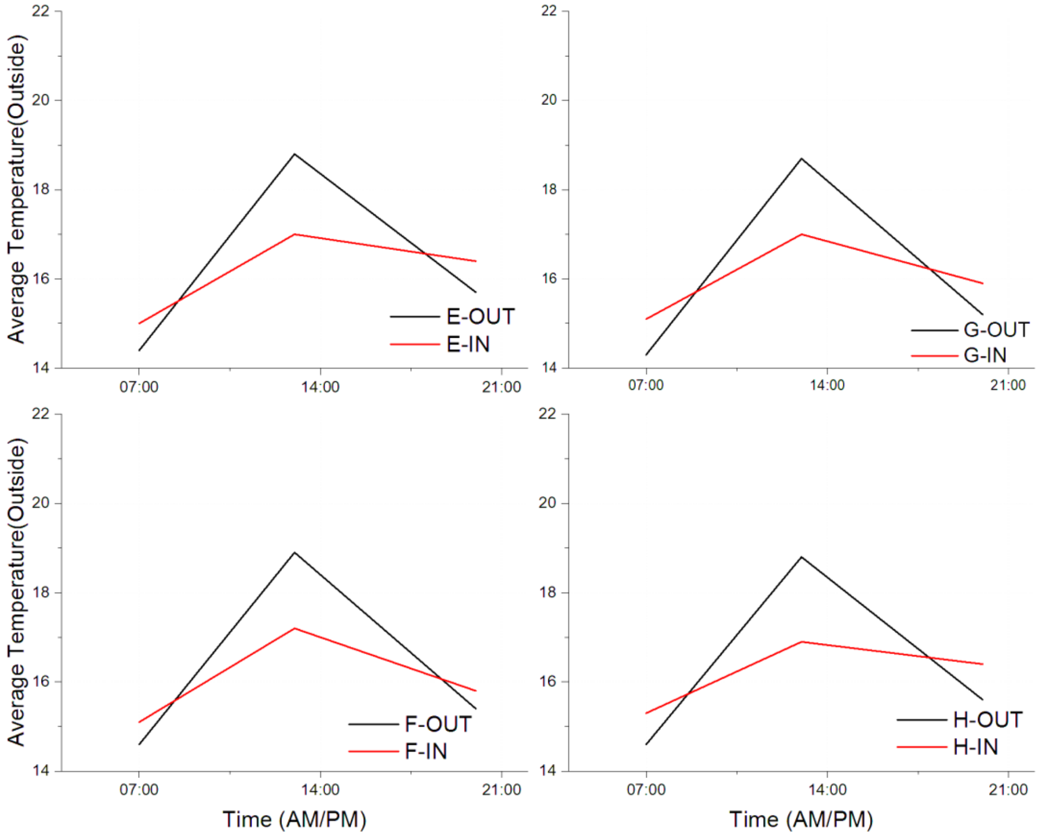


Figure 4.12 PIT average temperature of non-mud shelter in mountain

In a modern non-mud shelter, the ventilation area and the total number of ventilations around the structure are more and opened more frequently. Therefore, the inside temperatures are less than that in the mud shelters and are closer to the outside environment. Relatively, the indoor temperatures are less in the single-storied structure due to attachment to the ground than in the double-storied structure. Another plausible reason would be the low thermal performance of the wall itself as the wall is constructed with SMC (stone masonry with cement mortar) and plastered with cement. A comparatively better thermal performance can be seen clearly for mud shelters after comparing with the non-mud shelters in temperatures. Since the location of every house is near to each other, the outdoor temperature differences don't very much. As house C and house H are attached, their average temperature comparison shows that house C has higher control over the changing temperatures.

- <u>Mud shelters in the hilly region</u>

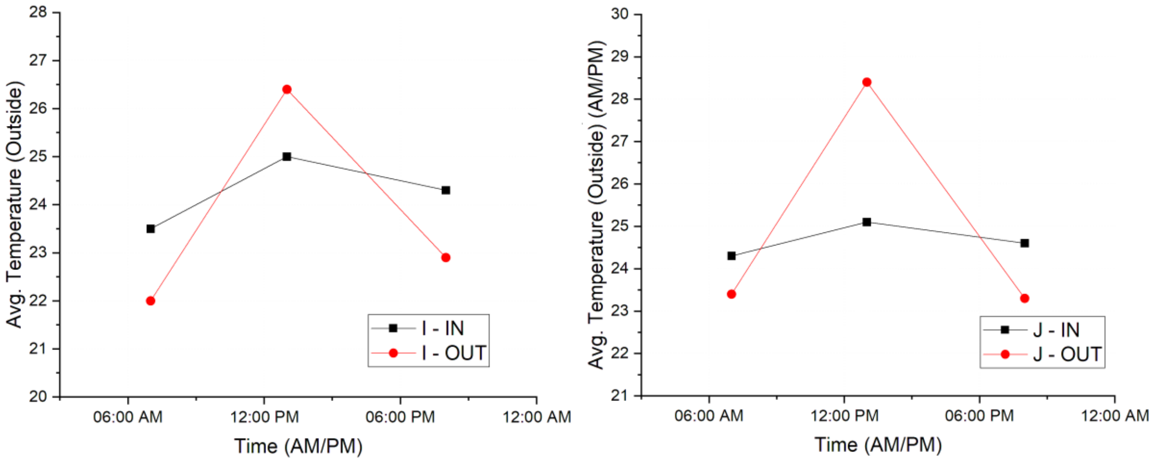


Figure 4.13 PIT average temperature of mud shelter in hilly

The rammed earth which has been chosen as a mud shelter for study performs well in maintaining the stability of the temperature as shown by the high-temperature differences. The time lag for House J is better than the time lag for house I which may be due to the thickness of the wall envelope in addition to the measurement of house J being taken on the ground floor. House I has more open plans than house J, and the height of the floor is also more in house I. Since the temperatures were taken during the period closer to summer, house J seems cooler than the house I.

- <u>Non-mud shelter in the hilly region</u>

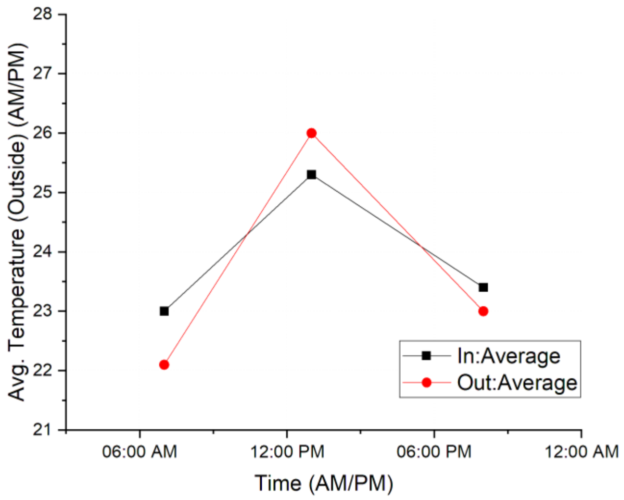


Figure 4.14 PIT average temperature of non-mud shelter in hilly

House K which is a modern concrete structure is worse than the mud shelters and the point-in-time temperatures show that the temperature fluctuations almost follow the outside temperatures and the time lag is also short. The structure is however better in maintaining the temperature in the morning which soars to a higher degree in the daytime. The structure has a lower time lag than the rammed earth structure and the primary reason may be due to the wall material which is BMC (brick masonry with cement mortar) which has a lower thermal capacity than the rammed earth structure. Another reason would be the placement of the opening windows as the structure is located in an open area.

4.1.4 PIT daily average temperatures differences

- Mud & non-mud shelters in the mountainous region

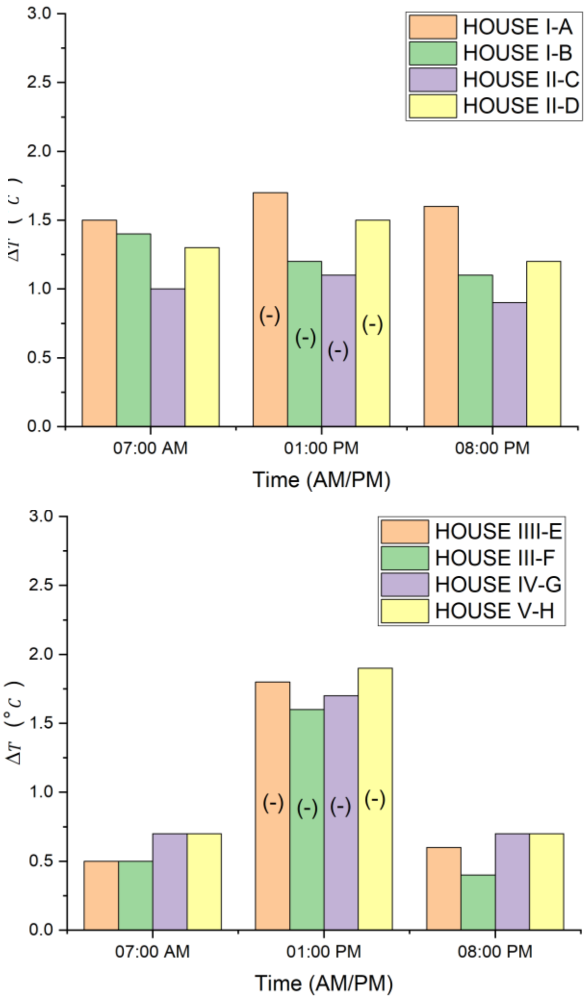


Figure 4.15 PIT daily average temperature differences of shelters in mountain

For the mud shelters, the temperature differences are much more than in the non-mud shelters due to the lack of ventilation as well as the low thermal transmittance of the mud shelter. The extra layer of coating both the inside and outside face with local mud allows the stable temperature in mud shelters. The difference is more prominent in the night time than the day time due to many reasons like cooking at the night time. All the temperature differences at different times are greater than the difference observed in the non-mud shelters. The differences are much more prominent in the morning and evening time than in the daytime, which implies that SMM mud shelters are not as good for increasing temperatures as for decreasing temperatures.

The non-mud shelters in mountainous regions are more vulnerable to temperature changes and the temperature changes are less than the mud shelters. Therefore, these structures are more susceptible to temperature changes in the colder climates which may be due to the construction materials and the construction process, The construction material is mainly used in concrete and cement plaster whereas the construction process may have caused some air leakages which may lead to the strong fluctuations along with the outside temperatures.

- <u>Mud & non-shelters in the hilly region</u>

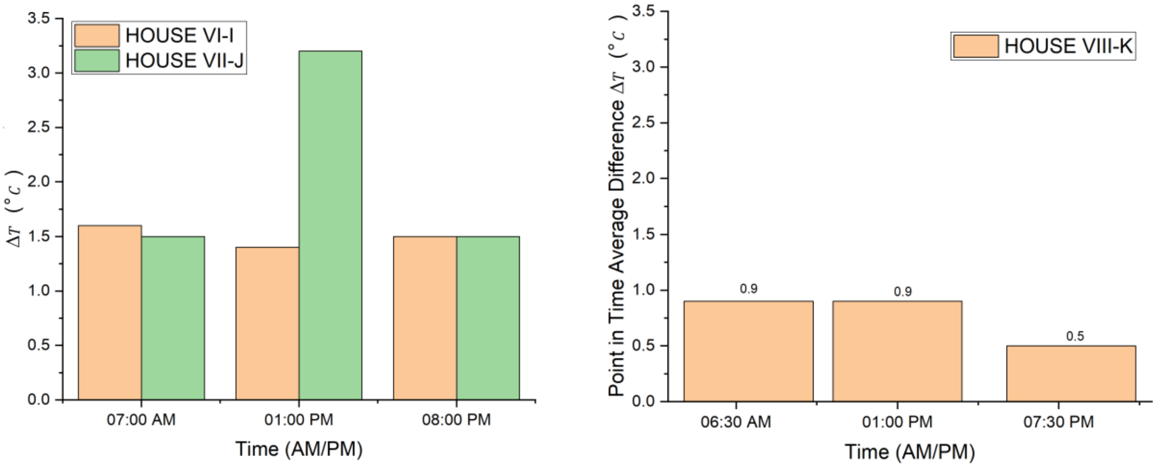


Figure 4.16 PIT daily average temperature differences of shelters in hilly

The temperature differences are absolute; hence it is independent of whether the temperature was cooler or warmer than the outside temperature. The temperature differences between single-storied and double-storied rammed mud shelters showed that double-storied mud shelters perform much better in the daytime than in the morning and evening hours. The results for morning and evening are similar for both storied houses. Comparing the results of the rammed mud shelter with modern concrete structure, the rammed earth structure outperforms at every time of the day which may be due to the adoption of passive design strategies in the modern rammed earth structures. Thermal transmittance of mud shelter.

4.1.5 Thermal transmittance of different houses

- <u>Rammed earth-(Mato Ghar)</u>

  - For Wall:

Wall thickness = 18” = 450mm

External Surface Conductance(f_i) = 812$W/m^2 °C$

Internal Surface Conductance(f_o) = $W/m^2 °C$

Rammed Earth Conductivity = $W/m^2°C$

The thermal resistance of the wall(R_1) = 0.45/1.25 = 0.35

Also assuming 1" thick plaster on both sides.

The conductivity of earthen plaster = 0.65 $W/m^2°C$

The thermal resistance of plaster(R_2) = $2 \times \frac{0.25}{0.65} = 0.0769$

U-value of wall = $\left(\frac{1}{f_o} + \frac{1}{f_i}\right)$ +$(R_1 + R_2) = \left(\frac{1}{8.12} + \frac{1}{10}\right)$ +$(0.36 + 0.0769) = 0.54 \frac{W}{m^2}°C$

- For window:

Double glazed aluminium window panel width air cavity(conductivity) = 2.5W/mk

Cavity(Conductivity) =2.50W/mK

Thickness =10mm(used in site)

Glass(standard) = 10mm = 0.1

$\frac{1}{f_o}$ =2.32

The thermal resistance of glass = $\frac{0.4}{1.38} \times 2 = 0.57$

The thermal resistance of the air cavity = $\frac{0.1}{2.5}$

U-value = $\left(\frac{1}{f_o} + \frac{1}{f_i}\right)$ +$(R_1 + R_2) = \left(\frac{1}{8.12} + \frac{1}{10}\right)$ +$(0.05 + 0.04) = 0.31$

- <u>Thermal transmittance of houses in the mountainous region</u>

- For Wall:

	Thickness			**Thermal Conductivity**					**Surface conductance**		
Type	Mud plaster	Cement plaster	stone wall	mud W/m°C	stone W/m °C	Concrete mixer W/m°C	Brick work W/m °C	Cem-ent plaster W/m °C	Internal (fi)	Exter-nal (fo)	U-value $W/m^2°C$
House A	0.0762	-	0.3048	1.25	0.25	-	-	-	8.12	10	0.6
House B	0.0762	-	0.5588	1.25	0.25	-	-	-	8.12	10	**0.5**
House C	0.0762	-	0.3048	1.25	0.25	-	-	-	8.12	10	0.63

	Thickness			Thermal Conductivity					Surface conductance		
House D	0.0762	-	0.5588	1.25	0.25	-	-	-	8.12	10	**0.5**
House E	-	0.0508	0.3556	1.25	0.25	-	-	-	8.12	10	0.56
House F	-	0.0508	0.1016	-	-	2.3	-	0.72	8.12	10	2.44
House G	-	0.508	0.3556	1.25	0.25	-	-	-	8.12	10	0.56
House H	-	0.3055	0.2286	-	-	-	1.5	0.72	8.12	10	2.21

The two houses with the lowest U-values out of the eight homes are Houses B and D. The remaining two mud houses, A and C, are not significantly more valuable than B and D. While Dwellings F and H have extremely high u-values, Houses E and G have values that are similar to traditional houses. According to the aforementioned statistics, slate has the lowest thermal conductivity rating. Slate is therefore more effective in insulating because temperature dispersion is less effective in slate.

- For Roof:

The U-values of houses A, B, C, and D are close to one another and differ little from one another. Even though they are both made of the same material, the difference in roof thickness is what causes the least amount of variation in the u-Values between them. While F and H have values greater than mud houses but less than E and G, Houses E and G have the highest U-values. Despite having different numbers of stories, the use of CGI for roofing gives houses E and G their highest value.

	Thickness	**Thermal Conductivity**		**Surface conductance**		
Type	roof(L1)	cement plaster(L2)	mud (W/m°C)	Internal (fi)	External fo)	U-value $(W/m^{2}°C)$
House A	0.3	-	1.25	8.12	10	2.15
House B	0.2032	-	1.25	8.12	10	2.59
House C	0.254	-	1.25	8.12	10	2.34
House D	0.254	-	1.25	8.12	10	2.34
House E	-	-	-	-	-	7.95
House F	-	-	-	-	-	3.35
House G	-	-	-	-	-	7.95

	Thickness	Thermal Conductivity		Surface conductance		
House H	-	-	-	-	-	3.35

- For Window:

	U-Value ($W/m^2°C$)			
Type	North window	South window	East window	West window
House A	-	-	-	-
House B	-	-	-	-
House C	-	-	-	-
House D	-	-	-	-
House E	5.67	-	5.67	4.48
House F	5.67	4.48	5.67	-
House G	-	-	-	4.48
House H	-	-	-	4.48

The thermal performance is improved by a reduced U-value. The mud houses have a 0 u-value because they lack windows. In contrast to mud dwellings, the non-mud structure's opening has a higher U-value. As a result, mud buildings have better thermal performance than non-mud structures.

4.2 Thermal comfort survey

4.2.1 Mountainous region

- <u>Profile of the sample</u>

Table 4.1:Profile of the sample

Age * Gender Crosstabulation			
	Gender		
	Male	Female	Total
15-25	4	1	5
26-40	7	4	11
41-60	8	3	11
Above 60	8	1	9
Total	27	9	36

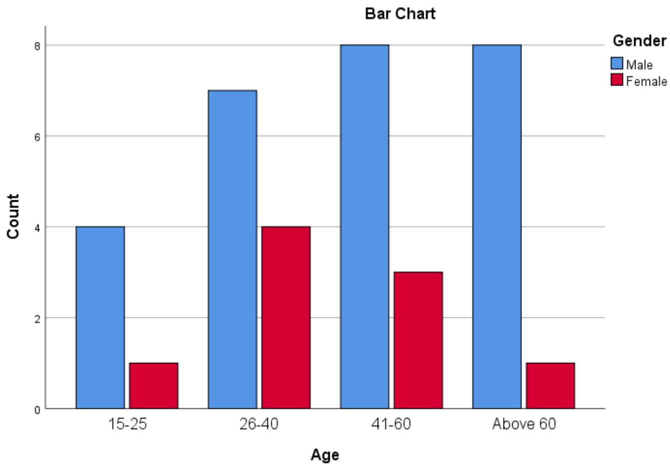


Figure 4.17 Profile of the respondents in mountain

36 people volunteered to take part in the survey. The demographic makeup of the sample is shown in Table 7. Respondents were assigned to various tasks throughout the facility, with the majority of the sample (30.5 percent) focusing on the 26-40 and 41-60 age range. The information gathered from measurements and questionnaire surveys were first entered into spreadsheets and then analyzed using the Statistical Package for Social Sciences (SPSS). The subjective evaluation was done using NVivo software for pattern recognition and finding the similarity in answers. To undertake the thermal assessment, the findings of subjective (point-in-time surveys) and objective evaluations (long-term and point-in-time measurements) were compared.

- <u>Thermal Responses</u>

- Modified Thermal sensation Votes

Table 4.2:mTSV of different age groups

Count		Thermal Sensation Vote(TSV)				
		Cold	Slightly Cool	Neutral	Total	%
Age	**15-25**	3	2	0	5	13.88
	26-40	5	5	1	11	30.55
	41-60	6	4	1	11	30.55
	Above 60	2	5	2	9	25
Total		16	16	4	36	
Percentage(%)		44.44	44.44	11.11		

The general thermal sensation for the respondents was more for cold sensation in the entire 5-point scale used in the questionnaire. The overall temperature both inside and outside the house is cold according to the survey. The highest number of vote for cold sensation reached 47% followed by slightly cool with 27.7%. Most of the residents were from the young and middle-aged group who generally can resist cold temperatures. However, even these age groups are indicating signs of low temperature which can be a problem for the productivity of the area.

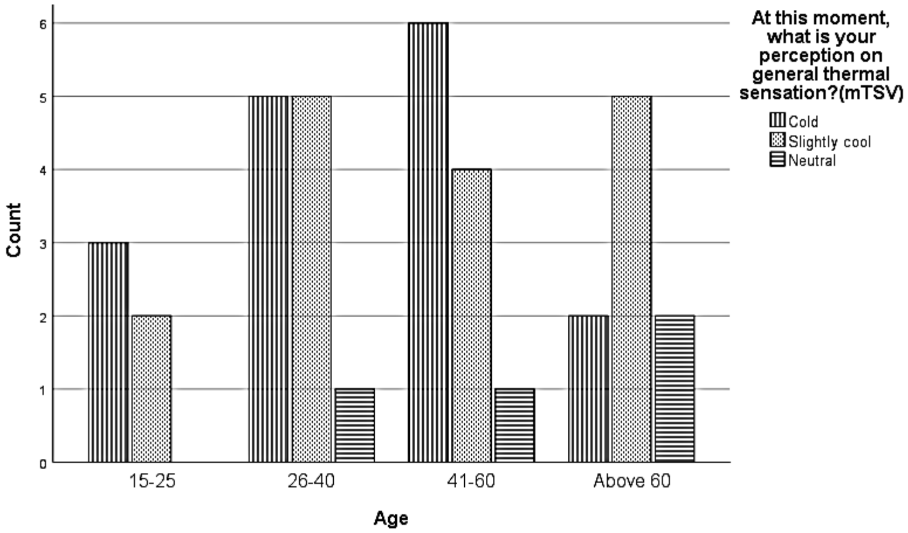


Figure 4.18:TSV of number of respondents for different age groups

- Current Thermal preference

Table 4.3:Thermal Preference of different age groups

		Thermal Preference(TP)			Total	Percentage
		Much Warmer	Bit Warmer	No change		
Age	**15-25**	2	2	1	5	13.88
	26-40	5	4	2	11	30.55
	41-60	3	7	1	11	30.55
	Above 60	1	5	3	9	25
Total		11	18	7	36	
Percentage		30.55	50	19.44		

Most of the residents living in the mountainous region prefer a bit warmer thermal condition as they are mostly feeling very cold in thermal sensation. The plausible reason might be the cold season in which the questionnaire survey is being conducted in which the respondents prefer a bit warmer indicating that they can adjust to the thermal conditions. Respondents from all the age groups indicated bit warmer conditions. The age group above 60 preferred highest number of votes among other age groups for no change conditions. This shows that the old age people had adapted the climatic condition of the specific place.

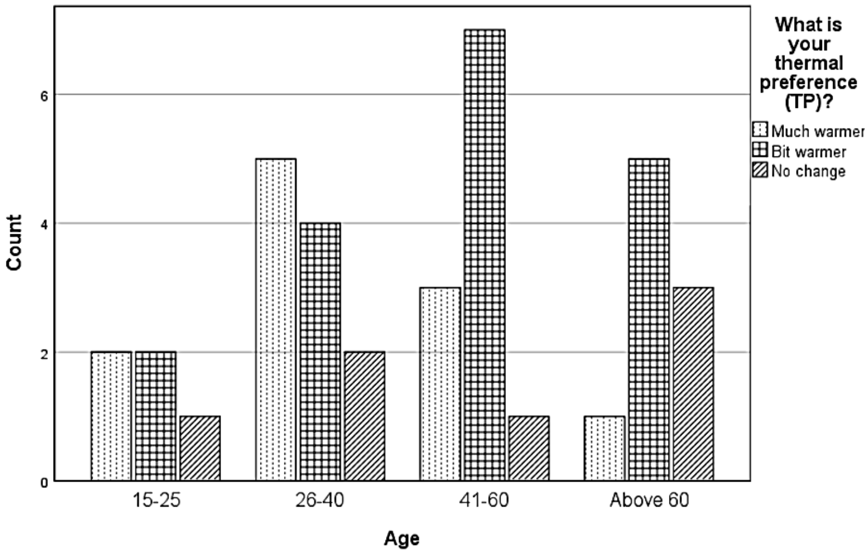


Figure 4.19: Thermal preference for different age groups in mountain

- Thermal Satisfaction

Table 4.4:Thermal Satisfaction of respondents based on activity status

	Thermal Satisfaction			**Total**	**%**
Activity status	**Moderately satisfied**	**Slight satisfied**	**Slight unsatisfied**		
Sitting	0	1	0	1	2.7
House cleaning	2	0	0	2	5.5
Lying/Sleeping	1	3	0	4	11.11
Occasionally walk	4	9	1	14	38.8
Others	0	1	0	1	2.7
Pick and shovel work	1	0	1	2	5.5
sitting	1	10	1	12	33.33
Total	9	24	3	36	
%	25	69.4	8.3		

Among them, most people were occasionally walking (38%) and 69.4% of the respondents were slightly satisfied with the thermal performance of the structure during the winter period. Among them, 25% of the respondents were moderately satisfied. The overall satisfaction is high for occasionally walking and sitting, indicating that the people are more satisfied with the structure of mud shelters. In addition, among all of the respondents, only 8% were slightly rejecting the thermal performance of the mud shelter.

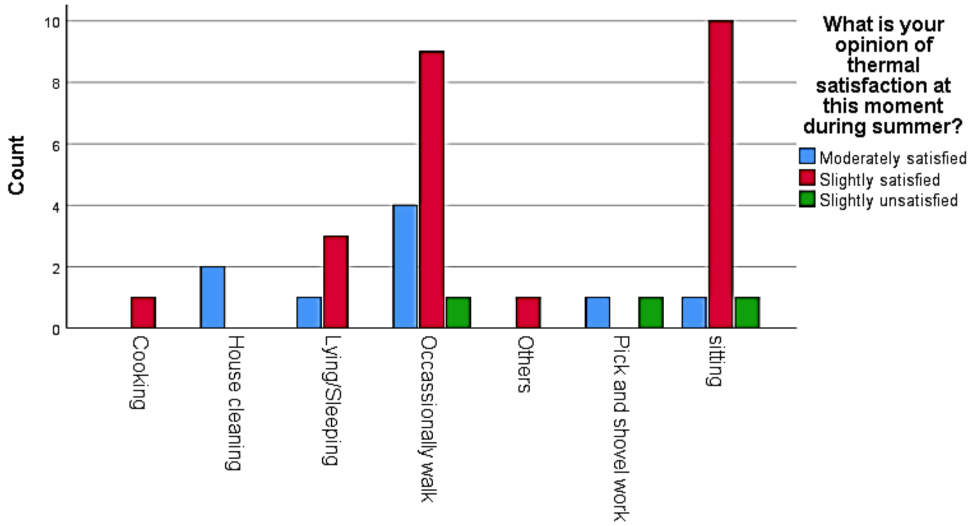


Figure 4.20:Thermal satisfaction of respondents for different activity status

- <u>Building Preference, thermal problem causes, and solution</u>

- Preference of type of building

TYPE	N	%
RCC structure	4	11.1
Mixed type	21	58.3
Others	1	2.8
Rammed earth	6	16.7
Stone masonry (SMM)	4	11.1
Total	36	100

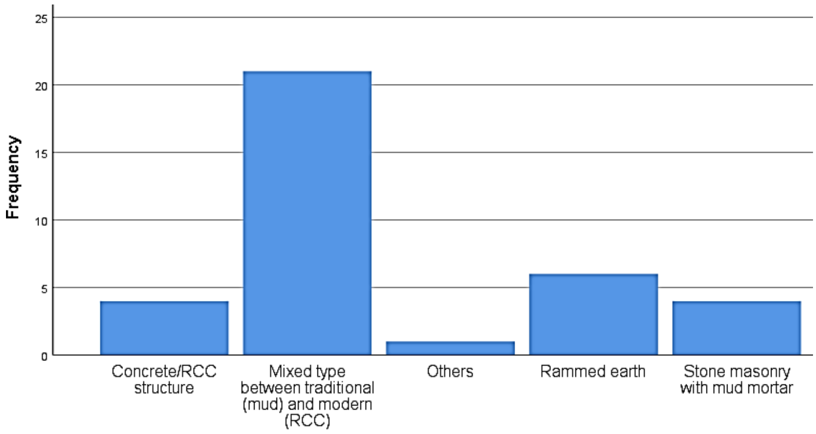


Figure 4.21:Preference of type of building in mountain region

Among 36 respondents, around 60% of people prefer a mixed-type structure that has qualities of both traditional mud structures and modern RCC structures. However, after some conversation, it was realized that there is a huge gap in the knowledge of the new and upcoming methods of mud structures. Their response indicates a mixed type because they observe modern structures and their ease in maintaining the overall comfort of the house without any consideration for the energy need and sustainability of the structure. We believe that once the residents know the new techniques of construction and the advantages of the traditional structure with modern and scientific improvements, they may prefer traditional structures more.

- Preference between mud and concrete structures

The thermal preference comparison between mud and concrete shelters by the respondents indicates that 50% of them slightly prefer traditional mud shelters rather than concrete structures as they believe in their better performance and their higher cultural value. If we combine the proportion of people that said positive about their thermal preference, local people support traditional mud structures more than concrete structures. It may also be due to poverty, lack of supply of construction materials for concrete structures, etc. The younger generation seems more confused about the preference for mud shelters over concrete structures. As they generally have different views toward mud shelters. However, the older generation highly prefers mud structures which are based on their belief and a good experience while living for years in mud shelters.

Table 4.5 Preference between mud and concrete shelters

				Preference			Percentage
Age	**Maybe**	**No**	**Slightly No**	**Slightly Yes**	**Yes**	**Total**	
15-25	1	1	1	1	1	5	13.8
26-40	2	0	0	4	5	11	30.5
41-60	0	0	0	8	3	11	30.5
Above 60	2	0	0	5	2	9	25
Total	5	1	1	18	11	36	
%	13.8	2.7	2.7	50	30.5		

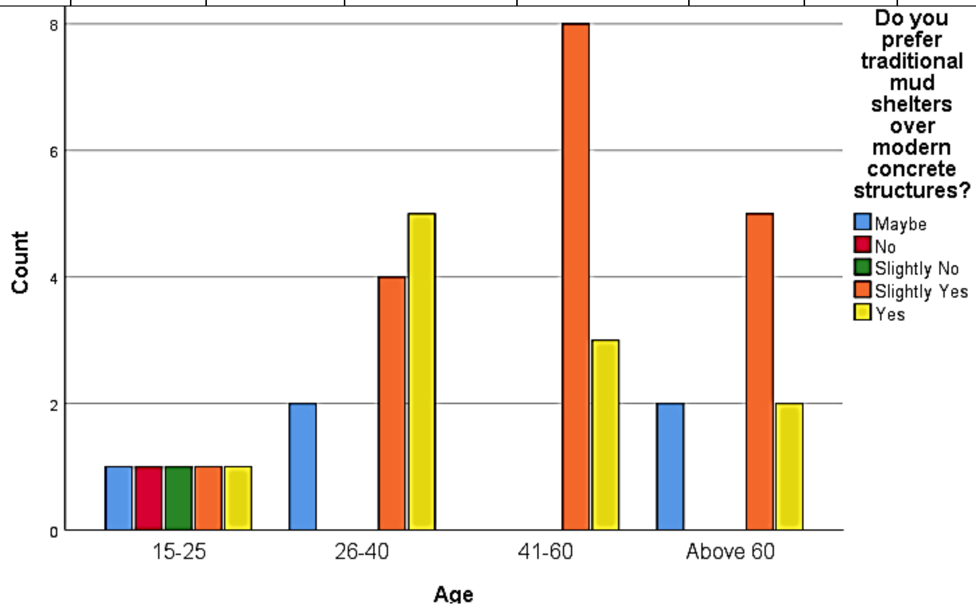


Figure 4.22 Preference for mud shelters over concrete in mountain

- Causes of thermal problems

The respondents primarily indicate that the main source of thermal discomfort is a lack of heating equipment and maintenance problems in the mountainous region. The material, energy, and technical resources for using heating equipment are difficult in such regions. Also, from this data, it can be said that people prefer electric or other types of heating equipment rather than traditional methods of heating like cow dung and wood. In terms of the building, the majority of people responded to the maintenance problem of the structure which is due to the structure being 80-200 years old and not maintained from time to time. Therefore, people indicate different problems which require major energy resources and skilled manpower. It can be argued that people in mountainous regions desire quick results that can maintain thermal comfort rather than rely on local resources. Contrary to our assumption, people are satisfied with wall thickness for SMM plastered structures as well as RCC structures in the mountainous region.

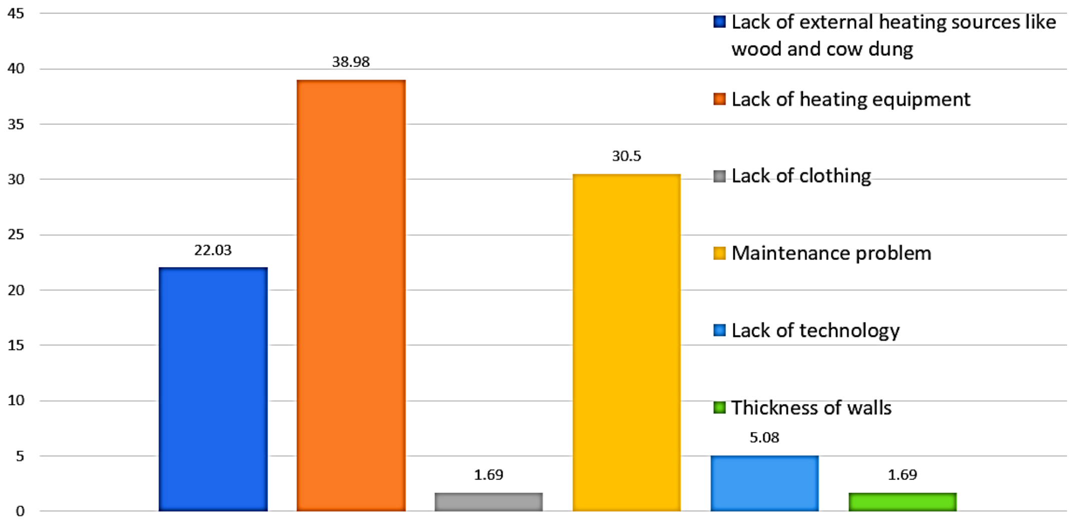


Figure 4.23 Causes of thermal problems in a mountainous region

- Solutions to thermal problems

The respondents primarily indicate that heating equipment like electric heat and gas heaters are the solution to thermal problems. The second most sort after solution is wearing more clothes to maintain thermal comfort. However, people have not considered lack of clothing as a problem. Therefore, more extra clothes are required to maintain thermal comfort than in normal conditions. The solution suggested by local respondents requires more heating equipment as well as a reliable energy source whether it be electric or gas. Using non-renewable resources like wood, fuel, etc, the thermal problems can be solved according to the respondents. However, this practice needs to be as minimized as possible for pollution control and sustainability.

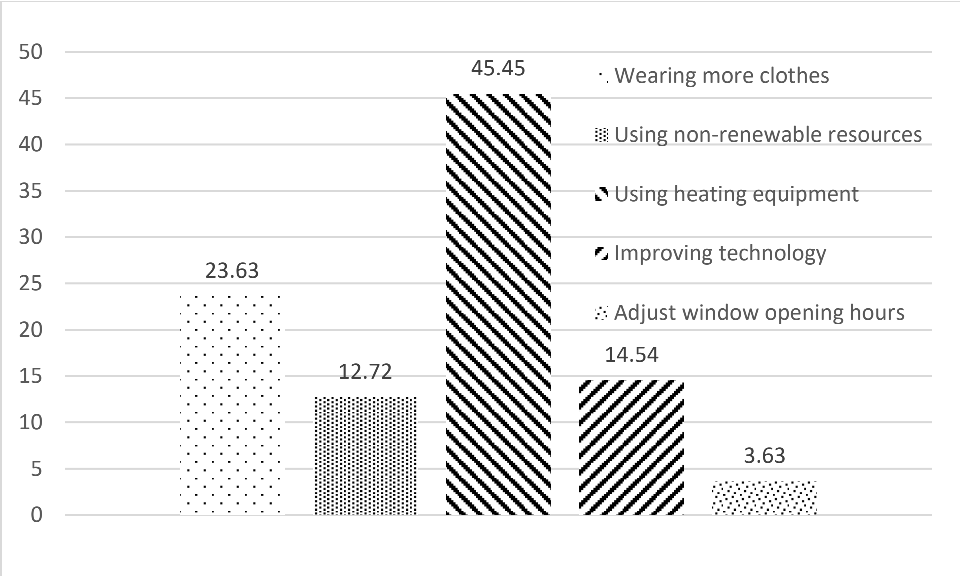


Figure 4.24 Solutions to thermal solutions in mountain

- <u>Humidity Responses</u>

- Humidity Sensation

Table 4.6: Humidity sensation of respondents

Air Humidity		**%**
Condition	**Frequency**	
Very dry	2	5.6
Dry	4	11.1
Slightly dry	24	66.7
Neither humid nor dry	5	13.9
Humid	1	2.8
Total	36	

Figure 4.25 Sensation of Air Humidity inside the building

During the survey, 66.7% of the respondents considered that the air humidity level was slightly dry as they reacted with either dry or slightly dry sensations. The overall humidity condition is dry as (66+11+5) = 83% of people respond to the humidity condition as dry. Dry conditions can cause skin problems and respiration problems. Even though the overall condition of the house is humid according to the humidity measurements, the results mostly reflect the dry conditions of the outer environment which is experienced by the residents throughout the day.

- Humidity Preference

Table 4.7: Humidity preference of respondents

Air Humidity		%
Condition	Frequency	
Much more humid	2	5.6
Bit more humid	31	86.1
No change	2	5.6
Bit drier	1	2.8
Total	36	5.6

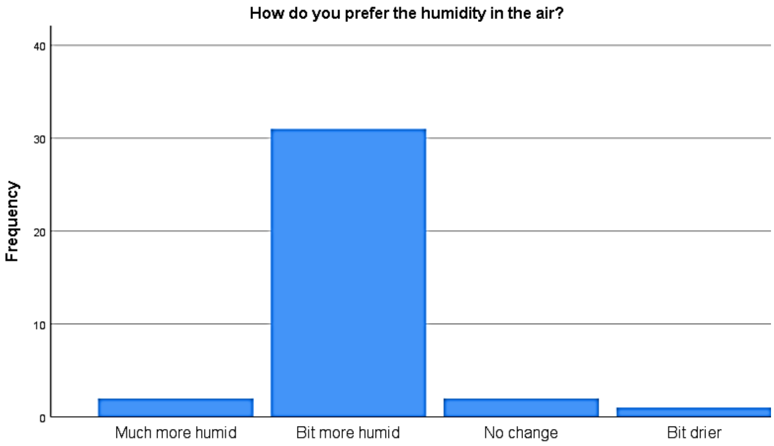


Figure 4.26 Preference for air humidity inside the building

Since the humidity in the mountainous region is dry or slightly dry, most respondents around 80% preferred a bit more humid environment. Both, the respondents in the mud as well as the concrete shelters preferred a bit more humid environment. The reason may also be due to the time of the survey taken which was during the daytime. During site investigations, we observed that the humidity is high in the morning and evening periods in mud shelters due to cooking.

- Comfort Responses

  - Overall comfort

For mud shelters, most of the respondents felt slightly comfortable conditions in the SMM mud shelters. If we combine the proportion of the comfortable group, the results become 91% of the total surveyed population. The overall thermal comfort level vote indicates evident satisfaction in SMM mud shelters in terms of comfort. Almost all the respondents of different age groups are marginally comfortable with the current conditions of thermal comfort provided by the shelters in the mountain region. As the comfort survey was conducted in the largest room available in the structure, it represents the thermal comfort of the whole house on the particular floor.

Table 4.8:Thermal comfort responses based on age group

		Moderately comfortable	Slightly Comfortable	Slightly uncomfortable	Total	%
Age	**1-25**	1	4	0	5	13.8
	26-40	3	7	1	11	30.5
	41-60	1	9	1	11	30.5

	Above 60	1	7	1	9	25
Total		6	27	3	36	
%		16.67	75	8.33		

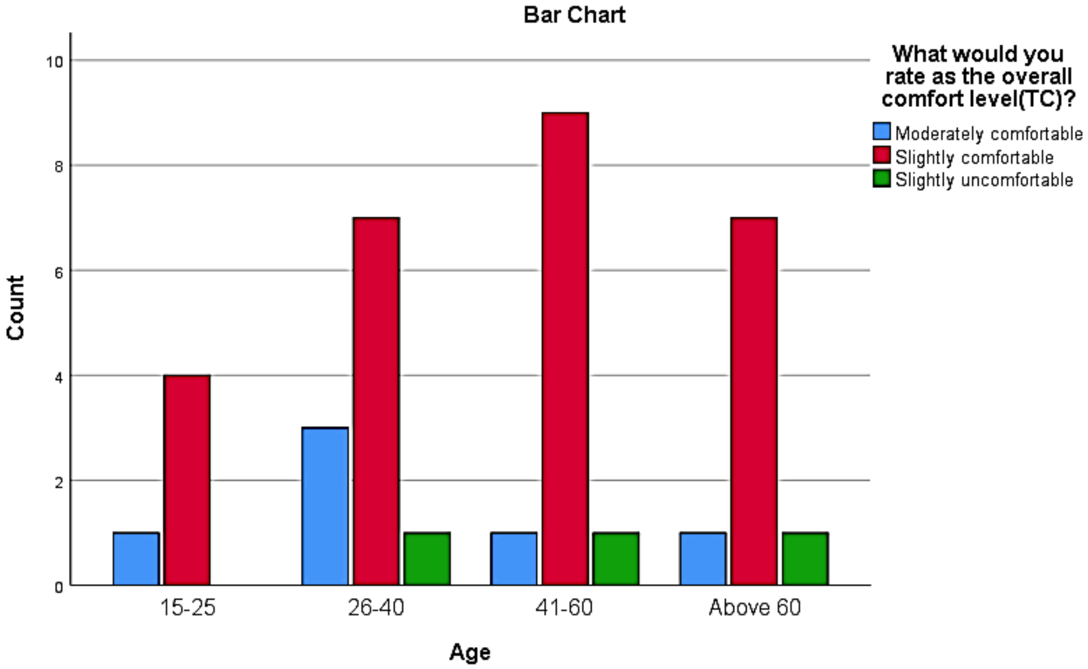


Figure 4.27:Overall thermal comfort level in mountain

- Ventilation and Air Quality

From the results, it can be argued that most people are optimistic about opening windows for ventilation. The results here only represent the beginning of the transition season from winter to summer. Therefore, considering their humidity conditions due to the unopened windows in the winter, they seem positive about opening the windows for better ventilation and air quality. The people are only considering opening windows in the daytime rather than in the evening and morning time which allows warm air to come inside the building. Therefore, it can be argued that people are also conscious of the indoor air quality conditions which are important for respiration as well as the overall well-being of an individual. Traditional mud shelters, simply want to keep their homes fresh without the smell gathered while cooking.

Table 4.9 Preference for the Opening window for ventilation

Preference	N	%
Yes	7	19.4
Slightly Yes	9	25.0
Maybe	13	36.1
Slightly No	6	16.7
No	1	2.8
Total	36	100.0

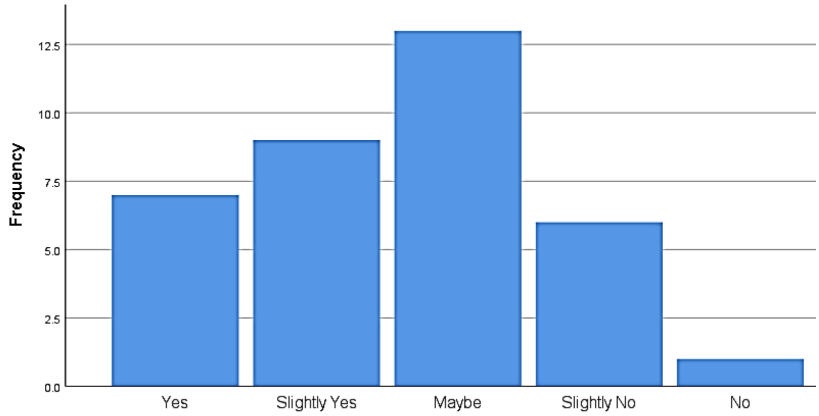


Figure 4.28 Comparison of opening windows for ventilation

- Activities to maintain thermal comfort during summer and winter

We asked about the personal activities that the respondents preferred during the summer and winter periods to regulate their thermal comfort, most of the respondents preferred to open the windows during summer whereas in winter people opted to use more clothes to maintain thermal comfort. During summer using light clothes was preferred as a 2nd option and in winter using the fireplace is an efficient choice for the respondents considering the age of the respondent which is a mostly middle-aged and old group. Most of the women preferred taking a shower in the summer and doing more household activities in the winter to maintain thermal comfort.

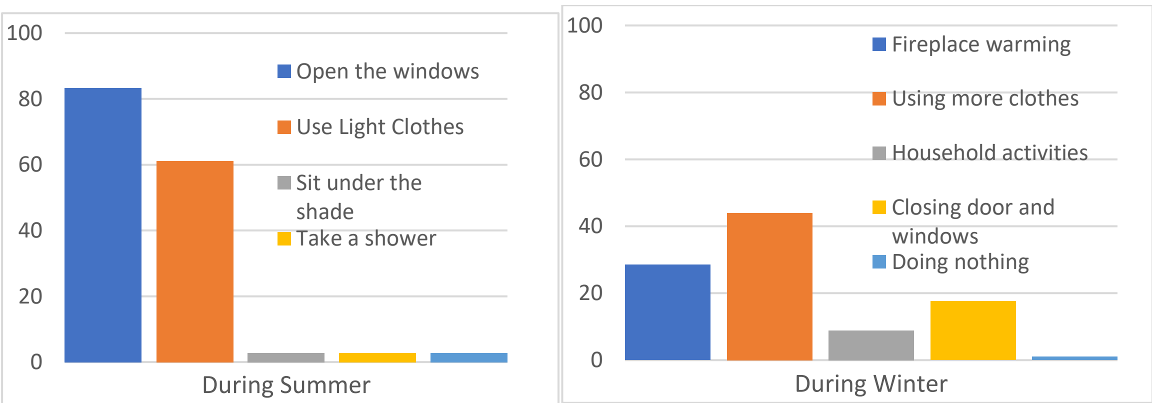


Figure 4.29:Preference of activities during summer and winter in mountain region

4.2.2 Hilly region

- <u>Profile of the sample</u>

A total of 14 people volunteered for the thermal comfort survey out of which 6 were male and 8 were female. We tried to take the same sample population of both males and females as much as possible. The majority of the respondents belong to the middle age group(26-40) which is mainly the working population. The thermal comfort and its various responses also differ based on sex and age. Using the Statistical Package for Social Sciences, the data acquired from measurements and questionnaire surveys were initially imported into spreadsheets (SPSS). Using NVivo software for pattern recognition and answer similarity, the subjective evaluation was carried out. The results of subjective assessments (point-in-time surveys) and objective evaluations (long-term and point-in-time measurements) were compared to conduct the thermal assessment.

Table 4.10: Profile of the sample

Age * Gender Crosstabulation			
	Gender		
	Male	Female	Total
15-25	1	3	4
26-40	1	4	5
41-60	3	1	4
Above 60	1	0	1
Total	6	8	14

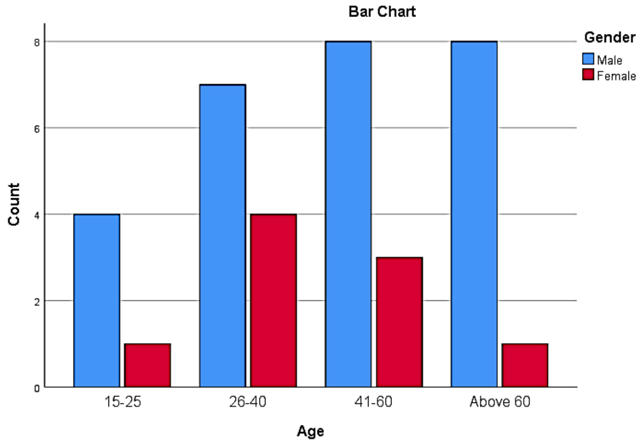


Figure 4.30 Profile of the respondents in hilly

-
- <u>Thermal responses</u>

- Modified Thermal sensation Votes

Count		Thermal Sensation Vote(mTSV)				
		Neutral	**Slightly Warm**	**Hot**	**Total**	**%**
Age	**15-25**	1	2	1	4	28.5
	26-40	2	2	1	5	35.7
	41-60	3	1	0	4	28.6
	Above 60	1	0	0	1	7.1
Total		7	5	2	14	
Percentage(%)		50	35.7	14.3		

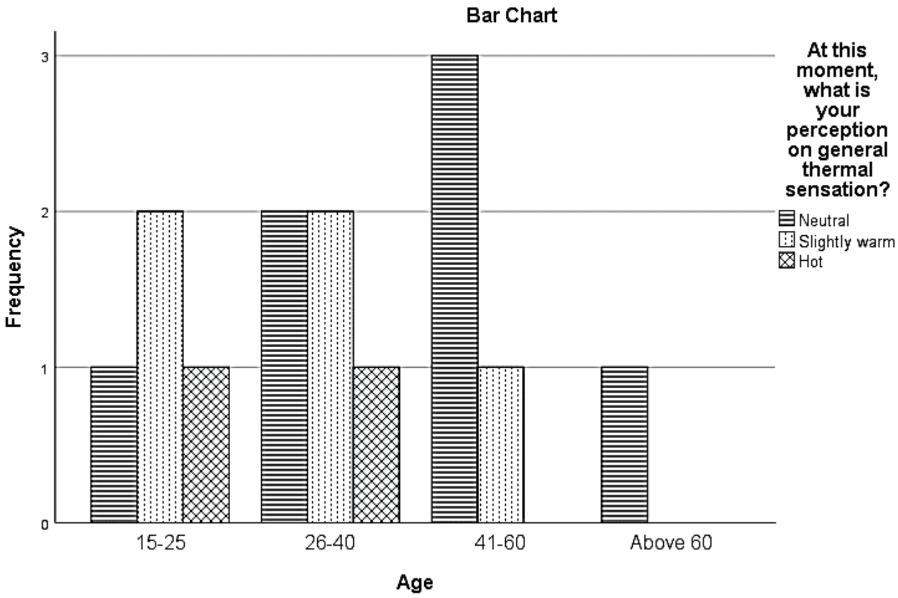


Figure 4.31 Thermal sensation vote in Hilly Region

Most of the people are satisfied with the existing thermal conditions as 50 % of them voted neutrally which indicates neither hotness nor coldness. Since this survey was taken during the summer, younger age groups are considering the conditions to be slightly warm and some middle-aged respondents are even considering the conditions old. The results may slightly vary due to the time of the day in which this survey was conducted as it is impossible to conduct all the surveys at the same time during the day. However, the obtained thermal sensation responses show that there is less requirement for active cooling systems in these structures. The above table shows the actual thermal sensation votes (TSV) distribution illustrated in Fig. 4. The thermal sensation with the largest percentage of votes, or 50%, was neutral, and the thermal sensation with the second-highest percentage, or 28.15%, was slightly warm. Only voters aged 26 to 50 chose the chilly thermal sensation, while 7.14 percent chose the hot thermal sensation. The age brackets of 26 to 50 had the highest voter turnout (35.7%), followed by 41 to 60 and 15 to 25 with identical percentages (28.5%). The age group over 60 had the lowest percentage of respondents who favored hot sensations.

- Current Thermal Preference

Table 4.11: Thermal Preference of different age groups

Thermal Preference			
Age	Gender		Total
	No change	Bit Cooler	
15-25	1	3	4

26-40	1	4	5
41-60	2	2	4
Abv 60	0	1	1
Total			14

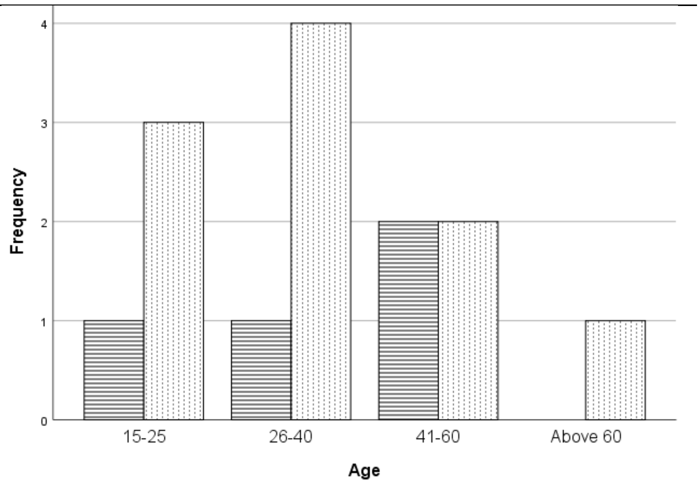


Figure 4.32: Thermal preference from different age groups in hilly

Only 21.42 respondents chose no change, while the majority of respondents, or 78.57, favored the somewhat cooler thermal preference. All age groups, except those over 60, were represented by respondents who voted for no change. 50 percent of Type-VIII respondents (who made up 78.57 percent) favored a slightly cooler thermal preference, compared to 14.28 percent of Type-VI and VII respondents. Most of the residents living in the hilly region prefer a bit cooler thermal condition even though they felt neutral conditions as their thermal sensation. Here, respondents from all the age groups prefer a bit cooler conditions. The temperature in the warm temperature region during summer is hot and the residents consider a bit cooler thermal situation. However, since their thermal preference is only concentrated on being a bit cooler, it can be achieved by passive cooling strategies also. Solutions to thermal problems.

- Thermal Satisfaction

Table 4.12: Thermal Satisfaction of respondents based on activity status

	Thermal Satisfaction				Total	%
Activity status	**Satisfied**	**Moderately satisfied**	**Slight satisfied**	**Slightly unsatisfied**		
Eating	0	0	1	0	1	7
House Cleaning	1	0	0	0	1	7
Kitchen Work	0	0	1	0	1	7
Sitting	2	5	0	3	10	71
Sleeping	0	0	0	1	1	7
Total	3	5	2	4	14	
%	21	35	14	28		

Among the total number of respondents, most of them are sitting (70%), (21+35+14 = 70)% of them were overall satisfied whereas 28% were overall unsatisfied. As the temperature was hot during the summers, it is plausible that the respondents could not cope with the increasing temperatures. However, the percentage satisfaction of overall satisfaction is also not very low (21+35+28). Since the survey was taken in more modern rammed earth structures than modern RCC structures in the hilly region, it can be said that the results reflect the passive designs considered in the modern rammed earth structures. Among those people who were seated, most of them are satisfied (7/10=70%). The most plausible reason for dissatisfaction during sitting and sleeping may be due to the humidity conditions of the region.

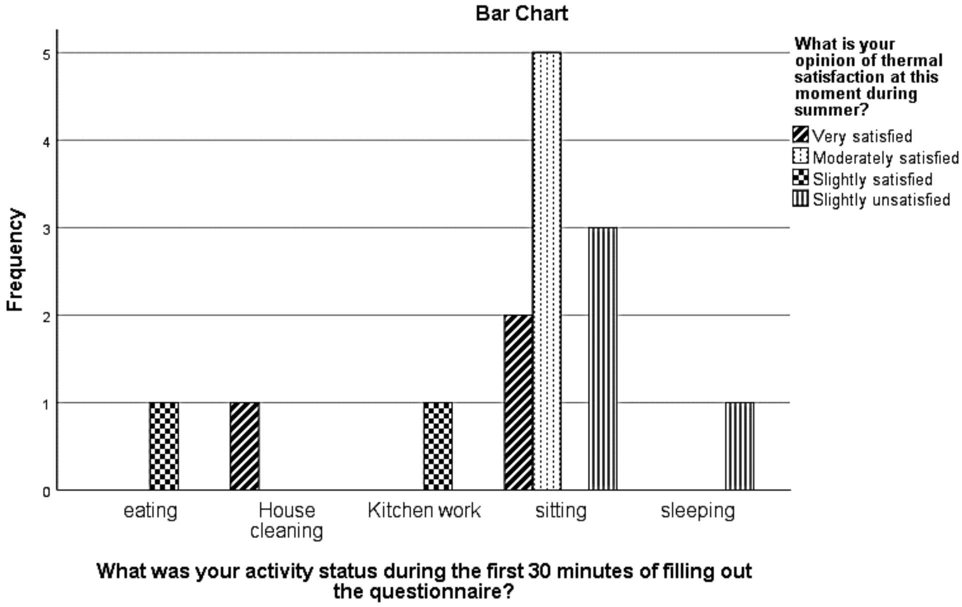


Figure 4.33: Thermal satisfaction based on different activity in hilly

- <u>Building Preference, thermal problems, causes, and solution</u>

- Preference of type of building

Most of the residents preferred RCC structures (42%) which is the general trend among the type of houses in Kathmandu Valley. The obvious bias of the respondents towards the type is reflected as they consider their house types to be superior to the others in terms of thermal performance. The respondents of rammed earth houses have some experience of both rammed earth as well as modern RCC houses, however, their preference is either rammed earth or mixed type of houses where they want the thermal conditions of rammed earth with all the modern facilities of active and passive strategies to obtain thermal comfort.

TYPE/House		
	VIII	%

RCC structure	6	42.8
Mixed type	4	28.5
Rammed earth	4	28.5
Total	14	
%	57	

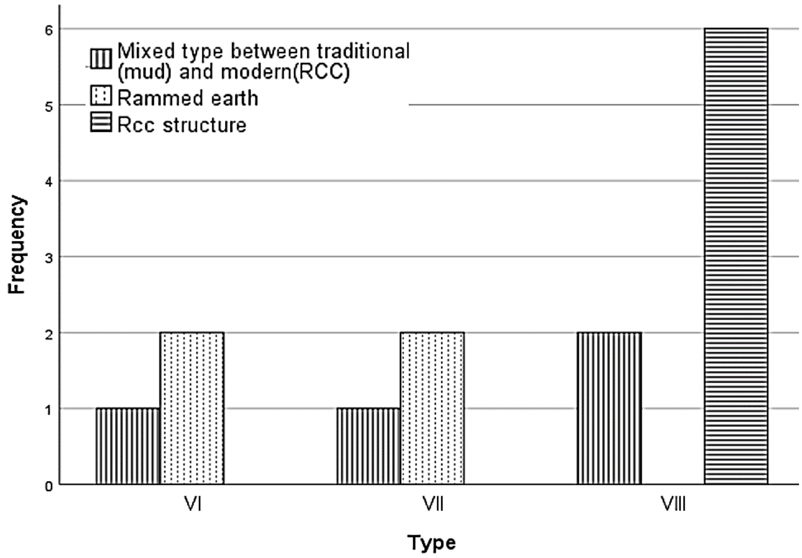


Figure 4.34 Building preference in hilly

- Preference between mud and concrete structures

Most of the respondents from both modern rammed earth and modern concrete shelters preferred mud shelters over concrete shelters. The reason for choosing this option is similar to the ones that we found in the mountainous regions like saving our culture and better thermal performance in the form of modern rammed earth structures. People from all age groups prefer mud shelters rather than modern concrete structures.

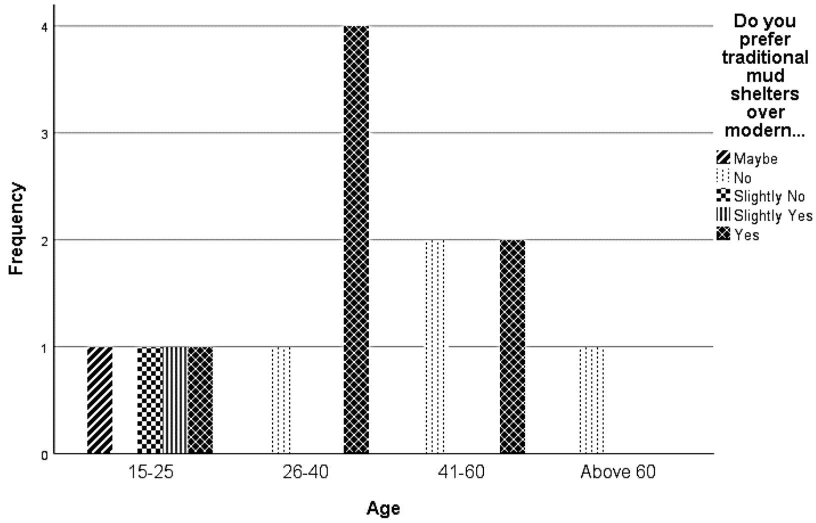


Figure 4.35 Preference for mud shelters over concrete in hilly

However, there are also those people who are unaware that such a modern mud shelter exists having different modern facilities as well. Some still prefer concrete shelters due to their unawareness of modern mud shelters being old and outdated. The older generations who have some experience with mud shelters and still living in modern mud shelters are confident that mud shelters are good enough for providing all the resources and services that a modern RCC structure can provide.

Table 4.13 Preference between mud and concrete shelters

Age	Maybe	No	Slightly No	Slightly Yes	Yes	Total	Percentage
				Preference			
15-25	1	0	1	1	1	4	28
26-40	0	1	0	0	4	5	35.7
41-60	0	2	0	0	2	4	28
Above 60	0	1	0	0	0	1	7
Total	1	4	1	1	7	14	
%	7	28	14	14	50		

- Causes of thermal problems

The main thermal problems are during the winter season rather than the summer season in Kathmandu Valley as the temperature doesn't soar very low. Therefore, most of the thermal problems indicated here are focused on thermal deficiency in the winter season. The worst thermal problem is lack of clothing, lack of opening/closing hours of windows, and lack of use of heating equipment in the winter. Some respondents are also considering the problems of wall thickness and improper insulation as bigger thermal problems in the winter season. The thermal conditions of summer are not included because most people consider using a fan and lighter clothes to be enough to deal with the hotter temperature problems. As there is less use of fossil fuel as well as gas in the urban areas for heating, most people think that people require more heating equipment running under electricity for the winter season.

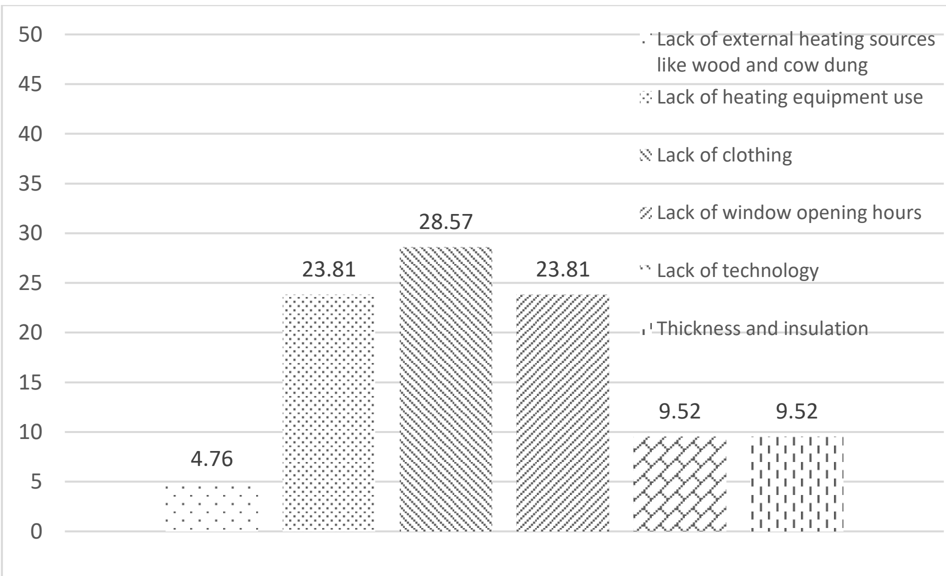


Figure 4.36 Causes of thermal problems in hilly region

- Solutions to thermal problems

The thermal solutions are more focused on the use of renewable resources rather than using other passive technology as most of the respondents are unaware of such techniques. However, modern rammed earth structures already have some passive design techniques in their shelter design. In the winter, wearing more clothes and adjusting windows opening/closing hours(which is also a passive design concept) have been included as a thermal solution of the respondents as major choices for reducing thermal problems during the winter. In the summer as well the thermal solutions are either using external cooling equipment like the fan or opening/closing windows which have not been shown in the graphical representation. Some respondents also consider using a thicker wall or insulation for better thermal performance which would be beneficial for both the summer and winter seasons. However, in the urban area, the area available for construction becomes limited which reduces the sizes of the rooms and creates other problems for the residents like accommodation areas, and available space for other activities.

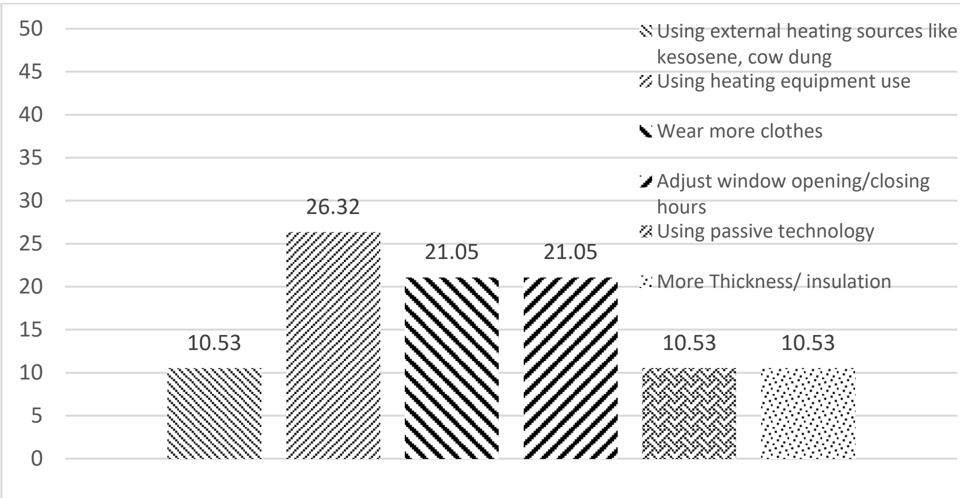


Figure 4.37 Solutions to thermal solutions in hilly

- Humidity Responses

- Humidity Sensation

Table 4.14: Humidity sensation of respondents

As the thermal comfort survey was taken during the month of Baishakh(March-April) which is usually the transition period between winter to summer in Nepal and also the driest period throughout the year, the resident's respondents reflect on slightly dry conditions followed by neither humid nor dry conditions inside the house properly in the survey. The humidity is governed by the amount of water present in the air, which is higher in tropical regions, and during the time of precipitation. Mostly, if humidity is high during higher temperatures, it creates different health problems like strokes and respiration problems.

Air Humidity		%
Condition	Frequency	
Very dry	1	7.1
Slightly dry	5	35.7
Neither humid nor dry	5	35.7
Slightly dry	3	21.4
Total	14	100.0

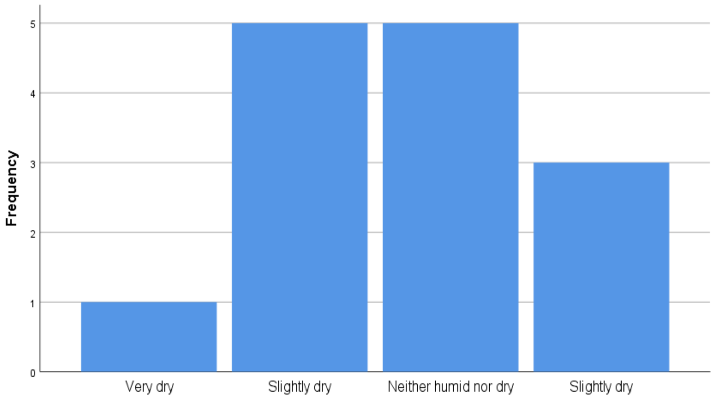


Figure 4.38 Sensation of Air Humidity inside the building

- Humidity Preference

Air Humidity		%
Condition	**Frequency**	
Bit more humid	3	21.4
No change	5	35.7
Bit drier	6	42.9
Total	14	100.0

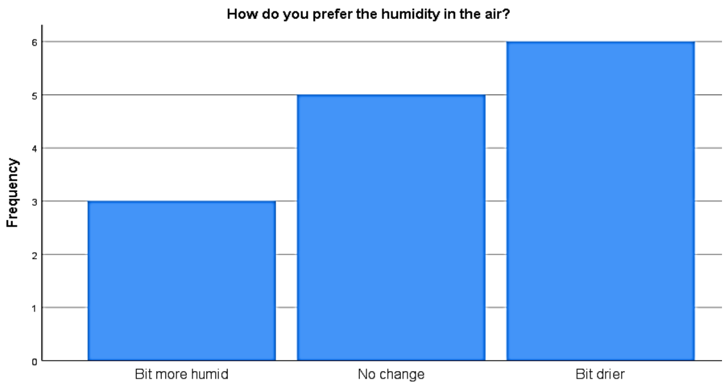


Figure 4.39 Preference for air humidity inside the building

The Kathmandu Valley lies in the warm temperature region where temperature and are humidity higher than the high altitude cold regions from humidity measurements for such locations. In summer, the humid conditions don't allow the air to cool quickly and cause a longer time for the decrease in temperatures. Even though the humidity sensation states the conditions of slightly dry, more respondents desired drier conditions as the temperatures were increasing day after day. The 2nd most vote is considered for neither humid nor dry which states that the humidity conditions are suitable for their optimum performance during that time of the day. This response is also supported by the humidity measurement in the rammed earth houses located in this region as the humidity is within a comfortable range according to the temperatures as indicated by the Psychrometric chart.

- <u>Comfort Responses</u>

- Overall comfort

The overall comfort in the Kathmandu region is very comfortable as most of the respondents voted for very comfortable conditions. Both the respondents from the rammed earth house, as well as RCC structure, consider that their house provides comfortable overall comfort conditions in the house. If we combine all the proportions of the comfortable group, the result becomes 84% of the total surveyed population. The overall thermal comfort level vote indicates high satisfaction in both types of structures. Almost all the age groups are very much comfortable with the overall comfort condition which was conducted in the largest room available in the surveyed shelters.

Table 4.15:Thermal comfort responses based on age group

		Very Comfortable	Moderately comfortable	Slightly Comfortable	Slightly uncomfortable	Total
Age	1-25	1	1	2	0	4
	26-40	3	1	0	1	5
	41-60	0	2	1	1	4
	Above 60	1	0	0	0	1
Total		5	4	3	2	14
%		35.7	28.5	21.4	14.2	

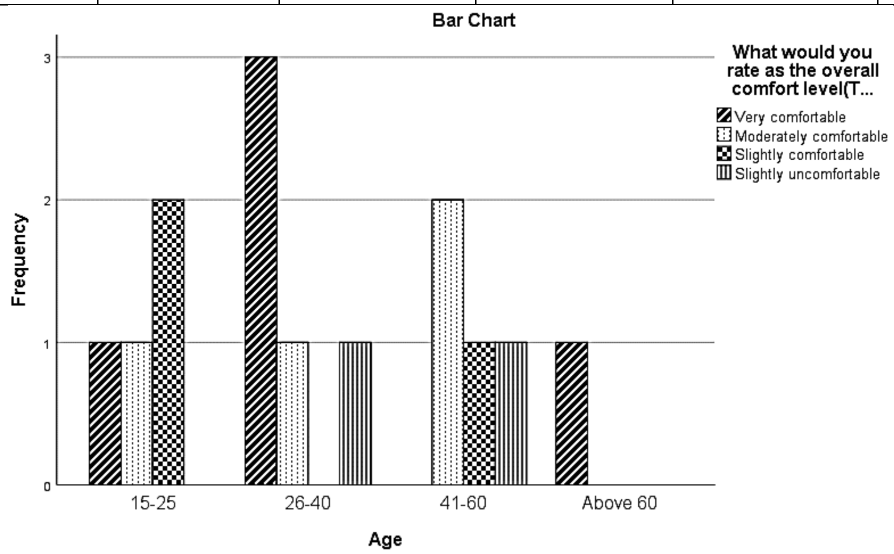


Figure 4.40 Overall thermal comfort responses in hilly

- Ventilation and Air Quality

Table 4.16 Preference for the Opening window for ventilation

Preference	N	%
Yes	11	78.5
Slightly Yes	3	21.4
Total	14	100.0

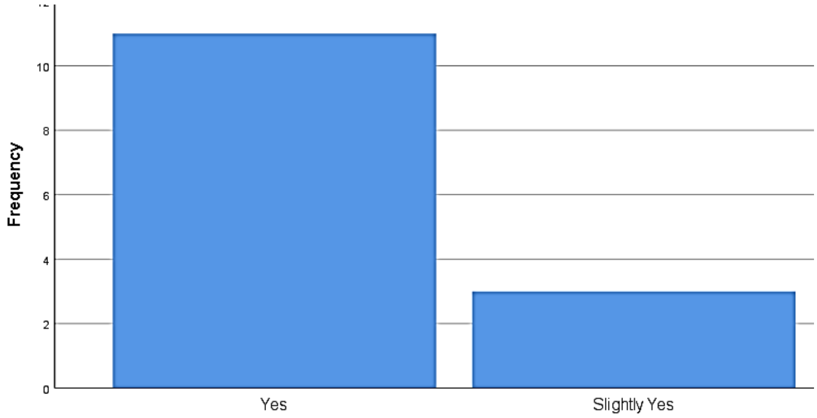


Figure 4.41 Comparison of opening windows for ventilation

The results indicate that all the respondents in the survey consider ventilation to be opened for the current scenario as it is at the end of the transition season from winter to summer. Therefore, considering humidity and hot air-cool air circulation, all the respondents in the rammed earth house, as well as the RCC house, are positive about opening the windows. When asked, some respondents like to open the windows throughout the night whereas most respondents consider closing the windows in the nighttime. There are several windows in the house in both modern rammed earth and RCC structures, hence, during the summer, they are aware of the indoor air quality conditions also by opening the windows.

- Activities to maintain thermal comfort

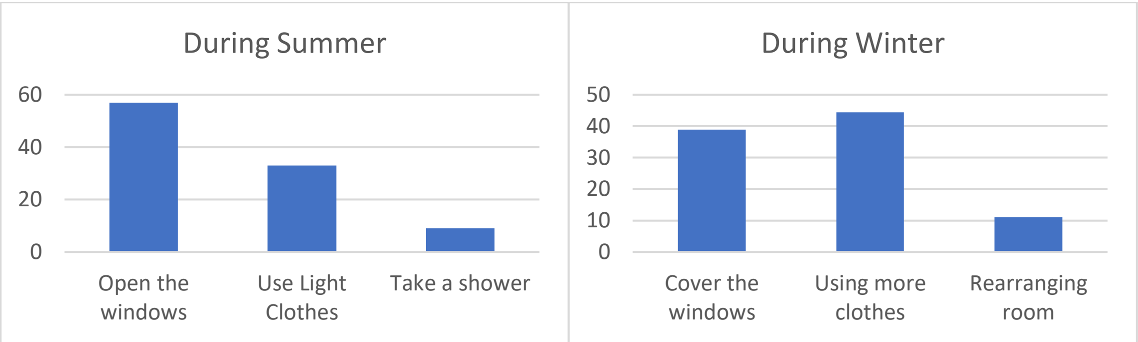


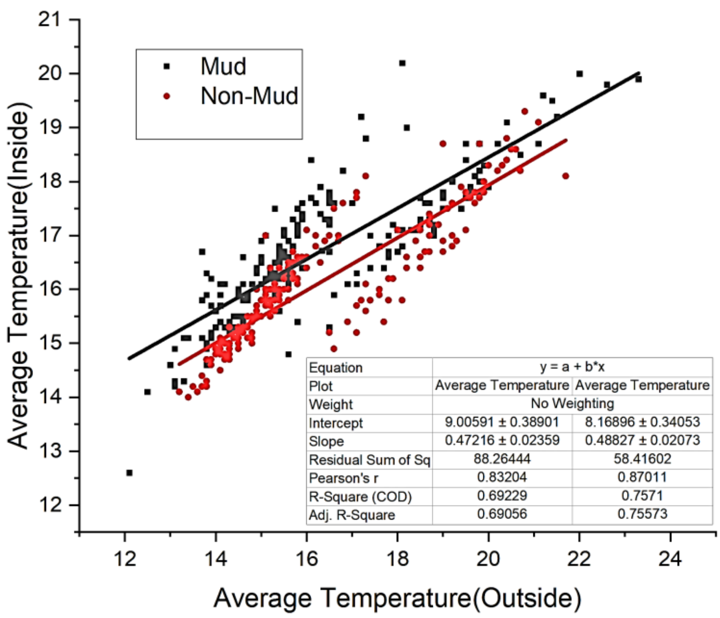
Figure 4.42:Preference of activities during summer and winter in hilly

During the summer, the most preferred activity for maintaining thermal comfort is opening the windows to regulate air circulation during the daytime. Other respondents also considered using lighter and brighter clothes while taking frequent showers to cool off the heat during the summer as an activity. However, in winter, the most liked activity is an activity which is more personal than other options which are using more clothes. Using more clothes is a subjective aspect as the choice of wearing the number of clothes depends not only on the type of clothes but also the requirement of the individual. Surprisingly, some individuals shift their room arrangement towards a more heated area of the room or arrange the room such that the overall thermal comfort condition becomes high. To reduce the effects of cooling the 2nd most chosen option was to close/cover the windows during the morning and nighttime.

4.3 Discussion

4.3.1 Relation between indoor and outdoor air 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 Figure 4.20 Since the temperature measurements in the hilly region were done in the transition period which was closer to the summer season. The temperatures are higher compared to the mountainous region. The indoor-outdoor temperature relation is calculated using the regression analysis which is shown by the equation below.



Region

Mountain:

Mud: $T_i = 0.47T_o + 9$ (4.1)

Non-Mud: $T_i = 0.48T_o + 8.16$ (4.2)

Hilly:

Rammed Earth: $T_i = 0.37\, T_o + 14.7$ (4.3)

Non-Mud: $T_i = 0.61T_o + 9.3$ (4.4)

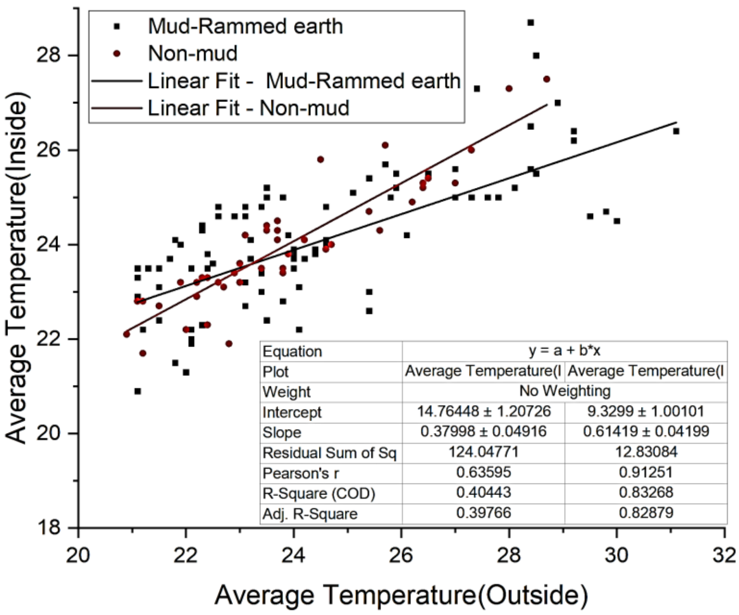


Figure 4.43 Regression analysis of Mountain and Hilly Region

The relationship between the observed air temperatures inside and outside of mud and non-mud homes in a cold climate is depicted in Figure 3.16. 360 plots are available from both residences. Generally speaking, the inside air temperature will increase as the outdoor air temperature rises. In equations 4.1 and 4.2, 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 Figure 4.1 reveal that the indoor air temperature (Ti) 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 during the summer, the traditional house is 0.62 °C warmer than the modern house. This might be because the kitchen, which doubles as a bedroom, burns firewood twice or three times daily, but in non-mud houses, the kitchen and bedroom are different rooms.

In hilly regions, the regression of rammed earth and non-mud shelter near the summer season shows that rammed earth shows better thermal performance than non-mud shelter. Using the regression equation, at 28°C, the inside temperature of rammed earth is calculated to be 25 °C whereas for non-mud shelter the value is 26.38°C. The high thermal mass of rammed earth in the summer season along with other passive design strategies work excellently to control the thermal environment in comparison to non-mud shelters. This represents that rammed earth is 1.38 °C cooler than the RCC structure. In both, the period's winter and summer, mud shelters perform better than non-mud shelters. Especially, rammed earth shelters perform better than both the traditional mud and modern RCC structures.

4.3.2 Comfort and Preferred Temperature

The comfort temperature and preferred temperature are calculated using the equation provided in (4) and (5). 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. () The equation provided in the reference are as follows:

Region

Mountain (Cold region):

$$\text{Summer:} \quad T_g = 0.54T_o + 7.7 \quad (4.1)$$

Hilly (Temperate region):

$$\text{Summer:} \quad T_g = 0.47T_o + 13.4 \quad (4.3)$$

- <u>Mountainous Region</u>

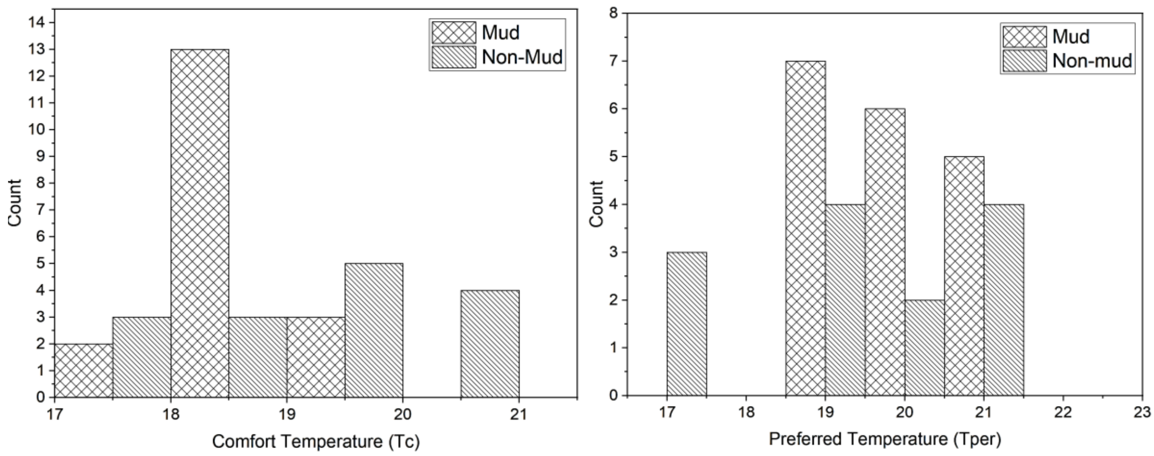


Figure 4.44 Comfort and Preferred Temperature for mud and non-mud shelter

For the mountainous regions, 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 of the respondents desired a higher temperature. Similarly, for non-mud shelters, the comfort temperature is higher than that for mud shelters as the average comfort temperature is 19.5°C. The preferred temperature of a non-mud shelter is 20.1°C which is 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 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.

- <u>Hilly Region</u>

Since both the thermal measurements and thermal comfort survey were conducted in a period close to summer, the comfort temperature and preferred temperature are higher compared to the mountainous region. The average comfort temperature for mud (rammed earth) shelters is binned around 23.8°C whereas, for non-mud shelters, the comfort temperature is 22.8°C which shows that people are comfortable in higher temperatures in mud shelters compared to non-mud shelters. Similarly, the average preferred temperature of mud (rammed earth) shelters and concrete shelters are 23.3°C and 21.69°C respectively. This shows that residents of non-mud shelters prefer temperatures 1-1.2°C lower than in mud shelters. The comfort temperature of the two structures states that mud shelters can save up to 10% of energy making them an energy-efficient design(Bajracharya, 2014). However, the comfort temperature calculated from the Nicol graph for both Budhanilkantha and Godawari in section 3.3.2 is 24.7°C which shows that Matoghar and Narayan Acharya's residence comfort temperature is less by 0.9°C.

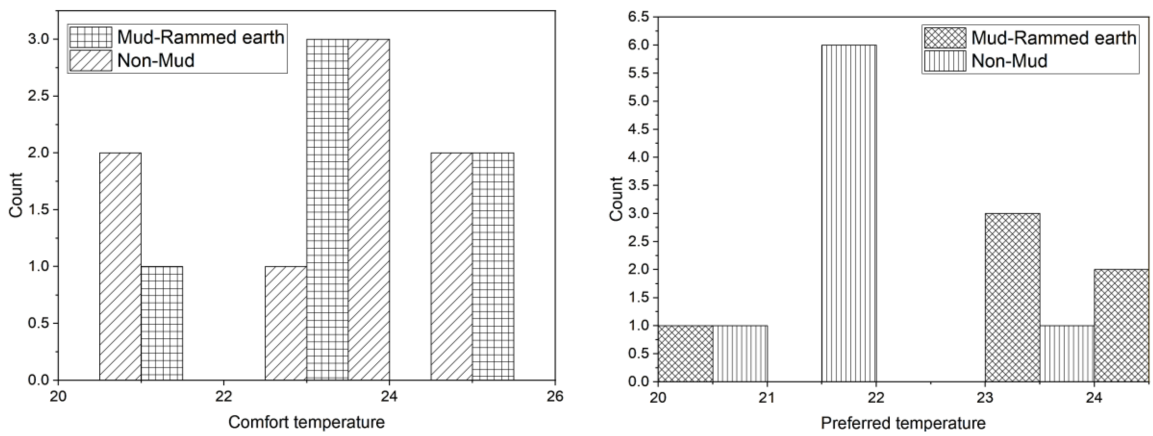


Figure 4.45 Comfort and Preferred Temperature for mud and non-mud shelter

4.3.3 Comparison between traditional mud shelters and modern rammed earth

- <u>Indoor-Out temperature difference</u>

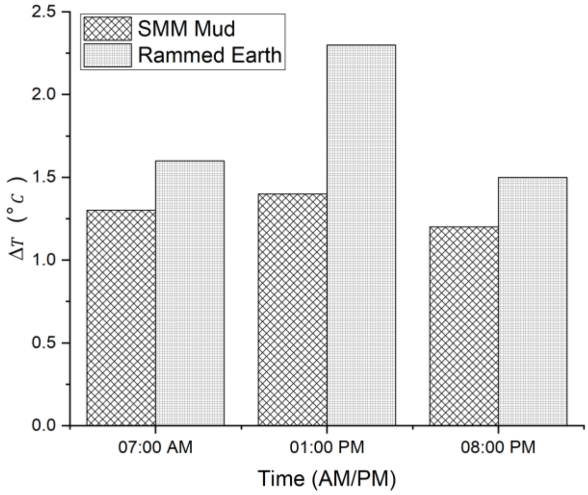


Figure 4.46 PIT Temperature difference in a mud structure

The graph shows the average values of SMM mud shelters and rammed earth structures in different periods of the day. The comparison between indoor and outdoor air temperature differences between mud and rammed earth structures shows the superiority in thermal performance of 1-1.5℃ as shown in the figure. The differences are at least greater by 0.5℃ in all the periods, morning, noon, and evening of the day which shows that rammed earth is better than SMM mud structures. However, the construction process using rammed earth technology is time-consuming, costlier, and requires more skilled manpower. Both require types of construction require mud but rammed earth construction has superior strength as well as durability if proper care is taken during construction and maintenance. In terms of sustainability and comfort which is connected with humans and the saving of natural resources, rammed earth construction should be done more in the rural areas which are cheaper in the long run and don't require any extra material. For this, more training and equipment are needed on the local level for increasing the use of rammed earth houses for constructing residential buildings.

- <u>Thermal performance during Morning, Day, and Evening</u>

The temperature measurements for SMM mud and rammed earth structures were done in different periods of the season and at different locations of NEPAL. Therefore, the measurements are very different between rammed earth and SMM mud structures. However, the transition of temperature from morning to noon and noon to evening are similar. The increasing slope and decreasing slope of rammed earth structure are lower than the slope in SMM mud structure indicating that the fluctuation in rammed earth structure is less. This shows that the thermal conditions are more stable in rammed-earth structures than in SMM mud shelters. The graph shows better performance of rammed earth structures during the noon hours than SMM mud structures.

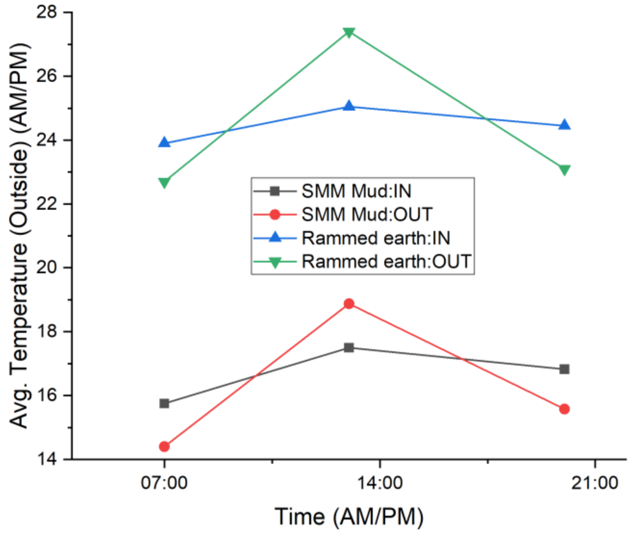
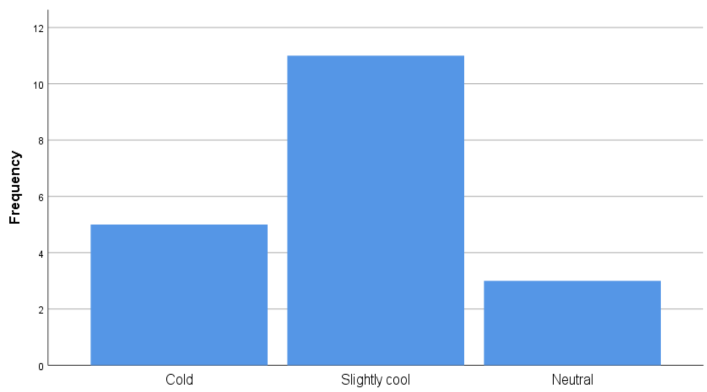


Figure 4.47 Indoor Outdoor Temperature Timeline

- <u>Thermal response</u>

\- Thermal Sensation Vote

When comparing the thermal sensation votes, the maximum respondents in SMM mud shelters felt slightly cool whereas respondents of rammed earth shelters felt neutral conditions of temperature. The thermal comfort is highly favorable if the sensation is neutral to the respondent. On a subjective scale, rammed earth is better in terms of thermal performance compared to mud shelters as people feel neutral towards the existing thermal conditions in rammed earth compared to SMM mud shelters.



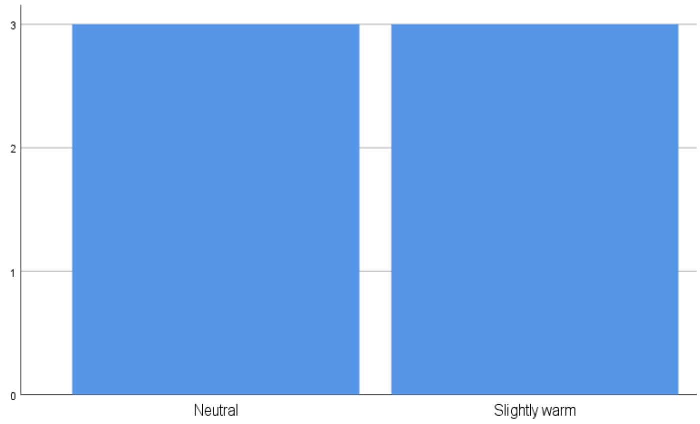
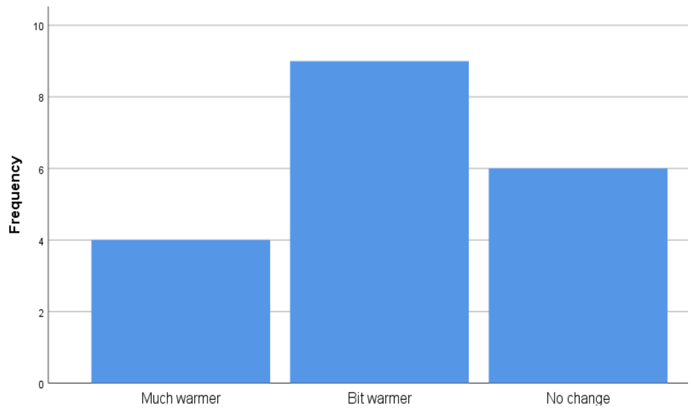


Figure 4.48 mTSV comparison - SMM (right) mud and rammed earth (left)

- Thermal Preference

In terms of the degree of preference, respondents of both rammed earth (78%) and SMM mud shelters (52%) considered a single degree of change to obtain the preferred thermal conditions. As thermal comfort is a subjective choice also, the response of the residents shows that the percentage of people wanting no change is very similar to each other (around 30%). The adapting nature of humans towards the thermal environment in mud structures can be seen in both the vernacular as well as the modern mud shelters, however, the results indicated in the histogram have a very small sample size and a larger sample size must be taken for the reliability of the outcomes.



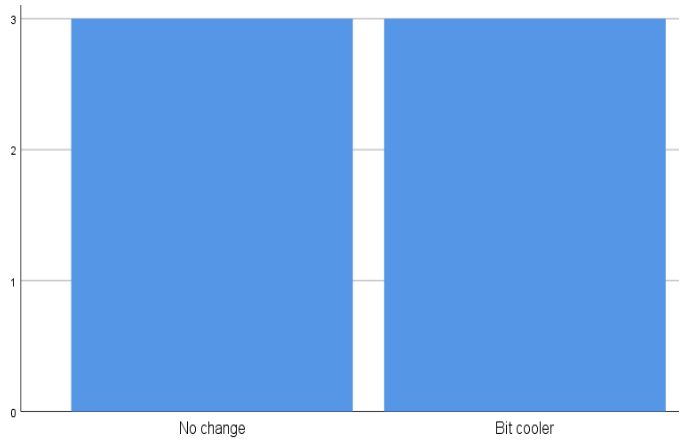


Figure 4.49 TP comparison - SMM mud structure(left) and rammed earth(right)

- Thermal comfort

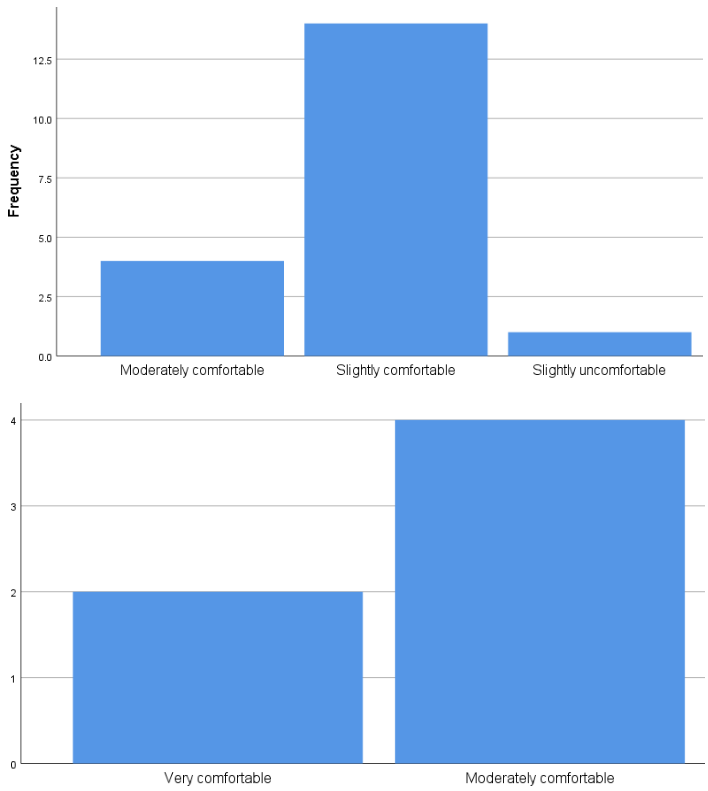


Figure 4.50 Thermal Comfort - SMM mud shelter vs Rammed earth

The thermal comfort indicators show that respondents are more comfortable in rammed-earth mud shelters (100%) compared to SMM mud shelters (73%). The results show that the respondents of rammed earth are moderately comfortable in their house, to say the least whereas, most votes in SMM mud shelters are for slightly comfortable only. The number of respondents in both types of shelters is different, hence, there may exist some bias in the comparison of thermal comfort responses.

- <u>Opening to Wall ratio</u>

The overall ratio of opening to wall area in SMM shelters compared to rammed earth houses is very low which affects the entrance of air which is important for air circulation and thermal transmission through the convection process. The opening-to-wall ratio not only affects the thermal performance but also decreases the overall air quality inside the room. In addition, the only available opening in doors has two significant drawbacks, namely, low amount of heat and air circulation and low direct solar gain.

	Shelter Type	
	SMM mud	Rammed earth
Opening to Wall ratio	Single storied: 4.9%-6.5% Double storied: 16.9%-20%	Single: 26-28% Double:30-33%

A building's interior thermal comfort and overall energy use are significantly impacted by the orientation and window opening ratio utilized in the structure. The passive solar design solutions are mostly affected by the direction and opening ratio. Rammed earth buildings use passive design techniques according to table 4.3. By exposing living spaces to the sun, passive solar design helps in the utilization of the sun's energy for heating and cooling. Additionally, the larger openings in rammed earth structures result permit the free movement of air in places along the building's east-west axis in the summer. Moreover, during the summer, shade trees, ponds, and overhangs on south-facing blocks reduce the heat effect on buildings, whereas the opposite is true during the winter. These fundamental reactions to solar heat influence design decisions, material selections, and placements.

- Roof

The vernacular SMM mud shelters have naturally rammed mud roofs which is very beneficial for direct solar absorption which is released very slowly due to the high thermal lag of rammed earth. However, the roof type of modern rammed earth structure is a CGI roof with well-insulated layers and ventilation gaps. However, these structures are both built with passive design strategies in which one came as a natural solution whereas another is the technological advancement in achieving thermal comfort.

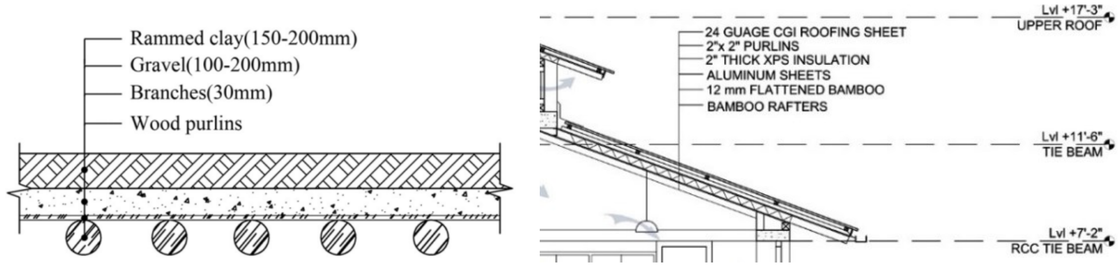


Figure 4.51 Roof Section Detail of rammed roof(SMM) & CGI roof(rammed earth)

4.3.4 Influence of mud as an insulating material

Rammed earth which is made up of mud has a high thermal mass which helps to stabilize the thermal fluctuations compared to RCC structures from this study as well as previous literature. However, 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 the figure below. The figure shows the temperature fluctuation between indoors and outdoors throughout the day in an hourly format for mud shelters in the mountainous regions and rammed earth in the hilly regions. The comparison between these two results shows that rammed earth has a time lag of around 4 hours whereas the SMM mud shelters have a time lag of at least 1.5 hours. The thermal performance of an 18” rammed earth wall in comparison to an 18” SMM mud shelter with 3” thick mud plaster shows that it is better to use rammed earth instead of SMM mud shelters. However, it is difficult and costly to construct the rammed earth, instead, a thicker mud plaster could be used for better thermal performance as shown in the figure.

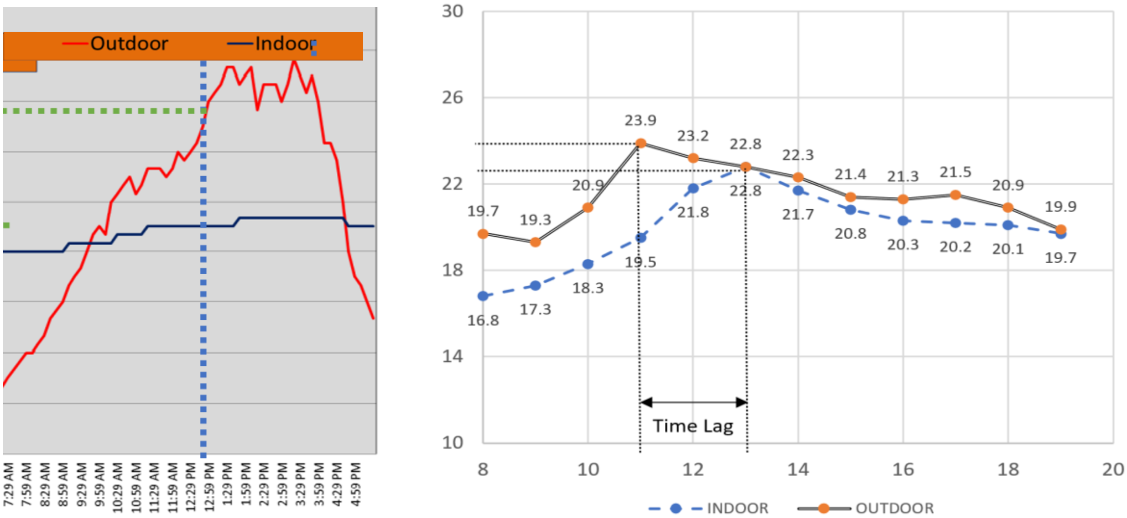


Figure 4.52 Approximate Time Lag in rammed earth and SMM mud-shelter

4.3.5 Influence of clothing on thermal comfort

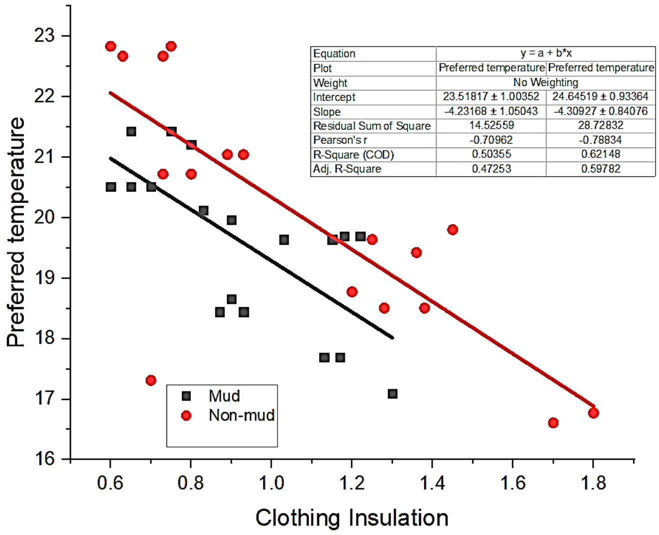


Figure 4.53 Influence of clothing in the mountain region

The ideal temperature drops as garment insulation rise. To perform a regression analysis, we have the following equation.

Mud: $T_{per} = -4.23\ I_{cl} + 23.5$ ....(1)

Non mud: $T_{per} = -4.30\ I_{cl} + 24.64$ ....(1)

The preferred temperature is inversely associated with apparel insulation, as seen in Figure 6. 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. We can infer that the lower clothing insulation value is what causes the higher preferred value in both mud and non-mud constructions. The preferred temperature of mud constructions is, nevertheless, lower than that of non-mud structures. We can claim that people need to dress more when the indoor temperature is lower in non-mud constructions and less when the indoor temperature is greater in mud structures.

CHAPTER 5: CONCLUSION

5.1 Summary of key research findings

Mud shelters in Nepal have a significant role in representing the vernacular architecture which blends with surrounding nature. It is found in all the different geographic and climatic regions of Nepal in different forms. However, mud shelters as residential dwellings are rapidly being replaced by modern concrete structures due to their better serviceability in day-to-day life. Recent researches and case studies show that mud shelters have better thermal performance compared to modern structures in various parts of the world. In Nepal, there is a lack of thermal performance studies from an architectural perspective where the material, space, and planning play an essential role in providing comfortable conditions. To study and compare the thermal performance of traditional and modern mud shelters with modern concrete structures, thermal environment measurements, and a thermal comfort survey was conducted. Additionally, their inherent architectural strategies, problems of thermal comfort, and solutions were also studied. Those studies have respective outcomes. In the cool temperature region, the thermal measurement during the initial months of winter to summer transition shows that traditional SMM mud shelters are on a daily average of 0.5 °C warmer 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. In the warm temperate region, the thermal measurement in summer shows that rammed earth mud shelters were 0.7−1°C cooler than concrete structures. The thermal comfort comparison also shows that rammed mud shelters have 0.5°C lower comfort temperatures than non-mud shelters. This indicates that people are more comfortable in mud shelters in such regions. While calculating preference, the residents of the mountain region during the initial months of winter to summer transition prefer 0.5°C higher temperatures in mud compared to 1°C higher temperature in non-mud shelters. Similarly, in the hilly region during the summer season, the comfort and preferred temperature are the same in rammed earth mud shelters whereas, for non-mud shelters, the preferred temperature is 1°C cooler than the comfort temperature. This indicates that people are statistically preferring mud shelters for better thermal comfort.

A comparison of traditional mud and modern rammed earth structure in the different regions showed that modern rammed earth structures are even better than traditional mud structures which may be due larger thickness of mud walls as a scientific passive design strategy for avoiding harsh summer and winter climates. The influence of mud as an insulating material shows that rammed earth mud shelters have a higher time lag than the SMM mud shelters as mud shelters used more in width and thickness are better in providing excellent thermal lag due to their high thermal mass.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. The conditions before and after the modifications of such passive strategies on the specific location are shown and its effect on the surrounding vernacular architecture is discussed.

5.2 Recommendations

From the above investigation of thermal performance, the following recommendations are proposed. The findings might not be applicable in all the regions but they mostly can be applied to rammed earth structures and SMM mud shelters in cool temperature and warm temperate regions. The recommendation mainly concerns the further investigations that need to be done in the future in this particular area of interest.

- Rammed earth and SMM mud structures are sustainable structures as both structures are made from local natural materials. Their active and embodied energy consumption is also lower. Hence, more studies are required for these structures to compete with concrete structures in market construction. Architectural studies which involve balancing space, material, economy, and sustainability are required in the future.
- Nepal has different climatic conditions in different parts, therefore more studies on different mud shelters in different parts of the country like tropical, alpine and semi-arid locations should also be conducted in the future.
- Rammed earth carries a huge social and cultural value in the different parts of the local community; hence its construction should be made easier by providing necessary documentation for its faster and more durable construction according to the available materials around the different regions of Nepal.

- The thermal comfort of rammed earth is superior; however, it has higher maintenance costs due to it being constructed using compression of mud as it might get washed away due to rainwater, and weathered away due to wind. Therefore, sustainable and cost-effective prevention methods should be developed soon.

5.2.1 Improved Architectural Design of traditional shelters

The knowledge of thermal performance, thermal comfort, and passive design strategies have been used to propose a sustainable thermal improving technique across different architectural elements. The main focus is kept on the composition of walls, floors, ceiling, and the roof which is considered an integral part of maintaining the thermal comfort of the shelter. We have tried to combine the current knowledge of rammed earth with the traditional practices of SMM mud shelter construction to create dwellings without hampering the social and cultural significance of the visual architecture in the respective region. The suggested improvements in the architectural design are as follows:

- <u>Walls:</u>

The proposed composite wall structure is made up of rammed earth(73%)+SMM(23%) and mud plaster(4%) 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. The width of the rammed earth is considered the highest as it provides higher thermal stability than the SMM walls. In addition, the rammed interior walls are required to be constructed as a monolithic wall which prevents thermal leakages and provides a better envelope. A study conducted on various composite walls made up of mudstone and plaster showed that the combination of Stone-mud-stone had the same thermal characteristics as the mud-stone-mud configuration (Energy and Buildings). Hence, we preferred a higher amount of mud in the form of rammed earth to be used in the wall structure for better thermal endurance during extreme periods of the season with or without wooden planks inside at the height of 2’6”. The U-values of the planned wall vary significantly depending on whether the wooden planks are present or not. Without the wooden planks, the wall has a U-value of 0.37W/m°C, however, with the added, it drops to 0.31W/m°C, which is 0.23 W/m°C and 0.29 W/m°C less than the U-values of the nearby mud shelters. Therefore the type of wall is suggested so that it can store heat during the day and slowly release it during the nighttime.

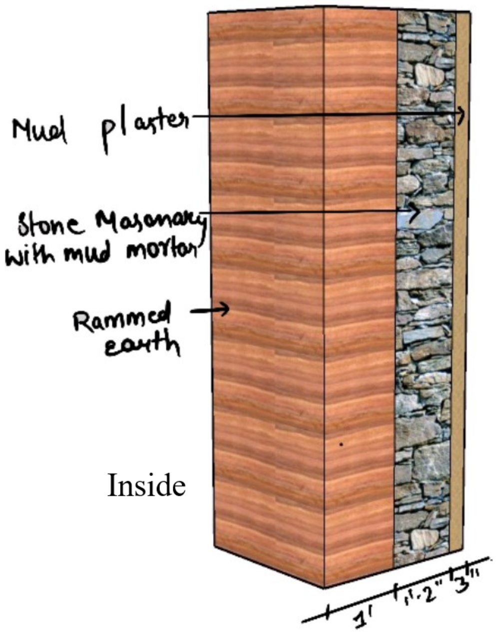


Figure 5.1 Composite wall w/o wooden plank

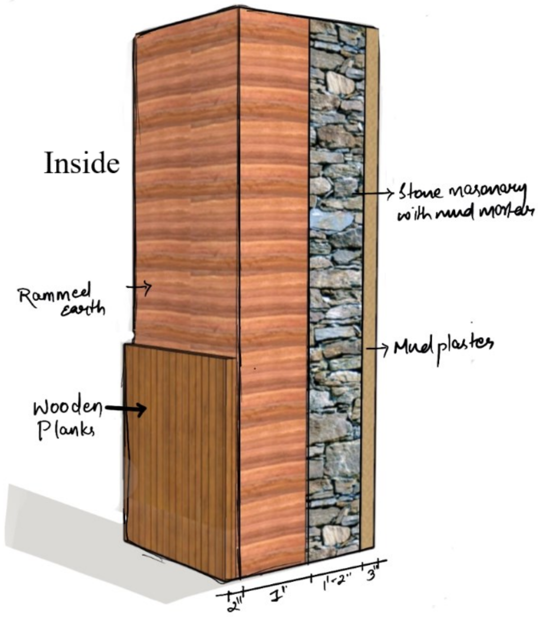


Figure 5.2 Composite wall with a wooden plank

- <u>Floors:</u>

The traditional buildings in the cool temperate climate of Nepal have floors directly attached to the ground with rammed earth underneath the floor level. During the colder season when snow falls, the ground temperature becomes around 0degC as well as the overall temperature of the surrounding falls way below the comfort level. To maintain better thermal comfort inside the structure, we propose an air gap between the ground and floor level to create thermal insulation as air is a bad conductor of heat. 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, 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. We have thought about a straightforward yet environmentally friendly strategy that keeps the building above the ground.

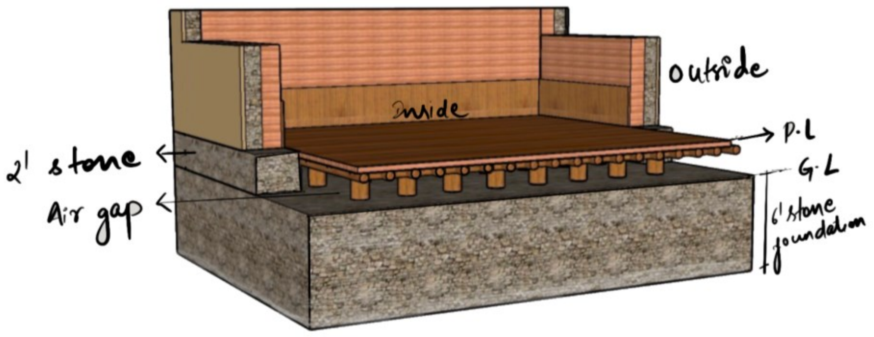


Figure 5.3 Proposed floor design

- Roofs:

Unlike most of the modern structures made in Nepal, older traditional structures still have rammed earth roof structures as a vernacular architectural element. The roof consists of rammed earth placed over the small wooden planks which are naturally compressed by the residents walking over the roof. Our design considers additional two layers of branches and gravel so that there is less use of rammed earth 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" wooden pegs, and 1" dried branches which are covered by 8inch of sand/gravel followed by 8inch of rammed earth on the top. According to calculations, the planned roof has a U-value of 0.43, which is lower than the U-values of the existing mud huts in the mountainous area. It has been determined that the intended mud roof is less by 2.16 and 1.72 when compared to this value and the maximum and minimum values, or 2.59 and 2.15, of the roof of the existing mud shelter.

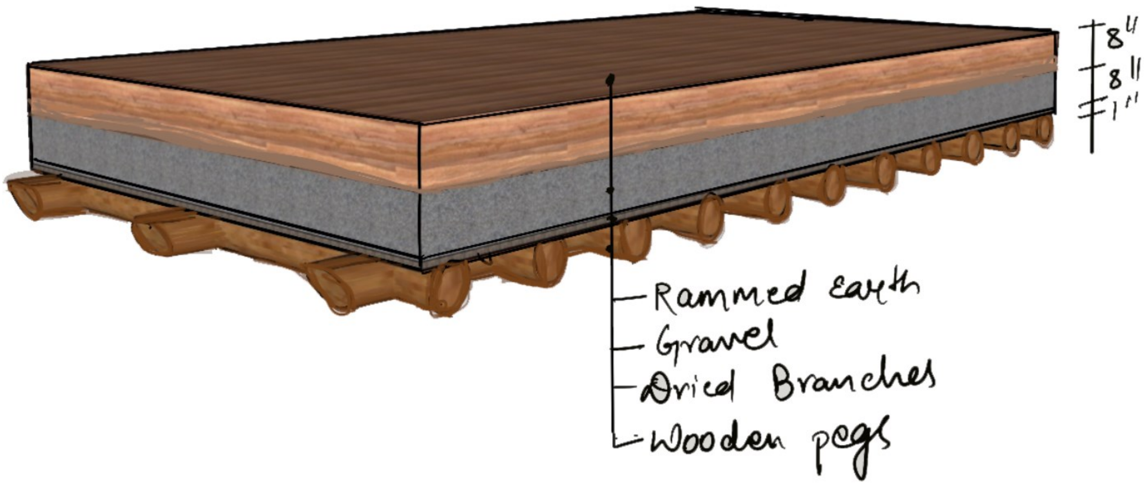


Figure 5.4 Proposed roof design

- <u>Orientation, Opening, and location of heat source:</u>
-

- Other architectural features:

The arrangement of the house is compact with no spaces between such that heat conduction towards the outer environment is minimized. We considered the design of the buildings on either side of the road along the east-west direction such that the façade of the houses is always facing 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 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. For summer seasons, double glazed windows are provided in the east direction which can be opened during the summer period. 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 homestay-like environment has been developed which can improve the ambiance of the house and provide a homestay experience that can be used for tourism purposes.

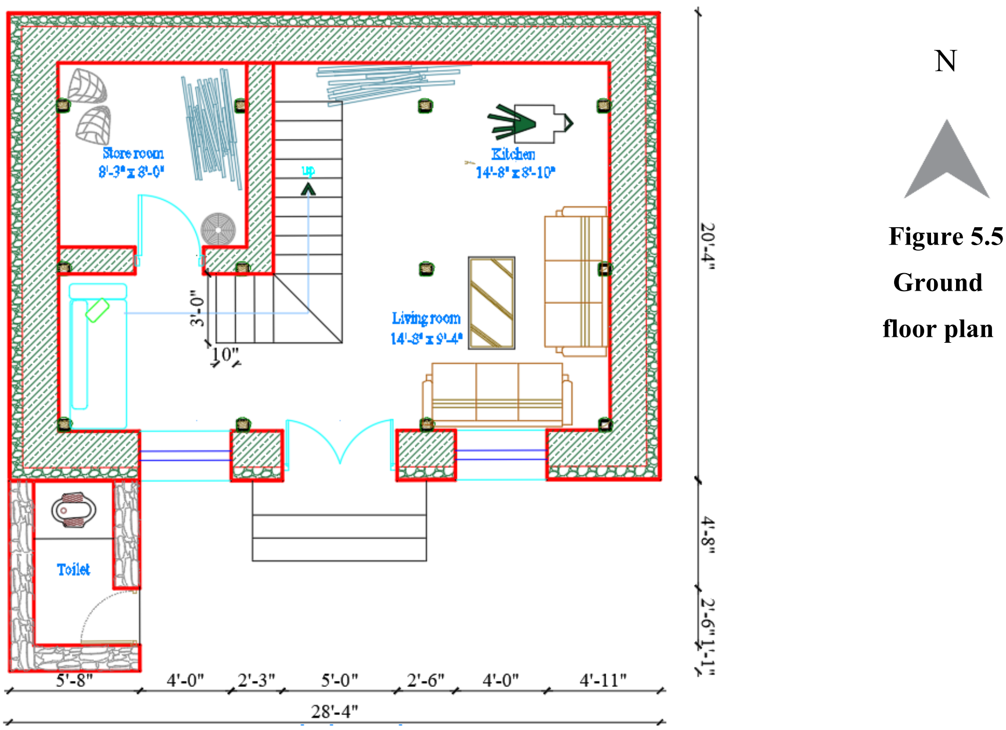


Figure 5.5 Ground floor plan

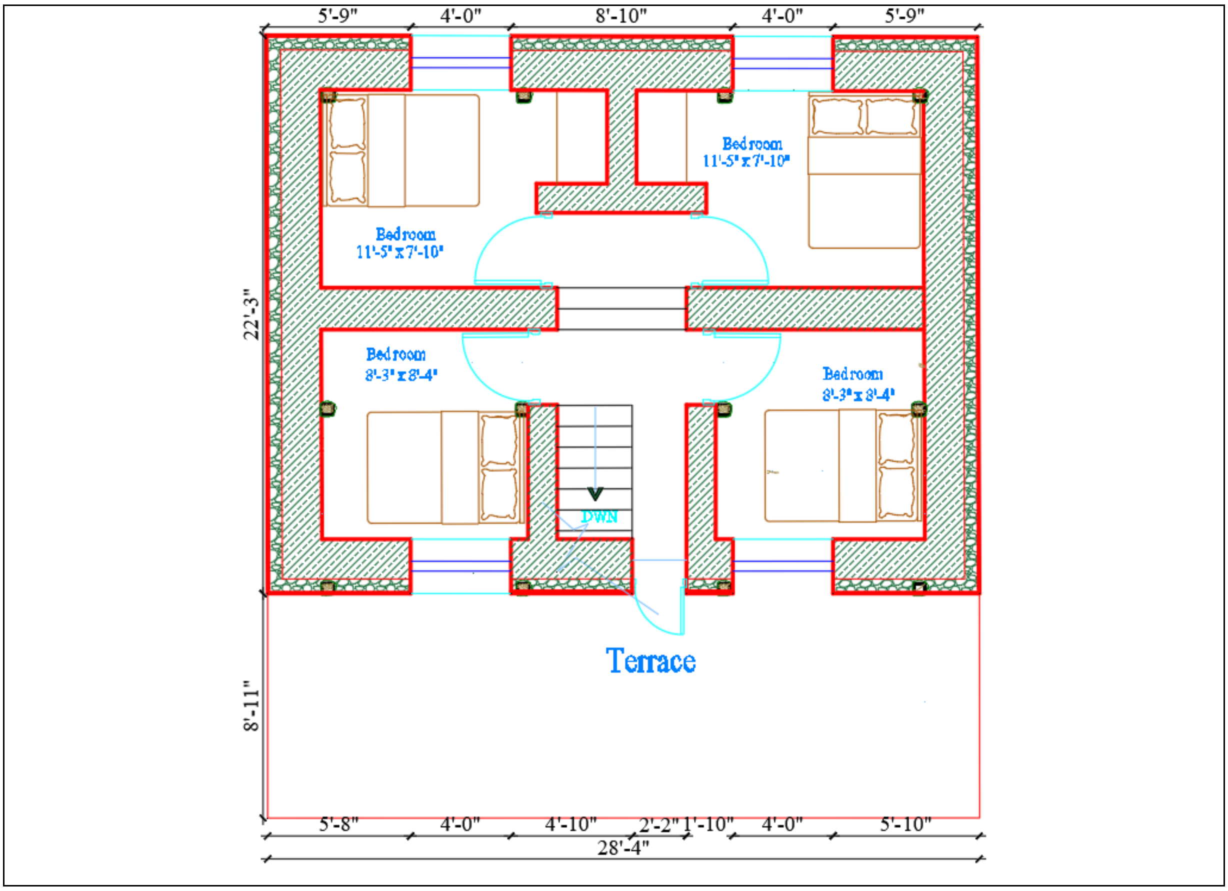


Figure 5.6 First floor plan

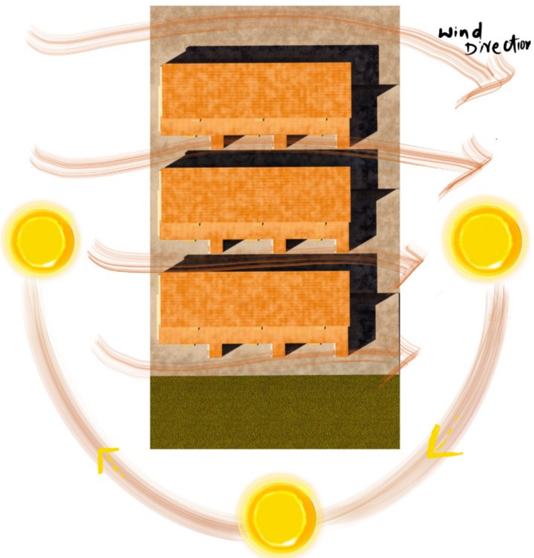


Figure 5.7 Front view of the proposed building

Figure 5.8 Proposed settlement pattern

Figure 5.9 Perspective view

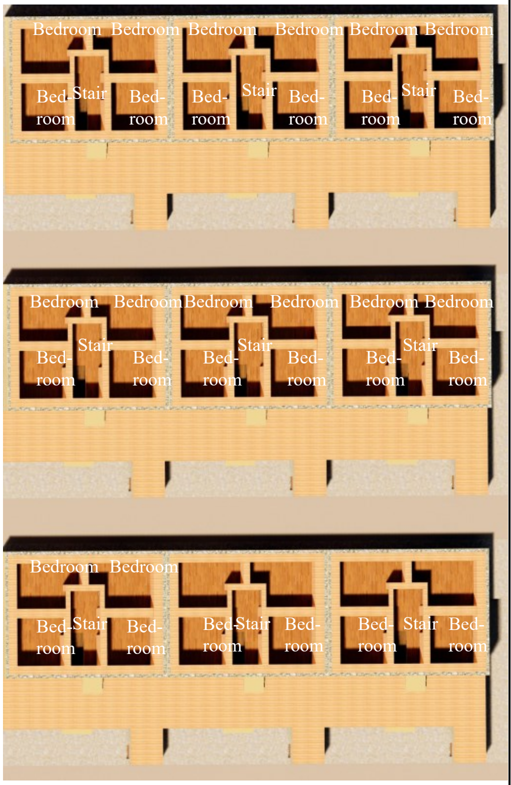


Figure 5.11 Proposed floor plan

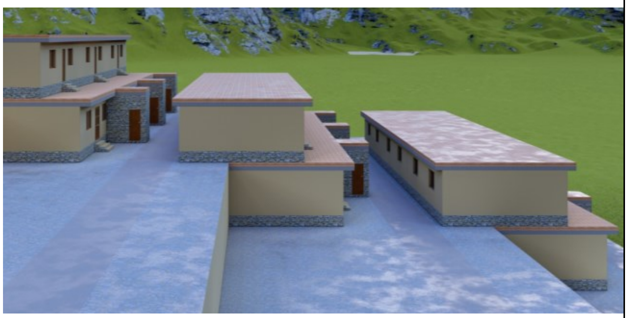


Figure 5.10 West View

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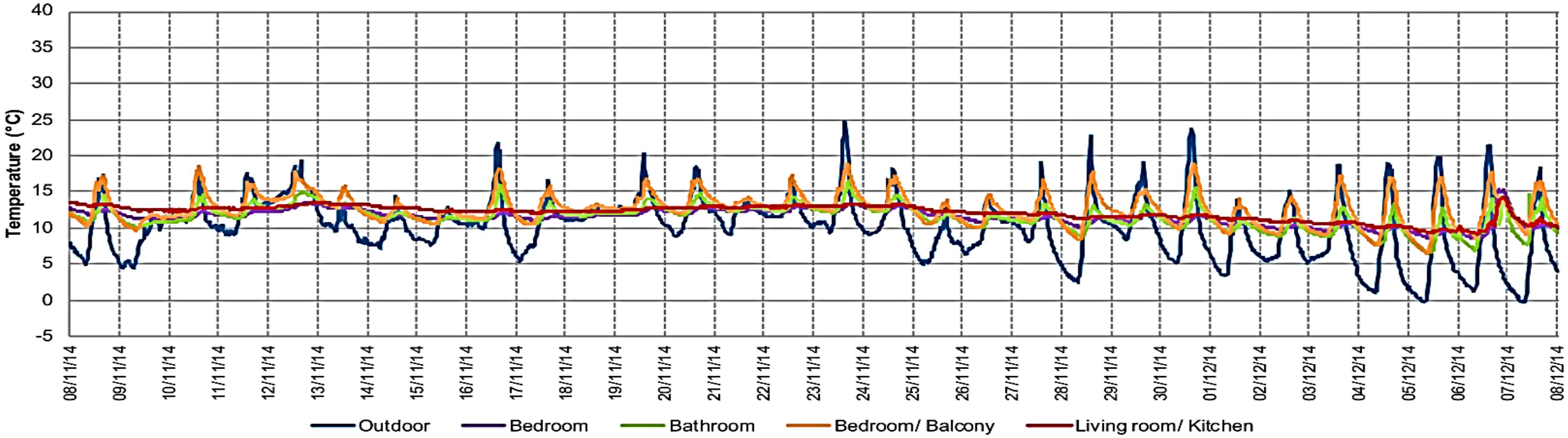
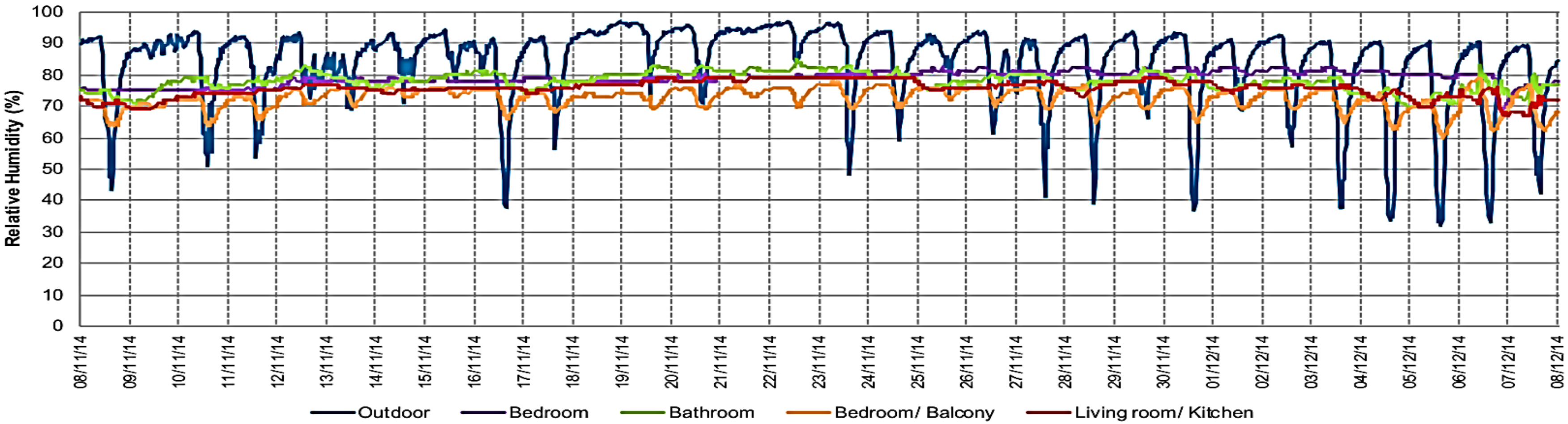
ANNPENDIX A : Indoor Outdoor Temperature & Humidity Profile

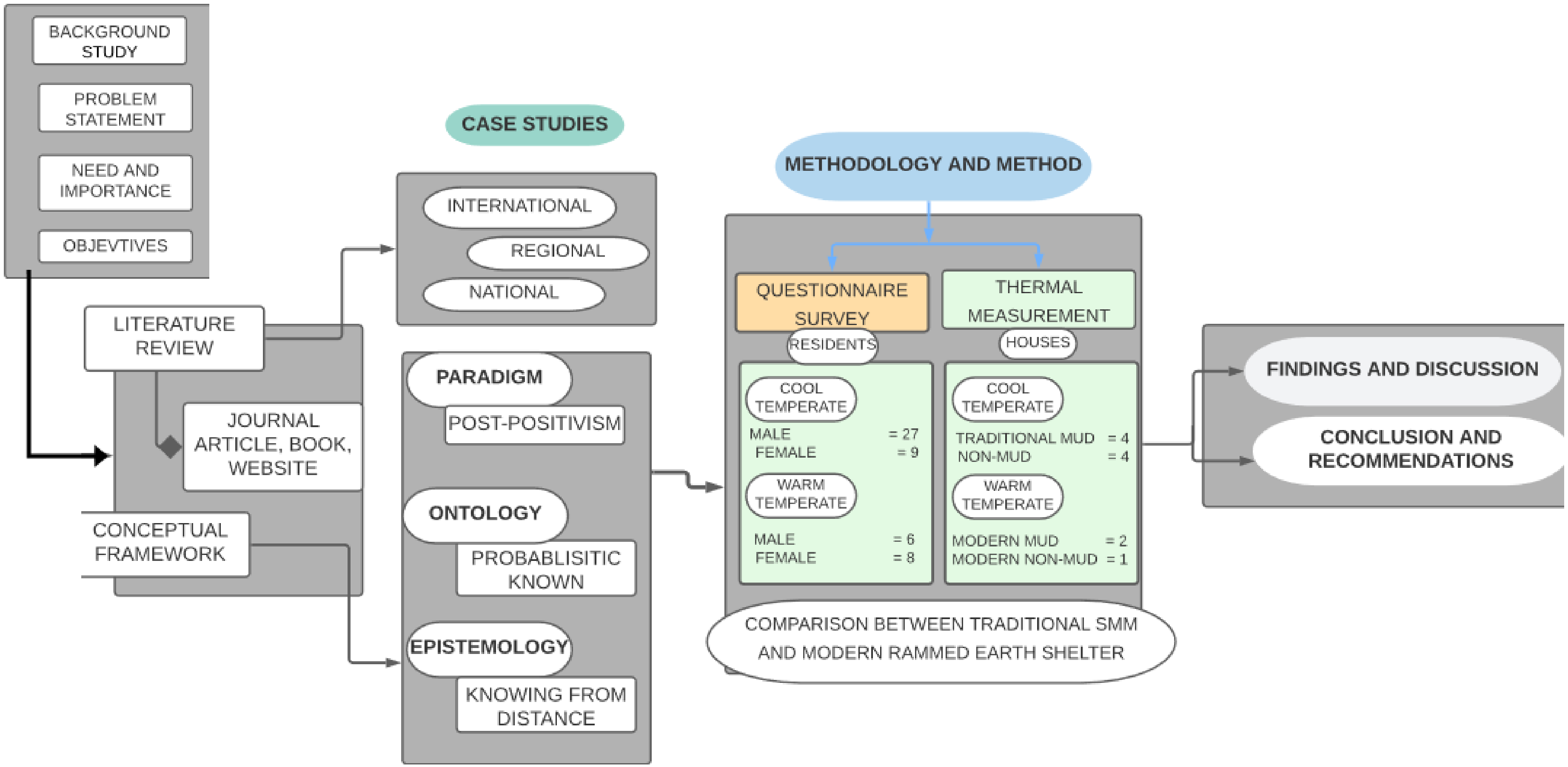
Appendix A(1): Autumn monitoring:



Appendix A(2): Autumn monitoring: Indoor and Outdoor air relative humidityprofile

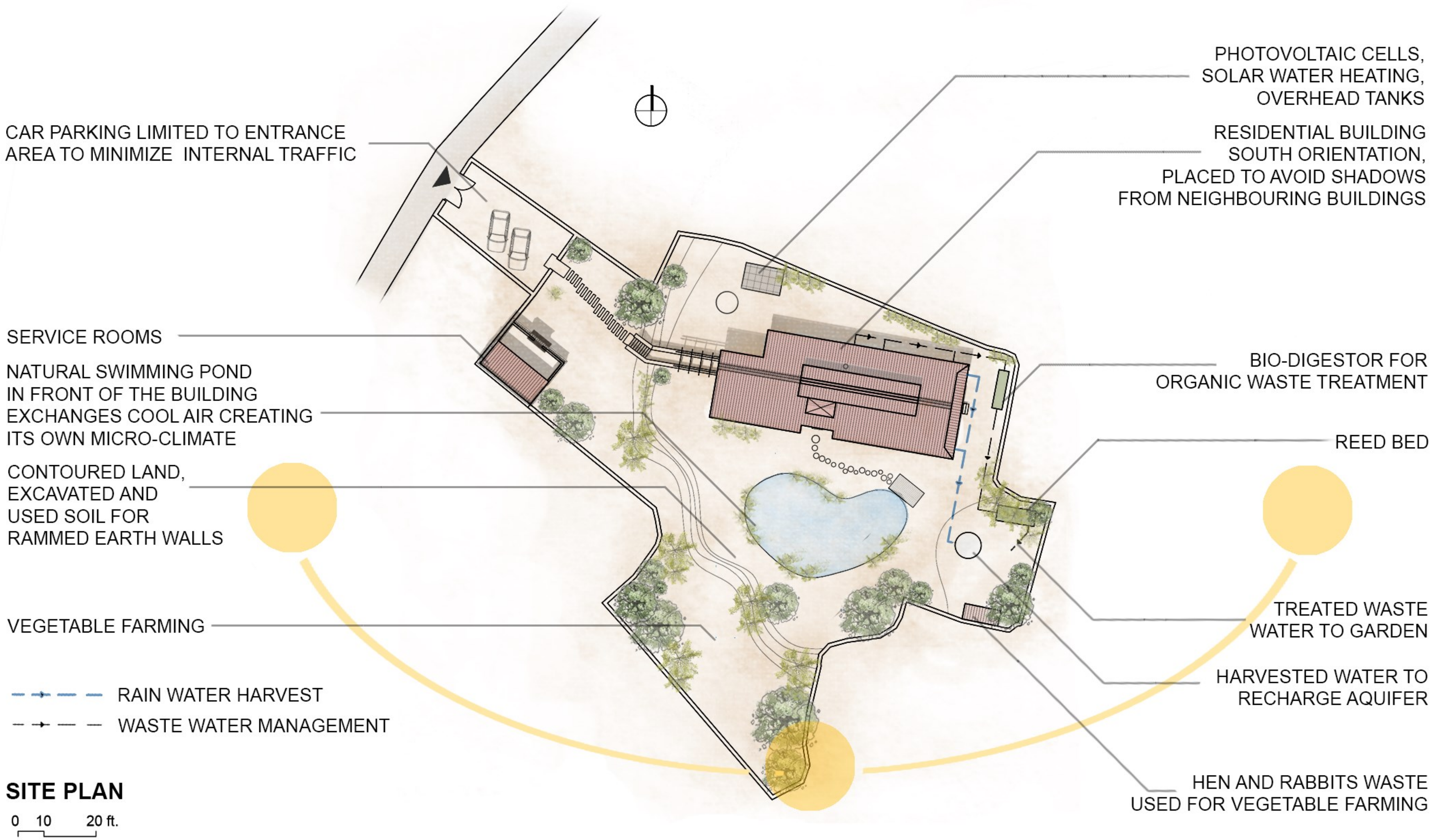


APPENDIX B: Flow diagram of Research



Note:

APPEENDIX C: Site Plan of MatoGhar



APPEENDIX D: Properties and Pictures of Studied Houses

- Mountainous Region

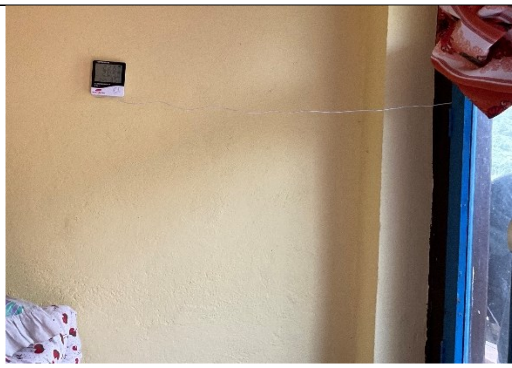
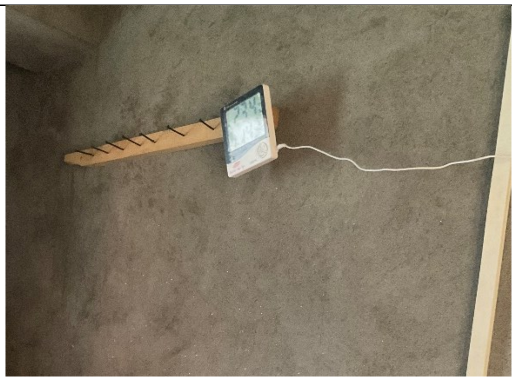
Parameters	**House A**	**House B**	**House C**	**House D**	**House E**	**House F**	**House G**	**House H**
Type	Traditional	Traditional	Traditional	Traditional	Modern	Modern	Modern	Hybrid
No.of story	1	1	2	2	3	1	2	1
Building Form	Rectangular, attached houses	Rectangular	Rectangular, attached houses	Rectangular, attached houses	Rectangular	Rectangular	Rectangular, attached houses	Rectangular, attached houses
Building Orientation	East	North	West	West	North	East	West	West
Internal space and planning	Compact planning, terraces as open spaces	Compact planning, terraces as open spaces	Compact planning, terraces as open spaces	Compact planning, terraces, and balcony as open spaces	Compact planning, open spaces as the ground area	Compact planning, open spaces as the ground area	Compact planning, open spaces as the ground area	Compact planning, terrace, balcony, and ground area as open spaces
Load resistance	Wooden beam Post	Wooden beam Post	Load bearing, shear wall	Wooden beam post	Rcc column: 1’ x 1’	RCC column : 1’ x 1’	Wooden beam post	RCC column : 1’ x 1’
Wall materials	Stone with mud mortar	Stone with mud mortar	Stone with mud mortar	Stone with mud mortar	Stone with mud mortar+ 2” plaster	4” RCC shear wall, 2” plaster +2’-7” height planks	SMM+ 3” mud plaster on both sides	RCC

Wall thickness	1’-6”	1’-10”, 8” for partition	1’-6”	1’-10”	14”	6”	1’-6”	9”
Sill height	No windows	No windows	No windows	2’-4”	2’-6”	2’-4”	1’-11”	2’-3”
Lintel height	6’-0”	4’-6”	6’-0”	6’-7”	7’-10”	7’-4”	7’-0”	6’-8”
Flooring/ceiling materials	Mud	Mud	Wooden planks	Mud	Wooden planks	Rcc	Wooden planks	RCC
Foundation	6' stone wall	6' stone wall	6' stone wall RCC	6' stone wall	6' stone wall	6' stone wall	6' stone wall	6' stone wall
Roofing materials	Mud (void for ventilation)	Mud (void for ventilation)	Mud (void for ventilation)	Mud (void for ventilation)	Sloped CGI roofing	RCC	Sloped CGI Roofing	RCC
Thickness of roofing	1’	8”	10”	10”	.01” leaving a gap of 3’ for false ceiling	5”	.01” leaving a gap of 3’ for false ceilings	4”
Openings	No windows	No windows	No windows	Windows on north	Southside	Windows on north, south, and east	Windows on south, east, and west	Windows on west
Lintel height	6’-0”	4’-6”	6’-0”	6’-7”	7’-10”	7’-4”	7’-0”	6’-8”
Floor height	5’-10”	5’-9”	7’-8”	6’7”	8’-6”	8’-0”	7’-9”	7’-8”

- Hilly Region

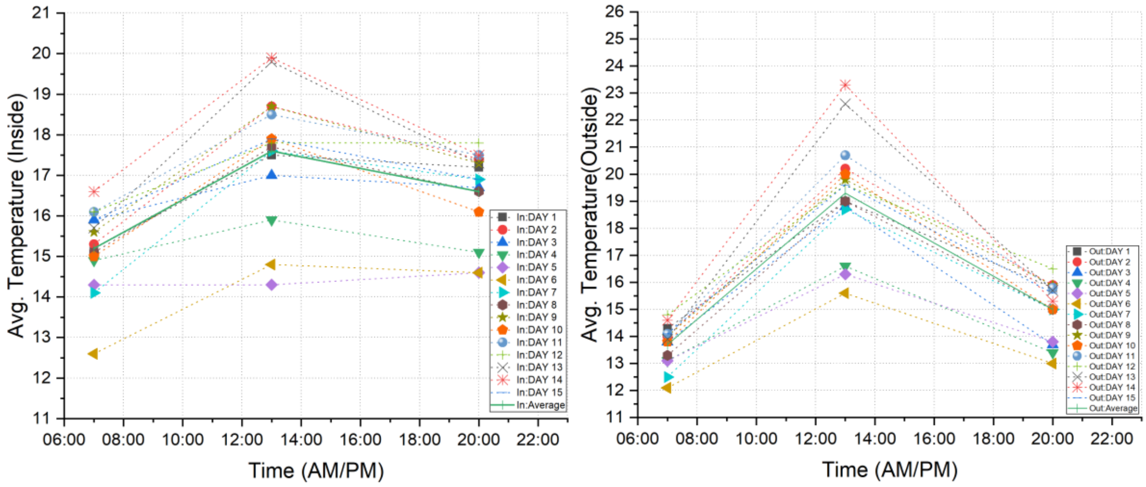
Parameters	**House I**	**House J**	**House K**
Type	Modern	Hybrid	Modern
No.of story	1	2	1
Building Form	Rectangular, attached houses	Rectangular	Rectangular, attached houses
Building Orientation	East	North	West
Internal space and planning	Compact planning, terraces as open spaces	Compact planning, terraces as open spaces	Compact planning, terraces as open spaces
Load resistance	Rcc frame	Wooden beam Post	Load bearing, shear wall
Wall materials	Stone with cement mortar	Stone with mud mortar, cement plaster	4” RCC shear wall, 2” plaster +2’-7” height planks
Wall thickness	14" with 2" plaster	18"	14”
Sill height	No windows	No windows	No windows
Lintel height	6’-0”	4’-6”	6’-0”
Flooring/ceiling materials	Wooden planks	Wooden planks	RCC
Foundation	6' stone wall	6' stone wall	6' stone wall
Roofing materials	Sloped CGI roofing	CGI roofing	5"
Thickness of roofing	1’	8”	10”
Openings	No windows	No windows	No windows
Lintel height	6’-0”	4’-6”	6’-0”
Floor height	6’-5"	8’-6"	6’-6”

- <u>Location of thermal equipment in different house types</u>

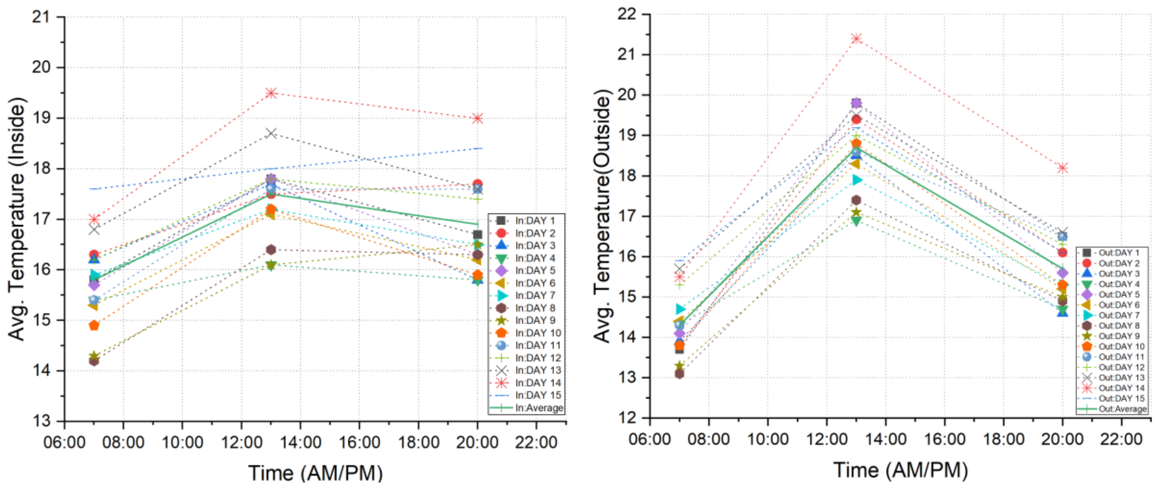
 **TYPE I-A**	 **TYPE I-B**
 TYPE II-C	 TYPE II-D
 TYPE III-E	 TYPE III-F
 TYPE V-G	 TYPE IV-H

APPEENDIX E: Average temperature of individual houses in mountainous region

- <u>Single storied SMM with mud roof</u>

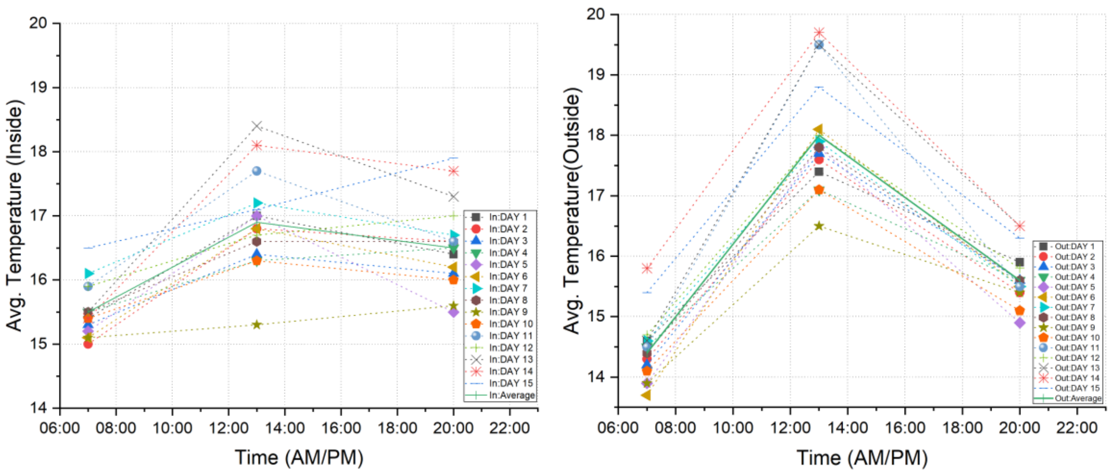


HOUSE I-A

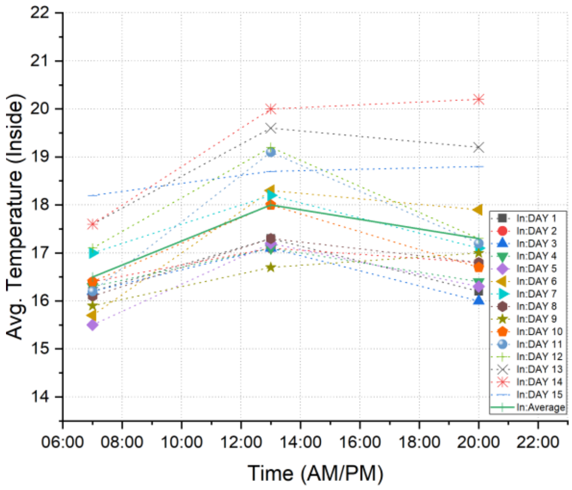


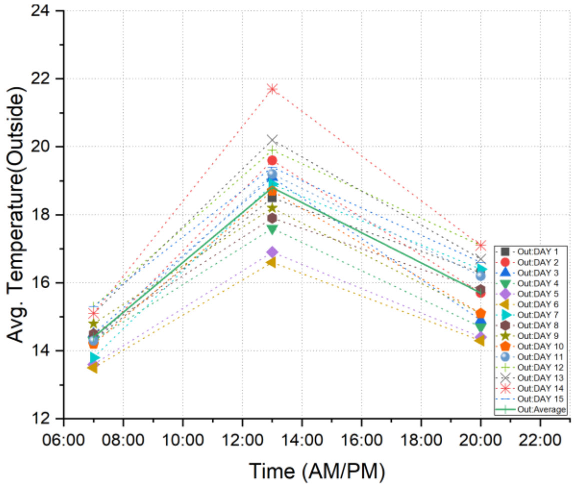
HOUSE I-B

- <u>Double-storied SMM with mud roof</u>



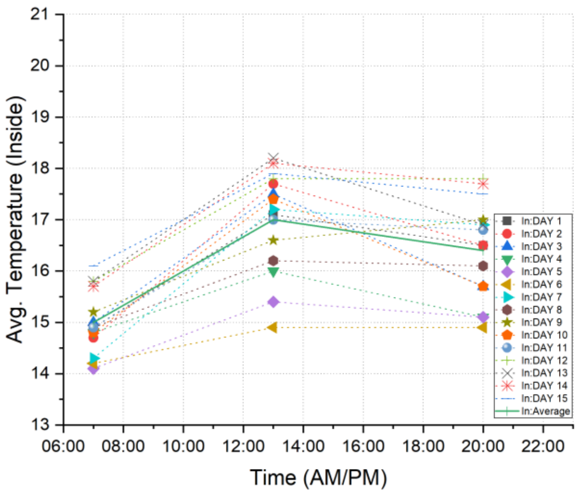
HOUSE II-C

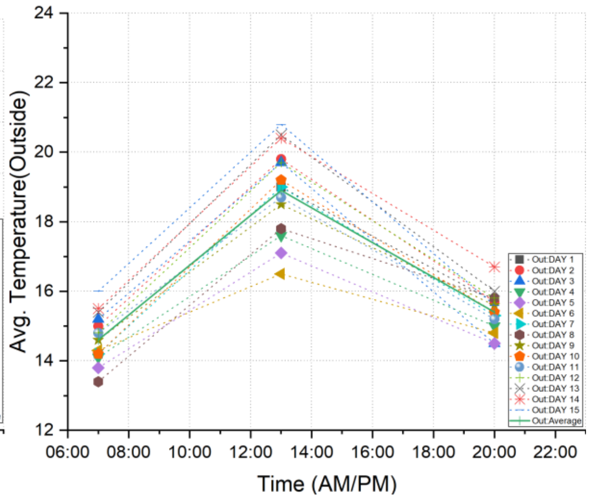




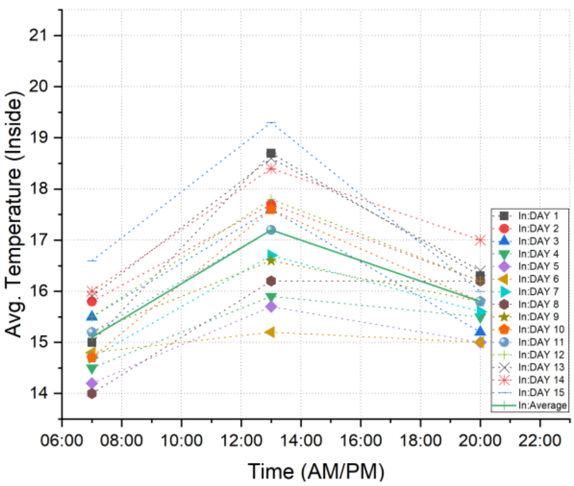
HOUSE II-D

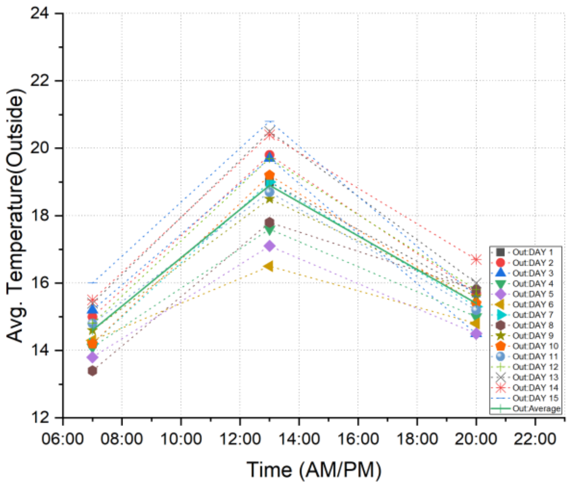
- <u>Single storied RCC</u>





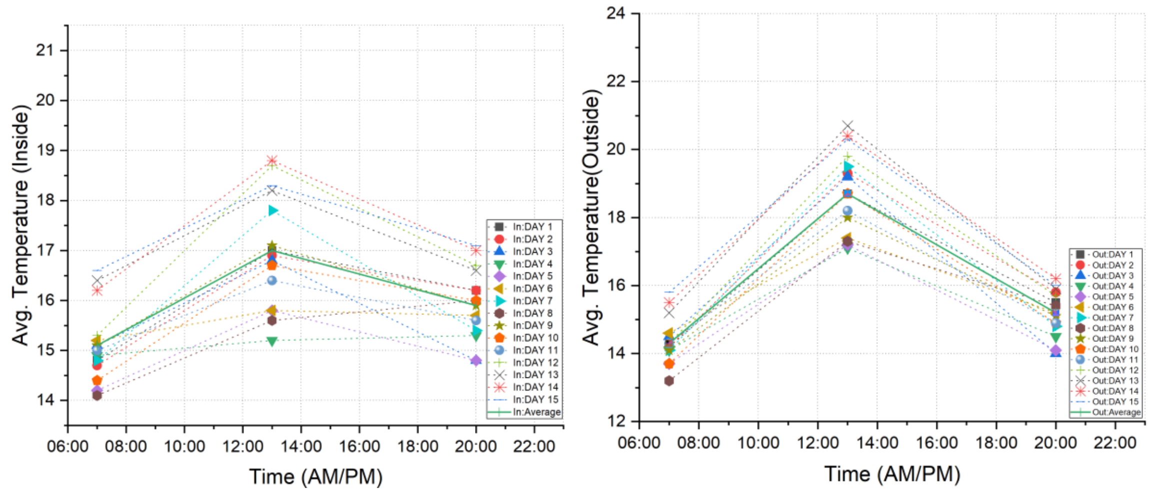
HOUSE III-E





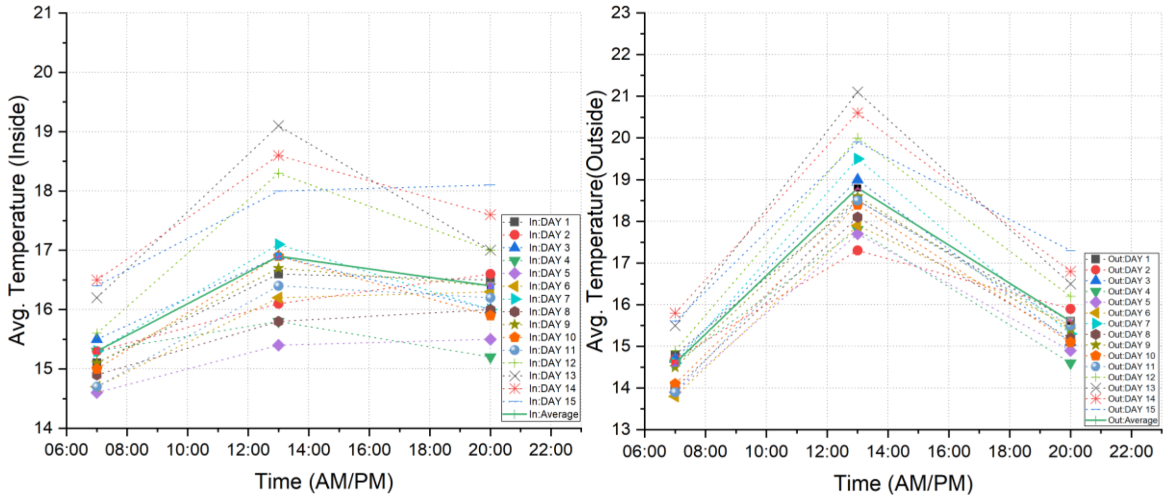
HOUSE III-F

• Triple storied RCC



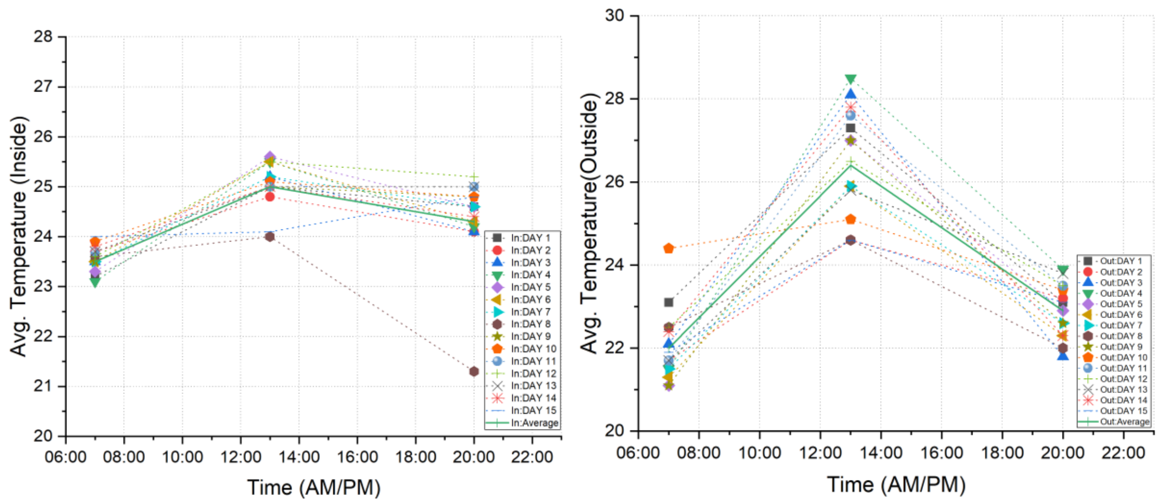
HOUSE IV-H

• Double storied SMM with cement plaster



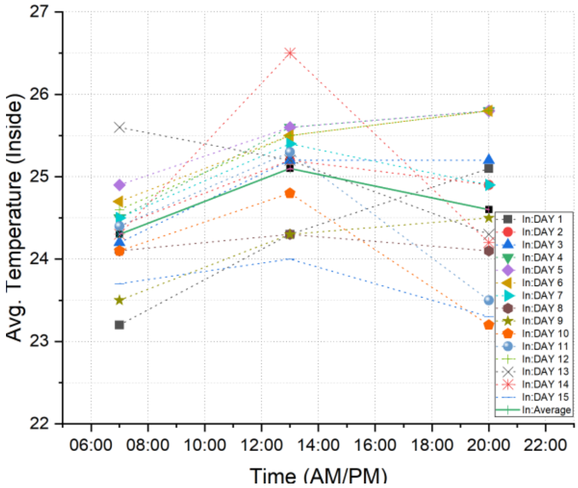
HOUSE V-G

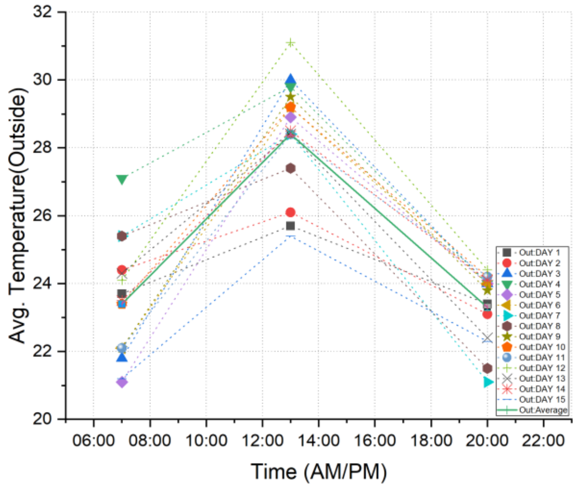
• Single storied rammed earth



HOUSE VI-I

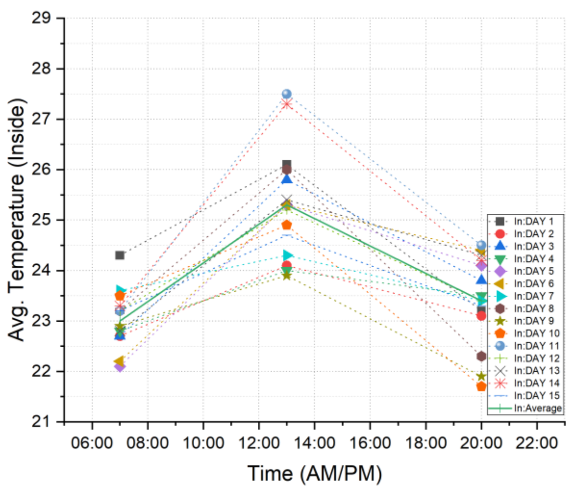
- <u>Double storied rammed earth</u>

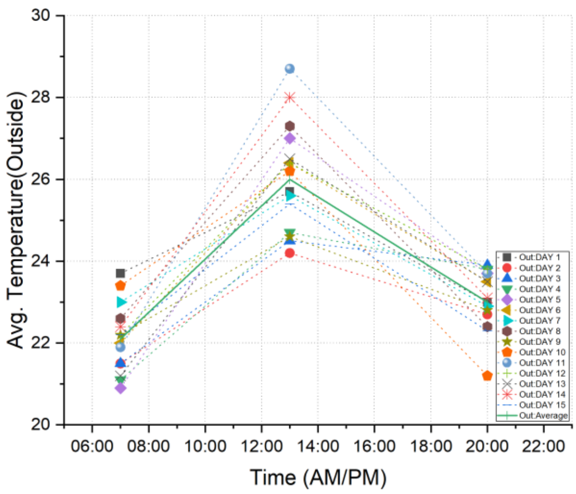




HOUSE VII-J

- <u>Double storied RCC concrete</u>





HOUSE VIII-K

APPEENDIX F: Questionnaire for Survey

Note: Point In time of Survey
Inside Temperature:
Outside Temperature:
Relative humidity:

A. Demographic Data		
A1. Name of the respondent	A2. Age	A3. Gender
	□ 15-25 □ 26-40 □ 41-60 □ 60 above	□ Male □ Female

B. Date, Time and Location			
B1. Date:	B2. Time	B3. Location	B4. Specifics
		Latitude: ____________ Longitude: ____________	Living Rom □ Kitchen □ Bedroom

C. Building Information		
C1. Type of building	C2. Number of storeys	C3. Housing Occupancy
□ Traditional □ Modern	□ Single □ Double □ More than 2	Housing Occupancy

D. Building environment, Activity, and Clothing		
D1. Current scenarios of openings(windows/doors) based on four different sides?	D2. What was your activity status during the first 30 minutes of filling out the questionnaire?	C3. Housing Occupancy

D. Building environment, Activity, and Clothing		
East: West: North: South: Note: Size of Opening ____________________	□ Sitting □ Lying/Sleeping □ Occasionally walk □ Cooking □ House Cleaning □ Pick and shovel work □ Machine work □ Dancing/ exercise □ Other If others, please specify	Housing Occupancy

D3. Clothing Insulation

Only large variables of clothing are considered, the rest are assumed. Based on ISO 9220.

Garment Description	Tick	Iclo	Garment Description	Tick	Iclo
Inner Layer			**Head Gear**		
Shirt, short-sleeved		0.09	Cap, Hat or comparable		0.01
Shirt, Long sleeved		0.12	Warm winter cap		0.03
Pants, short		0.03	Scarf		0.01
Pants, Long		0.1	**Gloves**		
Middle Layer			Gloves/mittens, thin		0.05
Shirt, Thin		0.2	Gloves/mittens, thick		0.08
Shirt, thick		0.35	Gloves/mittens, thermal or leather		0.11
Pants, middle layer		0.25	**Socks and shoes**		
Tights		0.03	Socks, thin		0.02
Outermost layer			Socks, second thin		0.02
Jacket, thin		0.26	Socks, thick		0.05
Jacket, Thick		0.4	Woollen footwraps		0.1
Trousers, thin		0.25	Safety shoes		0.04
Trousers, thick		0.35	TOTAL		

E. Thermal Preference	
E1. At this moment, what is your perception on general thermal sensation?(mTSV) यस क्षणमा, सामान्य तातो चिसोको अनुभूतिमा तपाईंको धारणा के छ?	
□ Very cold(1) (धेरै चिसो) □ Cold(2) (चिसो) □ Slightly cool(3) (थोरै चिसो) □ Neutral(4) (तटस्थ)	□ Slightly warm(5) (थोरै तातो) □ Hot(6) (तातो) □ Very hot(7) (धेरै तातो)
E2. What is your thermal preference(TP)? तपाईको तातो चिसोको प्राथमिकता (TP) के हो?	
□ Much warmer(1) (धेरै तातो) □ A bit warmer(2) (अलि तातो) □ No change(3) (कुनै परिवर्तन)	□ A bit cooler(4) (अलि चिसो) □ Much cooler(5) (धेरै चिसो)
E3. Are you able to accept the current thermal environment? (Thermal Acceptance) तपाईं वर्तमान तातो चिसोको वातावरण स्वीकार गर्न सक्षम हुनुहुन्छ?	
□ Highly Acceptable(अत्यधिक स्वीकार्य) (1) □ Moderately Acceptable(मध्यम रूपमा स्वीकार्य)(2) □ Slightly Acceptable(अलिकति अस्वीकार्य)(3) □ Acceptable(अस्वीकार्य)(4)	□ Slightly Unacceptable (अलिकति अस्वीकार्य)(5) □ Moderately Unaacceptable(सामान्य रूपमा अस्वीकार्य)(6) □ Highly Unacceptable(अत्यधिक अस्वीकार्)(7)
E4. How would you describe the air's humidity? तपाईं हावाको ओसिलोपन कसरी वर्णन गर्नुहुन्छ?तपाईंको धारणा के छ?	
□ Very dry (धेरै सुक्खा)(1) □ Dry (सुख्खा)(2) □ Slightly dry (थोरै सुक्खा)(3) □ Neither humid nor dry (न त ओसिलो न सुख्खा) (4)	□ Slightly humid (हल्का ओसिलो)(5) □ Humid (ओसिलो)(6) □ Very humid (धेरै ओसिलो)(7)
E5. How do you prefer the humidity in the air? (हावामा कति ओसिलोपन मनपर्छ?)	
□ Much more humid (धेरै ओसिलोपन)(1) □ A bit more humid (अलि बढी ओसिलोपन)(2) □ No change(परिवर्तन छैन)(3)	□ A bit drier (अलि सुक्खा)(4) □ Much drier (धेरै सुख्खा)(5)
E6. What would you rate as the overall comfort level(TC)? समग्र आराम स्तरको रूपमा के मूल्याङ्कन गर्नुहुन्?)	
□ Very comfortable(धेरै आरामदायी)(1) □ Moderately comfortable (मध्यम आरामदायी)(2) □ Slightly comfortable (अलिकति आरामदायी)(3) □ Comfortable (आरामदायी)(4)	□ Slightly uncomfortable (अलिकति असहज)(5) □ Moderately uncomfortable (सामान्य असहज)(6) □ Very uncomfortable (धेरै असहज)(7)
E7. What is your opinion of thermal satisfaction at this moment during summer? (गर्मीको समयमा यस क्षणमा थर्मल सन्तुष्टिको बारेमा तपाईको राय के छ?)	

□ Very satisfied (धेरै सन्तुष्ट)(1)
□ Moderately satisfied (मध्यम सन्तुष्ट)(2)
□ Slightly satisfied (अलिकति असन्तुष्ट)(3)
□ Satisfied (असन्तुष्ट)(4)
□ Slightly unsatisfied (अलिकति असन्तुष्ट)(5)
□ Moderately unsatisfied (मध्यम असन्तुष्ट)(6)
□ Very unsatisfied (धेरै असन्तुष्ट)(7)

E8. How do you get better air quality this summer?
(तपाईं यस गर्मीमा कसरी राम्रो हावा गुणस्तर प्राप्त गर्नुहुन्छ?)

□ Open the windows (झ्यालहरू खोल्नु) (1)
□ Use Fan (फ्यान प्रयोग)(2)
□ Use Light Clothes (हल्का लुगाहरू प्रयोग)(3)
□ Take a shower (नुहाउनु)(4)
□ Sit under the shade (छायामुनि बस्नु)(5)
□ Change Posture (मुद्रा परिवर्तन)(6)
□ Nothing in particular (विशेष गरी केहि छैन)(7)

E9. Do you prefer to open the windows to allow cool breeze inside the building??
के तपाई भवन भित्र चिसो हावा चलाउन झ्यालहरू खोल्न रुचाउनुहुन्छ?

□ Yes (हो)(1)
□ Slightly Yes (अलिकति हो)(2)
□ Maybe (हुनसक्छ)(3)
□ Slightly No (अलिकति छैन)(4)
□ No (छैन)(5)

F. Building Preference

F1. Do you prefer traditional mud shelters over modern concrete structures?
(के तपाइँ आधुनिक कंक्रीट संरचनाहरू भन्दा परम्परागत माटो आश्रयहरू मनपर्छ?)

□ Yes (हो)(1)
□ Slightly Yes (अलिकति हो)(2)
□ Maybe (हुनसक्छ)(3)
□ Slightly No (अलिकति छैन)(4)
□ No (छैन)(5)

F2. In transition period between traditional and modern, what type of building do you prefer?
(परम्परागत र आधुनिक बिचको संक्रमणकालमा, कस्तो प्रकारको भवन परम्परागत र आधुनिक बिचको संक्रमणकालमा तपाई कुन प्रकारको भवन रुचाउनुहुन्छ ?)

□ Stone masonry with mud mortar (माटो मोर्टार संग ढुङ्गा चिनाई)(1)
□ Rammed earth (थिचिएको माटो/ घ्यन्का)(2)
□ Concrete/RCC structure (कंक्रीट आरसीसी)(3)
□ Mixed type between traditional(mud) and modern (RCC) (परम्परागत माटो र आधुनिक बीच मिश्रित प्रकार)(4)
□ If others, specify (यदि अरू, निर्दिष्ट गर्नुहोस्)(5)

F3. If you prefer traditional structures, what do you think are the main causes of creating thermal problems in existing mud shelters? (यदि तपाइँ परम्परागत संरचनाहरूलाई प्राथमिकता दिनुहुन्छ भने, अवस्थित माटो आश्रयहरूमा थर्मल समस्याहरू सिर्जना गर्नुको मुख्य कारणहरू के हुन् जस्तो लाग्छ?)

□ Lack of clothing (कपडाको अभाव)(1)
□ Lack of heating equipment (तताउने उपकरणको अभाव)(2)
□ Specify others (अरूलाई निर्दिष्ट गर्नुहोस्)(3)
□ Lack of external heating sources like wood and cow dung (बाहिरी तताउने स्रोतहरू जस्तै काठ र गाईको गोबरको अभाव)(4)
□ Thickness of walls (पर्खालहरूको बाक्लोपन)(5)

F4. If you prefer traditional structures, what do you think are the existing thermal solutions in existing mud shelters? (यदि तपाइँ परम्परागत संरचनाहरूलाई प्राथमिकता दिनुहुन्छ भने, तपाइँ के सोच्नुहुन्छ अवस्थित माटो आश्रयहरूमा अवस्थित थर्मल समाधानहरू के हुन्?)	
□ Wearing more clothes (बढी लुगा लगाउने)(1) □ Using heating equipment (ताप उपकरण प्रयोग गर्दै)(2) □ Using wood, petrol products, and cow dung (काठ, पेट्रोल उत्पादन, र गोबर प्रयोग)(3)	□ Adjusting window opening hours (सञ्झ्याल खोल्ने घण्टा समायोजन गर्दै)(4) □ Specify others (अरूलाई निर्दिष्ट गर्नुहोस्)(5

APPEENDIX G: Proof of submitted article

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Date: September 14, 2022

To Whom It May Concern

This is to confirm that the paper titled "*Achieving thermal comfort through passive design strategies in energy-efficient rammed earth building*" submitted by **Ankita Yonzan** with Conference ID **12033** has been accepted for presentation at the 12th IOE Graduate Conference being held in October 19 – 22, 2022 at Thapathali Campus, Kathmandu.

Khem Gyanwali, PhD
Convener,
12th IOE Graduate Conference

IOE Graduate Conference
[Placeholder for Publication Information]

Achieving thermal comfort through passive design strategies in energy-efficient rammed earth building

"..............." a, "..............." b,

a ....
b ....
Corresponding Email: a "................"

Abstract

Rammed earth is an ancient technological marvel that has been constructed in various parts of the world and refined for better mechanical performance and sustainability with a low carbon footprint. In recent years, rammed earth investigations point out its cheap nature, durability, low embodied energy, and high thermal mass. In the context of Nepal, rammed earth construction is slowly growing in numbers despite some skepticism about its thermal and mechanical performance compared to modern concrete structures. This study highlights the thermal comfort based on the thermal performance of two energy-efficient rammed earth structures, namely, Mato-Ghar and Madan Puraskar Pustakalaya in the warm temperate climate of Nepal during the winter season. Both of these buildings incorporate modern passive design strategies. The comparison between the indoor thermal comfort of traditional houses,modern houses, and energy-efficient rammed earth buildings showed that both Mato-Ghar and Madan Pustakalaya appear warmer than the historic and contemporary structures in Kathmandu, with Matoghar being the warmest of all of them. Mato-Ghar structure is atleast 1-2℃ warmer than the other structures. Moreover, it requires less energy to maintain thermal comfort in rammed earth structures than in other contemporary structures.

Keywords

Rammed earth,Thermal comfort, Thermal Performance, Comfort Temperature, Passive design strategies

1. Introduction

1.1 Background

In recent years, the rejuvenated emergence of raw earth construction is associated with its cheap nature, durability, and low embodied energy. Rammed earth, one of the most long-lasting earth materials, is an ancient technological marvel that has been constructed in various parts of the world and refined for better mechanical performance and sustainability with a low carbon footprint. While comparing with widely used concrete, it has a less environmental impact and good insulation for heat and sound [1]. The reason is due to it's high thermal mass property which is also an important aspect of the passive design strategies[2]. It has allowed people to build completely load-bearing high buildings up to 4 stories in high seismic zones while also providing high thermal comfort, waterproof, fireproof, sustainable buildings[3].

In Nepal, the Annapurna region, Mustang, traditional rammed earth structure can be seen in both monumental and vernacular architecture of the high altitude dry region of the Mustang Kingdom[4]. These traditional structures provide insights into how people used their practical knowledge to obtain climate-responsive designs to fulfill their desired levels of thermal comfort. Modern rammed earth construction, which is an updated form of traditional rammed earth technology, have been constructed in different locations of Nepal. The most fascinating aspect of these rammed earth structures is their blend with the local nature even when seen in clusters and different arrangements from an architectural viewpoint. It is necessary to understand the thermal behavior of rammed earth to assess the thermal environment as it impact the individuals in their day to day life and health.

Maintaining thermal comfort by decreasing the hours of thermally uncomfortable periods is necessary for human performance, which can achieve in rammed earth houses. If thermal comfort conditions are provided, then the increased confidence along with good health conditions helps to improve the output efficiency in both physical as well as intellectual tasks. This fact has been proven in many studies related to office buildings and research facilities[5]. In recent times, thermal comfort studies have been done by many scholars to advance technologies for low thermal energy consumption, sustainability, and carbon efficiency[6]. Examination of residential rammed earth dwellings in Lalitpur, Nepal, and local people have admired its decent thermal performance with temperature variance between outside and inside the room nearly (15–20°C) in cold and around (9–12°C) in hot summer[7].

The main significance of this study is gaining more information about the traditional and present rammed earth construction techniques, their performance difference, and their feasibility in the context of Nepal so that much more research and construction of rammed earth structures can be done in the future as it is sustainable.

1.2 Problem Statement

Thermal performance studies for rammed earth structures have been previously done, showing the immense possibility of it being used in small-scale housing construction and replacing the concrete jungle that we live in in the name of urbanization. However, despite its emerging innovations and advantages, rammed earth construction has not taken the height of the common concrete structures. This down surge may be due to the ignorance of its positive aspects, which is based on a lack of research in comparison to the concrete structures, difficulty in gathering required labor for rammed earth construction, and difficulty in construction. People's opinion is largely based on the skepticism that whether rammed earth houses can withstand the various static(self-weight) and dynamic loads(earthquakes) and maintain the thermal standards for living inside the house. Their judgment might be based on the traditional rammed earth structures, which were not designed with modern technologies to enhance thermal properties like thermal resistance. In the context of Nepal, the gap between the number of rammed earth and concrete construction is higher. Some organizations like UN-habitat have working projects to spread awareness about sustainable structures that produce fewer greenhouse gases which is important to reduce urban poverty[1]. In terms of rammed earth building, it is a surprise that even with low cost and sustainability, such structures are limited to only a handful. Bodach et al. defined the bio-climatic zones in Nepal by using the psychrometric chart to identify passive design strategies for each location [1]. Taylor has suggested that in hot climates, the width of the rammed earth walls may be increased for the structure to perform better as less heat is conducted due to more width[8]. The theoretical heat transfer analysis and the in-situ site experiments have shown that rammed earth provides good thermal performance due to its low thermal conductivity and high heat capacity allowing thermal control[9]. More analysis is necessary for more clarification and comparison between rammed earth structures and conventional structures. The research is focused on fulfilling the gaps in understanding the relationship between thermal comfort, thermal performance, and the local climatic conditions to understand the influencing factors that affect the structure's thermal performance.

1.3 Research Objective

The scope and limitation of research are limited to the following question:

- What is the relationship between thermal comfort and rammed earth technology in the context of Nepal?
- What are the differences between traditional structures and modern rammed earth structures in Nepal?
- Does present rammed earth technology outperform common construction methods like concrete in terms of thermal performance and comfort?

2. Methodology

2.1 Investigated area

Budanilkantha and Patan are study areas for modern rammed earth buildings which is located in the valley of Kathmandu. Both cities are located in Kathmandu Valley which generally has a relatively mild, warm, and temperate. There is significantly less rainfall in the wintertime than in the summertime. Köppen and Geiger classify this location as Cwb. This study is conducted to effectively quantify the thermal performance to achieve the occupant's needs for thermal comfort and direct further research towards the alternatives of thermal comfort by considering adaptation to a comfortable environment. Therefore, quantitative analysis with both a field questionnaire survey and site measurement of physical properties of the surrounding is done. Thermal conditions within buildings are assessed utilizing field data, sample analysis, regression analysis, discussion, and an effort to arrive at findings. Below is a detailed explanation of the study's methodology. With the aid of the SPSS program, all of the field data was statistically examined.

2.2 Investigated buildings

The two rammed earth structures that are investigated in this study are shown in Figure 1. Madan Puraskar Pustakalaya(M.P.) was established in 1955; however, it was reconstructed in 2016. The building was planned and constructed at the edge of the site with orientation North-South to gain maximum north light creating a welcoming and comfortable environment. The building walls are constructed of rammed earth that contains clay, some gravel dust, and stone. Wattle and daub are used as binding materials. Reinforcements are used to make the building a single unit. The thickness of the wall is 16 inches having large windows on the north side to allow the natural light to enter throughout the day. The size of the window openings is 5'x5', consisting of 2 numbers on the ground floor and 3 on the first floor on both the north and south side. In addition, the size of the main door on the west side is 4' x 7'. The roof is constructed using bamboo as the primary support in which the other layer is laid and covered with tiles. Similarly, struts are used to support the external bamboo.

Another rammed earth structure, Mato-Ghar(M.G.) of Buddhanilkantha, was built around 2011 and designed with passive solar techniques. Mud or "Mato" in the local Nepalese language is the main ingredient for construction. The building form is rectangular, and its form and utility have been described in previous studies[10]. The room has been arranged linearly along the east-west direction, with living spaces on the southern side while other utility rooms are towards the north. The structure has also been referred to be an autonomous structure because no problems were encountered throughout the blockade The structure was created using passive design methods. The project took 1.5 years to complete in all, with a lot of trial and error along the way. The foundation was built of stone with a maximum depth of 2' and a 6' coat of bitumen to avoid the cold. The outer walls are 18" thick, while the internal walls are only 4". Linseed oil is used to finish the flooring in the structure.

2.3 Measurement of air temperature

Figure 2: Digital Thermometer placed for thermal measurement

A digital hygrometer is used to determine both the inside and outside temperatures. The Digital Hygrometer comes with a thermo-hygrometer that measures relative humidity as well as air temperature. It features a large LCD to allow users to view both time and humidity. 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. Field measurements of the structure's environmental characteristics were taken from February 17 to February 23, covering the whole week of the winter season. For both buildings, same type of thermometer was used. The placement of the digital thermometer is shown in Figure 2. The main screen of the thermometer is 150 cm above each floor level for interior measurement stations. To measure the temperature of the outdoors, a wire that was attached to a thermometer within the structure was placed outside beneath the roof overhang. Nearly 30 cm below the level of the roof, the external measurement point was carefully recorded as displayed on the LCD screen. The thermometer was shielded from the sun the entire day. By using a digital hygrometer, all data were manually monitored three times every day for one week. Every day at seven in the morning, one in

Figure 1: Two Rammed earth structures:(Madan Pustakalaya and Matoghar)

the afternoon, and seven in the evening, all data were collected. Data that were measured were used for further analysis.

2.4 Thermal comfort survey

The thermal comfort survey was done to find the comfort temperature and preferred temperature of the users of the respective rammed earth buildings. More emphasis is given to Madan Pustakalaya as it is a library with a more significant number of users that can be surveyed. A total of thirteen [illegible]ans were surveyed, among which 3 respondents were the citizens of Matoghar while the other 10 were readers from the library. To evaluate the overall thermal responses, the 'thermal comfort zone' of this research are classified as ± 1 for thermal sensation (on a 7-point scale), ±1 for thermal preference (5-point scale), and ±1 for overall comfort (6-point scale). The comfort temperature (T_c) and preferred temperature (T_p) are calculated using the equations below. It is considered useful when linear regression is unreliable to estimate the comfort temperature. Based on the respondents' votes of thermal sensation and the corresponding values of measured indoor globe temperature, we estimated the comfort temperature by using the equation:

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

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

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. More details about the equation (1) (2) in reference[11].

3. Data Presentation and Analysis

3.1 In-Out temperature difference between Madan Pustakalaya and Mato Ghar

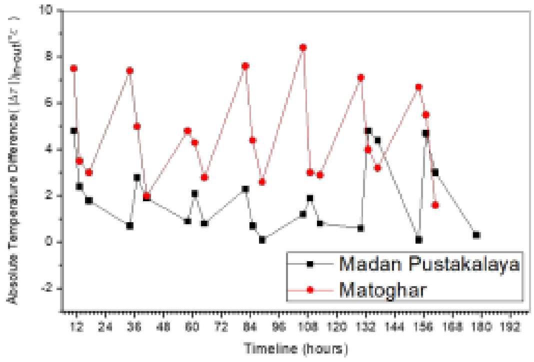

Figure 3: 7 days in-out temperature difference

Figure 3 shows that the indoor to outdoor temperature difference in Matoghar is greater than that in the Madan Pustakalaya. The average absolute in-out temperature difference for Madan Pustakalaya and Matoghar is 1.778 °C and 4.638 °C,respectively. The plausible reason for such results may be due to the presence of additional insulation layers in Matoghar and the difference in thickness of walls. The wall thickness of Matoghar is 2 inches thicker than the thickness of Madan Pustakalaya, the walls have a higher thermal mass for stabilizing the temperatures for a longer duration during the winter. Furthermore, The application of these results primarily suggests more research on the thickness optimization of the rammed earth walls. This helps in reducing dependencies on other non-energy efficient methods of heating and helps save energy while maintaining comfort.

3.2 Comparison of thermal performance during the morning, day, and evening

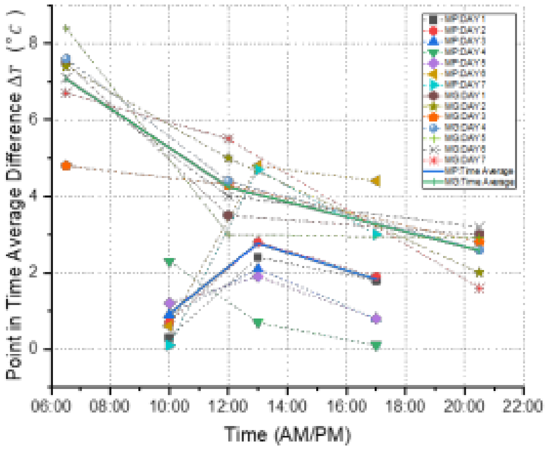

Figure 4: Morning, day and Evening Temperature Differences

Figure 4 shows the point-in-time average difference between indoor and outdoor temperature between Matoghar and Madan Pustakalaya for the 7 days in the morning, day, and evening period. The in-out temperature difference in Matoghar in the morning period shows very good insulation as the morning outside temperature is lower than the temperature inside the structure for all the 7 days in the winter period. This implies that the rammed earth walls and floors of Matoghar provide better thermal performance in the morning hours than the walls of Madan Pustakalaya. The calculated hourly average temperature gradients from morning to noon for Madan Pustakalaya and Matoghar are +0.61 and -0.51 respectively. Similarly, the values for noon to evening for Madan Pustakalaya and Matoghar are -0.23 and -0.19 respectively. This shows that the temperature in Matoghar rises rapidly with the increasing outside temperature in the morning whereas for Madan Pustakalaya the increasing temperature gradient indicates a slower temperature rise. From, the afternoon to the evening period, Madan pustakalaya cools down faster than the Matoghar.

3.3 Comfort and Preferred Temperature

Before calculating the comfort and preferred temperature, a linear fit between outside and inside temperature for Madan Pustakalaya was done which is shown in Figure 5. In Gautam et al.'s article, our linear fit was compared with the linear fit curve of the three different regions of Nepal in the article for the winter period[11]. The comparison showed that the linear regression equation for the temperate region is similar to Madan Pustakalaya and Matoghar; hence, we used the regression equation to calculate the indoor globe temperature given by Gautam et al. for the winter period in the temperate region. The applied regression equation is shown in Equation 4, The comfort temperature and preferred temperature are calculated according to the equations.

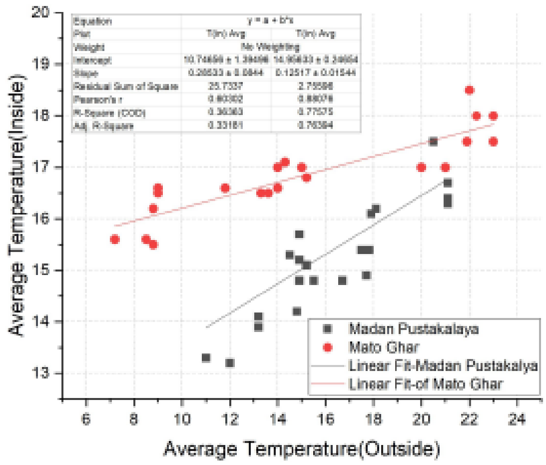

Figure 5: Linear fit of in-out temperature for both rammed earth

The linear fit curve for the temperate region in the winter period is given by[12]:

$$T_i = 0.15T_0 + 13.5 \qquad (3)$$

Where; T_i = Indoor temperature, T_0 = Outdoor Temperature, T_g = Indoor Globe Temperature

$$T_g = 0.47T_0 + 9.1 \qquad (4)$$

The obtained comfort temperature and preferred temperature for Madan Pustakalaya and Matoghar are shown in Figure 6. The mean value of the comfort temperature in Madan Pustakalaya and Matoghar during the winter season is 18.75°C and 14.83°C . The comfort temperature ranges from 16.75°C to 20°C in the Madan Pustakalaya and from 14°C to

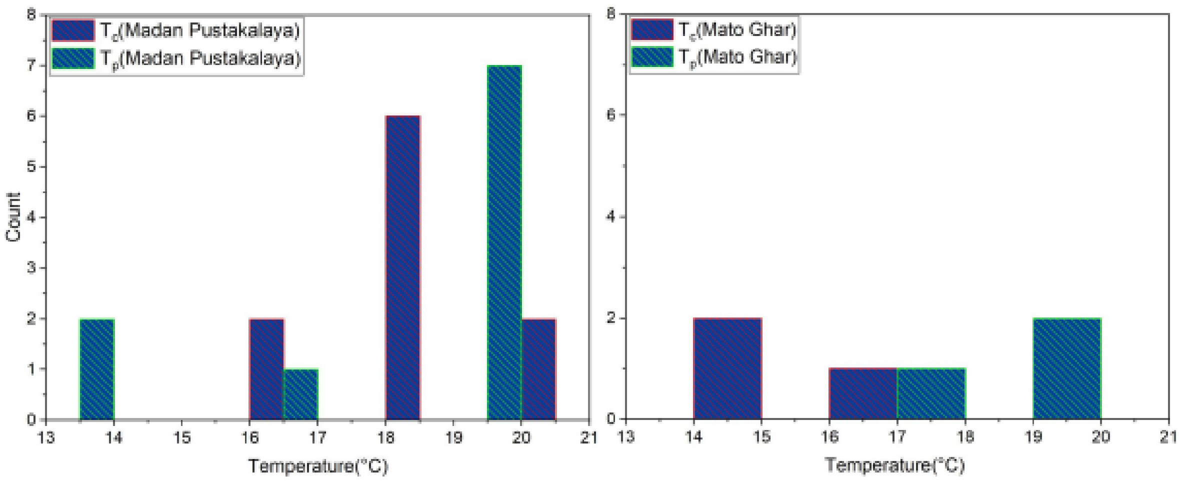

Figure 6: Comfort and Preferred Temperature Comparison between Madan Pustakalaya and Mato Ghar

16°C in the Matoghar. However, the estimated mean preferred temperature of Matoghar(18.26°C) and Madan Pustakalaya(18.18°C) is close. However, the gap between preferred temperature and comfortable temperature for Matoghar is high, indicating that residents of Matoghar require warmer conditions to maintain thermal comfort. Considering the mean value of the comfort temperature and preferred temperature, the preferred temperature is quite close to the comfort temperature for Madan Pustakalaya, while it is a little far from Matoghar.

3.4 Traditional and modern structures vs rammed earth structures in Nepal

The data for this study is taken from previous research conducted on traditional and modern residential buildings in Kathmandu Valley for thermal performance and thermal comfort survey for temperate climates in Nepal[11, 13]. As the location of the sites is in the vicinity of Kathmandu Valley, the climate is complex due to the temperate climate and high altitude hills around the valley of around 1300. Table 1 shows the comparison between indoor, outdoor and comfort temperatures of different types of structures found in Nepal with the rammed earth structure. The comfort temperature lies around 15–18°C as shown by literature reviews. The outdoor mean maximum air temperature for residential buildings ranges from 11 to 14°C whereas indoor mean maximum air temperatures range from 12 to 15°C during morning till evening.

Table 1: Comparison of mean indoor,outdoor and comfort temperatures

	Temperature in C		
Type	Indoor	Outdoor	Comfort
Traditional	12-15	11-14	15
Modern	10.5-11.5	11.5	15
M.P.	15.2	16.3	18
M.G.	16.8	15	14

Through the above data analysis, it is observed that the comfort temperature for traditional buildings is less than that of the Madan Pustakalaya, whereas, it is almost equal to that of the Mato-Ghar. It implies that Madan Pustakalaya requires more energy to maintain thermal comfort than the traditional houses as well as Mato-Ghar. For Matoghar, since the comfort temperature is less than both traditional and Madan Pustakalaya, it requires less energy. However, for Madan Pustakalaya, even though the indoor temperature matches the comfort temperature of previous studies, the response votes have increased the comfort temperature. When comparing the temperature difference between indoor and comfort temperature between the two rammed earth structures with the contemporary structures, Mato-Ghar has the most thermally comfortable environment as the difference between comfort temperature and indoor temperature is the lowest among them. In addition, both Matoghar and Madan Pustakalaya seem warmer than the traditional and modern buildings in Kathmandu; Matoghar being the warmest of them all. Therefore, it can be implied that rammed earth structures are thermally superior in maintaining and regulating indoor temperatures close to comfort temperatures than other types of structures.

4. Conclusion

The earlier chapters have covered the various objectives which show the higher thermal performance of rammed earth structures in the context of Nepal, especially during the winter period. This study backs the existing plethora of knowledge about rammed earth structure and its superior thermal performance as a result of high thermal mass and temperature stabilizing properties. Because of the current energy crisis which is becoming a global problem, this research contributes toward how effective is the natural thermal stability when rammed earth is used. Hence, this research quantifies the thermal performance of rammed earth structures in Nepal and compares it with traditional and modern structures to clarify the position of rammed earth structures as a viable, sustainable, and cheaper option. The findings from this study suggest that rammed earth structures can out-perform traditional and modern structures in terms of thermal performance while maintaining thermal comfort. The thermal performance is related to the thermal characteristics of the rammed earth walls and thermal comfort depends on the physical and psychological conditions of the users.

- Modern Rammed earth structures are generally 1-2°C warmer than the traditional and modern residential structures. The maximum outdoor to indoor temperature differences range from 2-7°C in rammed earth structures which shows that there is heat stored in rammed earth structures.
- The indoor temperature exceeds the outdoor temperature in the morning and the evening, whereas, at noon time, the outdoor temperature exceeds the indoor temperature. However, this temperature difference is greater in the morning and evening than in the afternoon. Hence, it is good for maintaining thermal conditions inside the structure to a close-range during the winter period.
- The comfort temperature and preferred temperature are very close to the existing indoor temperatures for the rammed earth structure. Therefore, it requires less energy to maintain the thermal comfort in rammed earth structures than the contemporary structures

4.1 Recommendations

From the above investigation of thermal performance, the following recommendations are proposed. The findings might not be applicable in all the regions but they mostly can be applied to rammed earth structures in colder regions. The recommendation mainly concerns the effective construction of rammed earth structures for a thermally comfortable environment.

- There is no provision for rammed earth structure construction in the guideline of the building code of Nepal. Therefore, it should be included.
- There is less number of rammed earth structures which are sustainable for the future. The authorities should increase awareness of its proper construction procedure at the societal level.
- Space is very important as an architect, however, the wall thickness of rammed earth structures is huge compared to the equivalent concrete structures. More methods should be explored in reducing the size of the wall to create usable space in the future.

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APPEENDIX H: Measured Data

(a) Temeperature Data

HOUSE	AVERAGE TEMPERATURE(T℃)																
	Time	**DAY**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	7:00 AM	IN	15	15	16	15	14	13	14	15	16	15	16	16	16	17	16
		OUT	14	14	14	13	13	12	13	13	14	14	14	15	14	15	14
		R.H.(%)	54	53	57	65	59	62	63	68	66	68	67	65	67	74	71
	1:00 PM	IN	18	19	17	16	14	15	18	18	19	18	19	18	20	20	18
		OUT	19	20	19	17	16	16	19	19	20	20	21	20	23	23	20
		R.H.(%)	55	55	57	67	59	60	67	68	68	69	62	66	64	65	70
	8:00 PM	IN	17	17	17	15	15	15	17	17	17	16	18	18	17	18	17
		OUT	16	16	14	13	14	13	15	15	16	15	16	17	16	15	16
		R.H.(%)	58	61	62	62	65	67	67	64	65	60	67	70	74	63	69

HOUSE	AVERAGE TEMPERATURE(T℃)																
	Time	**DAY**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
B	7:00 AM	IN	15.8	16.3	16.2	15.4	15.7	15.3	15.9	14.2	14.3	14.9	15.4	16.2	16.8	17	17.6
		OUT	13.7	13.8	13.9	14.3	14.1	14.4	14.7	13.1	13.3	13.8	14.3	15.3	15.7	15.5	15.9
		R.H.(%)	55	56	56	65	61	65	66	72	70	74	72	66	68	72	65
	1:00 PM	IN	17.8	17.5	17.7	16.1	17.8	17.1	17.2	16.4	16.1	17.2	17.6	17.8	18.7	19.5	18
		OUT	19.8	19.4	18.5	16.9	19.8	18.3	17.9	17.4	17.1	18.8	18.6	19	19.5	21.4	19.2
		R.H.(%)	49	51	50	59	49	56	60	65	63	66	59	57	60	51	62
	8:00 PM	IN	16.7	17.7	15.8	15.8	16.3	16.2	16.5	16.3	16.5	15.9	17.6	17.4	17.6	19	18.4
		OUT	16.5	16.1	14.6	14.7	15.6	15.2	15.3	14.9	15	15.3	16.5	16.3	16.6	18.2	16.1
		R.H.(%)	59	64	58	58	59	63	62	62	64	65	63	62	67	59	64

HOUSE	AVERAGE TEMPERATURE(T℃)																
	Time	**DAY**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
C	7:00 AM	IN	15.4	15	15.3	15.5	15.2	15.1	16.1	15.5	15.1	15.4	15.9	15.9	15.5	15.4	16.5
		OUT	14.6	14.3	14.2	14.5	13.9	13.7	14.6	14.4	13.9	14.1	14.5	14.7	14.6	15.8	15.4
		R.H.(%)	49	46	44	51	46	52	53	58	50	58	58	65	52	57	55
	1:00 PM	IN	17	16.8	16.4	16.3	17	16.8	17.2	16.6	15.3	16.3	17.7	16.7	18.4	18.1	17.1
		OUT	17.4	17.6	17.7	17.1	17.8	18.1	17.9	17.8	16.5	17.1	19.5	18	19.5	19.7	18.8
		R.H.(%)	48	48	45	52	48	52	56	58	52	59	63	52	55	53	60
	8:00 PM	IN	16.4	16.6	16.1	16.5	15.5	16.2	16.7	16.6	15.6	16	16.6	17	17.3	17.7	17.9
		OUT	15.9	15.4	15.6	15.6	14.9	15.5	15.5	15.6	15.4	15.1	15.5	15.8	16.5	16.5	16.3
		R.H.(%)	49	49	48	48	51	55	55	47	57	58	57	56	60	55	59

HOUSE	AVERAGE TEMPERATURE(T℃)																
	Time	**DAY**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
D	7:00 AM	IN	16.2	16.4	16.2	16.3	15.5	15.7	17	16.1	15.9	16.4	16.2	17.1	17.6	17.6	18.2
		OUT	15.4	14.9	15.1	15.2	14.5	14.1	15.1	14.2	14.5	14.9	15.2	15.5	17	16.2	16.8
		R.H.(%)	63	60	61	67	62	67	69	72	70	77	74	70	67	66	66
	1:00 PM	IN	17.3	17.1	17.1	17.1	17.2	18.3	18.2	17.3	16.7	18	19.1	19.2	19.6	20	18.7
		OUT	18.5	18	18.4	18.1	18.5	19.9	19.8	18.7	17.8	19.8	20.4	21.5	21.2	22	21.1
		R.H.(%)	60	64	61	68	60	67	71	72	70	78	71	70	70	70	72
	8:00 PM	IN	16.2	16.8	16	16.4	16.3	17.9	17.1	16.8	17	16.7	17.2	17.3	19.2	20.2	18.8
		OUT	15.6	15.7	14.5	15.2	15.3	16.3	15.8	15.4	15.8	15.4	16.5	16.4	17.2	18.1	17.3
		R.H.(%)	66	66	64	64	66	71	70	72	71	75	74	71	71	69	74

HOUSE	AVERAGE TEMPERATURE(T°C)																
	Time	DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
E	7:00 AM	IN	14.9	14.7	15	14.8	14.1	14.2	14.3	14.9	15.2	14.8	14.9	15.8	15.8	15.7	16.1
		OUT	14.3	14.3	14.5	14.3	13.6	13.5	13.8	14.5	14.8	14.2	14.3	15.3	15.1	15.1	15.3
		R.H.(%)	42	41	40	50	44	55	54	61	62	65	60	54	52	53	52
	1:00 PM	IN	17.1	17.7	17.5	16	15.4	14.9	17.2	16.2	16.6	17.4	17	17.8	18.2	18.1	17.9
		OUT	18.5	19.6	19.1	17.6	16.9	16.6	18.9	17.9	18.2	18.7	19.2	19.9	20.2	21.7	19.4
		R.H.(%)	47	48	50	51	47	51	56	57	60	64	60	56	58	55	57
	8:00 PM	IN	16.5	16.5	15.7	15.1	15.1	14.9	16.9	16.1	17	15.7	16.8	17.8	16.9	17.7	17.5
		OUT	16.3	15.7	14.9	14.7	14.4	14.3	16.4	15.8	15.1	15.1	16.2	17.1	16.7	17.1	16.6
		R.H.(%)	50	48	49	48	57	59	60	62	66	70	65	71	64	57	66

HOUSE	AVERAGE TEMPERATURE(T°C)																
	Time	DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
F	7:00 AM	IN	15	15.8	15.5	14.5	14.2	14.8	14.7	14	15.2	14.7	15.2	15.5	15.9	16	16.6
		OUT	14.2	15	15.2	14.1	13.8	14.3	14.2	13.4	14.6	14.2	14.8	14.8	15.4	15.5	16
		R.H.(%)	53	52	52	60	55	62	63	68	67	72	68	63	62	63	61
	1:00 PM	IN	18.7	17.7	17.6	15.9	15.7	15.2	16.7	16.2	16.6	17.6	17.2	17.8	18.6	18.4	19.3
		OUT	19	19.8	19.7	17.6	17.1	16.5	19	17.8	18.5	19.2	18.7	19.7	20.5	20.4	20.8
		R.H.(%)	52	54	53	59	52	58	62	64	64	69	63	61	62	58	63
	8:00 PM	IN	16.3	16.2	15.2	15.5	15	15	15.6	16.2	15.8	15.8	15.8	16.2	16.4	17	16
		OUT	15.7	15.7	14.5	15	14.5	14.8	15.3	15.8	15.6	15.4	15.2	15.8	16	16.7	15.6
		R.H.(%)	58	59	57	56	60	64	64	65	67	70	68	68	67	61	68

HOUSE	AVERAGE TEMPERATURE(T°C)																
	Time	DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
G	7:00 AM	IN	14.8	14.7	15.1	14.9	14.2	15.2	14.8	14.1	15.1	14.4	15	15.3	16.4	16.2	16.6
		OUT	14.2	14.2	14.5	14.1	13.7	14.6	14.1	13.2	14.1	13.7	14.3	14.3	15.2	15.5	15.8
		R.H.(%)	53	52	52	60	55	62	63	68	67	72	68	63	62	63	61
	1:00 PM	IN	17	16.9	16.8	15.2	15.8	15.8	17.8	15.6	17.1	16.7	16.4	18.7	18.2	18.8	18.3
		OUT	18.7	19.3	19.2	17.1	17.2	17.4	19.5	17.3	18	18.7	18.2	19.8	20.7	20.4	20.3
		R.H.(%)	52	54	53	59	52	58	62	64	64	69	63	61	62	58	63
	8:00 PM	IN	16.2	16.2	14.8	15.3	14.8	15.7	15.4	16	15.9	16	15.6	16.7	16.6	17	17.1
		OUT	15.5	15.8	14	14.5	14.1	15.2	14.8	15.4	15.1	14.9	14.9	15.7	15.9	16.2	16
		R.H.(%)	58	59	57	56	60	64	64	65	67	70	68	68	67	61	68

HOUSE	AVERAGE TEMPERATURE(T°C)																
	Time	DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
H	7:00 AM	IN	15.1	15.3	15.5	15.3	14.6	14.7	15.3	14.9	15.1	15	14.7	15.6	16.2	16.5	16.4
		OUT	14.8	14.7	14.7	14.6	13.9	13.8	14.6	14	14.5	14.1	13.9	14.9	15.5	15.8	15.6
		R.H.(%)	53	52	52	60	55	62	63	68	67	72	68	63	62	63	61
	1:00 PM	IN	16.6	16.1	16.9	15.8	15.4	16.2	17.1	15.8	16.7	16.9	16.4	18.3	19.1	18.6	18
		OUT	18.5	17.3	19	17.8	17.7	17.9	19.5	18.1	18.6	18.4	18.5	20	21.1	20.6	19.9
		R.H.(%)	52	54	53	59	52	58	62	64	64	69	63	61	62	58	63
	8:00 PM	IN	16.5	16.6	16	15.2	15.5	16.3	16	16	16.4	15.9	16.2	17	17	17.6	18.1
		OUT	15.6	15.9	15.1	14.6	14.9	15.5	15.3	15.2	15.4	15.1	15.5	16.2	16.5	16.8	17.3
		R.H.(%)	58	59	57	56	60	64	64	65	67	70	68	68	67	61	68

HOUSE	AVERAGE TEMPERATURE(T°C)																
	Time	DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
I	7:00 AM	IN	23.2	23.7	23.5	23.1	23.3	23.5	23.5	23.6	23.5	23.9	23.7	23.6	23.7	23.8	24
		OUT	23.1	21.7	22.1	21.5	21.1	21.3	21.5	22.5	21.1	24.4	21.7	22.5	21.7	22.4	21.9
		R.H.(%)	68	80	82	73	75	75	75	71	76	76	80	79	79	78	79
	1:00 PM	IN	25	24.8	25.2	25.5	25.6	25.5	25.2	24	25	25.1	25	25.5	25	25	24.1
		OUT	27.3	24.6	28.1	28.5	27	25.9	25.9	24.6	27	25.1	27.6	26.5	25.8	27.8	24.6
		R.H.(%)	73	74	74	79	67	64	67	76	73	74	79	75	74	74	84
	8:00 PM	IN	24.6	24.1	24.1	24.2	24.6	24.3	24.6	21.3	24.8	24.8	25	25.2	25	24.4	24.8
		OUT	23.1	23.2	21.8	23.9	22.9	22.3	22.6	22	22.6	23.4	23.5	23.5	23.8	22.3	23.1
		R.H.(%)	76	80	74	76	69	68	70	76	78	75	76	72	77	78	75

HOUSE	AVERAGE TEMPERATURE(T°C)																
	Time	DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
J	7:00 AM	IN	23.2	24.4	24.2	24.5	24.9	24.7	24.5	24.1	23.5	24.1	24.4	24.6	25.6	24.3	23.7
		OUT	23.7	24.4	21.8	27.1	21.1	22.1	25.4	25.4	22.1	23.4	22.1	24.1	24.3	23.5	21.2
		R.H.(%)	75	80	81	79	76	76	74	75	81	80	80	81	83	81	81
	1:00 PM	IN	24.3	25.2	25.2	25.6	25.6	25.5	25.4	24.3	24.3	24.8	25.3	25.5	25.2	26.5	24
		OUT	25.7	26.1	30	29.8	28.9	29.2	28.4	27.4	29.5	29.2	28.4	31.1	28.4	28.5	25.4
		R.H.(%)	82	87	84	79	76	76	74	77	84	82	82	81	82	81	82
	8:00 PM	IN	25.1	24.9	25.2	25.8	25.8	25.8	24.9	24.1	24.5	23.2	23.5	25.8	24.3	24.2	23.3
		OUT	23.4	23.1	24	24	24	24	21.1	21.5	23.8	24.2	24.2	24.4	22.4	24.1	22.3
		R.H.(%)	79	83	77	74	75	77	75	77	82	83	85	81	82	80	82

HOUSE	AVERAGE TEMPERATURE(T°C)																
	Time	DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
K	7:00 AM	IN	24.3	22.7	22.7	22.8	22.1	22.2	23.6	23.2	22.9	23.5	23.2	23.2	22.8	23.3	23.2
		OUT	23.7	21.5	21.5	21.1	20.9	22	23	22.6	22.2	23.4	21.9	22.2	21.2	22.4	22.2
		R.H.(%)	65	63	66	63	60	61	61	60	63	62	64	62	64	64	67
	1:00 PM	IN	26.1	24.1	25.8	24	25.3	25.3	24.3	26	23.9	24.9	27.5	25.2	25.4	27.3	24.7
		OUT	25.7	24.2	24.5	24.7	27	26.4	25.6	27.3	24.6	26.2	28.7	26.4	26.5	28	25.4
		R.H.(%)	63	65	64	58	57	56	54	57	60	63	66	65	63	63	68
	8:00 PM	IN	23.2	23.1	23.8	23.5	24.1	24.4	23.4	22.3	21.9	21.7	24.5	23.4	24.3	24.2	23.3
		OUT	23	22.7	23.9	23.8	23.7	23.5	22.9	22.4	22.8	21.2	23.7	23.8	23.5	23.1	22.3
		R.H.(%)	58	66	64	55	56	55	54	61	63	65	66	63	65	63	66

(b) Survey Data

Name	In T℃	Out T℃	Type of Building	E1	E2	E3	E4	E5	E6	E7	E8	E9	F1	F2	F3	If others please specify(F3)	F4
Dharma Jung Gurung	16	18	Modern	2	2	2	1	2	3	2	1	4	1	2	3	Maintennance problem	1,3
Pos Bahadur Gurung	23.5	21.9	Traditional	3	2	3	3	2	3	3	1, 3	1	2	4	2,4		2
Khusi Maya Gurung	18.2	19.5	Traditional	4	3	3	3	2	3	3	1, 3	2	2	4	4		2
Bhoj Bhadaur Gurung	19	20.2	Traditional	3	2	3	3	2	3	3	1	2	2	4	1,2,4		2
Rohit Gurung	19	20.2	Traditional	3	2	3	3	2	3	3	1, 3	3	2	4	2,3,4	Maintenance problem	2
Nim Bahadur Gurung	23.1	21.5	Modern	2	1	2	2	3	3	2	1	4	1	2	2		5
Kalpana Gurung	23.1	18.2	Modern	3	3	2	3	2	3	2	1	4	1	2	2		1,3
Dev Bahadur Gurung	19.8	21	Modern	3	1	2	4	2	2	3	1,3	3	3	3	2,3	Maintenance problem	1,2,5
Keshav Gurung	19.8	21	Modern	2	2	3	3	2	3	3	1,3	3	3	1	4		1,2,5
Tarka Bahadur Gurung	21.1	21.8	Modern	3	3	3	3	2	3	2	1	1	2	4	2,4		2
Mangal Raj Gurung	16.2	15	Traditional	3	2	3	3	2	3	2	1	1	2	1	2,4		2
Gupta Man Gurung	16.2	15	Traditional	3	2	3	3	2	3	2	1	3	2	4	2,4		2
Gham Bahadur Gurung	19.8	21.2	Modern	2	2	3	3	2	3	2	1	4	2	4	2,3	Maintenance problem	2,5
Diman Gurung	19.7	20.2	Modern	3	1	3	3	2	3	5	1	3	2	3	2,3	Maintenance problem	2,5
Sukh Bahadur Gurung	19.5	20.8	Modern	2	1	3	3	2	3	3	1	3	2	3	2		2
Karsangh Gurung	16.1	18.3	Modern	2	2	3	3	2	3	3	1	2	2	3	2		2
Hem Jung Gurung	19.8	21.3	Modern	3	1	3	3	2	3	3	1,3	3	4	4	2,3,4	Maintenance problem,lack of technology	1,2
Nil Jung Gurung	19.8	21.3	Modern	2	2	3	3	2	3	3	1,3	3	3	4	2,3,4	Maintenance problem	1,2
Krishna Gurung	22.1	22.7	Modern	3	2	3	4	2	3	3	1,3	2	2	4	2,3,4	Maintenance problem	1,2
Khar Man Gurung	18	20	Traditional	4	3	3	3	2	3	3	1,3	2	2	4	2,4		2
Aantari Gurung	17.8	17.3	Traditional	3	2	3	3	2	3	3	1,3	2	2	4	2,4		2
Chitra kumari Gurung	20	21.1	Traditional	4	3	2	2	2	3	3	1	4	2	5	3	Maintenance problem	2
Manila Gurung	20	21.1	Modern	3	2	3	4	4	3	2	5	2	2	4	1,2		1,2,3
Chok Bahadur Gurung	22.6	20.5	Modern	3	2	3	3	2	3	5	1	4	1	2	3	Maintenance problem	5
Ram krishna Gurung	18.5	21.2	Modern	3	2	2	3	2	2	3	1,3	2	2	4	2,5		2,3
Nishan Gurung	18.3	19.9	Modern	2	3	3	6	3	3	3	1,3,4,6	2	5	4	3	Lack of technology	2
Srijana Gurung	23.5	21.9	Traditional	3	1	2	5	2	3	3	1,3	2	1	4	3	Maintenance problem,lack of technology	1, 3
Lok Bahadur Gurung	18.9	21.2	Traditional	4	3	2	5	2	3	3	1,3	2	2	4	2		2
Yok Maya Gurung	18	20.5	Modern	2	2	2	1	2	3	3	1	3	1	2	3	Maintenance problem	1,3
Pin Maya Gurung	18	20.5	Traditional	2	1	2	3	2	3	2	1	3	1	1	3	Maintenance problem	1,3
Madan Gurung	18	20.5	Traditional	2	1	2	3	2	2	3	1	3	3	4	3	Maintenance problem	1,4
Mahesh Gurung	22.5	18.5	Traditional	2	1	2	3	2	2	3	1,3	3	3	4	3	Maintenance problem	1,4
Nanda Jung Gurung	22.5	18.5	Traditional	2	1	1	4	1	2	3	1,3	1	1	4	2		2
Kabina Limbo Gurung	18	21.4	Traditional	2	1	1	4	1	2	3	1,3	1	1	4	2		2
Mangal Bahadur Gurung	18	21.4	Traditional	2	2	2	2	2	3	5	1	4	1	2	3	Maintenance problem	2
Usha Gurung	18	21.4	Traditional	2	2	2	3	2	3	3	1,3	3	1	1	3	Maintenance problem	2

APPEENDIX H: Plagiarism check of thesis report

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