EVALUATING THE EFFECTIVENESS OF VERNACULAR BUILDING BIOCLIMATIC ELEMENTS IN MODERATING INDOOR ENVIRONMENT: THE CASE OF MERTI WOREDA, ARSI ZONE

Rahmate Seid Abdu

A Thesis Submitted to the Department of Architecture

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Masters of Science in Environmental Architecture

Office of Graduate Studies

Adama Science and Technology University

July, 2023

Adama, Ethiopia

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APPROVAL SHEET

I, the advisors of the thesis entitled **"Evaluating the Effectiveness of Vernacular Building Bioclimatic Elements in Moderating Indoor Environment: The Case of Merti Woreda, Arsi Zone**" and developed by Rahmate Seid Abdu, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Rahmate Seid have read and evaluated the thesis entitled **"Evaluating the Effectiveness of Vernacular Building Bioclimatic Elements in Moderating Indoor Environment: The Case of Merti Woreda, Arsi Zone"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Environmental Architecture.

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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DECLARATION

I hereby declare that this Master's thesis, **" Evaluating the Effectiveness of Vernacular Building Bioclimatic Elements in Moderating Indoor Environment: The Case of Merti Woreda, Arsi Zone "** is my original work. That has not been submitted for the award of any academic degree, diploma, or certificate at any other university. All sources of materials that are used for this thesis have been duly acknowledged.

Rahmate Seid Abdu	______________________	________________
Name of the student	Signature	Date

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LIST OF ACRONYMS AND ABBREVIATIONS

m/s	Metres per second
ACM	Adaptive comfort model
AEZ	Agro-Ecological Zone
AMR	Averege monthly range
AMT	Averege monthly tempreture
ANSI	American National Standards Institution
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
Av	Air Velocity
CI sheet	Corrugated Iron Sheet
Clo	Unit of clothing insulation [m²·K/W]
CPZ	Control potential zone
DB	Design builder
EPW files	Energy plus weather file
HCB	Hollow concrete block
IECC	International energy conservation code
ISO	The International Organization for Standardization
KW	kilowatt
M	Meter
Max	Maximum
Met	Unit of metabolic activity [W/m2]
Min	Minimum
MoA	Ministry of Agriculture
MRT	Mean radiant temperature [°C]
NRMRD	Natural Resources Management and Regulatory Department (Ministry of Agriculture)
RF	Rainfall
RH	Relative Humidity
Ta	Air temperature

TTC	Thermal time constant
W/L ratio	Width to length ratio
WBCSD	World Business Council for Sustainable Development

ABSTRACT

Studying the bioclimatic performance of vernacular buildings is a critical issue in this era in order to eliminate the current environmental problems associated with the increase in average temperature, which require high energy consumption to create a comfortable indoor environment. The research was conducted in Merti woreda, which is in the tropical savannah climate zone and experiences hot days and cold nights. The study's goal is to identify potential bioclimatic design strategies for Merti woreda vernacular dwellings and assess their impact on improving indoor thermal conditions. The evaluation was conducted using a qualitative and quantitative research approach. Three vernacular building typologies found in the areas have been selected through purposive sampling techniques. In addition, the data is processed using Design Builder (DB) and Excel software and presented using charts, drawings, and tables. The results demonstrate that the high thermal mass and smaller width-to-height ratio help for better thermal and energy performance in B2 and B3. The recorded temperatures and air movement in B2 and B3 are better than those in B1, whereas the humidity levels in all three buildings were within the comfort zone. Existing orientation (north), overhang width, and wall and roof thickness in B2 and B3 have better thermal performance, while in B1's south orientation perform better, increasing wall thickness and overhang width give better thermal performance in B1. In general, the study concludes that high thermal mass, the roof overhang, and the orientation of existing B2 and B3 were effective in moderating the indoor environment but in B1 increasing wall thichness and roof overhang helps in increasing the thermal performance of the building which indicates the positive role of bioclimatic element in achieving indoor thermal comfort.

Keywords: Bioclimatic, climatic analysis, energy eficiency, Merti woreda, passive design, thermal performance, vernacular architecture

CHAPTER ONE

INTRODUCTION

The building sector is one of the major energy consumers in the world. The proportion of total energy use attributable to buildings generally ranges from 10–15% in undeveloped countries. The purpose of this paper is to investigate the bioclimatic elements of vernacular buildings from two perspectives: one is thermal performance, and the other is energy savings. In Ethiopia, there are limited or no studies of vernacular architecture from an energy and thermal performance point of view. Most of the studies on vernacular architecture are qualitative based; for instance, the study conducted by (Darge & Nuramo, 2019), and the real energy performance of vernacular architecture of any region in Ethiopia is not conducted and its value for contemporary building practice is not being researched. For instance, a study conducted by Jetie, (2019) only explores the vernacular housing typology of Tigray qualitatively. To fill this gap the present research investigates qualitatively and quantitatively the vernacular architecture of Merti woreda of the Arsi zone. Which is found in the Aw climate i.e., tropical Savannah climate according to the Koppen climate classification characterized by: very hot days and colder nights during dry season.

The researcher's experience living in the vernacular buildings of the chosen study area and sense of comfort in comparison to a modern design-influenced mud house with a corrugated iron sheet roof is the justification for choosing this research area. Accordingly, Zune et al., (2020), state that the built form and materiality of vernacular buildings may suggest their climatic provenance, but by this alone, it's hard to proof of all year environmental performance of a vernacular building of any area.

1.1 Background of the study

A fundamental purpose of architecture is to provide shelter from the elements; that is, to purposefully shape the immediate physical, as well as social and aesthetic climate in which we live. Under the limitations imposed by distance and technology, architecture shaped climate and climate shaped architecture on a local level (Pearl mutter, 2007). According to Foruzanmehr & Nicol,(2020), Energy-related human activities can greatly contribute to current warming, mainly through carbon dioxide emitted from fossil fuels. Furthermore, the World Business Council for Sustainable Development (WBCSD) report of 2008 indicates buildings account for 40% of the world’s energy use and produce substantially more carbon emissions than the transportation sector, to achieve thermal comfort (cooling or heating) inside units (Aflaki et al., 2015). Moreover, studies prove that modern construction materials are thermally uncomfortable due to the undesirable thermal characteristics of the construction material; for instance, the cement industry accounts for 2% of the global energy consumption and 5% of the global anthropogenic CO2 emissions (Samuel et al., 2017). In contrast, vernacular architecture is a response to a combination of local climatic conditions, locally available materials, simple construction techniques, lifestyles, traditions, and the socioeconomic conditions of a particular region (Rajković et al., 2022) and (Singh et al., 2009).

Bioclimatic architecture refers to the design of buildings and spaces (interior and exterior) according to local climatic conditions for visual and thermal comfort by utilizing natural environmental sources such as the sun, air, wind, vegetation, water, land, and sky (Lake et al., 2022). Yusuf, (2020) Identify bioclimatic design principles as: building shape, orientation, landscape and shading, building fabric, ventilation, glazing and windows, insulation and space. Akadiri, (2016), argues bioclimatic design is achieved and the energy bill is saved by correctly orienting the house, using insulation to its best advantage, and correctly placing fenestration.

The principle behind bioclimatic design is the understanding of the climatic factors of a site by analyzing the influence of microclimate, including solar radiation, sunshine, temperature, humidity, rainfall, wind velocity, and direction (Hyde, 2000). Bioclimatic principles basically comprise three directions: energy, human health/wellbeing and sustainability (Yusuf, 2020). Rajković et al., (2022) discussed the bioclimatic design parameters in two parts: factors such as climate, soil, relief, water, and vegetation as "impacts"; choice of location, orientation, adaptation to topography, organization of space, materials, and structures; and, finally, the typology of houses and settlements as "responses" both at the settlement level and at the house level.

To put the passive design strategies effective, the criteria of thermal comfort, the local climate data, and the building’s thermal performance target should be examined first. (Zahiri, 2016) and (Lewis et al., 2018). Bioclimatic design concerns the disposition of buildings (orientation related to the sun and wind, aspect ratio), space (site planning), air movement, openings (size-position, protection), and the building envelope (walls, construction material thickness, roof construction detailing) (Manzano-agugliaro et al., 2015).

Fernandes et al., (2015) proves that vernacular architecture could contribute towards reducing waste and energy consumption through the use of passive solar design, traditional techniques, and local materials in a process of ongoing development in which solutions are adapted for specific cases in accordance with territory and climate. Because of their efficient and adaptable solutions that support sustainability, traditional structures are an important resource for modern construction Lake et al., (2022).According to Manzano-Agugliaro et al., (2015a) the bioclimatic solutions adopted differ from one region to another. Studies show that the bioclimatic elements of vernacular architecture in a hot climate concern efficient cooling, which is usually based on natural ventilation, use of water, roof overhang, thermal mass, thermal insulation, trees, or other shading elements that reduce overheating during the day and release the heat at night (Gallo, 1994).

The findings of a study conducted by Lake et al., (2022) on "Bioclimatic and sustainable features on vernacular architecture in Ternate" confirm that bioclimatic features of vernacular building styles aid in survival in the area's extreme climate (mountain and oceanic climate) and earthquake hazards. Whereas, a study carried out by Hailu et al., (2021), on “Indoor Thermal Comfort Analysis: A Case Study of Modern and Traditional Buildings in Hot-Arid Climatic Region of Ethiopia” shows that residences in vernacular buildings are comparatively thermally comfortable than those living in modern apartment housing. The study also concludes that high thermal mass materials (brick, wood, and mud) and straw (insulating materials), small uplifted windows, cross ventilation, a shading device using large trees in close proximity to buildings, and a bamboo basket shelter attached to vernacular buildings help reduce indoor temperature, humidity, and air velocity fluctuations. in the hot, arid climate of the area.

In Ethiopia, people used different traditional techniques of building construction based on locally available materials, ways of life, and climatic conditions. People in Merti woreda use traditional building techniques such as soil-roofed housing, which captures daytime solar radiation and re-radiates it at night, and low building heights to prevent heat captured from the sun from being quickly removed from indoors to help the building heat at night. They also use microclimate moderators such as trees in highland areas where the wind speed is high to protect the roof from being harmed by the wind.

1.2 Statement of the problem

Currently, most of human energy consumption is based on fossil energy sources. Fossil fuels (gas, oil, and coal) satisfied around 80% of the total energy consumption in the world (Fati et al., 2020a). The construction sector is responsible for nearly 40% of total CO_2 emissions and for 36% of total energy consumption (Algburi, 2019). The continued presence of global warming has intensified many atmospheric extremes, leading to significant increase in the frequency and severity of heat waves and their associated effects on human health (Petkar, 2016). A very significant part of the consumed energy is attributed to the lack of proper environmental design (Zoubi & Badarneh, n.d.). In residential buildings, the lack of concern to environmental design principles of locality such as temperature, wind movement, radiation, the proportion of buildings/spaces, materials, and vegetation causes an unsatisfactory level of indoor thermal comfort (Alzoubi & Almalkawi, 2019).

With little capacity to respond to current climate change, modern construction was practiced everywhere in Ethiopia without consideration of the local climate, and traditional construction was almost rejected, despite being proven to be climatically designed (Baron, N. and Donath, 2016). Present-day architecture does not pay attention to passive systems and techniques for enhancing indoor environments. Design happens without consideration of local climate or context. Or energy reduction strategies are considered only later in the process for code compliance-based prescriptive processes, which often fail to capture the potential of local climates. The majority of single-family and apartment housing units developed in various areas of the country were adapted using modern construction materials and techniques without taking local climatic conditions into account. For instance, the study carried out by Zewdu (2019) on the CO_2 emission and energy consumption of the top five construction materials used in commercial buildings in Bahirdar city proves cement, hollow concrete blocks (HCB), and reinforcement bars are the major consumers of energy and major CO_2 emitters. Cumulatively, they were responsible for 94% of the embodied energy and 98% of the CO_2 emissions. The trend towards adopting modern materials without taking into consideration the thermal efficiency of these materials in terms of indoor thermal comfort leads to many problems in the environment.

Only one study was conducted in Ethiopia, titled Indoor Thermal Comfort Analysis: A Case Study of Modern and Traditional Buildings in the Hot-Arid Climatic Region of Ethiopia by Hailu et al. (2021). But the study investigates the thermal performance of buildings through measurement of environmental parameters and the thermal preferences of their occupants.

The effect of bioclimatic elements of buildings, such as orientation, thermal mass, ventilation strategies, material properties, and the building's width-to-length ratio, on thermal performance is not quantified. Which find that the occupant in the traditional building is comparatively comfortable, and the temperature and humidity fluctuation are comparatively better in the traditional building of the area than in the apartment building. By this finding alone, it is impossible to identify which building element has the greatest impact on thermal and energy consumption. And also, the bioclimatic element proven to be effective for one climatic region with a specific topographic feature may not work for the other, to find the optimal passive solution, it is necessary to consider both regional climate variations and local building customs (Design et al., n.d), due to the local vernacular architecture is significantly influenced by the climate in a given place. The climate of Merti woreda is characterized by hot days with maximum temperatures reaching 34 °C in the spring months (March, April, May, and June) and colder nights for about eight months. According to studies, the temperature thresholds between 26°C and 32°C expose occupants to severe health problems such as respiratory illness, diabetes, and dementia symptoms (Tham et al., 2020). The increase in temperature in the areas and the decreasing rainfall pattern made the climate of the area abnormal, with extreme hot and cold temperatures, which affected the indoor thermal environment. Most of the householders in the village construct modern-design-influenced rectangular or square mud or HCB buildings with iron sheet roofing side by side with previously constructed round mud houses with thatched roofs. The use of modern materials, which are energy intensive and fabricated without considering local climatic factors, exposes the occupants of modern buildings to additional cooling costs and introduces indoor overheating. For this fact, the letter typologies (round thatch hut) are more commonly used than the former one; the hybrid and modern building styles serve only limited events and for a short period of time due to high daytime indoor temperatures. Compared to the corresponding outdoor temperatures, Comparatively The high thermal mass and insulation properties of traditional buildings help in dampening indoor temperature amplitudes.

1.3 Objectives

1.3.1. General objective

The overall goal of this research is to identify potential bioclimatic design strategies of Merti woreda vernacular dwellings and analyze the effects of these strategies on improving indoor thermal conditions.

1.3.2. Specific objectives

- ✓ to explore the bioclimatic design strategies employed in the vernacular dwellings of Merti Woreda.
- ✓ to analyze the existing indoor temperature, humidity and air velocity of the selected building.
- ✓ to investigate the suitability of the bioclimatic design strategies used on the selected building's thermal environment.

1.4 Research questions

1) What are the bioclimatic design techniques used in the vernacular building of Merti Wereda?
2) What is the magnitude of indoor and outdoor temperature, humidity, and wind speed level in the selected sample buildings?
3) Are adapted bioclimatic strategies moderating the indoor thermal environment?

1.5 Significance of the study

Studies of the bioclimatic element of vernacular architecture are greatly emphasized in different parts of the world during this time when energy efficiency is a critical issue and an increase in temperature affects the comfort of the occupants, but in Ethiopia, even though there have been different studies conducted recently in the vernacular architecture of different areas, there have been no such studies conducted before. The findings of this study will guide architects and planners on the energy saving potentials and thermal performance of various passive cooling strategies in the vernacular architecture of Merti woreda and other places with similar climate contexts. This paper will also increase academic interest in this under-researched area of study in Ethiopia, specifically in the tropical savannah (Aw) climatic category. Specifically, the output of the study will be used to:

- ✓ The study will be used as a guide for developers to develop climatic design features based on identified suitable climatic design features for the selected climate zone.
- ✓ Help the community of the study area save on its energy bill by adapting energy minimization strategies used in their traditional building techniques.
- ✓ Help different governmental organizations, such as the cultural and tourism office and the environmental protection office, to create awareness of the environmental quality of the vernacular style and motivate them to preserve it.

1.6 Scope of the study

Because of the difficulties in covering the entire range of climatic zones in Ethiopia, the current study was limited to the study of bioclimatic elements of vernacular architecture in the unresearched area of the Tropical Savannah climatic zone, which is characterized by hot days and colder nights during the dry season. Within a limited boundary of 08° 23′–08° 43′ N latitude and 39° 50′–40° 0′ E longitude, it focused on the analysis of monthly data, including maximum, minimum, and average temperatures; solar radiation; wind direction and speed; precipitation conditions; and relative humidity. The common bioclimatic design variables used in different literatures, such as shading devices, passive cooling systems, thermal mass, and ventilation strategies for summer (cooling design strategies) and winter (heating design strategies), were employed for the analysis of the bioclimatic aspect of the vernacular architecture of the study area.

1.7 Limitations of the study

The study was conducted for a limited time (for one week only) and within a particular season, so the validity of the results applies only to that season; summer in Ethiopia, specifically June, was preferred as the month to collect the on-site data for personal observation of the climate of Merti woreda, and previous secondary data shows the beginning of the rainy season in the woreda is characterized by extreme temperatures in recent years. The type of measuring instrument used in this study is another hindrance to the study; the instruments are hand-held manual equipment that needs measuring the environmental parameters within an identified time gap, which is challenging for the privacy of the householders. Moreover, due to only having three hygrometers available for the research, it’s difficult to concurrently measure both indoor and outdoor climatic parameters; as a result, the time gap between measurements may result in little variation. Finally, the two most difficult aspects of the data collection process are the country's political issues and the unwillingness of most householders to allow detailed surveys of their homes.

1.8 Organization of the Research

This research comprises five main chapters. Chapter one has nine parts, which include the background, the problem, the objectives, the research questions that will be answered, the significance of the study, the scope and limitation of the study, the organization of the research, and the definition of important terms in the study. Chapter two deals with the literature found regarding the topic: theoretical background, empirical experience, and contextual review. concerning bioclimatic design elements, thermal comfort, climate, and vernacular architecture. The third chapter deals with methodology, which discusses how the research and data have been collected. Chapter four deals with the results found from the study and analyzes these results as part of the discussion. The final chapter is the conclusion and recommendation section, under which the general finding from the study is provided and recommendations for different bodies are given.

1.9 Operational Definition of the study

The following terms are frequently used in the results and discussion chapters as well as in other sections of the research. Therefore, it's crucial to define each one independently.

Bioclimatic design- refers to the design of buildings in accordance to the local climate implies maximizing the utilization of the available natural resources, prior to any energy supplement by active means (Ness, 2017).

Building envelopes- contain non-translucent component of building (e.g., wall) and a fenestration system or a translucent component (e.g., windows) that separates the interior of the building from the exterior environment (Sinergi & Buana, 2019).

Infiltration: The movement of air into the conditioned space of a building through cracks, leaks, or other building envelope openings (Sadineni et al., 2011)

Passive system - The design that maintains a comfortable temperature within the building using the climate and natural elements to get the optimum benefit and to reduce or eliminate the independence on mechanical systems for heating, cooling and lighting (Lewis et al., 2018).

Temperature swing –the range of indoor temperatures in the building between the day and night

The relative humidity (RH) : is the ratio of the vapor pressure of water in the air to the vapor pressure in saturated air at the same temperature (Mcl, 1973).

Thermal mass: High-heat capacity materials that can absorb heat, store it, and then release it later are referred to as "thermal mass." They include structural elements like a building's walls, ceilings, floors, and furniture that store thermal energy. By absorbing and gradually releasing the heat produced by both internal and external sources, it aids in controlling the temperature inside buildings (Sadineni et al., 2011).

Thermal properties: refers to the greater or lesser capacity to transmit heat or accumulate it, thus determining the thermal inertia of a construction (Guadalupe, 2020).

Time-lag: It is the time difference between the occurrences of the temperature maximum at the outside and inside when subjected to periodic conditions of heat flow. It is expressed in hour (h) (Kisan & Sangathan, 1987).

U-value: ability of the component to gain-lose heat through conduction, convention and radiation. This depends mainly on the thermal conductivity and the thickness of each material (Energy & Note, n.d.).

Ventilation (natural) - air flow through and within a space stimulated by either the distribution of pressure gradients around a building, or thermal forces caused by temperature gradients between indoor and outdoor air.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Throughout history, among other influences like social-cultural, economic, defensive, and religious ones the availability of materials, technical, and constructive resources, and climate and environmental elements have always been one of the most crucial considerations in the design process (Mahdavi et al., 2009), Over time, a variety of passive building techniques have emerged. As the times and technology changed, other components and strategies were created. Examples of such strategies span from building management, such as room arrangement, to design features, such as window size and orientation, to construction (Sinergi & Buana, 2019).

Modern design styles and building methods have increased the inclination for unconventional buildings to overheat (Roaf et al., 2015). the sustainable qualities of vernacular architecture are gaining increasing interest from the scientific community in the field of the built environment. This is in part due to pressure to address climate change and global pollution, and discover ways to reduce the use of non-renewable energy in buildings (Berkovİć & Canan, 2020).

2.2. Conceptual framework

In this section, descriptions of important concepts in the literature were provided.

Bioclimatic design and Environment: Bioclimatic design means that a building is designed in such a way that, based on local climate data, environmental sources such as sun, wind, air, vegetation, soil and sky are taken into consideration as much as possible for heating, cooling and lighting to reduce the overall energy consumption of the building and to provide comfortable and pleasant living spaces for the inhabitants (Communities et al., 2015).

Evaluation of Bioclimatic design principle: Evaluating effectiveness of any passive climate control system is impossible through qualitative investigation alone, comprehensive field measurement of comfort parameters should support the qualitative investigation Dili et al., (2010).which implies evaluation of bioclimatic element of a buildings should be performed by qualitative investigation of bioclimatic element and quantitative measurement of environmental parameters.

Bioclimatic design strategy: The adoption of strategies in the design of a bioclimatic building significantly influences its performance in terms of thermal comfort and also leads to a reduction in energy consumption (Cruz et al., n.d.). During the project and building deployment, several aspects should be taken into account, such as:

- ✓ The local climate characteristics
- ✓ The location that best fits its effective use in terms of human comfort
- ✓ Technical factors associated with aspects like building orientation, the orientation of glazed façades, the building's shape, ventilation and air movements, the environment (heat gains and losses) and the internal and external temperatures
- ✓ The effects of surrounding buildings in terms of sunlight and wind exposure
- ✓ The solar radiation exposure during the year.

Vernacular/bioclimatic Buildings:

Vernacular building is the traditional and natural way in which communities house themselves. It is a continuing process that includes necessary changes and continuous adaptation as a response to social and environmental constraints. The survival of this tradition is threatened worldwide by the forces of economic, cultural, and architectural homogenization (Issues, 1999).

2.3. Theoretical Background

2.3.1. Concept of vernacular architecture

Vernacular structures are examples of architectural creations that arose in response to the needs of pre-industrial societies, the unsurmountable constraints imposed by geography and climate, and the special interaction between the human mind and knowledge gained from observing natural phenomena. The harmony between human behavior, architecture, and the natural environment is best demonstrated by vernacular buildings, whether they are found individually or collectively in a settlement. It contains intrinsic, unwritten knowledge on how to maximize the energy performance of buildings at low cost with local resources. In addition, it appears that employing locally accessible materials and well-established construction techniques to offer a pleasant shelter in a given climate is the result of hundreds of years of optimization.(Motealleh et al., 2018)

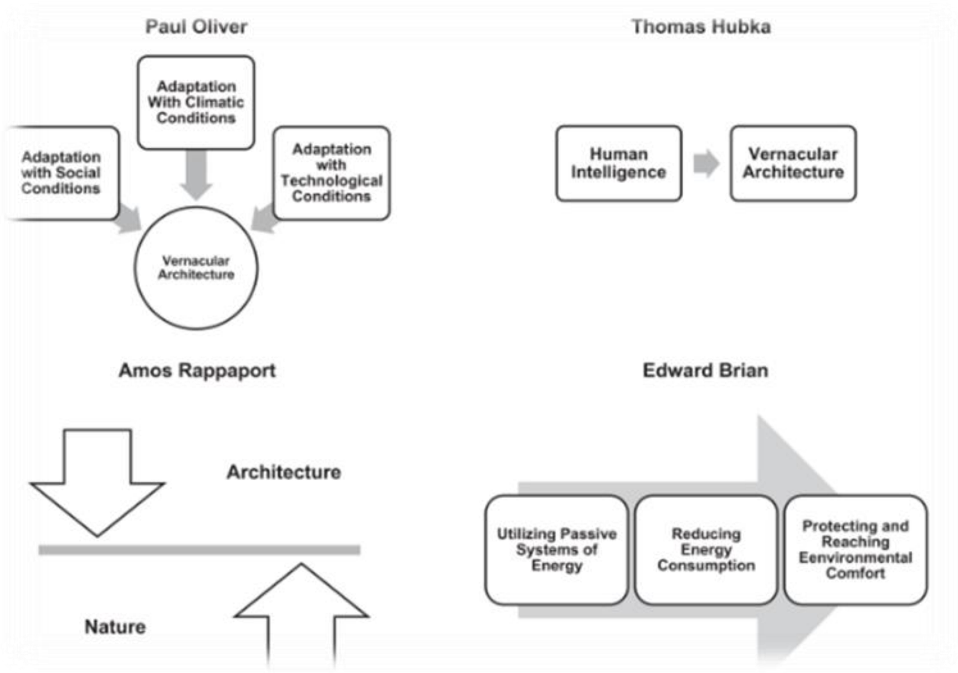


Figure 2.1: Conceptual diagrams of vernacular architecture (source: Parinaz Motealleh et al. ,2016)

Vernacular architecture is influenced by several variables, including the availability of materials and a skilled workforce, regional technology, an appropriate amount of sunlight, rain, humidity, wind, and temperature profiles, as well as regional cultures, the environment at the site, economic conditions, and historical context. (Ratree, 2020) It is essential as a cultural and scientific record to be preserved for future generations, but it also serves as a useful resource and teaching tool for rethinking the design of a more durable style of building. As a result, issues with social and economic equality, population expansion, global warming, and housing needs can all be addressed (Mohamed et al., 2019).

2.3.2. Energy efficiency in vernacular building

All life is dependent on energy. Even in the prehistoric era, a man recognized that energy from food, fire, and the sun was essential for survival, so he did everything to conserve it. He prepared food in advance, constructed a hut around his fire, and covered himself in skins. Two examples of thermal insulation were the shelter built around the fire to keep the heat within and the skin that covered his body to prevent heat from escaping through his skin and into the surrounding air. Thus, thermal insulation was one of the first technologies created by humans. This demonstrates that there has always been a need for energy conservation (Almusaed, n.d.)

The paradigm in the building industry has changed recently. The increased focus on the environment has brought to light a number of issues with environmental impact and energy efficiency. As a result, the industry is shifting from a paradigm that mostly relied on mechanical systems and materials with high levels of embodied energy and was less concerned with the climate context and environmental implications of buildings to one that takes a holistic approach (Silva et al., 2019). Nowadays, the majority of traditional environmental design principles have been ignored, and contemporary architecture does not effectively benefit from locus-specific and environmentally conscious vernacular architecture, resulting in structures with serious ecological footprints (Philokyprou et al., 2017).

It is commonly acknowledged that the current rise in primary energy use is unsustainable. As a result, initiatives are being driven to either prevent resource misuse or lower the demand for energy. Buildings are targeted since they represent one of the most promising industries in this sense (Cookson & Stirk, 2019). furthermore, Larasati & Mochtar, (2013) argues that buildings that respond to climate conditions have high-performance energy efficiency.

2.3.3. Climatic consideration in vernacular architecture

Architectural solutions must vary depending on the climate. Vernacular buildings that have evolved over time include a variety of innovative and fascinating design techniques to meet a wide range of needs (Singh, 2009). As a result, the local vernacular architecture is significantly influenced by the climate in a given place. High thermal mass and high insulation are required for buildings built in cold climates in order to prevent heat loss to the surroundings. Openings like doors and windows should be minimal in vernacular structures used in cold climates. On the other hand, buildings in hot regions need to be constructed from lighter materials and have numerous apertures to allow for extensive cross ventilation. Depending on the amount of precipitation in the area, buildings may take on distinct shapes (Kumar & Munoth, 2011).

Traditional building methods, such as thick walls to provide thermal inertia, shading and natural ventilation options, resistant roofing materials, wide eaves in snowy or rainy places are typically good examples of climate resilience and adaptability (Pardo, 2023) furthermore According to a study, the tropical humid climate vernacular building significantly considers air movement strategies through various strategies such as building orientation towards north and south to get dominant wind and sun directions; high porous walls with wide openings; and a wood scaffold (raised floor) to enhance air movements and remove humidity from the ground (Prianto et al., 2000). Vernacular architecture provides a good solution to climatic constraints, and there is more than one approach to solving the same climatic constraint (Soleymanpour et al., 2015).

Measurements of the wind environment and the thermal environment, such as air velocity, air temperature, humidity, and radiation, among others, can be used to determine the climatic conditions of a region (Borys et al., 2019). Several studies have proven that better thermal performance can be achieved by passive measures of vernacular architecture (Borong et al., 2004; Priya et al., 2012) and (Dili et al., 2011).

2.3.4. Bioclimatic design

creation of a thermally comfortable environment is an important parameter in the building design process due to modern man spends most of the day indoors (Air et al., 2008). As a result, over thousands of years, the inhabitants of every part of the world have developed bioclimatic methods and systems to lessen the impact of unfavorable weather conditions. The types of clothing worn, the diurnal-nocturnal work schedules, the building designs, and the activities carried out inside them all serve as direct indicators of the solutions appropriate for each region (Tuan et al., 2019).

A study conducted by M. Philokyprou & Michael, (2012) indicates bioclimatic elements of the vernacular architecture of Cyprus, mainly the passive heating strategies (solar gains, thermal mass, and thermal inertia), passive cooling strategies (sun shading and ventilation), and optimization of environmental microclimate (planting, evaporation). The study's findings indicate that bioclimatic elements improve indoor stability and create a significant time lag that prevents outdoor extremes from reaching indoors.

Mohammadi & Pazhouhanfar, (2018), In their study of the bioclimatic aspect of the traditional settlement of Qeshm Island, they argue that bioclimatic design is based on the physical condition of the building's effective use of microclimatic components such as sunlight, heat, and wind through the building shell at the exact time of the day and months of the year is significant. Furthermore, Hany & Alaa (2022) states the principle behind bioclimatic architecture is to use as little energy as possible to achieve indoor thermal comfort requirements by maximizing the advantages of the local environment and building siting. Studies demonstrate that bioclimatic components used in regional vernacular structures, like those in Egypt, Iraq, India, and Pakistan, successfully control the thermal climate within the structure and shield the interior from excessive heat (Okba, 2015).

For bioclimatic design techniques, a precise characterisation of the climate is necessary. All of these factors must be considered, including the highest and minimum average monthly temperatures, the temperature range, solar radiation, the direction and speed of the wind, the amount of precipitation, and the relative humidity. Then, specific climate definitions will require a number of design strategies, such as the building's orientation in relation to the sun and wind, exterior ground treatment and landscaping, wall thickness, choice of construction materials and colors, shading conditions, roof construction detailing, and permanent ventilation of the region between the ceiling and roof, commonly known as "attic ventilation," as well as the location, size, and presence of cross-veins (Labaki & Kowaltowski, 1998).

As stated by Wong & Li, (2007) the main points to take into consideration when designing a climate-responsive building are:-

- ✓ minimize heat gain during daytime and maximize heat loss at night in hot seasons, and reverse cold seasons,
- ✓ minimize internal heat gain in the hot seasons,
- ✓ select the site according to microclimatic criteria,
- ✓ optimize the building structure (especially regarding thermal storage and time lag),
- ✓ control solar radiation,
- ✓ regulate air circulation

bioclimatic architecture is achieved through passive design means primarily defined towards identifying the passive heating and cooling strategies (Bugenings, 2022). Furthermore, Rodriguez ubinas et al., (n.d.). argues that the passive design includes methods for hygrothermal comfort, daylighting, and air quality. In order to promote hygrothermal comfort, the heating period strategies seek to maximize direct and indirect solar gains, thermal energy storage, and the reduction of heat losses. On the other hand, cooling phase strategies include avoiding heat from building up, removing heat that has built up, and reducing sources of heat.

2.3.5. Passive design techniques in bioclimatic design

Under passive climate control, which presupposes that the structure is planned and configured in this manner, a good, stable interior atmosphere is produced by the thermal and hygroscopic properties of the building and its contents. The climate characteristics should be taken into consideration while managing the design, layout, orientation, and scale of dwellings and housing groups (Ammar & Mansouri, 2018). The criteria must be adjusted to the climate and geographic setting when using the passive design technique. To find the optimal passive solution, it is necessary to consider both regional climate variations and local building customs (Design et al., n.d).

Dimoudi, (2013). classifies Passive cooling techniques into three main categories, Heat prevention Techniques, Heat Modulation Techniques, and Heat dissipation techniques.

A) Heat prevention Techniques; are mostly related to solar radiation control, avoiding the entrance of heat from the external environment (Prieto et al., 2017). it may involve, and the use of outdoor and semi-outdoor spaces, building form, layout and external finishing, solar control and shading of building surfaces, thermal insulation, control of internal gains, etc.

i. Landscaping

Landscaping is one way to improve comfort and energy efficiency throughout the year. Planting trees can save energy, reduce noise and pollution, adjust temperatures and relative humidity, and improve people's psychologically. Moreover, Raeissi and Taheri,(1998) prove that properly planted trees reduce cooling load accordingly. The test is conducted in four buildings: one with no plantation on either side, one with a plantation on the east side, one on the west side, and one with a plantation on both the east and west sides. Buildings with plantation on both sides reduce their cooling load to 4.479 J, a 39.9% reduction from buildings without plantation on either side, which requires a cooling load of 7.45 J.

ii. Outdoor and semi-outdoor spaces

Gamero-salinas et al., (2021). argues that verandahs and balconies are examples of semi-outdoor spaces that protect indoor environments from solar radiation. As a result, a study conducted by Maragno & Roura, (n.d.) on the effect of six types and sizes of verandas confirms that long and inserted verandas can greatly minimize the solar radiation received by the walls and floors. Further, the study discusses the relationship between orientation and latitude on solar radiation increment and finds that north and east-west orientations receive the highest solar radiation with increments in latitude from 0° to 30°S, compared with south orientations, and the solar radiation received by a 15° S wall and floor reduces the solar radiation by 73% to 83% and 52% to 69%, respectively.

iii. Building form

The aspect ratio and compactness of the building determine the shape (form) of the building. The aspect ratio is the ratio between the building's length and width and is used to provide information on areas exposed to solar radiation. On the other hand, compactness is the ratio between the building's volume and its external surfaces, which displays the building's capacity to store heat as well as any potential heat losses through its façade. Heat loss decreases as a building becomes more compact (Bugenings, 2022).

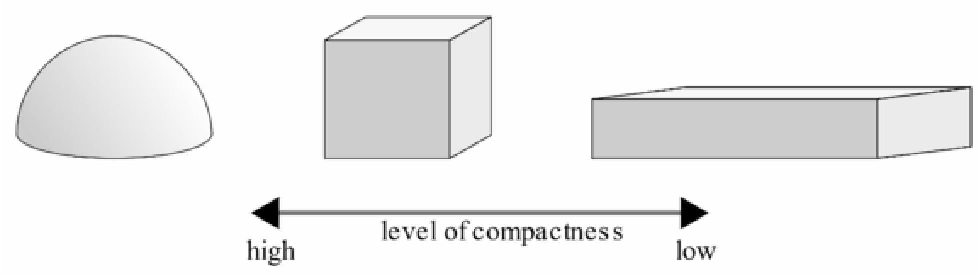


Figure 2.2: Building massing-level of compactness (source: Bugenings, 2022)

iv. Shading

Shading size and type depend on the orientation of the window. horizontal shading element works well in north and south orientation and vertical fenestration is required to cut the sun from east and west. However, the trickiest design of shading is concerning the southwest and southeast orientation. As in these directions, the altitude of the sun is in the midrange. Hence, only horizontal and only vertical shading devices will not cut the glare only a combination of both types of shading is required to cut the harsh sun (Altan et al., 2016).

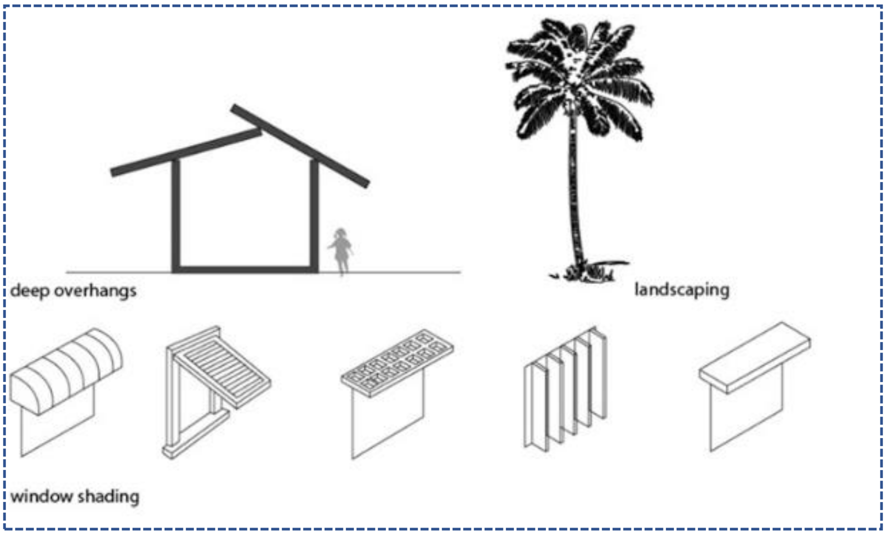


Figure 2.3: different shading system (source: Altan et al., 2016)

v. Thermal insulation

Insulation acts as a barrier to heat flow, reducing heat loss in winter to keep the house warm and reducing heat gain in summer to keep the house cool. Inadequate insulation and air leakage are the main causes of heat loss in buildings. Insulation is therefore used in walls, ceilings, and floors (Taleb, 2014).

B) Heat Modulation Techniques; Modulation of heat gain deals with the thermal storage capacity of the building structure, (Prieto et al., 2017). This strategy provides attenuation of peaks in cooling load and modulation of internal temperature with heat discharge at a later time. The larger the swings in outdoor temperature, the more important the effect of such storage capacity.

i. Thermal storage (mass)

Thermal mass is proposed as one of the most interesting passive methods for energy saving in indoor environments (Green Energy and Technology, n.d). which is essential design factor being the choice of materials to take advantage of thermal mass. As an illustration, heavyweight internal construction (high thermal mass) made of brick, solid concrete, stone, or earth can store the sun's heat during winter days and release it into the rooms at night once it has passed through. Plasterboard and wood paneling are two relatively low-mass materials that operate as insulators to the thermal mass, which decreases the efficacy of the lighter materials. Lighter construction reacts more quickly to temperature changes. This makes it appropriate for quick heating or cooling rooms (Kleerekoper et al., 2012) and (Lewis et al., 2018).

ii. **Building envelope**

The construction of the outer building envelope influences the physical processes taking place between the outdoor environment and indoor spaces. The objective is to limit thermal gains during the summer due to high outdoor air temperatures and incident solar radiation. Thermal insulation can reduce the heat conducted through the building materials. During the summer it reduces thermal gains and during the winter it reduces thermal losses (Santamouris et al., n.d.).For instance, A study undertaken by Porta-Gándara et al., (2002) shows that the upper openings designed in the external walls can release the block added heat and enhance cross ventilation.

Philokyprou et al., (n.d.) stated that the suitable use of materials in the building's envelope provides direct protection from the climatic conditions, while the materials of the buildings' surroundings contribute to the development of desirable microclimatic conditions. Their results indicates that, Thermal inertia secured by the thick mud brick and stone walls and the mass of the roof materials provide a small fluctuation in the internal temperatures. proper design and selection of building envelope and its components are among ways in which reducing the heat and air conditioning load in the buildings (Latha et al., 2015). Sharma et al., (2003) states that, Maximum solar radiation is gained through roof of the building. As a result, the design of roof geometry,form and material affect the ammount of solar radiation gained. As stated by Iyendo et al., (2016), orientation, building form, optical and thermo physical properties of the building envelopes are the most important design parameters affecting indoor thermal comfort and energy conservation on the building scale.

C) Heat dissipation techniques; These techniques deal with the potential for disposal of excess heat from the building to an environmental sink of lower temperature. The main processes of heat dissipation techniques are ground cooling based on the use of the soil, convective and evaporative cooling using the air as the sink, as well as water, and radioactive cooling using the sky as the heat sink. The potential of heat dissipation techniques strongly depends on climatic conditions: -

i. **Single/cross ventilation**

Single-side ventilation is where wind velocities move inwards and outwards through the same apertures on the same side of a building (Aflaki et al., 2015). On the other hand, Cross ventilation has many benefits, including the removal of hot air, the introduction of fresh air into the building, and a reduction in temperature to lower the loading energy. while drawing exhaust air outside, fresh air is brought inside the structure (Taleb, 2014).

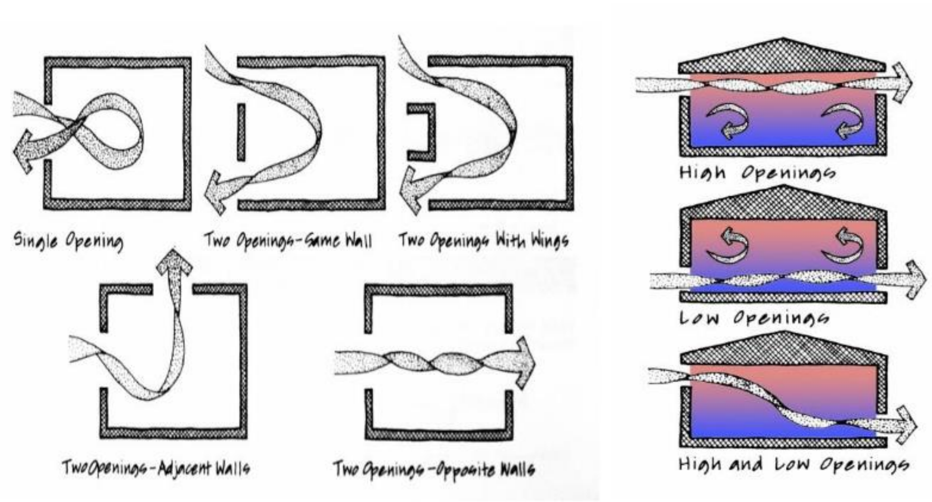


Figure 2.4: diagrams showing single and cross ventilation mode (source: adapted from Alibaba, 2018)

ii. Buoyancy

stack-effect ventilation (driven by the buoyancy of heated air even in the absence of external wind pressure) (Watson, 1992). The difference in temperature of the inside air and the outside makes this work. Since warm air is lighter than cold air, it moves upwards. When windows are opened at different levels, the warm air inside the building would leave out through the top opening and the cool air from outside would enter the building through the lower opening to replace it.

iii. Night ventilation

Since the temperature differences at night are substantially larger than the day, night ventilation in heavier buildings exhibits more benefits. High thermal mass buildings effectively transmit heat as the air is moved over their surface by the cool outside air. To remove the heat that has accumulated over the day from the building structure, ventilation is needed at night. (Beggs 2010). During the night, ventilated air can be used to cool buildings. Since nighttime temperatures outside are typically cooler than inside during the summer, natural night ventilation can help cool the structure (Lewis et al., 2018).

iv. Evaporative cooling

The amount of humidity in the air has a big impact on evaporative cooling. Bypassing the wind over water or supplying the wind with water droplets, water is generally employed to calm the blowing wind (Altan et al., 2016).

v. **Orientation**

Building block orientation governs the passive technologies implementation within the design (Altan et al., 2016). The adaptation of the right techniques used for orientation governs the right operation of openings which will in turn affect the overall performance of the building and also the contextual demand.

According to Jamaludin et al., (2014), the building orientation towards the direction of the local prevailing wind will enhance the natural ventilation for cooling purposes. Furthermore, Ackerknecht, (2021). Argues that Solar radiation, Prevailing wind and Topography are the critical features to define the optimal orientation of a building.

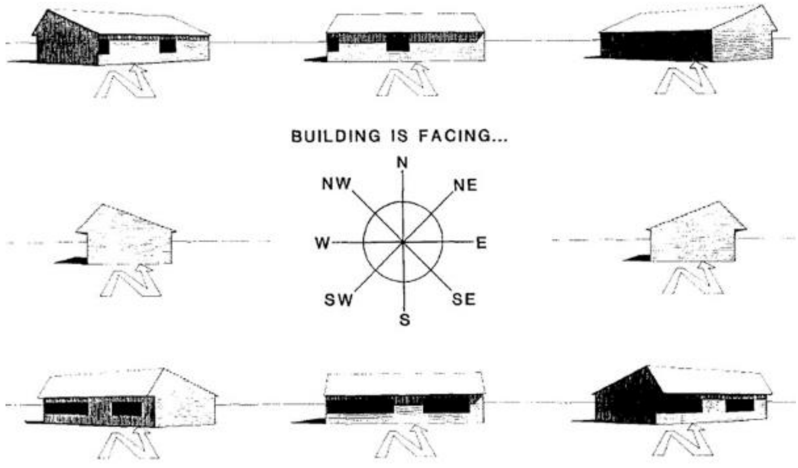


Figure 2.5: different orientation for a residential building (source: Morrissey et al., 2011)

2.3.6. Factors affecting climatic design

Rastegarpanah, (2018) claims that two factors affect climatic design for a specific location: the local microclimate and site factor (building context, vegetation, and topography); and the other is the architectural factor (form or shape, ventilation, building fabric, glazing, and orientation) (Douvlou, 2004).

i. **Local microclimate and site factor**

- ✓ Topography: elevation, slopes, hills and valleys, ground surface conditions.
- ✓ Vegetation - height, mass, texture, location, growth patterns.
- ✓ Built forms - nearby buildings, surface conditions.

ii. **Architectural factors**

- ✓ Shape: surface-to-volume ratio, orientation, building height.
- ✓ Building fabric - materials and construction, thermal insulation, surface qualities, shading.

- ✓ Fenestration -the size, position and orientation of windows, window glass materials, external and internal shading devices.
- ✓ Ventilation - air-tightness, outdoors fresh air, cross ventilation and natural ventilation.

2.3.7. Thermal properties of commonly used building materials

Energy & Note, (n.d.) lists acceptable U-values for different components of buildings in tropical countries as 1 W/m2*K for walls, 0.85 W/m2*K for roofs, and 5.00 W/m2 K for windows. In hot and humid or hot and arid climates, it is preferable to reduce these values by at least 20%, especially in buildings using air conditioning. Accordingly, the table shows that straw, wood, stone, and adobe have good thermal properties.

Table 1: Mostly used building materials and their properties **(**Source: **(**Energy & Note, n.d.) and (Nguyen et al., 2011)

Materials	**Thermal conductivity (W/Mk)**	**Thermal mass. Volumetric**
Thatch/straw	0.07	340
wood	0.11 - 0.23	1000 - 1300
stone	0.55 (porous stone) - 2.50 (blue stone)	1600 - 2300
(adobes) / *Compacted earth	0.50 - 1.50 / 0.70 - 1.70	1300 - 1600 / 1700 - 1800
Corrugated iron sheet	61.00	3700
glass	1.10	2100
Concrete blocks / reinforced concrete	0.19 (light) - 1.63 (heavy) / 1.40 - 1.80	600 (light) - 2300 (heavy) / 2000 - 2500
bars	47	3700

2.3.8. Climatic benefit of local materials

Climate of a region impacts the thermal comfort and energy demand which are the two prime movers of building performance (Zeleke et al., 2022). Result of a complex balance between material, shape, and natural context, vernacular architecture is the most integrated architectural form in communion with the environment. In many developing countries where the properties of earth construction are more widely appreciated, earth is utilized in the construction of floors and roofs, in addition to walls. Buildings made with earth are economical, energy saving, environmentally friendly and sustainable. Earth buildings include adobe, cob, straw and rammed earth blocks and walls (Niroumand et al., 2013).

Silva et al., (2019) proves that vernacular techniques using local materials which have high, thermal, and hygroscopic inertia of the envelope (floors, walls, and ceiling) regulate and stabilize the indoor humidity. The author further states local materials including earthen ones have low toxicity and the ability to regulate moisture. The vernacular architecture has different methods related to the climate factors: interaction with nature, designing with less need to energy resources, exploitation of renewable energy resources like wind and sun, low use of water and gathering precipitation (Karabag & Fellahi, 2017).

climatic conditions at a given location are not just determined by weather data, but are also affected by the topography of an area. The surrounding geometry modifies wind patterns and also sunlight (Cookson & Stirk, 2019). As a result, the climate conditions in the three topographical division of Merti wereda have some variations which affect the design of building

2.3.9. Thermal Comfort

According to ASHRAE standard 55- 2013, thermal comfort can be described as the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. Further, ISO Standard (International Standard Organization) 7730 define thermal comfort as, a complicated relationship between air temperature, air humidity, and airflow velocity, coupled with the type of clothing and activity and metabolic rate of the inhabitants that present an expression of feeling of satisfaction with the condition Air in an environment (Sinergi & Buana, 2019).

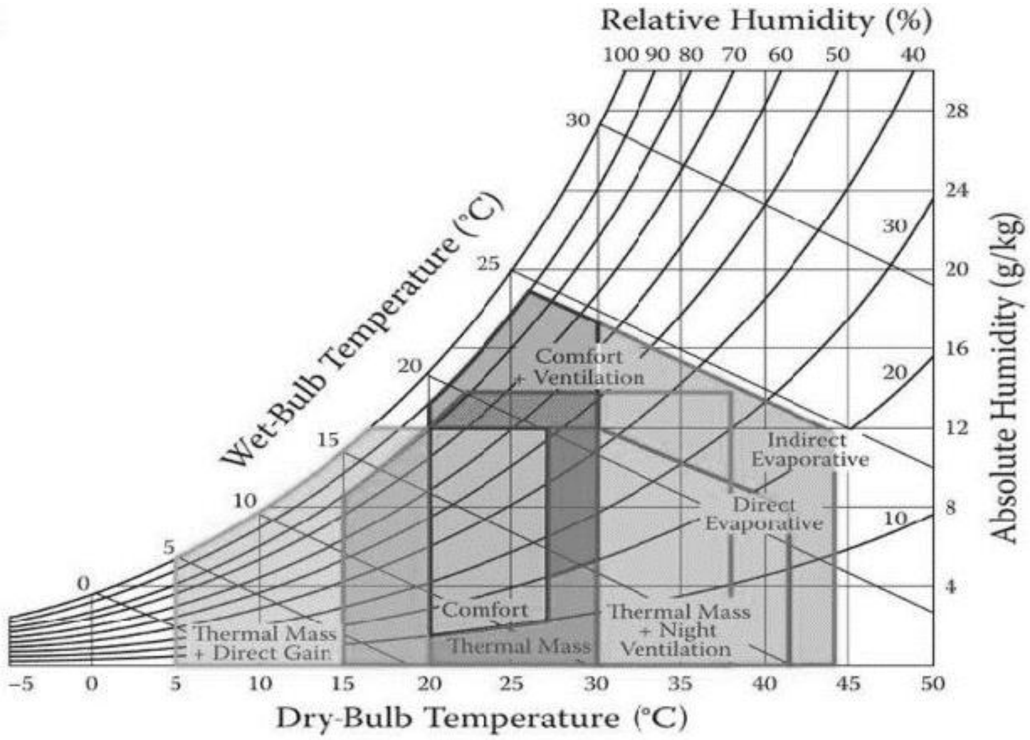


Figure 2.6: Comfort area and recommended passive design on psychometric chart (Source: Schiavon et al., 2014)

2.3.10. Factors affecting thermal environment

Thermal comfort is achieved through the combination four classical thermal environmental variables, (air temperature, air velocity, humidity and mean radiant temperature) and two subjective variables (metabolic activity and clothing), (Fanger & Toftum, 2002) furthermore, Jamaluddin et al., (2014), lists, the most common impacts caused by the climatic parameters of tropical climate as temperature, relative humidity, solar radiation, rainfall and prevailing wind. From the above listed parameters, the three comfort parameters which is used by different authors are discussed.

A. Thermal environmental variable

i. Air Temperature

Concepts & Thermal, (n.d.) states that**,** the air temperature, that is the dry bulb temperature is a very important factor affecting thermal comfort. When temperatures are low, people feel cold and when they are high people feel hot. Comfort can approximately be achieved between 16 and 28ºC. The temperature of the human body is an important indicator of its condition: comfort, heat or cold stress, performance (Environments, n.d.). Furthermore, in accordance with ISO 7730, the permitted temperature ranges are 20°C to 23°C and 24°C to

26°C in the winter and summer, respectively. The permitted relative humidity ranges are also specified at 70–30% in both seasons (Standard, 2005).

Minimizing the moisture content in the air elevate limit on the upper acceptable temperature. For instance, temperature in summer extends from 26 °C at moisture content of 12 g/kg to 27 °C at 4 g/kg. also, the increase air speed extends comfort temperature. but the acceptable upper humidity limit not affected by the increase in air speed (Givoni, 1992).

ii. Air Velocity

Air movement is very effective in increasing heat loss from the body at high temperatures when sweating occurs. According to Schoen et al., (2013) the allowable air speed in conditions were occupants control not required were 0.15 m/s to 0.8m/s. The air movement enhances the evaporation of sweat from the body thereby cooling down the body. Air velocity of up to 0.1 meter per second may lead to a feeling of stuffiness indoors. Outdoors wind speeds of up to 2.0 m/s can help achieve comfort, especially when the humidity is high. Wind speeds of over 5.0 m/s led to considerable discomfort.

iii. The Relative Humidity

When there is low humidity, the air is very dry and sweating is more effective in cooling down the body. However, when the humidity is high the air is damp and clammy and sweating is no longer very effective in cooling down the body. Thermal comfort can be achieved when the relative humidity is between 20 and 90%. the moisture picks up of materials depends on the RH of the atmosphere; low humidity may give problems with shrinkage of wood, and with static electricity. Prolonged periods of humidity greater than 70% encourage mould growth, and may give condensation on cool surfaces. a relative humidity in the range 35 to 65% should be satisfactory from both the comfort and structural aspects (Mcl, 1973).

iv. Mean radiant temperature

It is important meteorological parameters governing the human energy balance and thermal comfort (heat load) is defined as the ‘uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure’. can be calculated from measured values of the temperature of the surrounding walls and surfaces and their positions with respect to the person (Ã et al., 2007).

B. Subjective variables

i. Metabolic rate

Is represents the heat generated within the body and is the most fundamental comfort determinant, where M is the metabolic rate (MET, where 1 MET equals 58 W/m2). Increasing the metabolic rate from 0.9 to 1.5 could result in a 3.2K difference in thermally neutral temperature (temperatures when PMV equals 0) or a 1.5-unit scale difference in PMV. Not surprisingly, an accurate description of human metabolic rate is the basis for thermal comfort studies (Luo et al., 2018).

ii. Activity level

The insulation value of clothing, which is often measured in Clo units, is as important as the thermal resistance and insulation offered by any layer of trapped air. A comfortably sitting or resting average male requires a certain amount of insulation from his clothing system, or coat, in a regularly ventilated room. It is the thermal insulation of a person's whole attire, not just a specific garment, when the air is moving at a speed of 0.1 m/s, the temperature is 21 °C, and the relative humidity is under 50% (Luitel et al., 2020).

2.3.11. Methods of defining comfort and comfort zone

The static model based on PMV/PDD developed by Fanger and the adaptive thermal comfort model by Humphrey have been widely accepted to validate comfort conditions (Gokarakonda & Kumar, 2016). Both methods have been supported by a large number of laboratory and field studies (Li et al., n.d). For instance a study conducted by Dear & Brager, (2002) and (Rd, 2017). indicates that observed and predicted comfort temperature in HVAC building complemented using PMV model this indicate that the applicability and usefulness of PMV model for HVAC building only. Were as adaptive comfort model being useful in predicting comfort temperature in naturally ventilated building. ASHRAE Standard 55.

For instance, Programme, (2018), Use adaptive comfort model (ACM) to predict the thermal comfort in naturally ventilated. buildings to determining acceptable indoor thermal conditions. the field studies are conducted only for one week (did not cover the whole month). To determine indoor comfort temperature based on prevailing mean outdoor temperature weather data of mean monthly temperature is necessary. previous data that was conducted from metrological station has been used to identify the comfortable temperature of the study area (Singh et al., 2010). due to the above statement were compatible with study site adaptive comfort model were applied.

The Adaptive Comfort Standard is developed from a global database where the comfortable neutral temperature in winter is 22°C, for calculating summer comfort temperature the following formula were used by (Parkinson et al., 2020). Tco= 0.31* Tmot + 17.8 with three pre conditions:

- ✓ Average monthly outdoor temperature ranging between 10 °C and 33.5 °C.
- ✓ For buildings where occupants can directly operate windows.
- ✓ for buildings where the occupants perform low metabolic rate activity (<1.3 MET).

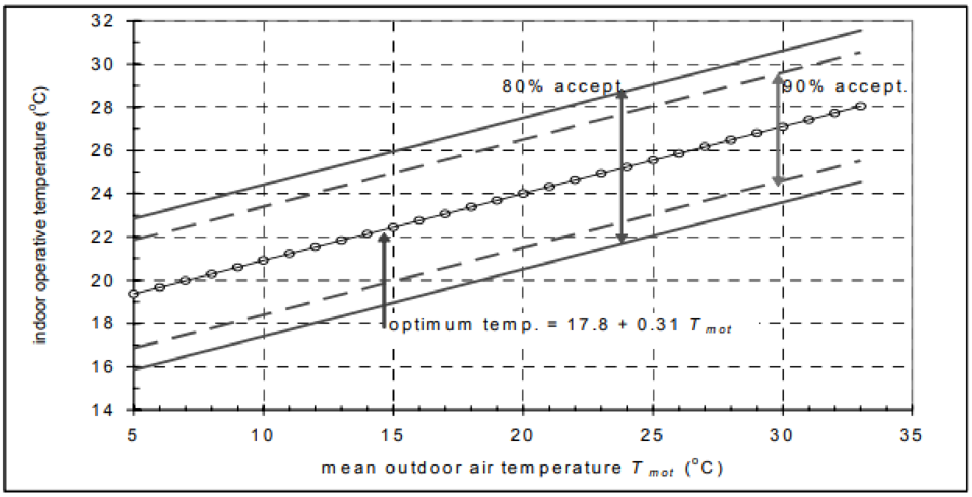


Figure 2.7: The adaptive comfort model used in ASHRAE Standard.55:2004. Optimum indoor comfort in a naturally ventilated building equates to 0.31*Tmot + 17.8ºC. The 80% thermal acceptability band is the optimum ± 3.5 ºC, while the 90% acceptability band is ± 2.5 ºC. (Source: R. De Dear, 2007)

The model can be defined as; Tcom f = 0.31 ×Tmot + 17.8, in which Tcom is the indoor comfortable operative temperature and Tmot is the prevailing mean outdoor temperature for the past 30 days.

2.4.Empirical Review

This section in the literature provides important points in other researches related to the title of current paper. Such that; techniques use for proposed methodology, techniques used for data analysis and in general discussing on effectiveness of bioclimatic element of vernacular buildings in different part of the world based on studied examples.

2.4.1. Global Experience

According to Green Energy and Technology, (n.d.) the criteria to classify and analyze indoor environments are: energy saving, work risk prevention, thermal comfort, biological source, preservation of materials and therapeutic effect. More over the study lists the different indoor environment as: industrial environment, office and school buildings, apartments, library and spas. Accordingly, this study evaluates indoor environments from thermal comfort and energy saving perspective.

According to ASHRAE Standard 55 (2004), there are two methods of evaluating buildings for compliance with comfort requirements. The first method involves an occupant survey, and the second method analyzes environmental variables to determine comfort conditions (Date, 2004). As a result, these studies employ the second method, which is the analysis of the environmental variables that critically affect thermal comfort. Moreover, Dili et al., (2010), Believes that evaluating effectiveness of any passive climate control system is impossible through qualitative investigation alone, comprehensive field measurement of comfort parameters should support the qualitative investigation.

According to Stijn, (2018). it is difficult to distinguish the impact of each influencing parameters on energy consumption and indoor thermal comfort in the building through measurement data and to identify contribution of each component in the building theoretical models and simulations are mostly adapted by different scholars.

Different authors used different approach for evaluating thermal performance of vernacular architecture of different region across the world. For instance, Dili et al., (2010) on study of vernacular building of Kerela used qualitative investigation of climatic feature and three days field measurements of temperature, humidity and air movement continuously within five minute interval.

Elshafei, (2021) states that analysis and evaluation of vernacular design strategies require methods that account for the inputs to the thermal equations and the building envelope and allow design strategies to be assessed for the vernacular envelope. These strategies were assessed using three tools adapted to hot climates: the bioclimatic graph, the psychometric chart, and the Mahoney table analysis. Accordingly, in this paper, bioclimatic design guidelines for the study site were generated using the Mahoney table analysis method and a psychometric chart.

Mahdavi et al., (2009) utilized the Mahoney Tables' climatic analysis approach to assess the methods utilized in the traditional architecture of the southern Caspian Sea region. The results from the Mahoney tables were then compared with the strategies discovered to ascertain how much the local traditional architecture was influenced by the weather. The tables are therefore organized into four sections, which comprise the following: data collection, design recommendations, remedial action, and thermal stress (Eusebius, 2011).

An approach used by Stijn, (2018) and Dili et al., (2010) was used for the present research to achieve the stated objectives in the studies.

i. Effect of roof construction on thermal and energy load

Maximum solar radiation is gained through the roof of the building (Sharma et al., 2003).The design of the roof (geometry, form, and material) affects the amount of solar radiation gained. Yildirim et al., (2014) conducted a comparative analysis on flat and conical roofs and discovered During the day, a unit area of the flat roof absorbs (4820 W/m2 day) more solar radiation than a unit area of the conical roof absorbs (2789 W/m2 day). Their results further state that the difference in inclination or degree of the roof affects the solar radiation received; the steeper the slope of the roof, the lower the solar radiation received.

ii. Effect of building form on thermal and energy load

Ling et al., (2007) Study "the effect of geometric shape and building orientation on minimizing solar insolation on high-rise buildings in hot humid climate" their result indicate circular shape with W/L ratio 1:1 received lowest amount of insolation (9,296 mWh/year), followed by square received 10,503 mWh/year. Moreover, A study carried out by Nongué et al., (2021) on Numerical Study of the Thermal Performance of Three Roof Models in Hot and Dry Climates shows that the geometric shape and physical properties determines the effectiveness of roof on reducing interior temperature of a room.

iii. Environmental performance of local materials

The result obtained by Nongué et al., (2021) By comparing clay and straw mixture in a clay detached house on reducing the air conditioning requirement of the building, the result shows that the clay and straw mixture in a walled building reduces 8% of the total air conditioning requirement of the building. Furthermore, Almusaed, (n.d.) argues that Straw can provide greatly improved comfort, and dramatic energy savings compared to more expensive traditional building structures because they allow smaller heating or cooling systems in conventional homes because of the increased insulation.

The use of skins, mud, space, fibers, and fillers have all been used as traditional materials for thermal insulation for thousands of years.(Almusaed, n.d.). Accordingly, For all kinds of applications in windows, doors, roofing, flooring, etc., wood and timber are recognized to be suitable thermal insulators and are acceptable in terms of their thermal insulation capabilities Latha et al., (2015). The research argues that, the use of wood and wood-based materials in furnishings and building envelopes regulates interior climate by reducing daily fluctuations in indoor humidity. Compared to other building materials: glass, rubber, plastic, concrete, brick, etc., wood has a lower density and a higher heat capacity (1.6-3 kJ/kg K).

A study conducted on a sustainable rural mud house with a pitched roof in India by Subhash Mishra, et al. proves that earthen housing appears to meet the requirements of green construction. The mud house was constructed with soil and cow dung. It is found that approximately 370 GJ of energy can be saved per year using these construction materials. The energy payback time for the mud house was 1.54 years. The emission of CO2 into the environment was reduced by 10 tons per year. The mud house was also more environmentally friendly compared to a conventional building (Engineering, 2013).

iv. Building orientation

Wong & Li, (2007) performed field measurements and computational energy simulations to examine the effectiveness of passive climate control methods such as building orientation in residential buildings in Singapore. Their results state that the best orientation for a building in Singapore with its tropical climate is for the long axis of the building to lie along an east-west direction. They also conclude that the cooling load for a residential building can be reduced to 8% -11% by following this orientation

2.4.2. Continental Experience

A study conducted by Naciri, (2007) investigated climatic control measures in the hot, arid region of the Middle East and North Africa. Two cases from North Africa and one from the Middle Eastern region are qualitatively investigated. The result indicates that vernacular building in southern Morocco and northern Africa with "casbah" typologies characterized by hot, arid climate types uses climate control methods: small windows, high building height, compact and close buildings that share an external wall to minimize exposure of the external wall to harsh environments, use of traditional material adobe for construction (high thermal mass), lower surface-to-volume ratio, and courtyard. On the other hand, vernacular buildings in the Middle East, such as Yazd in the Iranian desert, are characterized by a hot and dry climate. A wind tower captures passing wind and creates cool air movement inside the building; a dome and white lime plaster are used to reflect incoming intense solar radiation from reaching the building's walls, among other climatic control methods.

2.4.3. Influence of climate in forming vernacular architecture of Ethiopia

The diverse topography in Ethiopia extends the climate of the country to arid, semi-arid, tropical, savannah, and even sub-alpine. Much of Ethiopia lies at altitudes of more than 2000 m and has a tropical monsoon climate with fairly uniform mild temperatures all year, where the vernacular dwelling forms are numerous and reflect the regional and local climate. The northern part of the country (arid zone) is characterized by load-bearing stone masonry that is thick enough to store intense solar radiation during the day and release it at night to places where the external temperature is less than the internal temperature and is characterized by courtyard building typologies, whereas the southern part is characterized by bamboo structures. Local building cultures vary according to the country's climate ranges, but mud huts (Chika) with thatch roofs and hybrid mud houses with corrugated iron sheet roofing are abundantly available in most parts of the country where the materials are available (Cluster, 2018).

2.5. Lesson learned from literatures

According to a study conducted by Zhai & Previtali, (2010) on the energy performance of vernacular buildings in eleven different climatic regions, vernacular building techniques will reduce the cooling load by 38%, which is less than the International Energy Conservation Code (IECC) recommended standards. 29% of vernacular instances with lower heating loads than the IECC which indicate the potential of vernacular buildings in energy performance and pave the way in which one thinks the techniques will be adopted.

Widera & August, (2021) study on vernacular and low-tech building typologies in six Sub-Saharan African countries on thermal performance and user satisfaction the study concludes that 60% and 90% of vernacular dwelling occupants are comfortable during the hot dry season and the colder wet season, respectively. While in modern buildings, only 20% of users feel comfortable. which shows the thermal performance potential of vernacular architecture.

2.6. Research gap

Trends in the scientific literature in vernacular architecture studies revealed that there are few studies in Africa, and particularly in Ethiopia, that focus on the thermal performance and energy efficiency of vernacular buildings. (Benkari & Mahboobeh, 2020).

The study was conducted to fill the contextual gap observed in different related studies in both global and local contexts. For instance, the study conducted by Philokyprou et al. (2017) evaluated environmentally responsive design elements through the qualitative method alone, in which the bioclimatic elements of different climatic regions of the areas under study were explored and compared with Mahoney table recommendations based on the climatic data of the areas to judge whether the building was climatically designed or not. This is not supported by a quantitative investigation of the real performance of the sample building (a methodological gap). On the other hand, in our context, there are two related studies that assess the thermal performance of traditional buildings in hot, dry climate regions of Ethiopia: The Afar region, Semera City by Hailu et al. (2021), and the warm temperate oceanic climate of Ethiopia, Jimma Town by Yadeta et al., (2019). The thermal performance of sample buildings was only discussed from a published literature perspective. The second study was conducted by assessing indoor thermal comfort by measuring temperature, humidity, and air velocity and analyzing temperature and wind distribution in the room using computational fluid dynamics, which helps identify comfortable and uncomfortable spaces in a room and may give an indication about opening position and size. In this way, it's difficult to identify the effects of different bioclimatic elements on thermal performance and adapt at least one greater contributor of bioclimatic elements for thermal performance for every climatic zone.

Accordingly, the present study intends to fill this gap by evaluating the bioclimatic elements of vernacular buildings and quantifying the role of each bioclimatic element, such as shading (overhang), thermal mass, form, and orientation, on the thermal performance of sample buildings.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Description of the study area

The study was conducted in Merti woreda, Arsi zone, Oromia regional state, found in the mid-rift valley of Ethiopia. Merti woreda is located 168 kilometers south-east of Addis Ababa, the capital of the Federal Democratic Republic of Ethiopia. The woreda is geographically found between 08° 23′ and 08° 43′ N latitudes and 39° 50′ and 40° 0′ E longitudes. There are 19 rural and 4 town kebeles in Merti Woreda. The altitude of the woreda ranges from 873 to 2867 meters above sea level. The northern part of Merti ‘woreda is constituted by the broad Awash River valley, which drops to an altitude of fewer than 1,000 meters in its most northern part. The southwest part is characterized by humid highlands. The total annual precipitation ranges from 900 to 1400 mm per year. Merti woreda has three climatic zones: lowland (62%), midland (23%), and highland (14.3%). The wereda receives an average maximum of 8 hours of sunshine per day in January and a minimum of 6.2 hours per day in July. At lower altitudes of the woreda, such as Golgotha and Dembeka kebele, daytime temperatures hover at 34 °C at midday in June.

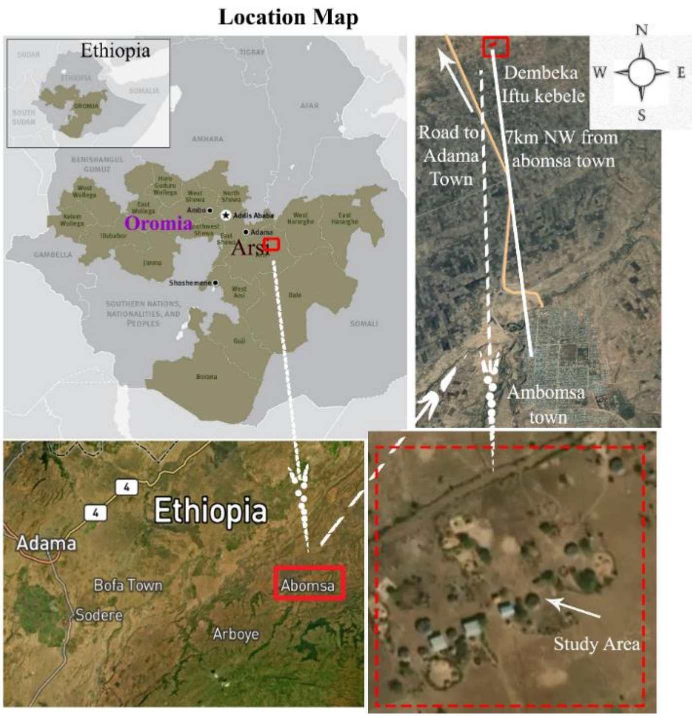


Figure 3.1: Location map

3.2. Research design

The study employs both descriptive and exploratory research methods, with the former focusing on the description and interpretation of existing indoor environmental variables via observation and surveys (measurements of indoor environmental variables), while the latter was used to explore existing bioclimatic techniques of selected buildings through observation, case studies, literature, and i interviews.

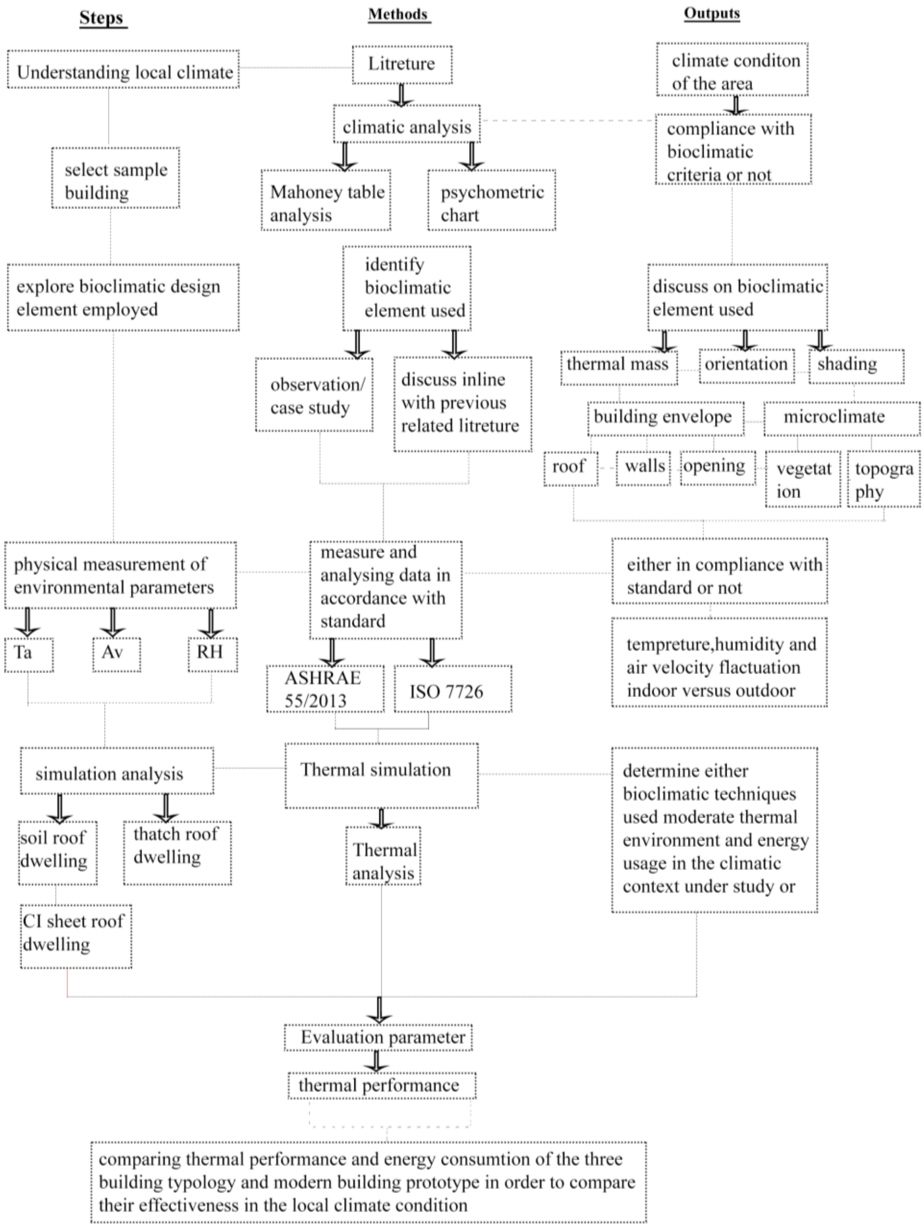


Figure 3.2: Methodological framework of the present study

3.3. Research approach

An abductive research approach was employed in the current research using both an inductive (qualitative) research approach through observation, interview, and document review and a deductive (quantitative) research approach using measurement of environmental parameters such as temperature, humidity, and air velocity, which are analyzed statistically and presented using numbers. Qualitatively investigated bioclimatic element of studied buildings supported by measured environmental data and simulation to give quantified results on the effectiveness of bioclimatic element used on moderating thermal environment.

3.4. Types of data and their sources

The study utilized both secondary and primary data sources. The secondary data were obtained from the NMA eastern and central metrological data centers, and the background of the town was taken from the Abomsa town administration office and bureau of culture and tourism office, as well as from the related journals and books. Primary data were obtained from observation (field survey), temperature, humidity, and air velocity measurements, and data obtained from simulation heating and cooling load and thermal performance are also classified under this category.

Table 2: source of data and their uses

S/n.	Type of data	Source of data	Use
		Primary	
1	Measurement of environmental parameters (air temperature, humidity, air velocity)	The researcher	To Analysis the thermal performance of the building
2	Observation	The researcher	Passive techniques, building materials.

		Secondary	
3	Metrological data (temperature, humidity, air velocity, rainfall)	(Eastern and central meteorological data center Adama branch)	Analysis climate responsive strategies of vernacular dwelling in the study area by using the Mahoney table
4	Background of Abomsa town	Abomsa town Administration office	Background of the town.
5	Related journal papers	Elsevier, Scopus, sci-hub, Gotcha, science direct, and google scholar	To explore the passive design techniques, the thermal performance analyzing method related to the specific zone

3.5. Sampling techniques and procedures

The sampling techniques selected for the study were non probability sampling techniques in which the sample was based on non-random criteria with predefined criteria. from different non probability sampling category purposive sampling techniques were used. Basically, the sample was selected based on objective of the study in mind it allowing selection of one typology from each varied vernacular building type in the areas. The population was divided into three main frames of traditional house: mud building with soil roof covering, round mud hut with thatch roof and rectangular or square mud building with corrugated iron sheet roofing.an element is peaked from each.

before beginning the data collection process. On May 29 and 30, 2022, field observation was undertaken to identify the different vernacular building typologies in terms of construction materials, method of construction, and level of detailing, which may have climatic influence accordingly. Three vernacular buildings were identified for detailed investigation from the three typology identified one from each typology ; they differ in construction materials (roofing materials) and building forms (rectangular and circular), and based on these differences, a large percentage of vernacular buildings are found in areas oriented north and north-west, so the selected vernacular buildings were oriented in north and north-west orientation with roof overhangs and high thermal mass buildings. But due to the availability of only three measuring instruments, it is difficult to cover buildings with different orientations, overhang sizes, and masses, making it difficult to generalize the results. To compensate the problems, the simulation was performed by considering different orientations, lengths of overhang, and thicknesses of walls and roofs (thermal mass), which helped to generalize the result for the selected climatic zones. Table 3 provides description of the case study buildings.

Table 3: Description of investigated buildings

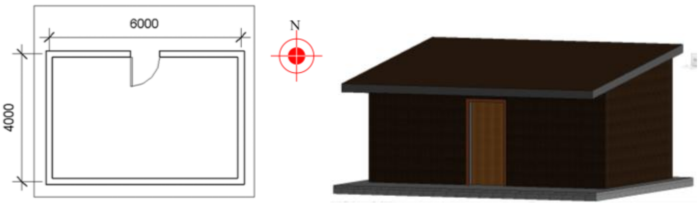
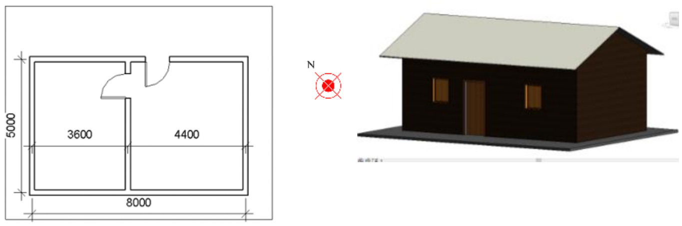
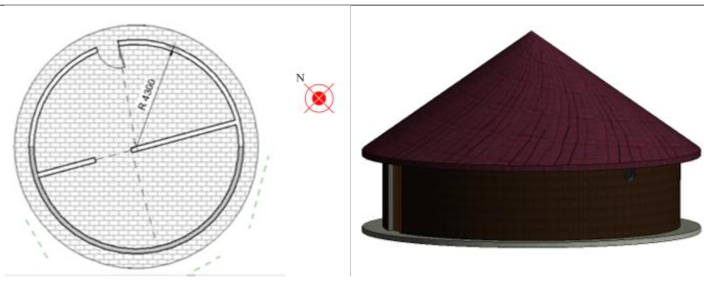
Name	Location	Plan and 3D views
Soil roof mud house	Golgotha/Merti woreda	
CI sheet roof mud house	Dembeka Iftu/Merti woreda	
Thatched roof mud house	Dembeka Iftu/Merti woreda	

Table 4: Comparison of the studied vernacular buildings

Name	Orientation	Location (Lat, long)	Area (m^2)	Opening direction	
				Window	doors
Soil roof mud house	East west	8º37′3196″ N 39º43′1811″E	$24m^2$	none	North
CI sheet roof mud house	East west	83º32′1215″N 39º48′9788″E	$40m^2$	North	North
Thatched roof mud house	none	8º32′6467″N 39º48′9788″E	$27m^2$	Small upper opening in all direction	North west

3.6. Methods of data collection

Thermal comfort, orientation, thermal mass, shading devices, ventilation, and building materials were identified as the variables to be researched in the previous chapter of this research. Accordingly, the techniques of data collection specify how the information related to these variables was gathered.

i. Physical measurement of environmental parameters

The field measurement was taken from June 1 to 7 (2022), which is the hottest month in Merti woreda according to metrological data obtained from the NMA Adama branch in March 2022. Three sensors were used simultaneously to take field measurements in three vernacular building typologies. The outdoor environment parameters, including ambient temperature, humidity, and wind speed, were measured using the same sensor as the indoor measurements. The data collection was allocated to a different session of the day to fairly represent the actual variety of daily indoor thermal conditions from 7:00 a.m. to 6:00 p.m. The three environmental parameters were measured five times at different times over a three-hour interval (7 a.m., 9 a.m., 12 a.m., 3 p.m., and 6 p.m.). in accordance with ASHRAE Standard 55 (2013). The measuring instruments were placed 1.6 meters above floor level in the center of each of the three buildings under observation because that is the place where extreme values of thermal parameters were observed (close proximity to doors), as suggested by Schoen et al., (2013). The sensor was protected from solar radiation both indoors and outdoors. Table 5 shows the detailed specification of the used sensor.

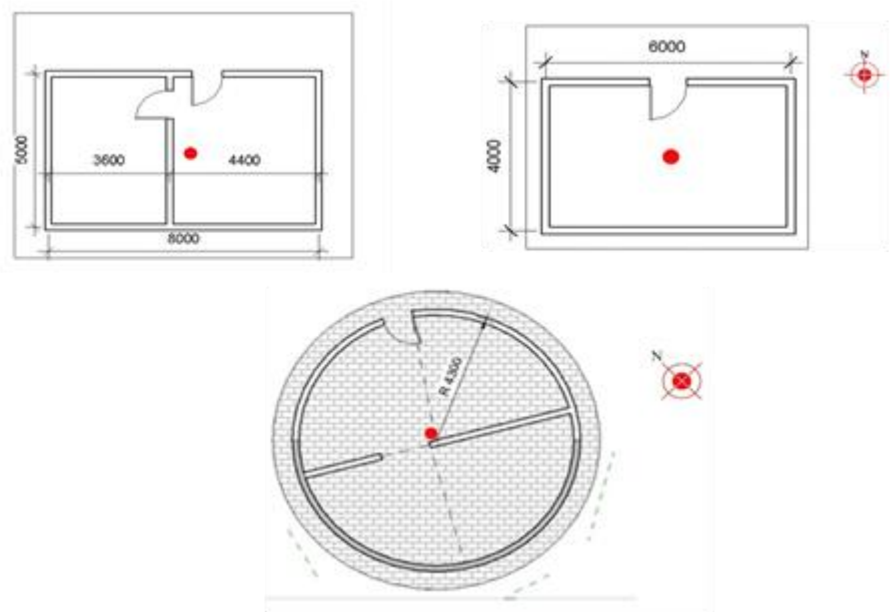


Figure 3.3: Placement of measuring tools inside the house

Figure 3.4: a) outdoor environmental measurement under verandah and used for cross checking the instrument reading b) indoor temperature measurement by the author

Table 5: The measurement equipment and their specification

Equipment used	Environmental parameter	Range	Accuracy	
Digital thermo-hygro meter (HTC-01)	Air temperature	-50~ + 70ºc (- 58 ~ + 158ºF)	±1ºC (1.8ºF)	
	Relative humidity	20%~99%RH	+5%RH (40%~80%)	
Thermo - Hygrometer Model at Rs 100	Air temperature	-50~70ºC	±1ºC	
	Relative humidity	10% RH to 99% RH	+5% RH	
Anemometer	Air velocity	0.3~45m/s	±3%+0.1dgt	
	Air temperature	0~45º	+2ºC	

ii. Observation

Through observation passive design elements in areas under studies identified both structured and unstructured observation techniques was used the structured observation was undertaken based on the predefined observation list prepared by the researcher which help to answer the research question. See Appendix A, while unstructured observation was used to collect data not included in the predefined list but have an influence on the study. Observation included the physical characteristics of selected typologies: building materials, wall height thickness orientation of building towards wind and sun, measurements of envelopes: roof, wall, opening are factors critically identified by using photographs, sketches and drawing were used.

Photographs

All the factors considered as bioclimatic techniques were captured in photographs and analyzed in drawing and computer-generated models. Which help in capture the existing situation of vernacular building construction techniques in areas under study. Image of exterior and interior part of all selected typology specially photo of construction aspect of building climatic advantage was taken.

Measured drawing

Images and computer-assisted measured drawings were crucial in communicating findings and observations. Plans and sections are drawn to give the climatic effect of the thermal mass of the building and the wall material. height, mode of air movement in the building, number and arrangement of fenestration, and its impact on air movement and general structure.

iii. Interview

The interview was conducted with the owners of the selected three vernacular building typologies and two local builders. Due to their experience living in and constructing such buildings, it was expected that they would know the indoor thermal conditions of the building. It is observed that females stay home for a longer time of the day than males, who perform different tasks like farming, which shows females have more experience with indoor climate problems than those of males in residential buildings. For this reason, both sexes were asked their preferences for building types. During the interviews, they were asked about their preferences for comfort in their home, the methods they used to protect the building from outdoor extreme climates, and the considerations they made during the selection of building sites and subsequent construction.

3.7. Data analysis and presentation

Data collected on environmental parameters (temperature, humidity, and wind speed) was compared with ASHRAE permissible comfort zone standards and analyzed by Excel software using line charts and presented by graphs and tables. Detailed identification of the selected building characteristics like material, form, and orientation has been analyzed through description using supportive images, tables and written descriptions. Ecotect software programs were used to identify the optimum orientation of location, wind speed, and direction, and a sun path diagram in which the building is judged whether it is climatically designed or not.

3.7.1. Simulation analysis

The buildings' thermal and energy performances were analyzed further by design-build software that used Energy Plus as the simulation engine. Energy Plus is an hourly energy simulation engine that follows these sequential steps: The buildings are first modeled in Autodesk Revit and then exported to design builder software for simulation. The weather data of the areas is imported into the software, which is extracted from Meteonorm 8 and the NMA Adama branch, and all materials in the actual building were corrected in detail for each layer of different building components. Building orientation, time, and months were adjusted in the DB software to perform simulation. Energy consumption for maintaining thermal set points of 23.9 °C for cooling and 21.1 °C for heating in the structure model was adjusted in line with the cooling and heating set points used by Wiseman & Thomas, (2016). The performance of the building was evaluated by shifting orientation, altering roof and wall thickness, and increasing and decreasing roof overhangs. The June 3 weather data were chosen purposefully because a high temperature was observed on that day and it was a typical clear day, according to the sky cover charts in the Climate Consultant software, which helps to quantify the energy consumption and thermal performance of selected buildings on overheating days.

Table 6: Used software's for data analysis

Sn.	Software name	Version	Use
1	Archi cad	2021	Represent sample house
2	Adobe photoshop	2017	Graphical photo editing
3	Meteonorm	8.3	To generate Climate data
4	Ecotect	2011	To generate optimum orientation and wind wheel diagrams of study area
5	Climate consultant	6.0	Climate analysis
6	Design builder	V4.0	Energy and thermal simulation

3.8. Data quality and control

According to the standard ISO-7726, (1998) The quality of the instrument has been checked before it was used for measuring selected environmental parameters, and the acceptable and desirable range, accuracy, and sampling period have been checked. Further, the instrument heights and locations were placed according to standard, and precautions were taken in placing the sensor away from the heat source to secure the reading value of thermal data. Due to the residents' being uneducated and the presence of children whose behavior was not under the researcher's control, The measurement of all environmental parameters is done manually.

3.9. Ethical consideration

The collection and analysis of relevant data for the studies was undertaken by following the four ethical consideration parameters of informed consent, confidentiality, security, and honesty (Leedy and Ormrod, 2010). Accordingly, before gathering any data, such as photos, videos, measurements of building components, and environmental monitoring, the purpose of the survey and the required information (data) were clearly explained. The privacy of the householders was respected, the data collection was undertaken during the day with an identified time gap, and the measurement of environmental parameters was taken in areas where the activity of the residents was not interrupted. Measuring results are presented and discussed in relation to a predefined standard.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1. Introduction

This chapter presents the results of the studies and discusses them in line with previous related literature, the ASHRAE standard, the Mahoney table recommendation and psychometric chart. To make the discussion process easier, the three building typologies are named by code: corrugated iron sheet building (B1), round mud walled thatched roof building (B2), and mud walled soil roof building (B3).

4.2. Climate data analysis

A. Psychometric chart

According to the psychometric chart, 52.9% (4491 hours) of outdoor temperatures fall within the comfortable range specified in the ASHRAE standard to improve comfort conditions. The main passive design techniques were sun shading of windows (overhang, verandah, etc.), which adds 29.7%; high thermal mass, which takes 16.2%; and internal heat gains, which add 27% to the comfort percentage.

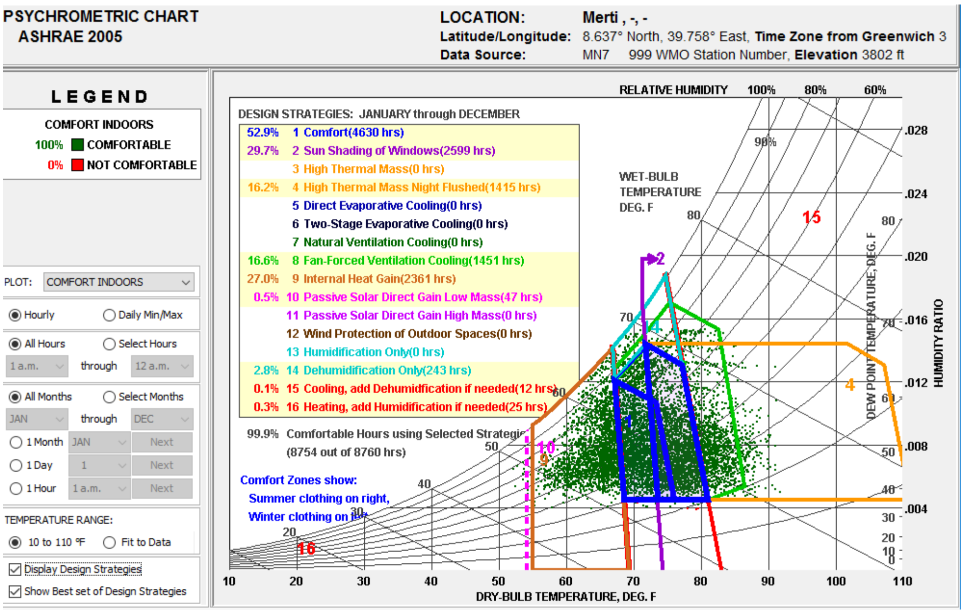


Figure 4.1: Psychometric chart of Merti woreda (source: climate consultant)

B. Szokolay bioclimatic chart

As recommended by (A. Kunle, 2015) and (A. A. Kunle et al., 2013) Average climate data for the five-year period (2016–2020) was employed for this analysis,. The monthly maximum and minimum data were plotted in the psychometric charts with the corresponding humidity data to define the control potential zones (CPZ). (Auliciems & Szolokay, 1997) is the range of outdoor conditions within which indoor comfort can be achieved by one of the passive control techniques. The control potential zones are then constructed on the psychometric chart in the form of overlays. The extent of these lines in relation to the comfort zone, that is, the aggregate length below (to the left), within, or above (to the right of) the comfort zone, gives an indication of the climatic problems.

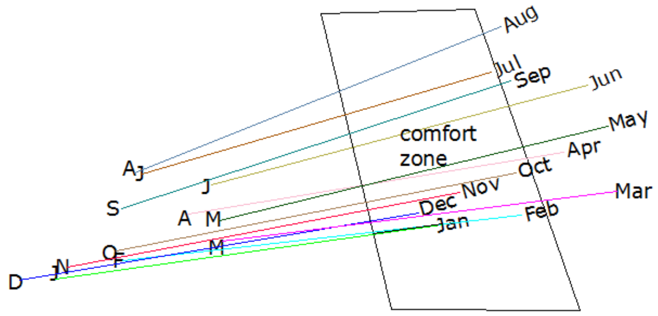


Figure 4.2: Merti Woreda's psychometric chart depicts underheated and overheated lengths in relation to comfort zone (source: own analysis)

The annual mean maximum temperature (AMT) was found to be 28.6 ºC, the length of overheated air (Lo) was 1.3m, which is the length of a line above comfort zones, and the length of underheated air (Lu) was 10m. which is the length of the line on the left side of the comfort zone boundary. The climatic conditions of the areas were relatively moderate, with cold, comfortable, and hot climate varieties, resulting in a short duration of daytime temperatures in November, December, and January that fall within the ideal comfort zone, but the nighttime temperatures for those months were cold.

C. Passive design need

Figure 4.3 illustrates how different passive design techniques increase the comfort percentages in the local climatic conditions accordingly. Passive solar heating, thermal mass, and natural ventilation moderate the climate of the areas by minimizing fluctuation and balancing the cold temperature at midnight with the hot temperature in the midday. The graph also shows the effect of these strategies on increasing the comfort percentage in the overheating months of the area: February, March, April, May, and June, from 30% to 90%.

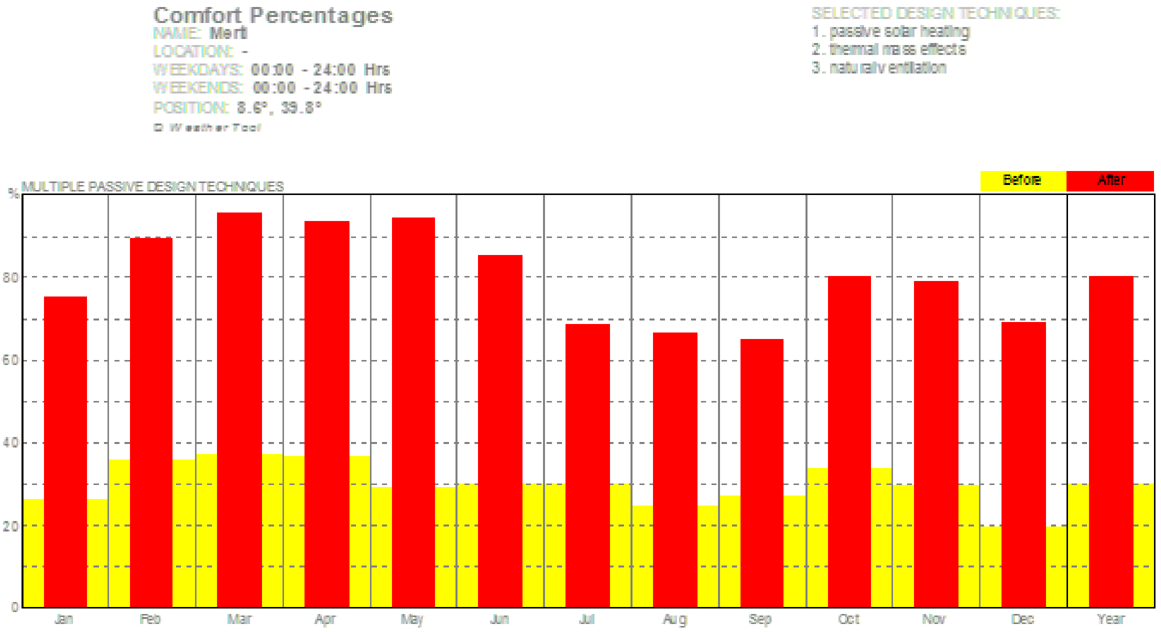


Figure 4.3: comfort percentage through applying passive design techniques (source: Ecotect analysis)

D. Temperature

The temperature condition of the areas under study with variation in time is shown in the figure 4.4 a, which shows that from midnight, 1:00 a.m. to 10:00 a.m., the temperature is below 21 ºC, which is classified as underheated period and comfort zones, which take up 32% of the total hours; in the midday, the temperature becomes extremely hot, which takes up 11% of the total hours; and the majority, 57%, falls in the comfort range. The daily average temperature shown in figure 4.4 b depicts the maximum temperature of the areas reaching 33 degrees Celsius in March, April, May, and June, while the minimum temperature never falls below 12 degrees Celsius.

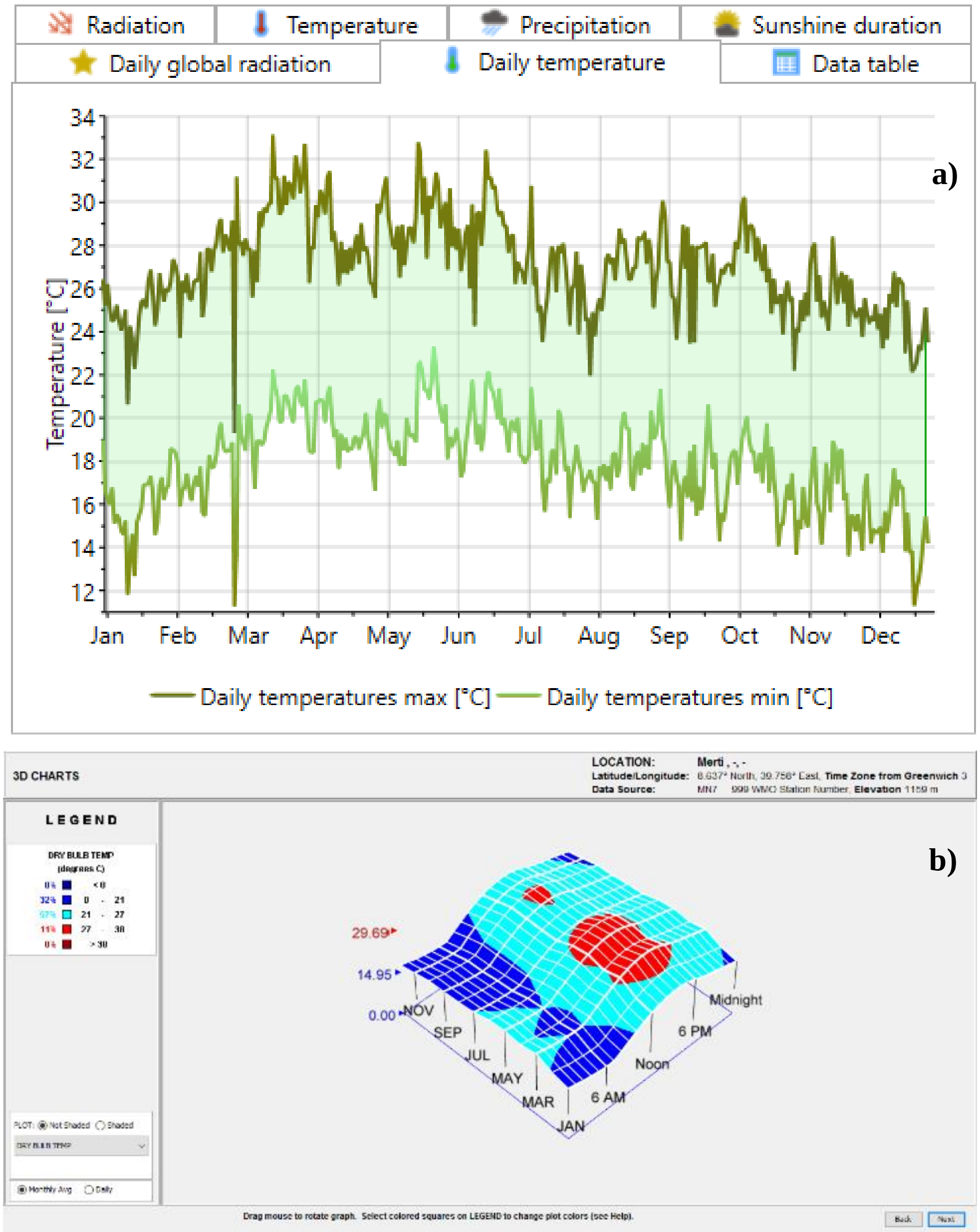


Figure 4.4: a) Daily average temperature (source: meteonorm) b) Monthly average temperature with temperature range and percentage (source: climate consultant)

E. Wind seed

Figure 4.5 (a) shows that the wind speed is 5 to 9 m/s 24% of the time (12 a.m. midday to 6 p.m.) and 3-5 m/s 70% of the time. Figure 4.5 (b) shows that for more than 408 hours, the prevailing wind has been blowing mostly from the east and south-west, with a maximum wind speed of 2.77 m/s. 4.1% and 4.6% of the total hourly easterly and southerly, and 122 hr., 1.8% easterly and 1.5% southerly (8.3 m/s), respectively.

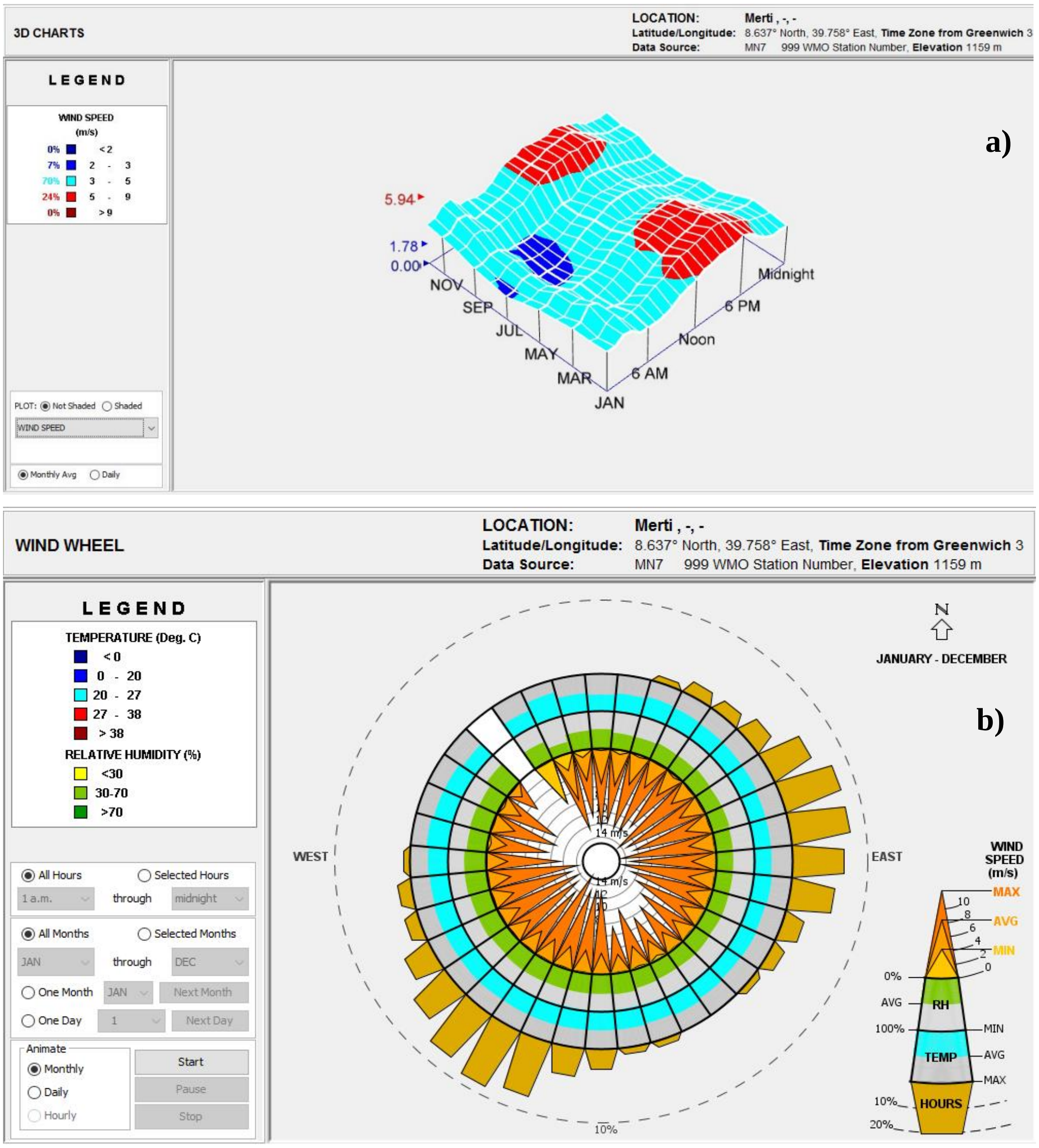


Figure 4.5: a: 3D wind speed chart with time variation and b: Merti wind wheel diagram

F. Relative humidity

The maximum relative humidity was found in April, May, June, July, and September from midnight to 12:00 a.m. (60-80%). In January, February, March, and April, the humidity is 40–60% from midnight to 8: a.m. Midday humidity ranges from 20 to 40% from 12 a.m. to 6 p.m.

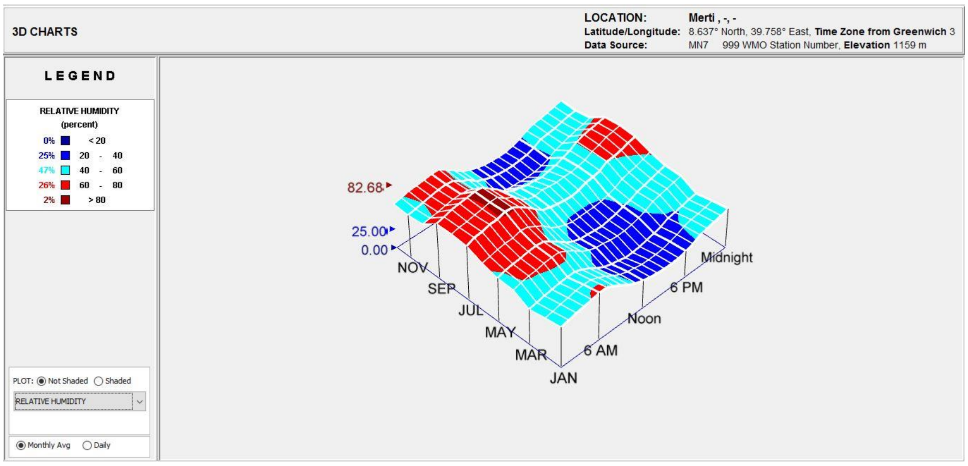
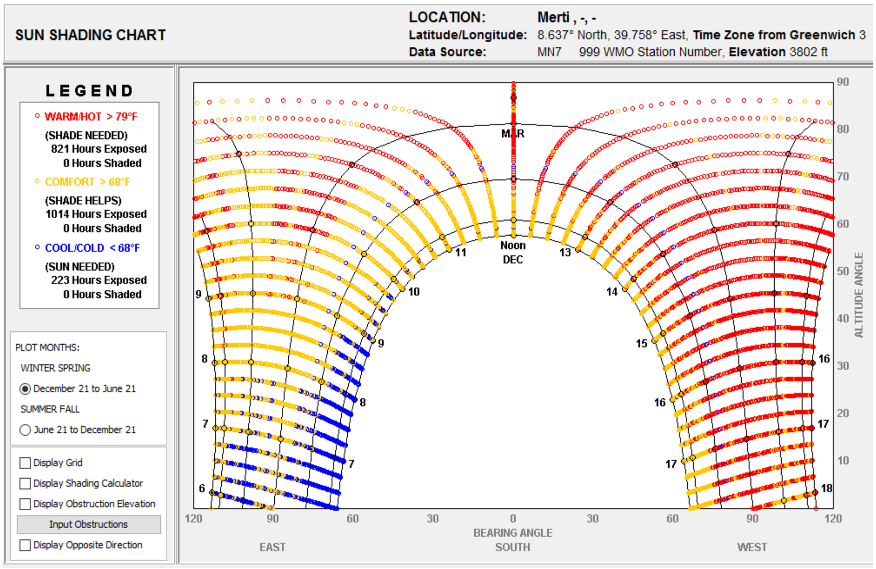


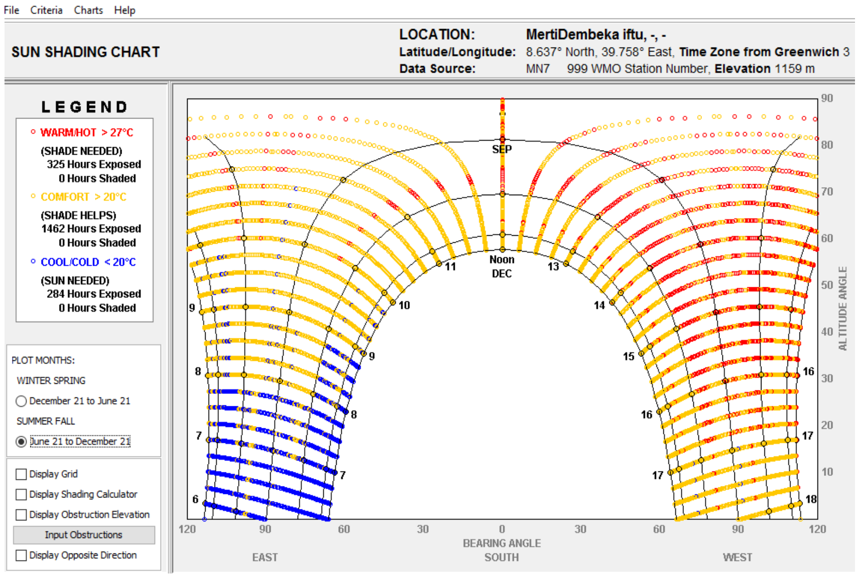
Figure 4.6: Relative humidity of Merti woreda (source: climate consultant)

G. Sun chart

The sun chart in Figure 4.7 shows the intensity of the sun according to orientation and time of day and the need for shading accordingly. In the morning, from 6 a.m. to 9 a.m., the area is in the comfort and cold range, in which shading helps to add comfortable hours, and from 3 a.m. to 5 p.m., it is in the comfort and hot/warm range, in which shading is needed to enhance comfort. This statement illustrates that the house's orientation in relation to the sun's path optimizes comfort and helps to take effective passive design measures in its correct position. Additionally, the diagram shows the shading need percentage for the hottest season (winter and spring, from December 21st to June 21st) and the coldest season (summer, from June 21st to December 21st) in winter and spring. 32% of time fails in warm or hot climates (>27° °C), 56% is in the comfortable range set by ASHRAE standards, and 11% is found in an underheated or cold period in which exposure to sunlight helps to achieve comfort. On the other hand, in summer, 29.5% have warm or hot temperatures, 71.8% fail under comfort zones, and finally 12.2% of hours fail in cold weather conditions. The chart suggests that the majority of hours in both winter and summer are spent in comfortable conditions, where the percentage of times that indicate the use of a shading device (warm or hot) is greater than the percentage of time that requires sun exposure. Accordingly, both shading devices to avoid midday warm temperatures and methods of harnessing the sun in the early morning were advisable for climate-responsive designs.



(a)



(b)

Figure 4.7: Sun chart diagram of Merti (a) winter and spring (b) summer (source: climate consultant)

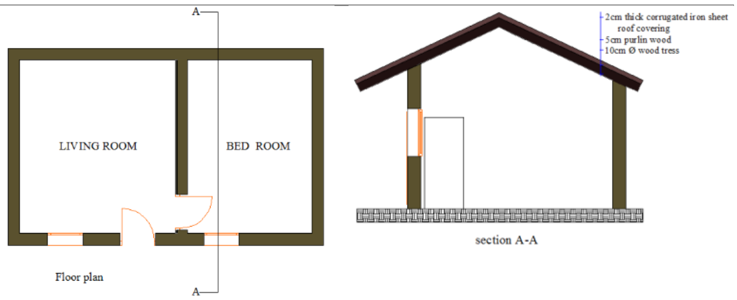
4.3. Analysis of existing bioclimatic design techniques

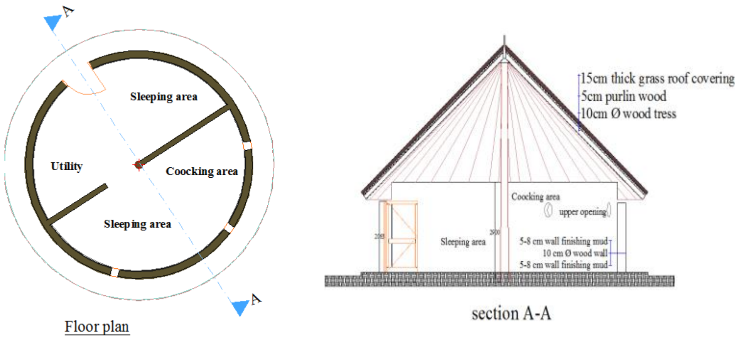
In the following sections, the bioclimatic elements of the study areas were discussed in line with the wind rose diagram of the areas, optimum orientation, Mahoney table recommendations, related literature, and psychometric charts undertaken for the study areas by the authors.

4.3.1. Typological analysis

To understand the vernacular dwelling of Merti Wereda, typical samples are given. Locals constructed these structures in accordance with their customs, the materials at hand, and their cultures. These individuals had a detailed understanding of their environment, particularly its climate. The following table shows the fundamental form's patterns and variations, as well as the layout, plan arrangement, and functional qualities housing in the study area.

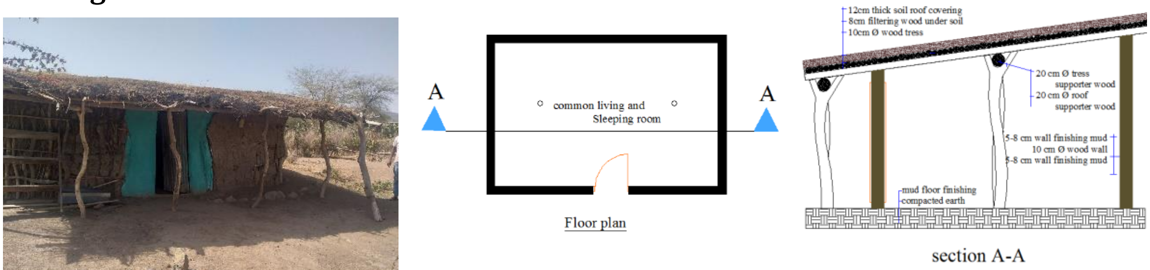
Table 7: Detail description of selected typology (source: own analysis)

<table>
<tr><th>Appearance</th><th>Plan, section, Description</th></tr>
<tr><td>Building 1
</td><td>

A two-room hybrid construction system with mud and wooden walls and corrugated iron sheet roofing.</td></tr>
<tr><td>Building 2
</td><td>

Upper openings in the eastern, south eastern, and south western directions aid in the removal of smoke from cooking areas as well as the exhaustion of contaminated air from the room.</td></tr>
</table>

Building 3



Soil-roof dwelling found only in the lowland areas of Merti circular column shown in the floor plan helps to support the soil roof.

The plan of a house varies in different ways. The first building typology is a two-room mud dwelling with corrugated iron sheet roofing used for living rooms and bedrooms, and these types of dwellings were modern design-influenced designs that adapted modern construction materials like corrugated iron sheet for roofing. According to informal interviews, most of the dwellers in the areas under study construct these typologies next to previously constructed thatched buildings. On the other hand, the second typology, or thatched buildings, are varied in their detailing across different agro-ecological zones (AEZ) in the lowland, midland and highland areas. In most lowland areas, the plan of thatch houses is small, with two rooms separated by short partition walls and one door; no windows were used, but upper hole-like openings were discovered in the south-western, eastern, and south-east directions, which helped to remove smoke and contaminated air from cooking areas located in the southern orientation, whereas in highland areas, the rooms are relatively large with different functions. Two doors were used in most highland thatched buildings placed in the windward and leeward positions of the winds, which helped to remove bad smells, and small wooden windows were also used in this area for lighting and ventilation purposes. The last typologies were soil-roof mud dwellings, which are one room with different functions. sleeping, living, and dining. According to an informal interview, this dwelling type is mostly used for guest receiving rooms and alternative sleeping, dining, and study areas when the indoor temperature of a corrugated iron sheet roof building is extreme.

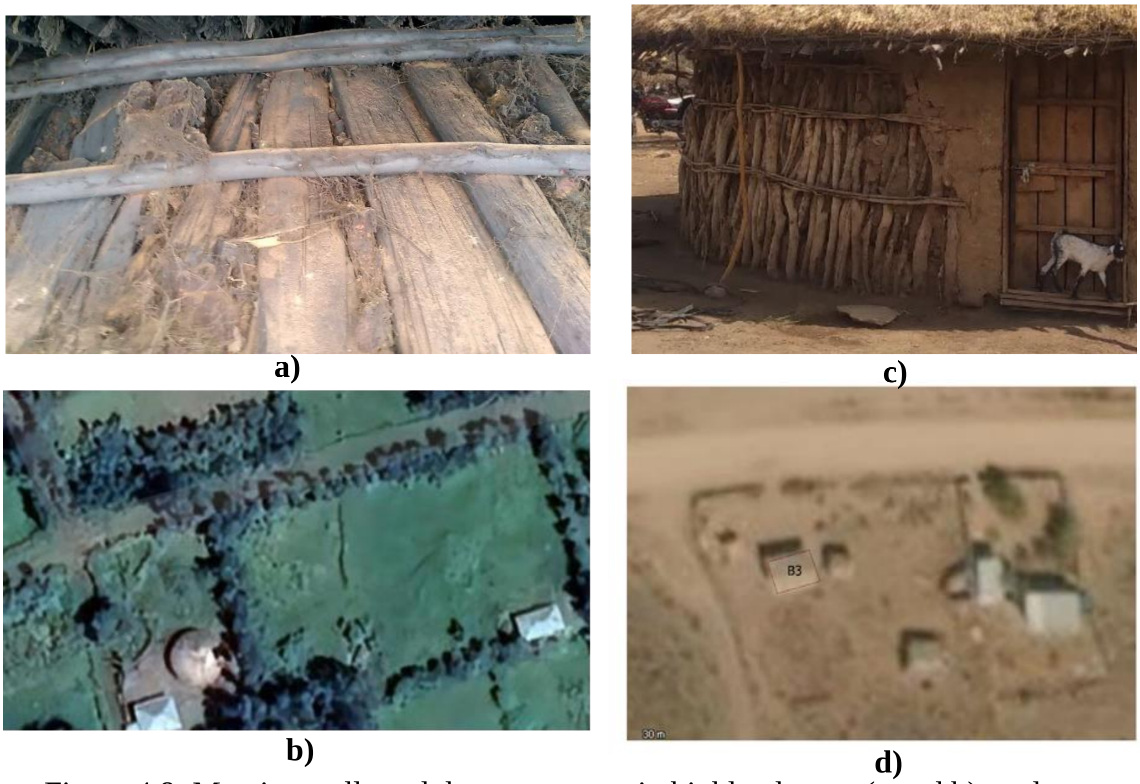
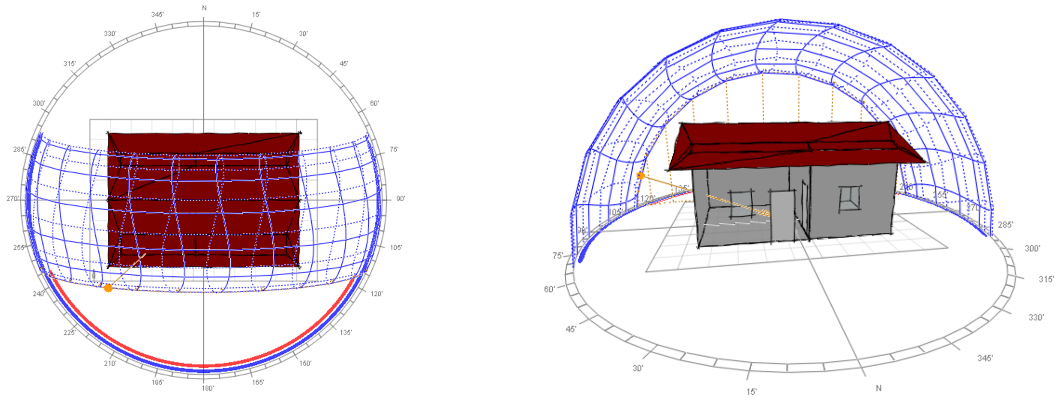


Figure 4.8: Massive walls and dense greenery in highland areas (a and b), and non-massive wooden wall material and scarce trees on building sides in lowland area c and d

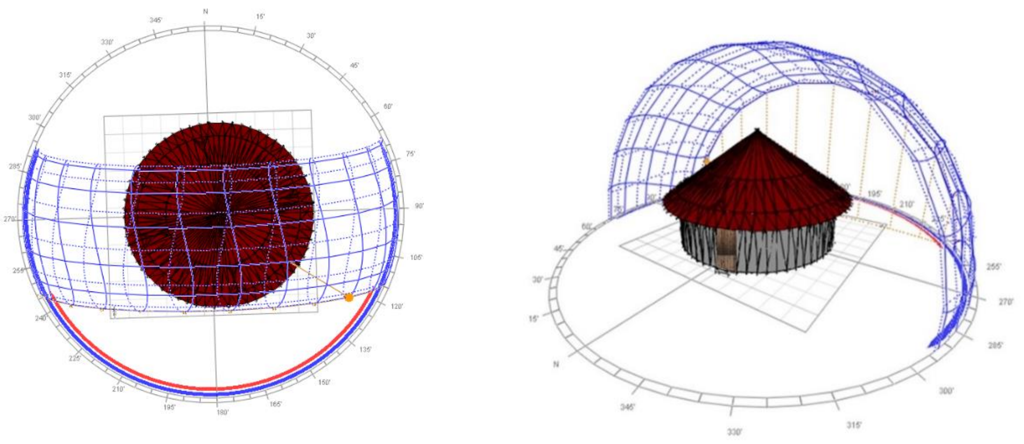
As shown in figure 4.8 due to the relatively cold climate, massive wood was preferred for wall construction in the highland areas to prevent cold outdoor air from entering indoors and keep heat within the building. Trees of tall heights were abundantly grown and had straight trunks, which were suitable for extracting the timber used for doors, windows, and rafters. On the other hand, the wood species in the lowland areas are smaller, not as massive, and not found in a straight shape due to the lack of suitable trees for timber. It is therefore observed that most of the openings in the lowland areas were constructed from corrugated iron sheet. Tall trees were used as a fence in the highland areas in the dominant easterly and north-easterly wind directions to protect the buildings from cold winds, and in their optimum position, the shadows of the trees didn’t block the sun. Trees were found sparsely but optimally located close to buildings in lowland areas where high solar radiations are observed.

4.3.2. Orientation

The front façade of most vernacular buildings in the study areas is oriented towards the north and north-west directions. Their long axis runs east-west, reducing the size of the east and west walls, which are exposed to morning sun and intense late afternoon sun. As a result, the short sides of the walls of B1 and B3 face east-west, implying that the longest wall faces north and south, and the front view of both buildings is facing north. B2 has circular forms, and the building orientation is defined by the direction of major openings; the entrance is faced in the north-west direction, where intense solar radiation is received by openings and north-facing walls, stored in the walls, roofs, and floors, and reemitted at night. According to an informal interview, the position of openings in a thatched house was considered primarily to avoid strong wind from the main openings (windows and entrance doors), which is basically to protect the thatch from being harmed by winds. the buildings were also used for cooking, orienting the main opening to the strong wind direction may introduce fire danger due to the characteristics of thatch, which include easily flammable materials and dry cow dung used in the interior plastering. The northern envelope received high solar radiation, which exposed the occupants to overheating problems. The high solar radiation received by the northern envelopes has an impact on the thermal comfort conditions of buildings. while the solar radiation affects the room temperature only through the doors in B2 and B3 the upper opening in B2 were found in the upper perimeter of walls which is shaded by roof overhang and not receive the direct solar radiation.



Sun path diagrams of B1 model top view(left) and front view (right)



Sun path diagrams of B2 model top view (left) and front view (right)

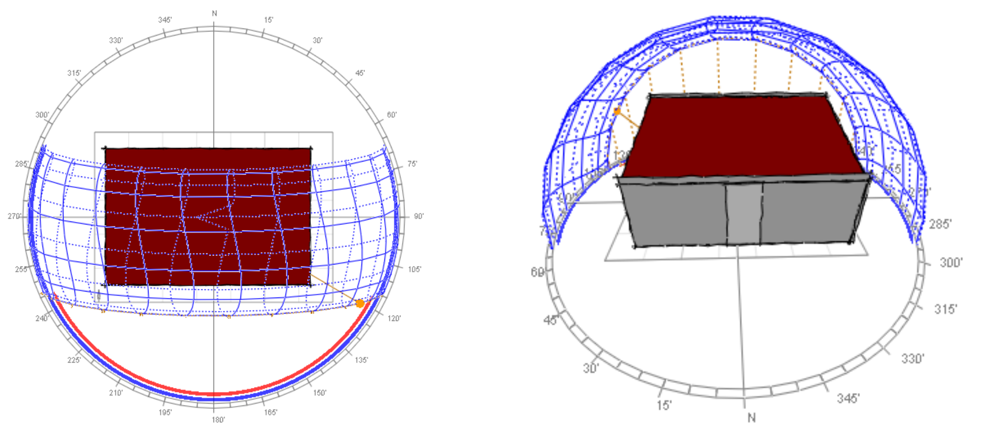


Figure 4.9: Sun path diagrams of B1, B2 and B3 model top view(left) and front view (right)

4.3.3. Shading device

a) Shading by roof overhang

Roof overhangs and trees are used as shading devices in study areas, which is supported by Mahoney table recommendations based on critical climatic parameter analysis (see Appendix D), which recommend the use of shading devices to exclude direct sun light from external building envelopes. The effectiveness of roof overhangs was determined by sun path diagrams, which aid in placing the shading device in an orientation that is highly exposed to solar radiation. The overhangs in the selected building typologies faced north, which is an orientation that receives intense solar radiation, in addition to the position sizes and angles of the overhang determine whether the building uses an effective shading device or not. In B1, the roof overhangs were placed in the north position, which is the position of intense solar radiation received according to the optimum orientation diagram. The overhang measures 1.08 m from the end of the external wall and has an inclined angle of 65 º, which is good for avoiding intense heat from reaching the exterior walls and openings. Similarly, the overhang in B2 extended in all directions and measured 0.6 m with a 40-degree angle. Finally, the overhang in B3 is oriented in the north direction and has an inclination of 8°. The effectiveness of roof overhang is determined by optimum solar radiation and the angle of the overhang, as a result of which the inclined angle is more effective for energy reduction than a 0° overhang angle, supporting the statement above.

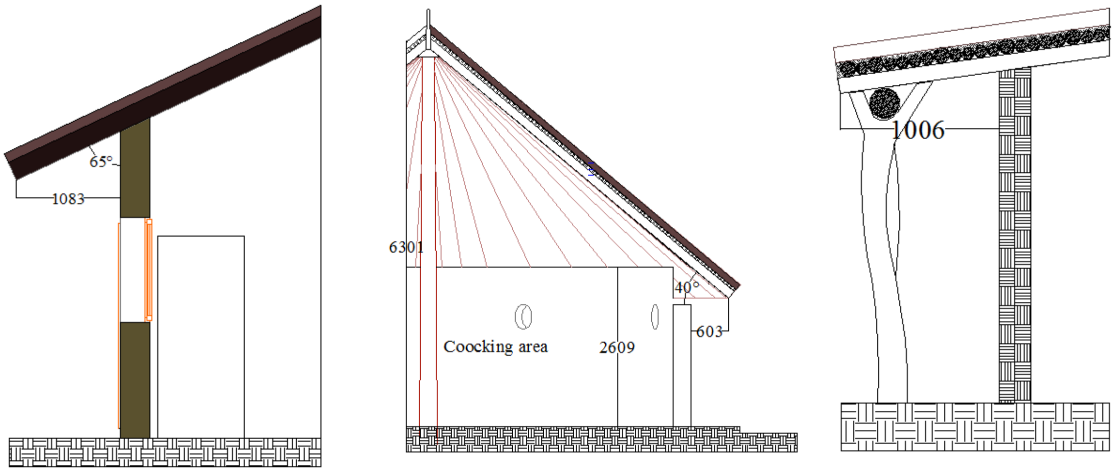


Figure 4.10: Illustration of roof overhangs B1 roof overhang (left), B2 overhang (middle), and B3 overhang (right)

b) Shading by trees

Small shade trees of four meters in height were observed close to the east walls of B3—three meters away from the building; the canopies of trees in the roof and walls reduce the amount of morning sun received by the east walls; whereas in B1, trees shade the western side 2.5 meters away, which had medium-sized trees of six meters in height on the same side. The observation of tree position, height, and proximity was supported by a study conducted by Wiseman & Thomas, (2016) demonstrated that small trees in close proximity to buildings provide better cooling than large trees at a distance from buildings. Essentially, the cooling effect of tree shading was determined by the length of the cooling and heating seasons as a result, March, May, and June were the cooling period seasons and January, February, November, and December were the heating period seasons. From this result, it was found that the trees' position should be considered, considering the cooling effect of shade in the cooling season and avoiding blocking the sun in the heating season by avoiding trees in the south orientation.

Figure 4.11: Position and proximity of tree shade (source: field work,2022)

4.3.4. Forms

It was observed that the forms of most traditional buildings in the study areas are either circular or rectangular. The effectiveness of building forms in one climate area is determined by the width-length (W/L) ratio, which determines the optimum building forms and amount of solar insolation received by the exterior walls. As a result, the width-to-length ratio of Building 1 (B1) is 1:1.6, with a width of five meters and a length of eight meters, while the ratio of Building 2 (B2) is 1:1 and the ratio of Building 3 (B3) is 1:1.5, with a width of four meters and a length of six meters. Accordingly, Ling et al., (2007) indicate that a circular building with a L/W value of 1:1 receives low solar insolation comparatively, and the forms of 1:1.7 receive 3-5% more solar radiation than buildings with a 1:1 w/l, which indicates that increasing the length to a width of 1:3 or more increases the total building envelopes' ability to receive solar insolation, and it is good to keep the w/l ratio moderate.

4.3.5. Thermal mass

The materials used in the construction of walls in the traditional buildings of the area are high thermal mass materials: thick mud walls and floors, which reduce maximum indoor temperatures (Fati et al., 2020b), soil roofing, wood for structural members (building frames), and thatch or straw used for roofing, which is a thermally tolerant fiber with a thermal resistance of 4.065 W/m2K for a 30 cm thickness. Furthermore, its porous nature aids in the removal of excess hot air generated at night by the walls' high thermal mass. A study found that the temperature of soil flooring is one degree Celsius (1ºc) lower than that of a ceramic floor or a rendered cement floor, lowering the indoor temperature by one degree Celsius (Galabada et al., 2021). which shows the better thermal performance of soil flooring. On the other hand, corrugated iron sheet roofing was used, which is a low thermal mass material with a high conductivity of 7.12 w/m2 K and a low resistivity of 0.14 m2K/W. According to table 8, corrugated iron sheet roofing has the lowest thermal resistivity and the highest thermal conductivity, which is due to metals' typically low heat capacity. A metal changes temperature quickly when heat energy passes through it (Bhatia, 2006).

As a result, mud walls' high thermal mass (20 cm), low thermal transmittance (U-value) of 1.291 w/m2*K, and high internal heat capacity (147.89 KJ/m2*K) help to dampen the temperature amplitude of the indoor environment and act as a storage for daytime extreme outdoor ambient temperatures, which re-radiate at night to compensate for the cold nighttime outdoor temperatures and help to create stable indoor thermal conditions. The discovered thermal properties of wall materials correspond to the findings of several published international studies that found that, depending on the wall's composition and thickness, the U-value for comparable rammed-earth walls without additional insulation ranged from 0.7 to 1.5 W/(m2K) and improved thermal performance (Lovec et al., 2017).

Table 8: Thermal properties of sample building components (Source: generated by design builder)

Building components	Heat capacity (KJ/m^2k)	Resistivity (m^2 k/w)	Conductivity (w/m^2k)
Wall (20cm)	147.89	0.774	1.291
Roof (B1) 0.2cm	33.7	0.14	7.123
Roof (B2) 30cm	69.51	4.065	0.246
Roof (B3) 30cm	147	0.598	1.671

According to the above table, the thermal performance was dependent on the materials' resistivity and conductivity. Straw has a low conductivity of 0.246 w/m2 and a high resistivity of 4.065 m2-k/w when compared to the identified vernacular materials used. Furthermore, the heat capacity of straw was 69.51 KJ/m2k and that of CI-sheet roofing was

33.7 KJ/m2k. This is due to the low heat capacity of straw and corrugated iron sheet roofing, but the thatched roofs compensated for it through their insulation properties. According to Bhatia, (2006) the higher the resistance of materials, the lower the rate of energy flows through the material, and the lowest the resistance of materials, the highest the energy flow rates are expected. Which support the above discussions.

Based on the analysis of metrological data the mean maximum and mean minimum temperature fluctuation of the areas were (11 to 17 ºc) accordingly the minimum fluctuation were observed in August 10.5ºC and the maximum fluctuation is found to be in February and march 13.9ºC which indicate the need of high thermal mass materials which help to reduce the temperature swing between day and night by storing the high solar radiation in the northern orientation received by building components and re radiate it at night. According to the Mahoney table recommendation except the month of March, April, May and June the night time thermal stress of the areas is cold which need heating strategies as a result the high thermal mass of the walls help to store heat during day time and release at night to moderate the cold night temperature. The thermal mass and the building U-values are directly related the highest the thermal mass the lowest the building conduct hot air to the indoor environment and vice versa.

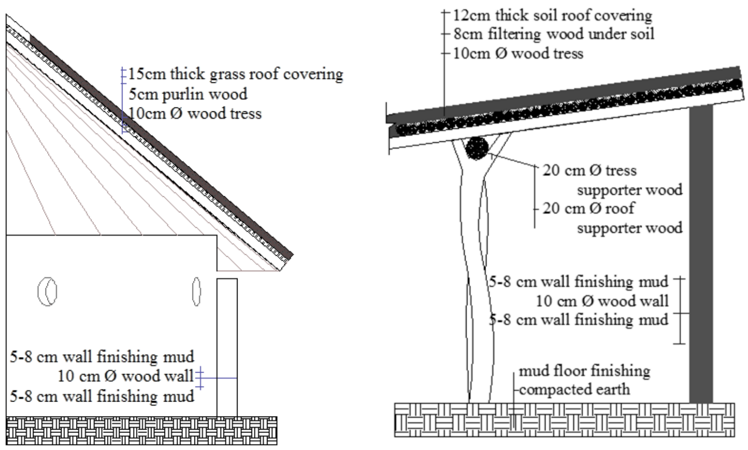
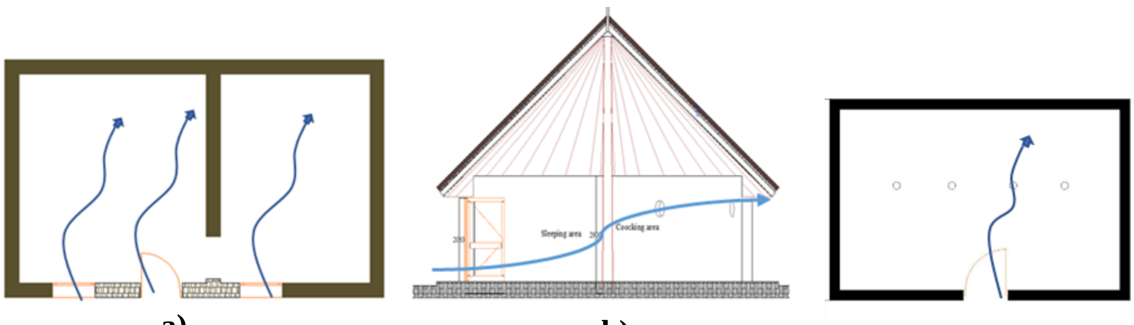


Figure 4.12: wall and roof thermal mass of B2(left) and B3(rights) prepared by AutoCAD software (source: authors' analysis)

4.3.6. Natural ventilation

B3 was naturally ventilated with single-sided single openings where the entrance door is the only source of ventilation, measuring 90 cm by 2.1 m, and B1 was ventilated by single-sided double openings where the two wooden windows measure 0.8 m by 0.7 m and the doors measure 0.9 m by 2.1 m facing north. The main openings (doors) of the B2 were oriented north-west, where there is almost no wind movement throughout the day (See Appendix F). Three upper hole-like openings, which measure 0.3 m by 0.3 m, were observed in B2 facing the north east and south east, which is the dominant wind direction of the area. Even though the small size of the windows does not enhance cross ventilation, it helps to remove hot air from the ground. Studies found that small ventilation openings located at the upper perimeter of walls allow for the removal of hot air from indoors, and due to their elevation and being covered with roof eaves, they don't cause any increase in indoor temperature, which helps to achieve better indoor thermal comfort (Widera & August, 2021)

As a result, the number of openings to ventilate a room is determined by the width of the building and the height from the floor; during the field survey it's found that the depth of B3 is four meters with a ceiling height of two meters, allowing the building to be ventilated to a depth of six meters (Hamdani et al., 2018), which indicates that single-size ventilation would be adequate for this building size. And the width of B1 is five meters, with a floor-to-ceiling height of three meters, and receives ventilation from double openings; as a result, the wind ventilates to 3H, giving the openings the capacity to ventilate up to nine meters; in this case, the wind movements are slightly improved due to the increased wind pressure from the two apertures. Finally, the ventilation in the B2 single-sided opening was insufficient for the size of the building, which was eight meters wide and three meters tall, and the wind with this single opening had the capacity to ventilate 2H (up to six meters), which was insufficient for the size of the building. But the upper openings may compensate for the ventilation.



a) b) c)

d) **e)**

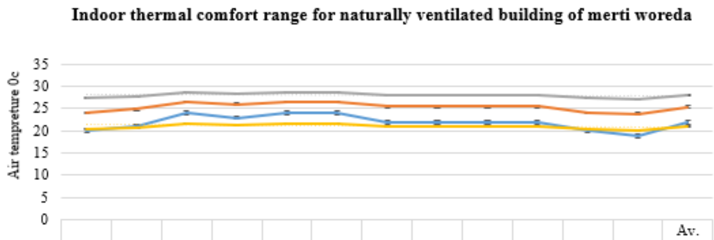
Figure 4.13: Ventilation techniques for B1 (a), B2 (b, d, and e), and B3 (c) (source: authors' analysis)

4.4. Temperature, wind and humidity data analysis

The measurement of temperature, humidity and wind speed was compared with ASHRAE Standard 55 and ISO 7730 and helps to evaluate whether the system is in compliance with the standard or not. The upper and lower comfort limits in the figure were calculated by using adaptive comfort temperatures for naturally ventilated buildings in ASHRAE 55 (2013). which is calculated by the following equations: whereas Tco is the comfort temperature and Tmo is the mean monthly outdoor temperature.

Tco=0.31*Tmot + 17.8ºC. The 80% thermal acceptability band takes optimum temperature of ± 3.5 which gives, For upper comfort limits, Tco = 0.31*Tmot + 17.8 ºC + 3.5 ºC, and for lower comfort limits, Tco = 0.31*Tmot + 17.8 ºC -3.5 ºC.

As seen in figure 4.14, the comfort temperature does not change significantly throughout the course of the year because of the relatively stable climate condition of the area. 28.74 ºC was found to be the upper comfort limit in the hottest month of the year (March, May and June).



	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Av. annual
Monthly mean temp °c	20	21	24	23	24	24	22	22	22	22	20	19	21.9
neutral tempreture	24.1	24.9	26.5	26	26.5	26.5	25.5	25.5	25.5	25.5	24.1	23.9	25.4
80% acceptable temperature °c upper	27.5	27.81	28.74	28.43	28.74	28.74	28.1	28.1	28.1	28.1	27.5	27.2	28.1
80% acceptable temperature °c lower	20.5	20.81	21.74	21.43	21.74	21.74	21.1	21.1	21.1	21.1	20.5	20.2	21.1

Figure 4.14: Upper and lower comfort zone limits of Merti Wereda (calculated by the authors)

The most significantly studied climatic variables affecting the thermal comfort of the dwellers, such as temperature, humidity, and air velocity, were recorded in the selected sample building to evaluate the thermal performance of the building accordingly. The results found are presented in the following section:

4.4.1. Temperature

According to figure 4.15, the maximum indoor temperature of 30 ºC was recorded in B1 at 3 p.m., afternoon and lower temperatures of 20.9 ºC were also found in B1 at 7 a.m., in the morning while the corresponding maximum outdoor temperature of 34 ºC was recorded at 3 p.m. with an indoor fluctuation of 9.1 ºC, indicating that the indoor temperature fluctuates with the outdoor temperature without time lag. which is probably due to the low resistivity of corrugated iron sheet roofing, 0.14 (m2 k/w), whereas indoor temperatures in B2 were found in the range of 21.2 to 28.9 ºC at 7 a.m. and 6 p.m., respectively, with a fluctuation of 7.7 ºC and the peak outdoor temperatures of 34 ºC, which gave a temperature difference of 5.5 ºC between outdoor and indoor peak temperatures and a time lag of 3 h, Accordingly, the indoor temperature found in the comfort zone beside the maximum temperature is above the upper comfort limit by 0.16ºc which may be due to the thermal insulation performance of a thatched roof, which has a high resistivity of 4.065 (m2 k/w), whereas temperatures in B3 ranged from 23.5 to 28.5 ºC, with a 5 ºC swing, indicating a 5.5 ºC difference in peak indoor and outdoor temperatures and a 3-hour time lag. The maximum outdoor temperature was 34 °C at 9 a.m., and the minimum outdoor temperature was 19.9 °C at 1 a.m., with a maximum temperature fluctuation of 14.1 °C.

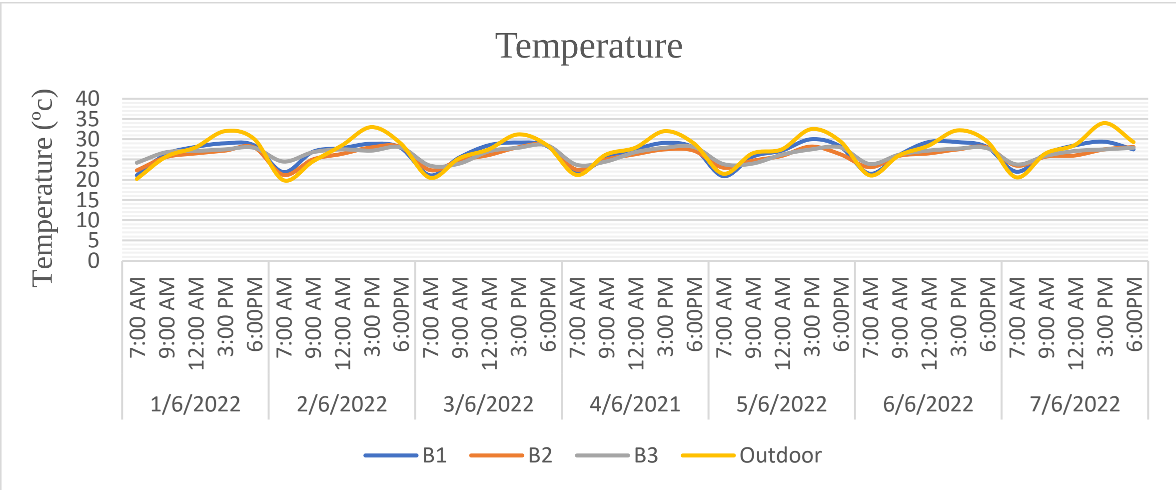


Figure 4.15: Temperature data in June 2022 (source: field survey, 2022)

Based on the results, the studies confirm that the maximum and minimum temperatures recorded in B1 were above and below the comfort limit ranges (21.74 to 28.74°C), whereas the temperatures in B2 were within the comfort zone but the maximum temperatures were above the comfort zone by 0.16°C, and the maximum and minimum temperatures in B3 were found in the comfort zone. Because of their high conductivity and low resistivity, the construction materials of the roofs of Building 1(corrugated iron sheet roofing) caused significant indoor temperature fluctuation. And the thatched huts have comparatively good thermal comfort conditions due to the thatch characteristics acts as an insulator which reduces heat during the day and provides cooling air at night. And the forms of the buildings (circular forms with a conical roof) with their high surface-to-volume ratio allow for a high indoor ceiling height, which helps to make the ground comfortable by scaping hot air to the upper part. Also, the availability Vegetation on the west side of B2 acts as an air-conditioning substitute by cooling the air through evapotranspiration.

According to Singh et al., (2010), indoor temperature fluctuation of all three buildings was within acceptable ranges, with indoor temperature fluctuation of less than 10 ºC being acceptable.

4.4.2. Wind speed

The figure illustrated below shows that recorded indoor wind speeds ranged from 0.0 m/s to 0.32 m/s.

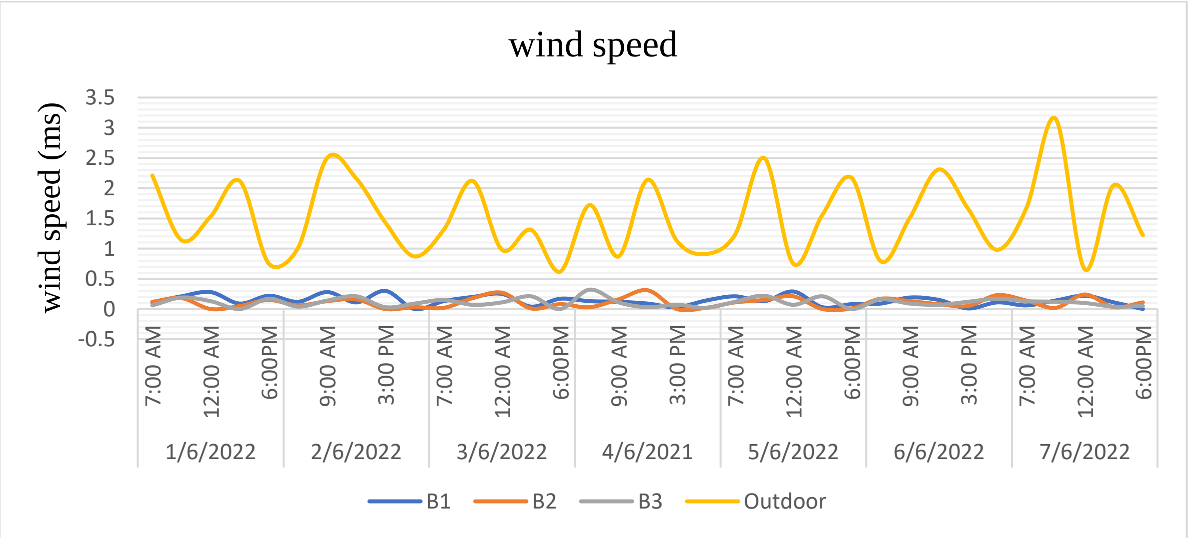


Figure 4.16: Data on wind speed in June 2022 (field survey, 2022)

As a result, 54.3% of wind speeds in B1 were below comfort limits; 45.7% of wind speeds in B2 were below comfort limits; 62.8% of wind speeds in B3 were below comfort zones; the remaining 37.2% were in the comfort zone; whereas 57.1% of wind speeds in B3 were also below comfort zones; and the outdoor wind speeds were in the range of 0.62 to 3.15 m/s. See Chapter 2 for the standard for allowable wind speed limits for comfort (0.15 to 0.8 m/s).

The study reveals that the limited openings facing the lowest wind speed direction contribute to the low indoor wind speeds below the comfort zone. But the qualitative exploration of evaluating the optimum wind movement based on the ratio of depth of building and floor to ceiling height undertaken by the method followed by Hamdani et al. (2018) shows that with existing width and floor to ceiling height, B1 and B3 are effectively ventilated by single-sided single openings and single-sided double openings, but the result of indoor measurements disproves the finding. This is mainly due to the fact that there are different factors for effectively ventilating the room beside width and floor to ceiling height, such as size of opening and position of opening to the wind direction.

Interestingly, the temperature measurement in B2 and B3 is found in the comfort range without having enough air movement; this confirms the Mahoney table recommendation, which states no air movement requirement for the climatic areas under study.

4.4.3. Humidity

Figure 4.17 shows that the lower relative humidity in B1 was 32% at 3 p.m. and the maximum humidity was 44% at 7 a.m., while the maximum humidity in B2 was 47% at 7.am and the lower humidity was 33% at 6.pm, and the maximum humidity in B3 was 48% at 9.am, with a lower humidity of 38% at 12.am, while the maximum outdoor humidity was 54% at 7.am and the lower outdoor humidity was 26% at 3.pm.

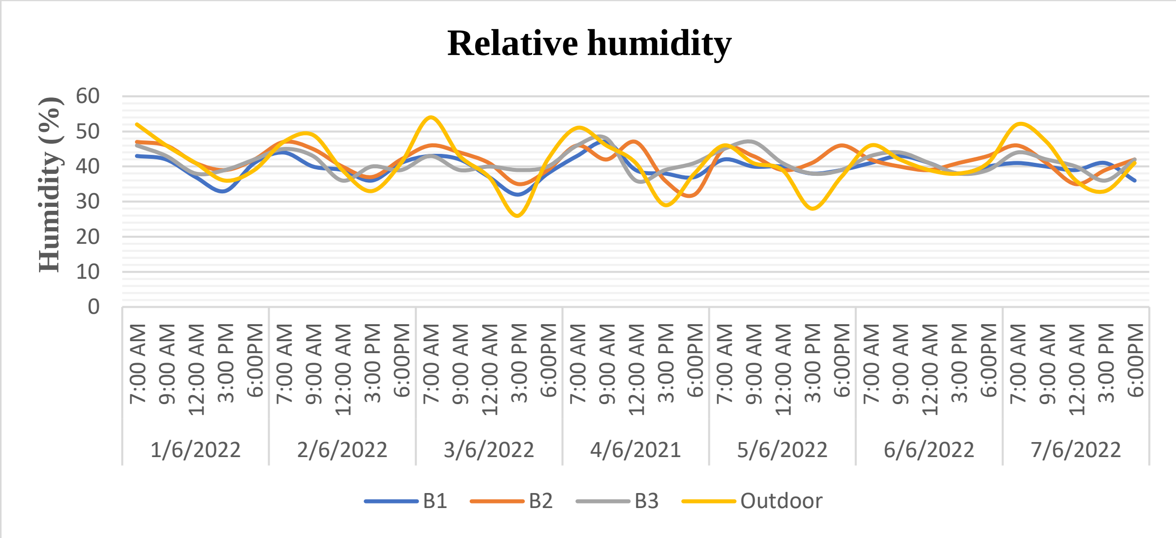


Figure 4.17: Humidity data in June 2022 (field survey, 2022)

The humidity analysis confirms that the lowest fluctuation level (10%) was recorded in B3, while in B2 a 14% swing was recorded, the fluctuation level in B1 was 12%, and the highest fluctuation level of 28% was recorded outdoors. The result also confirms that the indoor humidity levels of all three typologies (buildings) were within the comfort zone specified by the ASHRAE and ISO 7730 standards (30 to 70%). Stable indoor humidity fluctuation may be a result of the ability of the wood used in the building envelope, which breathes water in and out and has a lower density and a higher heat capacity (Ryan, n.d.).

4.4.4. Comparative analysis of measured temperature with ASHRAE and Mahoney day comfort temperatures

The average of measured values for seven days were plotted and compared with the upper and lower comfort ranges of temperatures in ASHRAE standards and the daytime comfort temperature limit in the Mahoney table for June (see Table 9 below); accordingly, 60% of the daytime temperatures in B1 were found in the comfort zone in both ASHRAE and Mahoney analysis, while 83% of the temperatures in B2 fell in the comfort zone according to the Mahoney table, and 100% of the temperatures were found to be in the comfort zone according to ASHRAE standards. Whereas 100% of daytime temperatures in B3 were found in the comfort zone in both the ASHRAE and Mahoney tables.

Table 9: Triangulation of measured indoor temperatures with the ASHRAE upper and lower limits and Mahoney's recommendation of upper- and lower-day comfort temperatures

Typology	Time	Temperature (ºc)	Mahoney table Upper=29ºc Lower=23ºc	ASHRAE Upper=28.74ºc Lower=21.74ºc
B1	7:AM	21.5	×	×
	9:AM	26.02	✓	✓
	12:AM	28.12	✓	✓
	3:PM	29.3	×	×
	6:PM	28.05	✓	✓
B2	7:AM	22.6	×	✓
	9:AM	25.2	✓	✓
	12:AM	26.2	✓	✓
	3:PM	27.7	✓	✓
	6:PM	27.74	✓	✓
B3	7:AM	23.9	✓	✓
	9:AM	25.4	✓	✓
	12:AM	27	✓	✓
	3:PM	27.6	✓	✓
	6:PM	28	✓	✓

- √ Where is used to represent its compatible and × were used to show it is incompatible

The result of the study confirms that the effectiveness of using Mahoney table analysis for calculating day time comfort temperatures for climate of Merti woredas.

4.4.5. Comparative analysis of simulated temperature with ASHRAE and Mahoney night time comfort temperatures

According to table 10, the nighttime temperature found from the simulation performed for June month was compared with the upper and lower night comfort temperatures for that month in both Mahoney table and ASHRAE (refer figure 4.14), and accordingly, the result indicated that 60% of indoor temperatures in B1 were found in the comfort zone in Mahoney table and 100% comfort temperatures in ASHRAE, while 80% of Ta in B2 was found in the comfort zone according to Mahoney and 100% comfort Ta in ASHRAE, whereas 0% comfort Ta in B3 according to Mahoney table and 100% in ASHRAE.

Table 10: Triangulation of simulated indoor temperatures with the ASHRAE upper and lower limits and Mahoney's recommendation of upper- and lower-night comfort temperatures

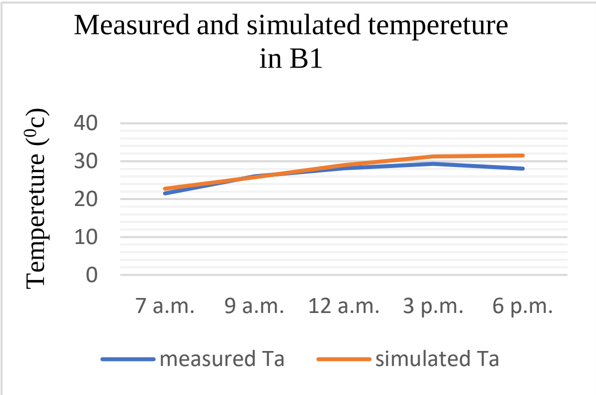
Typology	Time	Temperature (ºc)	Mahoney table Upper=24ºc Lower=17ºc	ASHRAE Upper=28.74ºc Lower=21.74ºc
B1	8:PM	27.4	×	✓
	10:PM	25	×	✓
	12:PM	23.6	✓	✓
	2:AM	22.7	✓	✓
	4:AM	22	✓	✓
B2	8:PM	26.7	×	✓
	10:PM	23.9	✓	✓
	12:PM	20.6	✓	✓
	2:AM	19.7	✓	✓
	4:AM	18.9	✓	✓
B3	8:PM	31.72	×	×
	10:PM	25	×	✓
	12:PM	25	×	✓
	2:AM	25	×	✓
	4:AM	25	×	✓

√ Where is used to represent its compatible and × were used to show it is incompatible

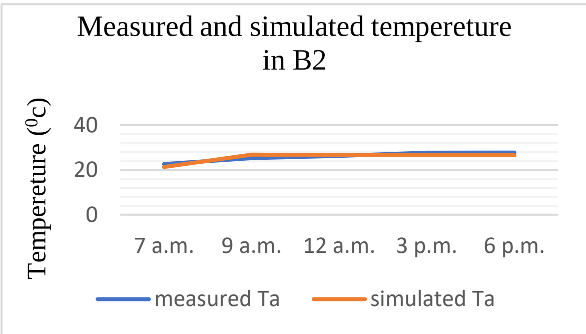
The result reveals that the better nighttime temperatures were found in B2, and the worst Ta was found to be in B3. The results of the comfort percentage of B3 during the day and night were consistent with the findings of Juliet et al., (2016), who discovered better thermal performance of the soil covering cell during the day and higher indoor temperature at night due to the high thermal capacity of the soil roof and the absence of any excess heat removal mechanism in the building, resulting in uncomfortable night temperatures in B3. Additionally, the study confirms Mahoney table analysis is better at calculating nighttime comfort temperatures than ASHRAE, which predict day and night comfort temperature equally without accounting for the actual outdoor temperature difference between day and night.

4.4.6. Validation of measured and simulated temperatures

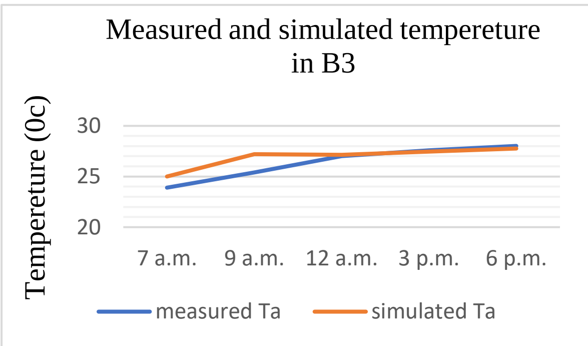
In order to identify the consistency of measured and simulated temperature results, validation (comparison) of the daytime temperature of measured and simulated data from 7 a.m. to 6 p.m. was performed, which identified the accuracy of the model for thermal simulation and used for comparison of the thermal performance of the model with different orientations, different overhang widths, and different thicknesses of the wall and roof.



B1	Time	Measured Ta (^{0}c)	Simulated Ta (^{0}c)
	7 a.m.	21.5	22.74
	9 a.m.	26.02	25.74
	12 a.m.	28.12	28.96
	3 p.m.	29.3	31.28
	6 p.m.	28.05	31.5



B2	Time	Measured Ta (^{0}c)	Simulated Ta (^{0}c)
	7 a.m.	22.6	21.31
	9 a.m.	25.2	26.82
	12 a.m.	26.2	26.55
	3 p.m.	27.7	26.55
	6 p.m.	27.74	26.57



B3	Time	Measured Ta (^{0}c)	Simulated Ta (^{0}c)
	7 a.m.	23.9	25
	9 a.m.	25.4	27.09
	12 a.m.	27	26.99
	3 p.m.	27.6	28.3
	6 p.m.	28.02	29.3

Figure 4.18: Measured and simulated temperatures B1 (top), B2 (middle), and B3 (bottom)

According to figure 4.18, it is possible to see that there is a slight difference between measured and simulated temperature in B1, B2, and B3, and as a result, there is a 5.46%, 4.2%, and 3.4% difference in average measured and simulated temperature in B1, B2, and B3, respectively. which shows the result is within the acceptable limit ±5% according to Tanasa et al., (2019). As a result, the simulated temperature results were used to assess the thermal performance of the base case model, as well as the impact of changing wall thickness, roof overhang width, and shifting building orientation.

4.4.7. Thermal performance of the base case model (B1)

The results of the heat gain of the B1 in summer show that the maximum indoor temperatures reach 31.54 ºC at 4 p.m. in the afternoon, with a minimum of 21.95 ºC at 7 a.m. in the morning, and the maximum outdoor temperature is 29.5 ºC at 2 p.m. in the afternoon, with a minimum of 18.23 ºC at 6 a.m. in the morning. which shows a swing of 9.59 ºC and 11.27 ºC indoors and outdoors, respectively. Accordingly, the indoor temperature swings are relatively lower than the outdoor temperature fluctuations, but the highest temperatures were observed indoors at 31.54 °C at 4 p.m., which is above the maximum outdoor temperature of 29.5 °C. The low thermal mass of the roof (2 cm) and the low resistivity of the metal roof observed in the building contradict the specific climatic design strategies of the area, which recommend a heavy roof with an eight-hour time lag and may contribute to the uncomfortable indoor temperature in the late afternoon.

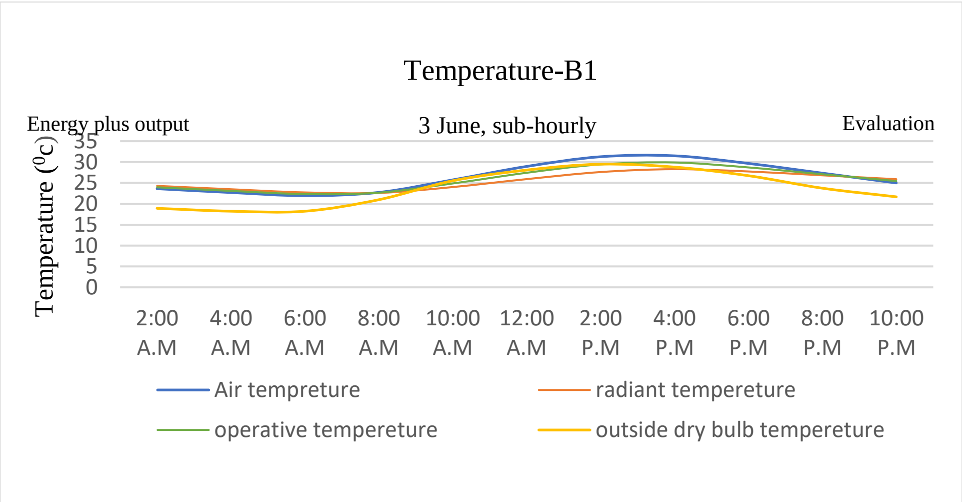


Figure 4.19: Temperature and heat gains in B1 (generated by the design builder software)

The uncomfortable states of B1 are caused by the adaptation of modern design styles that are incompatible with the Merti woreda microclimate, according to information obtained from key informant interviews and field observations.

i. **Heat balance**

According to Figure 4.20, the maximum percentage of heat received through the building's roof at 2 p.m. (midday), which is 4.19 kW at the time of the highest indoor temperatures observed, shows that during the intense time of the day, the indoor temperature was also extreme. That may be due to the low resistivity of corrugated iron sheet roofing.

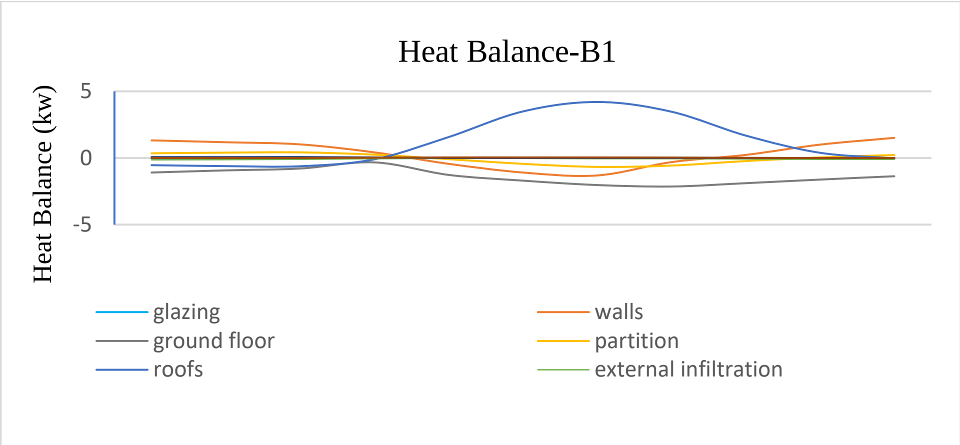


Figure 4.20: Heat balance data of B1 (source: generated by the design builder software)

The data on the thermal performance preference of buildings in the study areas was summarized as follows

> *"Recently most of the villagers construct metal roof building on the side of the previous thatch building but most of the time we didn't use it due to its characteristics of temperature fluctuation parallel to outdoor fluctuation even we never place drinking water in this building because of hostile indoor temperature. In contrast, the thatch building has a comfortable indoor environment on both hot days and cold nights. The high thermal mass material of the walls and the insulation properties of the roof store outdoor solar radiation and heat from cooking activity and make the night temperature suitable."*

4.4.8. Thermal performance of the base case model (B2)

The maximum indoor temperature of B2 is 26.82 ºc at 10 a.m. in the morning, with a minimum of 21.31 ºc at 8.a.m, and the maximum outdoor temperature is 29.5 ºc at 2 p.m. in the afternoon, with a minimum of 18.23 ºc 6 a.m. in the morning. which shows a swing of 5.51 ºc and 11.25 ºc indoors and outdoors, respectively. The results indicate that the indoor temperature swings are relatively lower than the outdoor temperature fluctuation, and the indoor temperature fluctuation is better than B1, which shows a difference in reduction of 4.08 ºc, whereas the outdoor temperature has a relatively high fluctuation rate due to outdoor climatic influence. The combination of the high thermal mass (mud) of the walls and the high insulation properties of the thatch roof with low density (240 kg/m^3), low conductivities (0.07 W/m *K), and high resistivity (4.065 m^2 k/w) helps to reduce the indoor fluctuation. The findings were consistent with the study conducted by Hashemi, et al., (2015), who found that replacing iron sheet roofing with thatched roofing reduced the frequency of thermal discomfort by 15% and improved thermal comfort conditions by 15 times.

During observation, it was found that all observed circular thatch buildings in the lowland areas have a small, high opening in the upper perimeter of the wall that is designed for smoke removal, lighting, and ventilating the room. Specifically, such an opening was provided in areas like the kitchen to remove the stored heat in the envelope during the night when other openings were closed for safety.

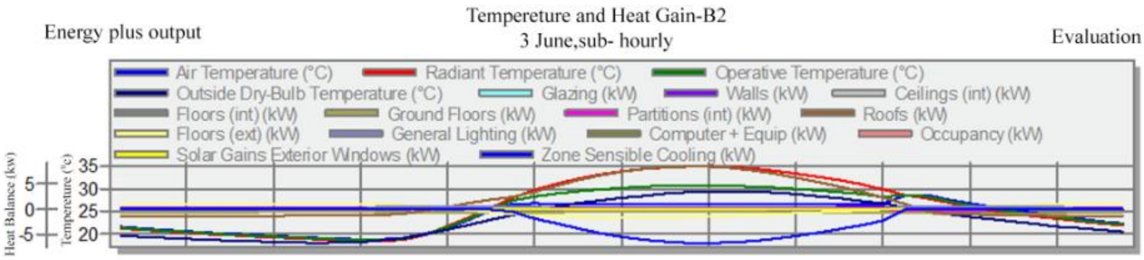


Figure 4.21: Temperature and heat gain diagram of B2 (source: generated by the design builder software)

The result of the study supports the finding of the study conducted by Zune et al. (2020) which found significant temperature increments by changing roof covering material from thatch to metal. This implies that the insulation characteristics of straw help balance heat gains and losses with a significant time lag.

The more compact form of the building and the lowest length to width ratio of 1:1, helping in decreasing heat loss at night and receiving low solar insolation in order to respond to the relatively hot climate of the day and cold night temperature of the area.

4.4.9. Thermal performance of the base case model (B3)

The simulation result shows that the maximum indoor temperature of B3 is 30.74 ^{o}c at 6 p.m. late afternoon, with a minimum of 25.0 ^{o}c at 6 a.m. in the morning, and the maximum outdoor temperature is 29.5 ^{o}c at 2 p.m. in the afternoon, with a minimum of 18.23 ^{o}c at 6 a.m. in the morning. which shows a swing of 5.74 ^{o}c and 11.25 ^{o}c indoors and outdoors, respectively. The results indicate that the indoor temperature swings are lower than the outdoor temperature fluctuation, whereas the outdoor temperature has a relatively high fluctuation rate due to outdoor climatic influence. The combination of the high thermal mass of the walls and the high thermal mass of soil roof resulting minimum temperature fluctuations. walls of the buildings have high heat capacity of 147.89 with low resistivity of 0.774 m2 k/w and the roofs have U-value of 1.671 W/m^2 K and have low resistivity of 0.598 m2 k/w. which is somewhat higher than the recommended u value for tropical countries Energy & Note, (n.d.)

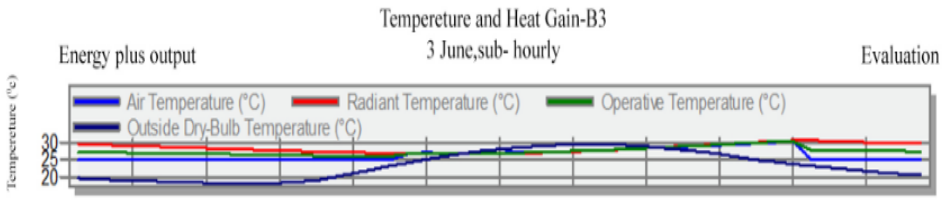


Figure 4.22 : Temperature and heat gain diagram of B3 (source: generated by the design builder software)

The results shown in figure 4.22 indicate that maximum indoor temperatures were found in the late afternoon compared with outdoor temperatures, which shows the thermal inertia of the building envelopes (roofs and walls) that delays the heat transfer from the external environment to internal spaces. The low ceiling height of the building protects the heat in the building. At night, the absence of any heat removal mechanism like a top opening or porous material made the nighttime temperature uncomfortable in this building.

The ground surface which is accessed by occupants is cooler due to cool air is heavier than warm air and heat radiating from the ground during the night causes a cold-air layer to form near the surface of the ground (Cooling & Buildings, n.d.).

According to the data from the key informant interview, this building typology was used mostly for occasional purposes or for some activity in the daytime, such as guest receiving, sleeping, or storing grain during the spring season, especially when the daytime temperatures of the areas make it difficult to stay home and affect the grain harvested.

4.4.10. The effect of different building orientation

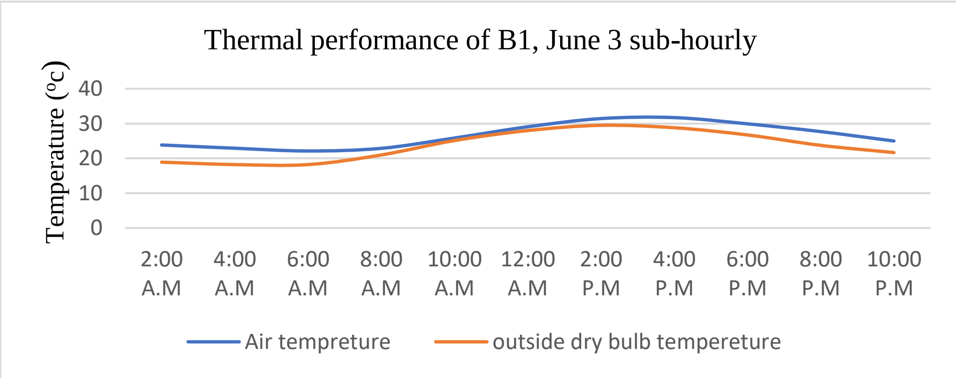
i. Building 1(B1)

Table 11 presents the highest and lowest temperatures and temperature fluctuations of the selected orientation; accordingly, the south orientation has relatively better thermal performance. And Table 11 shows the graphical presentation of the effects of orientation on the thermal performance of B1.

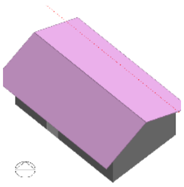
The detailed comparison of the effect of building orientation on thermal performance was performed by altering existing building orientation to the dominant wind directions and direction of optimum building orientation derived from Ecotect software for the study areas.

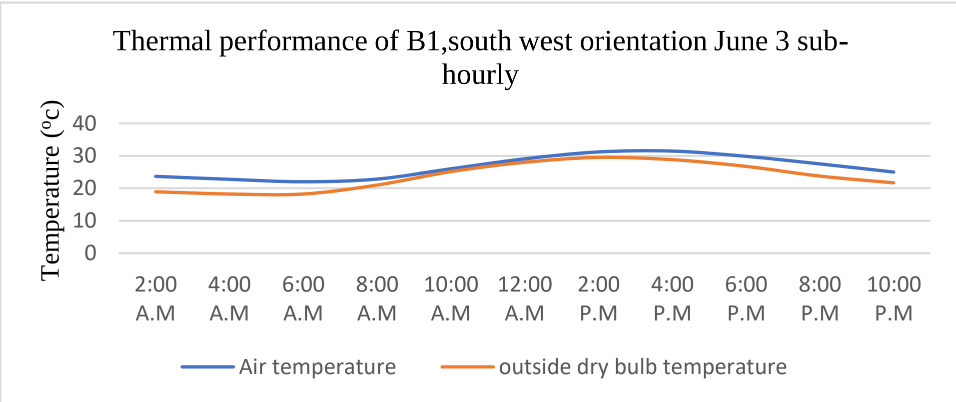
Table 11: Thermal performance effect of building orientation in (B1)

North orientation

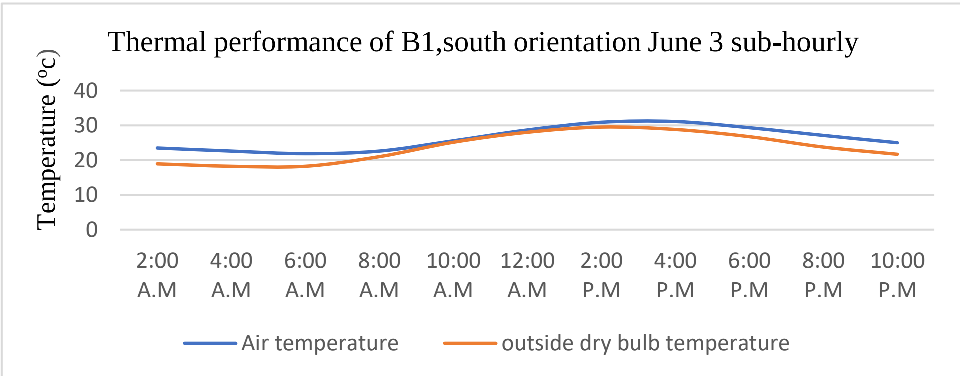


South west orientation





South orientation



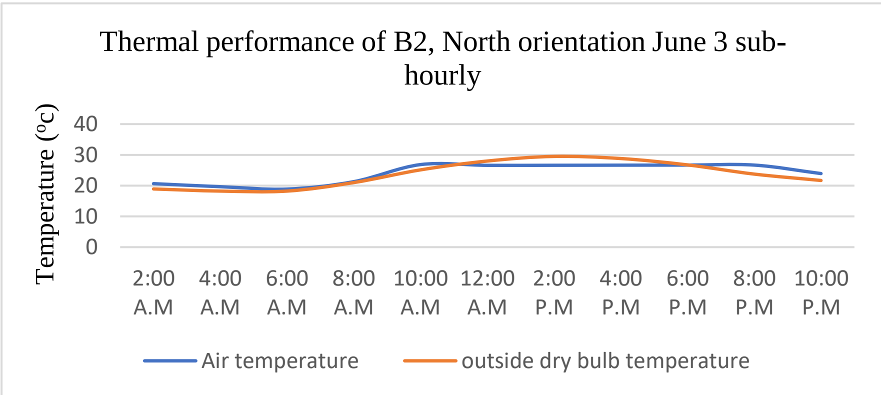
The results revealed that building orientation has little effect on the building's thermal performance in B1, but the south orientation shows a reduction of 0.35 ºC in indoor temperature fluctuation from 9.59 ºC (the base case model) to 9.24 ºC, which shows the south orientation has better thermal performance, which confirms the optimum orientation diagram of the area as south orientation at a compromise angle of 177.5 º. See Appendix E.

According to results found from observation, the buildings have rectangular elongated forms that receive high solar radiation, and there is vegetation on the south-east face of the building that is used as a microclimate moderator. Despite their availability, their position towards low wind movement direction reduces their effectiveness in reducing indoor temperature (see appendix F).

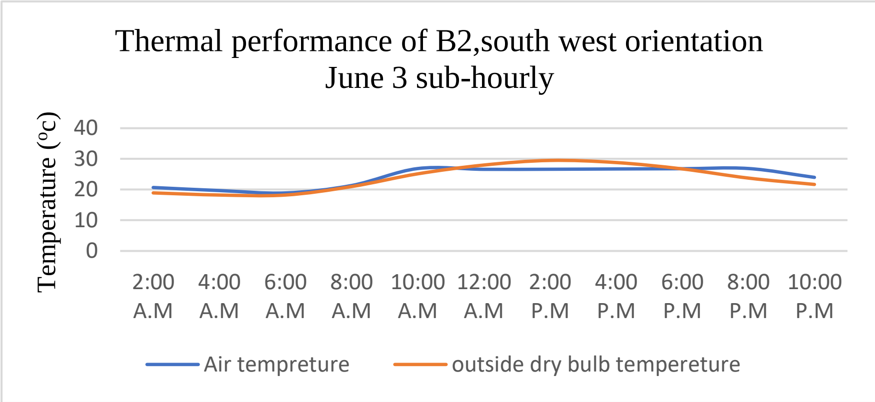
ii. Building 2(B2)

According to Table 12, the indoor temperature of the thatch house was stable with little fluctuation, and 63.6% of hours in all selected orientations were found to be in the comfort zone. The results indicate that indoor temperatures in all selected orientations were consistent and did not show much amplitude except in the midnight period from 2 a.m. to 6 a.m., which is below the lower comfort limits (21.74 ºC). See Appendix G.

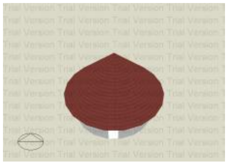
Table 12: Thermal performance effect of building orientation in (B2)

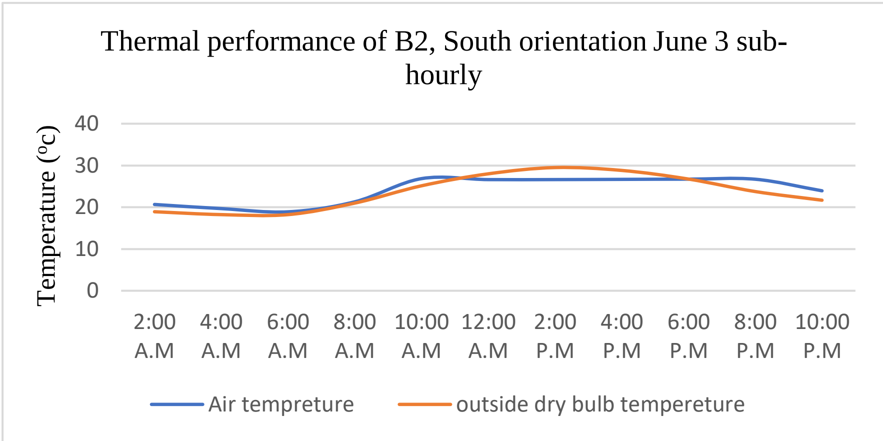
North orientation 	

South west orientation



South orientation



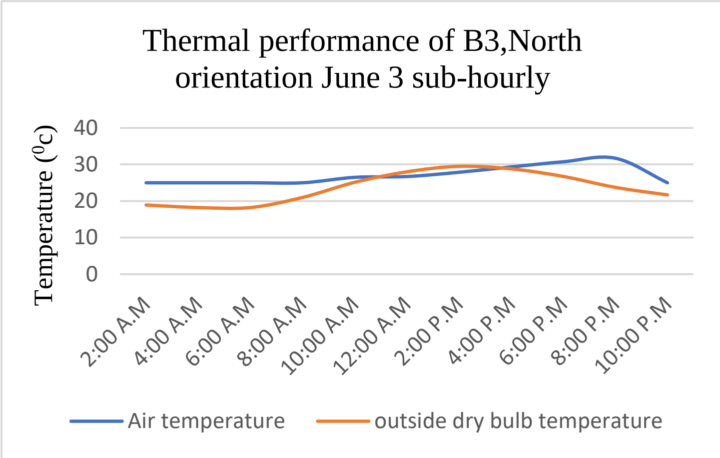
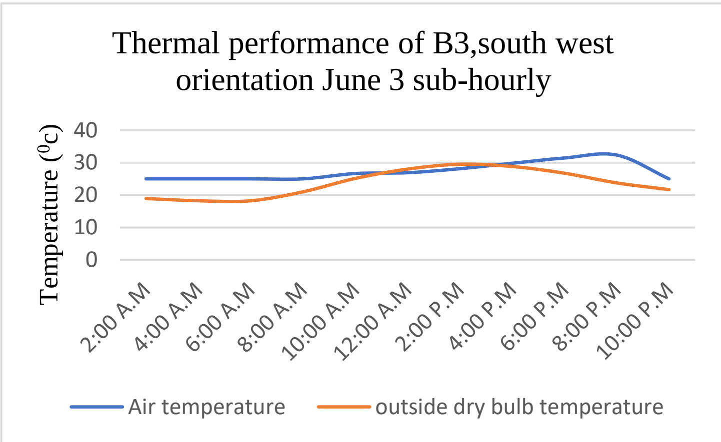
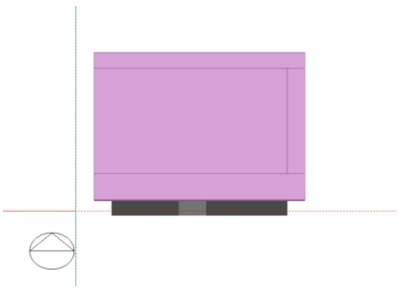
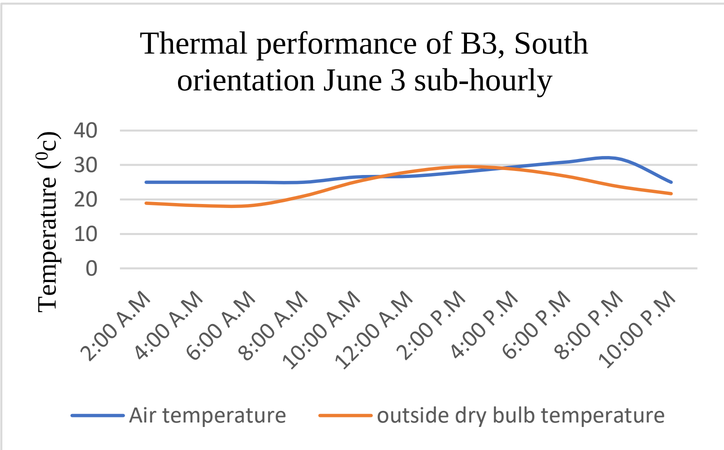


The lowest average temperature variation observed was probably due to the form of the buildings, which receive the lowest solar radiation (Ling et al., 2007), and the effect of building materials (insulation characteristics of thatched roof and high thermal mass mud wall), but the north orientation was comparatively better performed, with a maximum temperature of 26.84 °C and a minimum temperature of 18.89 °C, which is probably due to the position of top openings towards the highest wind movement direction (south east, south and east) when the front façade (main entrance) was facing in the northern direction as an existing building. The high windows allow nocturnal ventilation when all the other openings are shut for safety reasons and moderate indoor temperatures (Philokyprou et al., 2017).

Building 3(B3)

Table 13 depicts that the north orientation has better thermal performance than the south and south-west orientations by having a low maximum indoor temperature of 31.72 °C, a relatively low indoor temperature fluctuation of 6.72 °C. The highest indoor temperatures (32.34 °C) were observed in the south-west orientation.

Table 13: Thermal performance effect of building orientation in (B3)

North orientation 	
South west orientation 	
South orientation 	

The indoor temperature swings in the north orientation (6.72 °C) were slightly lower than those in the south and south-west orientations. The results also show that 72.72% of indoor temperatures in B3 were found in the comfort temperature ranges, and the remaining 27.2%

were above the upper limit of comfort, whereas 54.5% of outdoor temperatures were found below the lower comfort limits and 18.2% were above the upper comfort limitation.

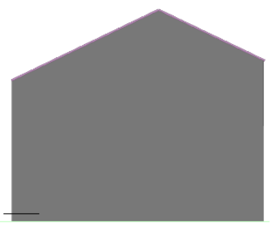
The lowest temperature swing in the north orientation may be due to the orientation of the building along the east-west axis or the shortest axis being faced towards the east-west direction, which helps to receive low solar radiation, and the high thermal mass of the walls and roofs contributes to the reduction of indoor temperature fluctuation. On the other hand, the existence of an overhang in the north façade may be the reason for the comparatively better thermal performance of the north orientation.

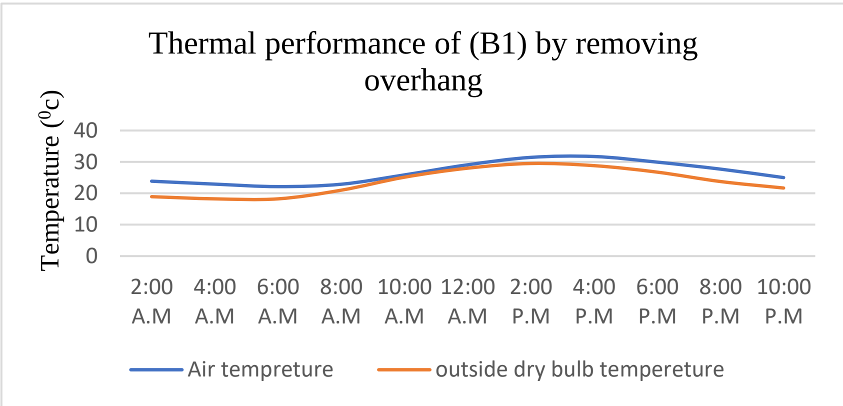
4.4.11. Effect of roof overhang width on thermal performance of building 1,2, and 3

According to table 14 below, removing roof overhangs in B1 raises the average indoor temperature by 0.2 ºc from 26.4 to 26.6 ºc, whereas extending roof overhangs to 1.5 m lowers the average indoor temperature by 0.02 ºc from 26.4 to 26.38 ºc. On the other hand, adding fixed door shading has increased the average indoor temperature in B2 by 0.06 but lowered indoor temperature fluctuation by 0.07ºc, and finally, extending and removing overhangs in B3 have increased the average indoor temperature by 0.31 and 0.42 ºC, respectively, which shows the existing overhang width is effective.

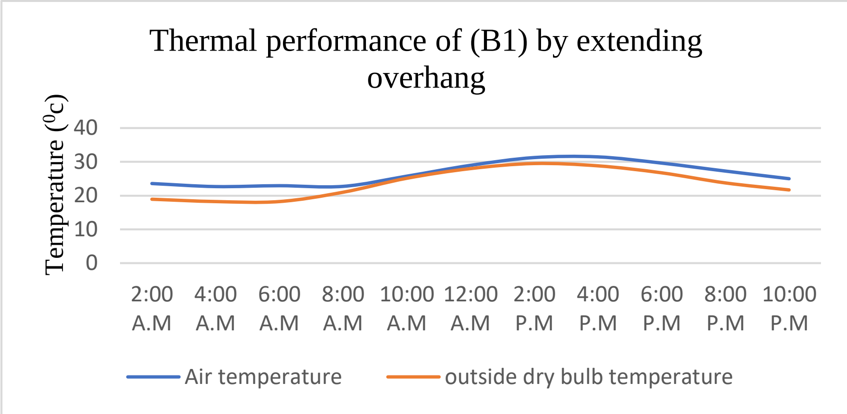
Table 14: Effect of overhang width on thermal performance of building 1,2, and 3

Removing overhang

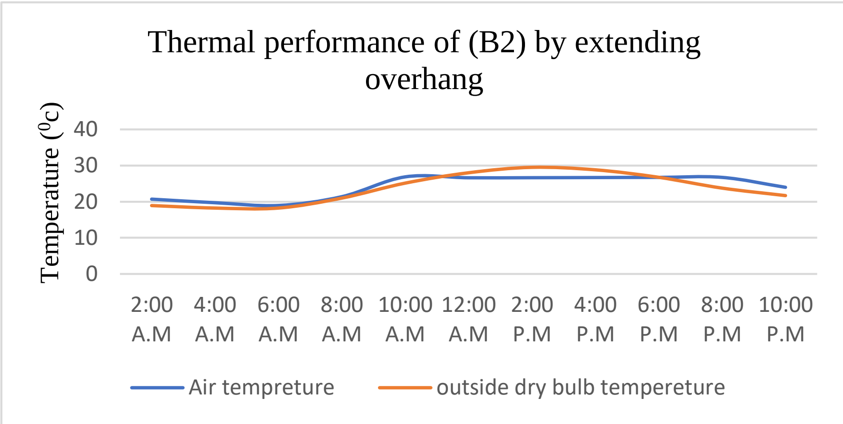




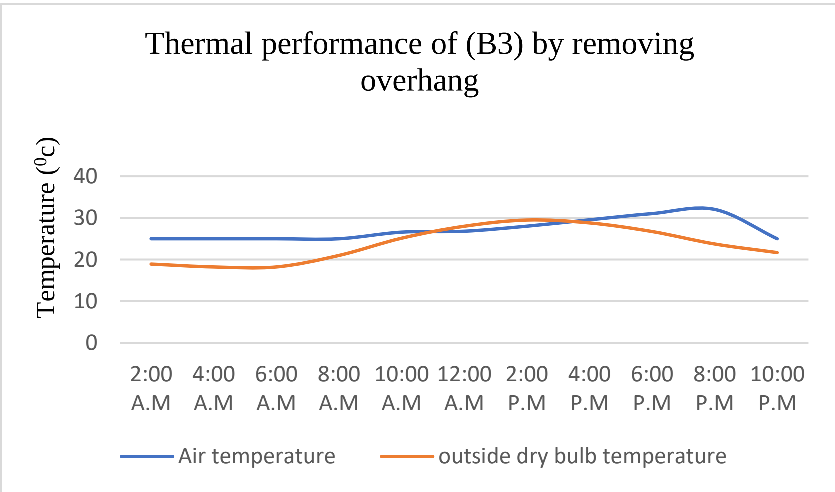
Increasing overhang width to 1.5m



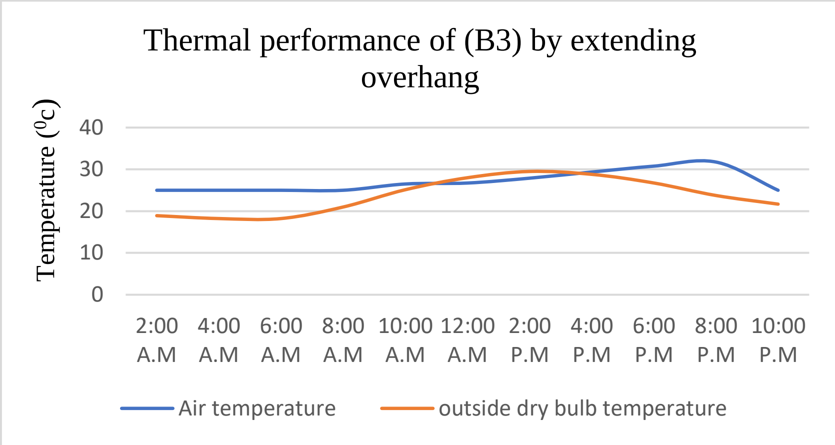
Fixed door shading



Removing overhang



Increasing overhang width to 1.5m



The result demonstrated that the effect of roof overhang width is related to the building materials and thermal properties of different components of the building. It’s found that the roof overhang width has a positive effect on average indoor temperature reduction and temperature fluctuation in B1. It compensates for the roofs' high solar conductivity by increasing shading in the building's walls, whereas adding a fixed roof overhang increases indoor temperature by 0.06 ºC but reduces temperature swing by 0.07 ºC in B2. In B3, existing overhang width has a lower average temperature of 26.78 ºC and the lowest temperature fluctuation of 5.34 ºC, which indicates existing building overhang width performs better than the altered case.

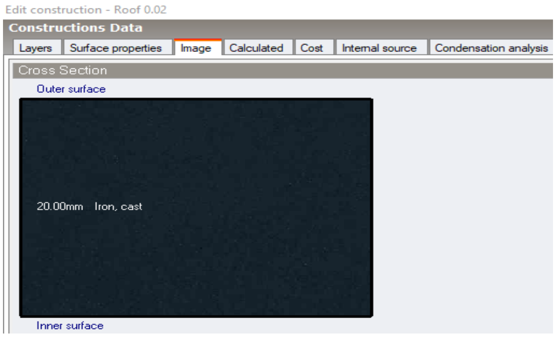
4.4.12. The effect of wall and roof thickness on thermal performance

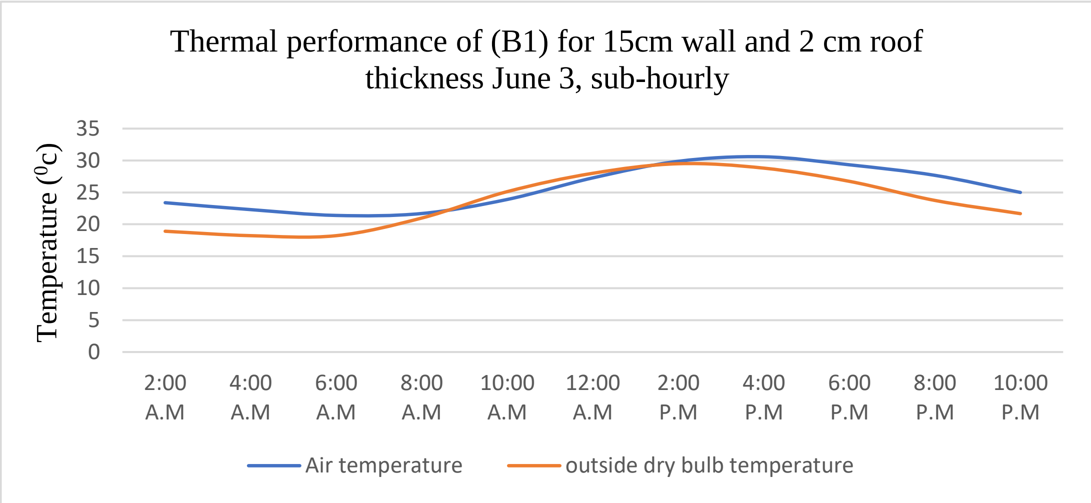
i. Building 1(B1)

The indoor temperature fluctuation potential of changing wall thickness while keeping roof thickness constant (2 cm) was investigated for B1, the base case thickness of 20 cm walls and 2 cm roofs, so simulations were run by reducing wall thickness to 15 cm and increasing wall thickness to 30 cm. Accordingly, the indoor temperature fluctuation of base-case buildings was 9.55 °C, and the lowest temperature swings were observed in a model with 30cm walls and 2cm roofs, which is 9.12 °C.The results show the performance of the high thermal mass of the wall in reducing indoor temperature fluctuation, which confirms the Mahoney table recommendation of high thermal mass for areas under study. Refer appendix D.

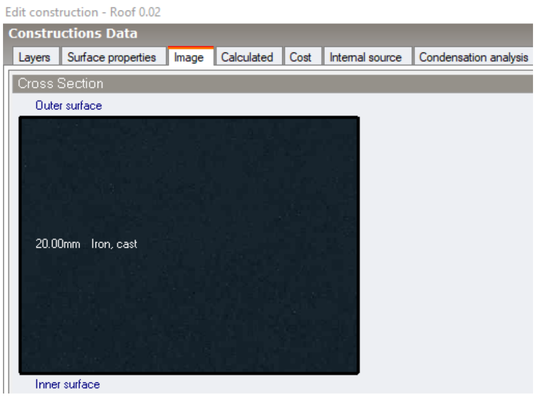
Table 15: Effect of wall and roof thickness on thermal improvement rate of (B1)

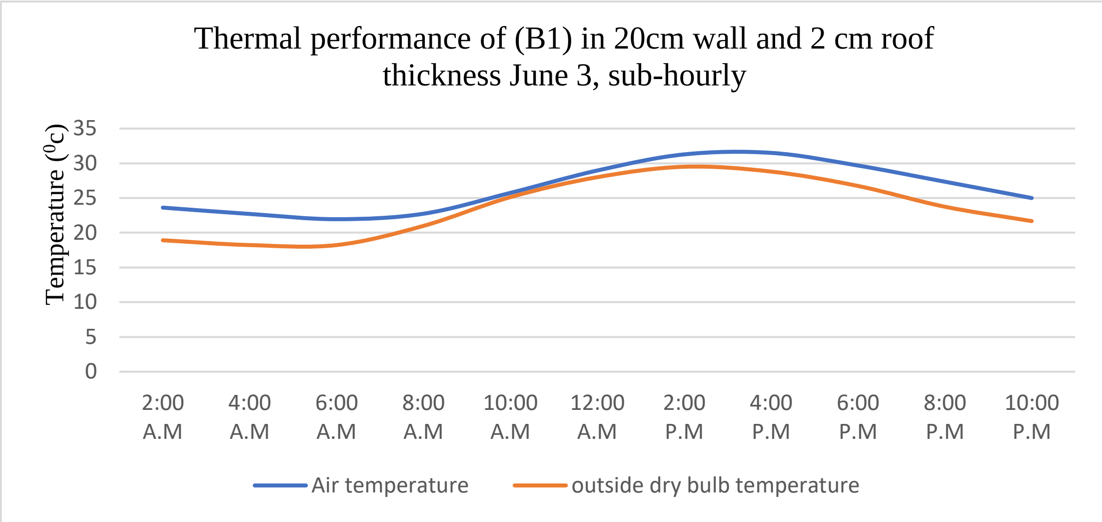
Wall 15cm and Roof 2cm (B1)



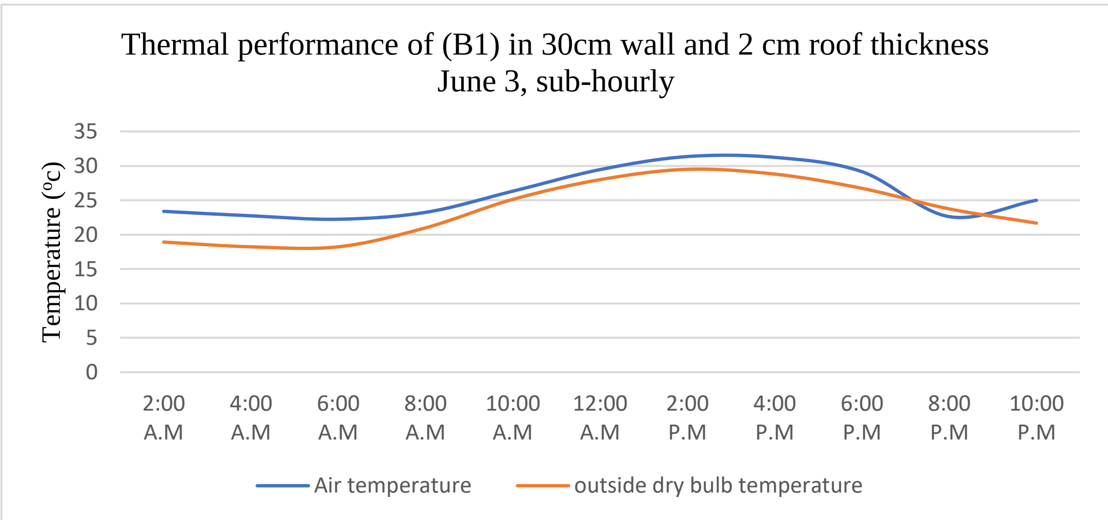


Wall 20cm and Roof 2cm (B1)





Wall 30cm and Roof 2cm (B1)



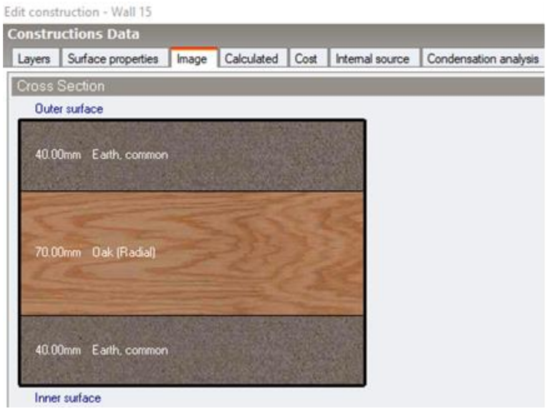
The results confirm that the better results in thermal performance were observed in the building, which has 30cm walls and 2cm roofs with minimum indoor temperature fluctuations of 9.12 °C, but the indoor temperatures were increased by 0.17 °C, which may be the effect of the high thermal mass of the walls to store heat and release it when it is needed. Increased wall thickness has improved indoor thermal performance.

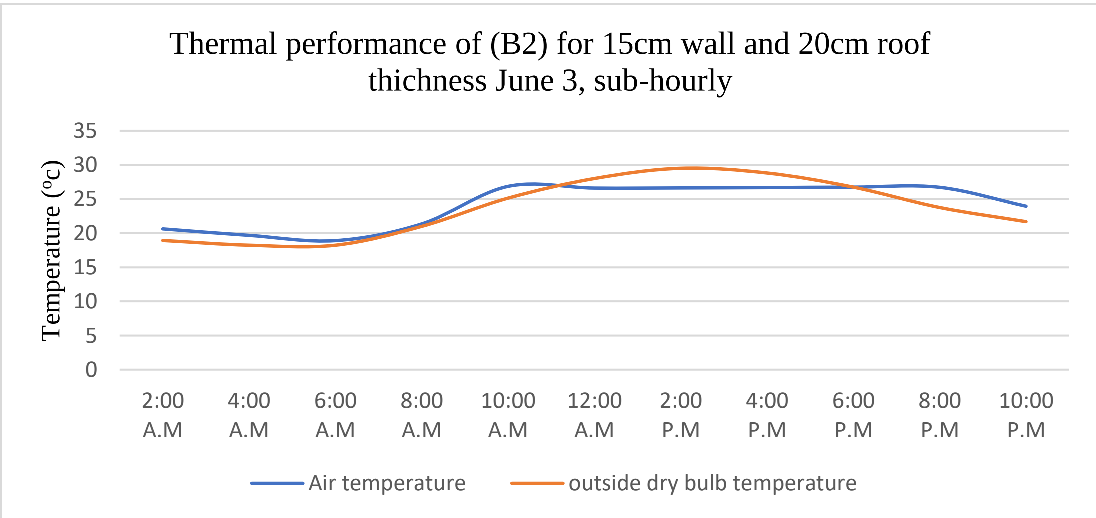
ii. Building 2(B2)

The simulation results in B2 show that the maximum indoor temperatures were 26.82 °C. Altering the thickness of the roofs to 15 cm and the walls to 20 cm showed an increment in maximum indoor temperatures of 0.07 °C (from 26.82 to 26.89 °C). whereas changing the thickness of both walls and roofs to 20 cm results in a maximum temperature of 26.85 °C, changing the thickness of the walls to 30 cm and the thickness of the roof to 20 cm results in a 0.03 °C increment in the maximum indoor temperature from 26.82 °C to 26.85 °C. Changing the wall thickness to 15 cm while keeping the roof at 20 cm, on the other hand, results in an increase of 0.03 °C.

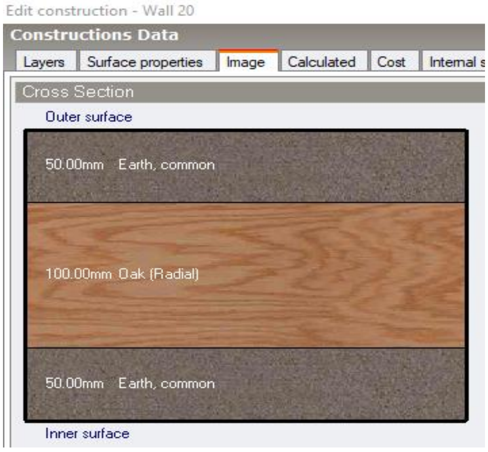
Table 16: Effect of wall and roof thickness on thermal improvement rate of (B2)

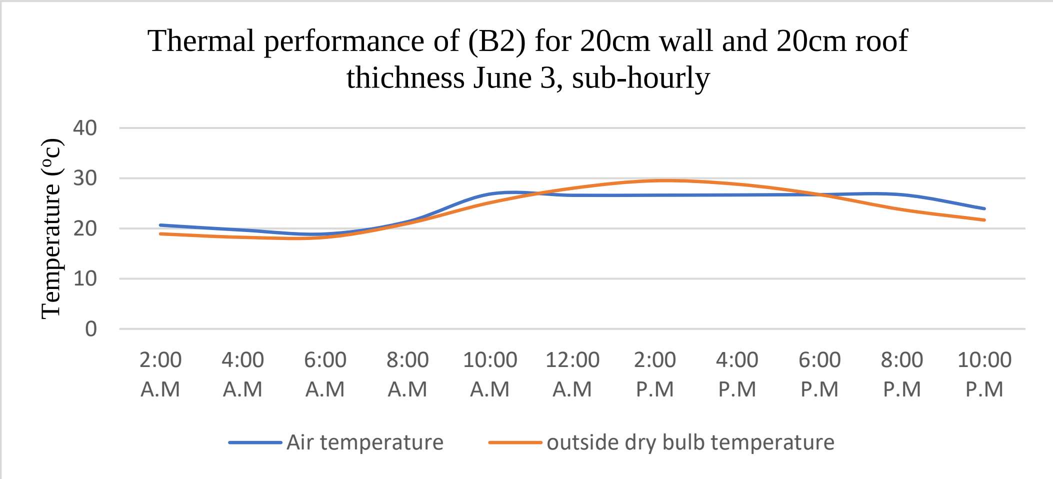
Wall 15cm and roof 20cm (B2)



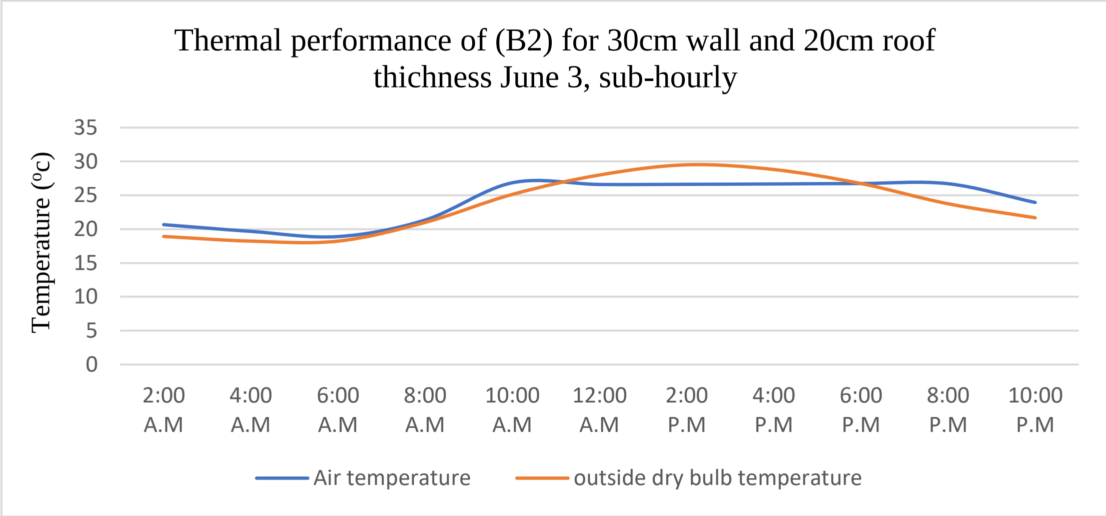


Wall 20cm and roof 20cm (B2)

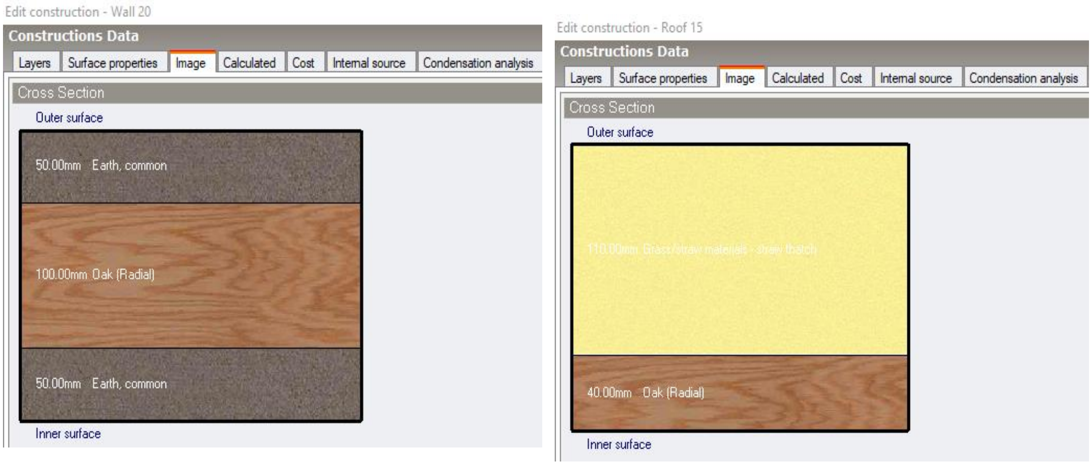


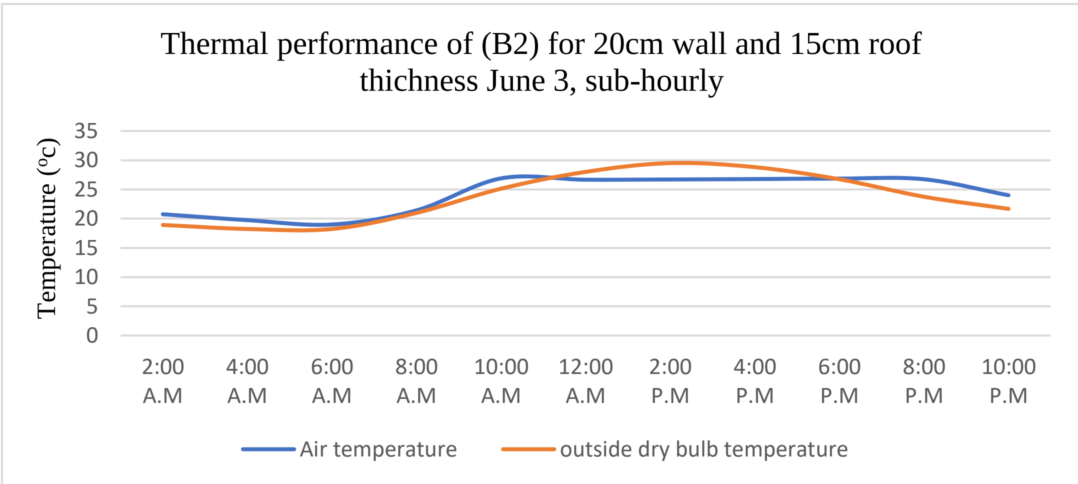


Wall 30cm and roof 20cm (B2)

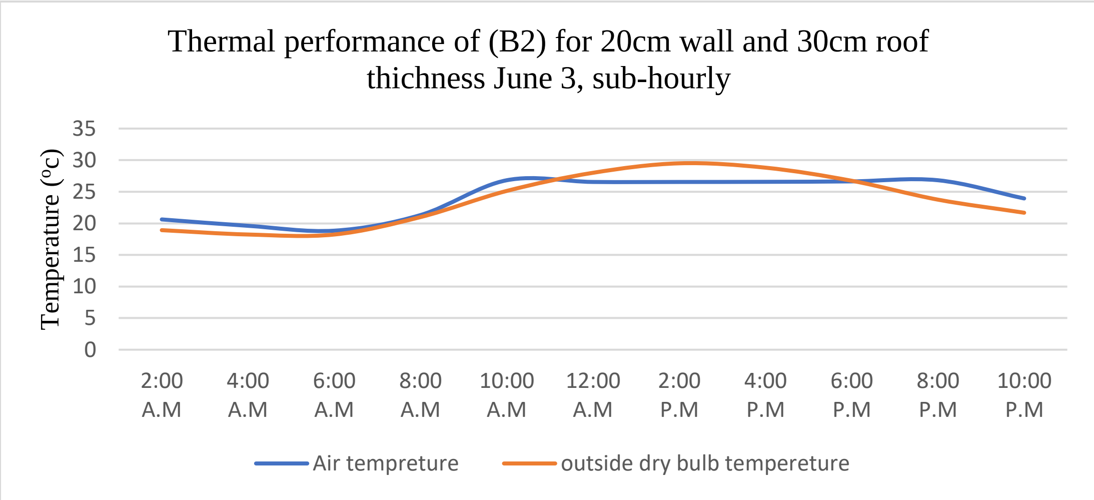


Wall 20cm and roof 15cm (B2)





Wall 20cm and roof 30cm (B2)



Unexpectedly, the results confirm that altering the thickness of roofs and walls had no significant impact on thermal performance. This may be the effect of a thatched roof, which has a porous nature and acts as insulation, and the form of the buildings (length to width ratio), which is 1:1 and receives little solar radiation, but the model with 20 cm walls and 30 cm roofs has a relatively low maximum indoor temperature of 26.82 ºC which is probably due to the relative medium thickness of the roof, which indicates that to save heating energy and reduce indoor temperature, increasing roof thickness is efficient. The low thermal conductivity of the high thermal mass roofs also contributes to the relatively lower maximum indoor temperature of the base case building.

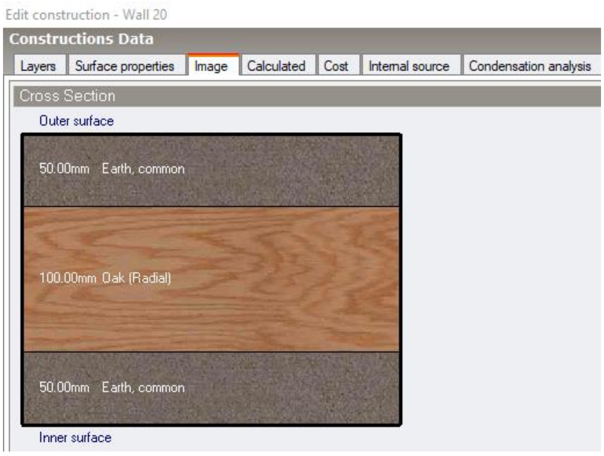
iii. Building 3(B3)

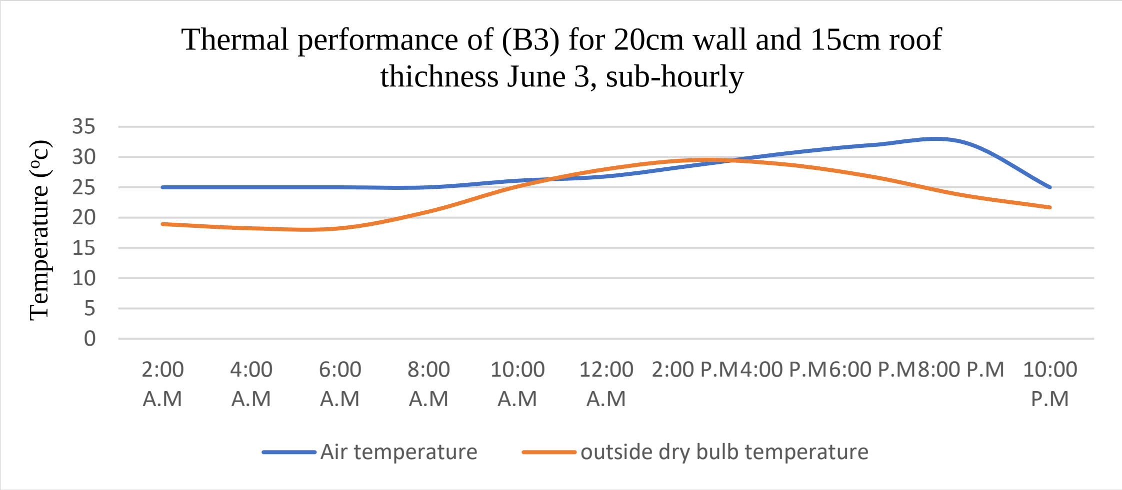
Altering roof thickness by keeping wall thickness at 20 cm and altering wall thickness while keeping roof thickness at 20 cm, the result shows that the maximum indoor temperature of the existing buildings with 20 cm walls and 30 cm roofs was 30.34 °C. As the roof thickness is reduced to 15 cm, the maximum indoor temperature is increased by 2.16 °C from 30.34 to 32.5 °C, whereas keeping walls and roofs at 20 cm increases the maximum indoor temperature by 1.41 °C from 30.34 to 31.75. On the other hand, reducing the wall thickness to 15 cm increases the maximum indoor temperature by 3.41 °C. Finally, increasing the wall thickness to 30 cm (keeping the roof at 20 cm) increases the temperature by 0.72 °C from the 30.34 °C of the base case (existing) model maximum temperature to 31.06 °C.

According to Hashemi, et al., (2015), Because the thermal conductivity of most walling materials differs slightly from that of roofing materials, improving the thermal performance of the roof is more important than improving the thermal performance of wall materials in naturally ventilated buildings in tropical climates. As a result, the study's findings confirm that existing buildings with 20-cm walls and 30-cm roofs have better thermal performance than altered buildings with 30-cm walls and 20-cm roofs.

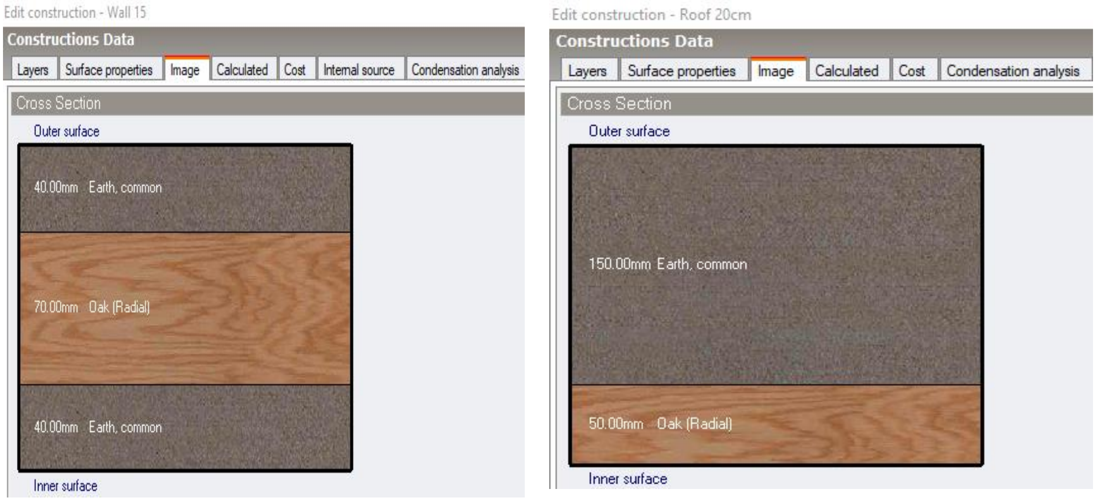
Table 17: Effect of wall and roof thickness on thermal improvement rate of (B3)

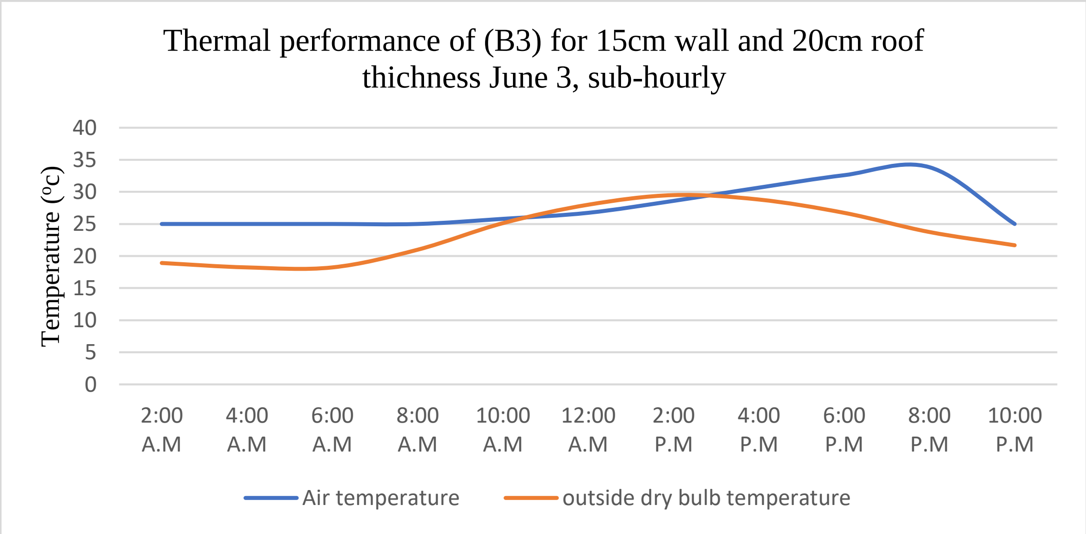
Wall 20cm and roof 15cm (B3)



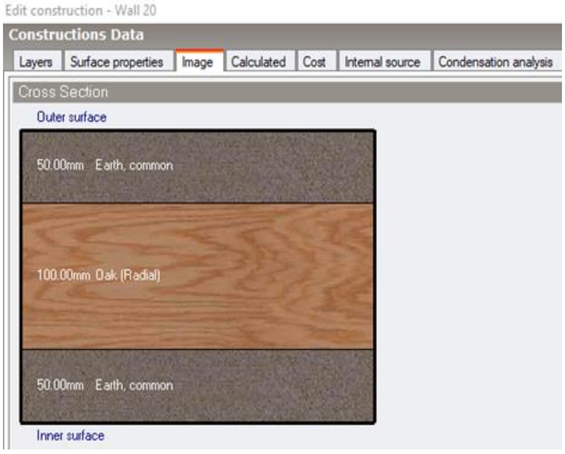


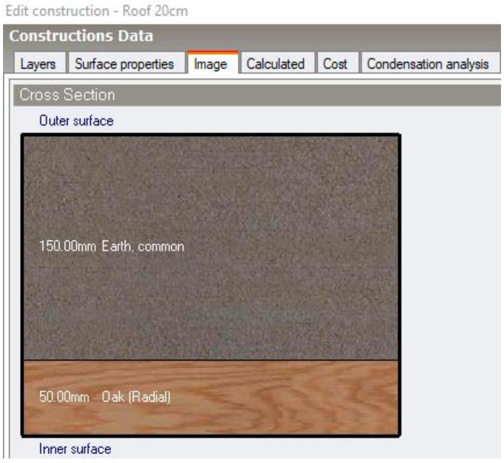
Wall 15cm and roof 20cm (B3)

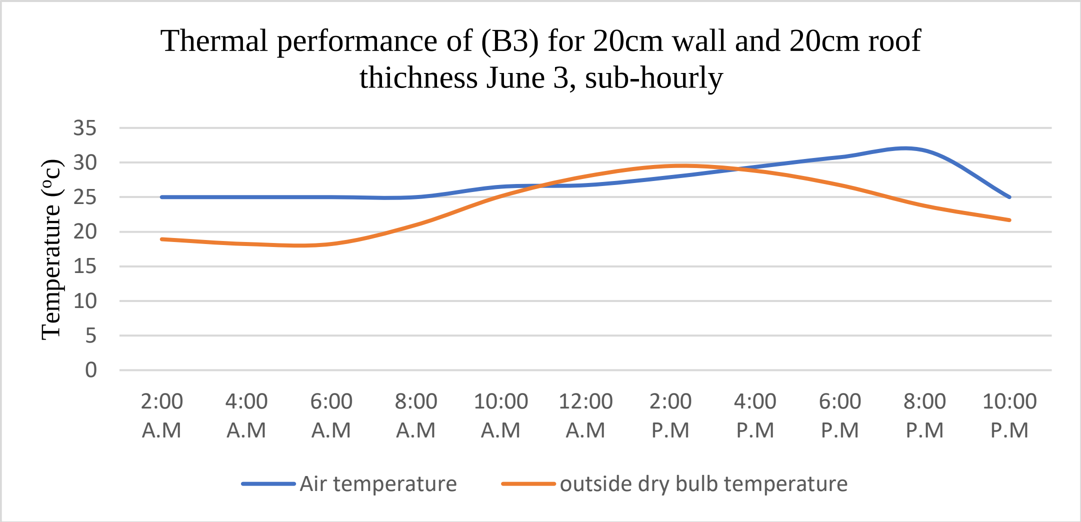




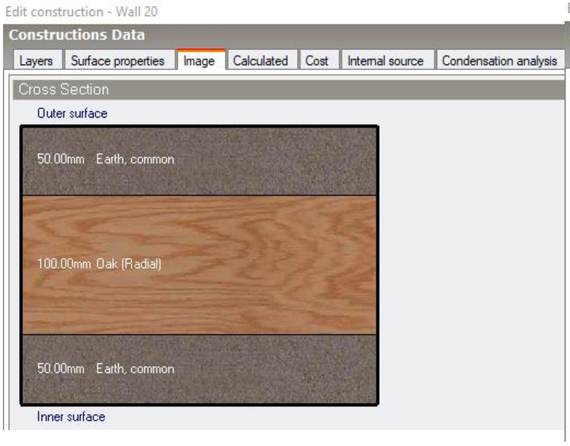
Wall 20cm and roof 20cm (B3)

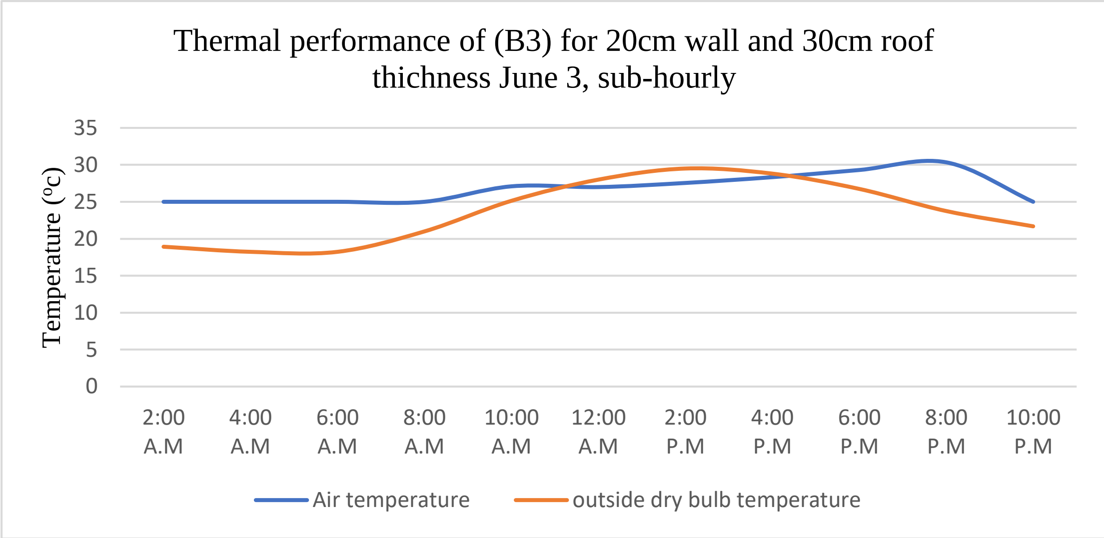




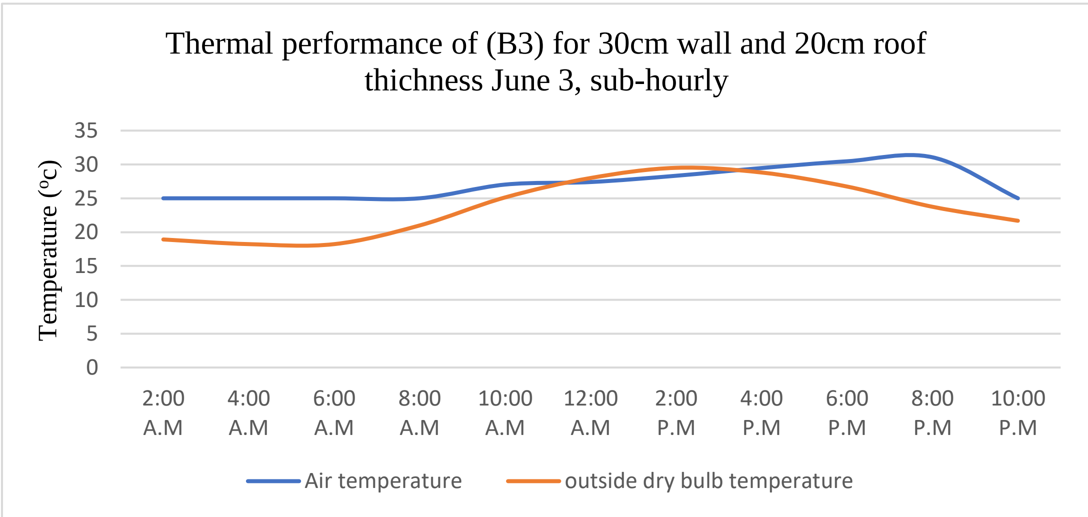


Wall 20cm and roof 30cm (B3)





Wall 30cm and roof 20cm (B3)



The results confirm that the better results in thermal performance were observed in the base case model, which has 20 cm walls and 30 cm roofs, a relatively lower maximum indoor temperature of 30.34 °C, and minimum indoor temperature fluctuations of 5.34 °C. In this study, the effect of placing thermal mass in its effective position on thermal performance was observed (see Appendix I).

The lowest maximum indoor temperature observed in the base-case model may be the highest thickness of roofs, which helps to slowly release the heat absorbed during the day in the evening when the outdoor temperature is lower than that of the indoors.

Table 18: Triangulation on results found from different methods of data collection used in the present study

Point of discussion	**Building**	**Observation**	**Indoor invironmental measurement**	**Simulation**
Thermal mass	**B1**	With thick mud walls and light-weight corrugated iron sheet roofing, the indoor late afternoon temperature is extreme.	The high thermal conductivity and low resistivity of corrugated roofing affect the indoor thermal environment by putting it out of comfort zone.	The simulation result revealed that the indoor temperature fluctuation has been reduced slightly by increasing wall thickness.
	B2	High thermal mass of mud walls with high thermal mass thatch roofs with	The indoor temperature and humidity throughout the day are in the comfortable range, which is due to the high insulation and heat resistivity properties of the thatch and the high thermal mass of walls and roofs.	It was found that the existing building with a 20cm wall and 30cm roof has lower indoor temperature and flactuation than the altered building. The thickness and properties of the horizontal envelope roof help reduce the average indoor temperature and flactuation.
	B3	High thermal mass of mud walls (20cm and high thermal mass of soil roofs (30 cm) were observed.	The daytime indoor temperatures and humidity in this typology are found in the comfort range with acceptable fluctuation.	The simulation was done for the thermal performance of the building 24 hours a day, and it was found that the high thermal mass of walls and roofs is effective in the daytime but extreme at night, which indicates

				the need for heat removal mechanisms at night. but the sample building has no such techniques, which results in uncomfortable nighttime temperatures in the early evening.
Orientation	**B1**	The building is oriented in an east-west direction, in which the short side of the building gets high morning sun and low afternoon sun, and there is no opening in this direction.	The max and min recorded temperatures in this base case building are above and below the comfort temperature of the area for June months, and the building is oriented on the north side, which is in the opposite direction of the recommended optimum orientation of the area (south).	The simulation result confirms the optimum orientation of the area, which is south; rotating the building façade from north to south gives lower maximum temperature and indoor temperature fluctuation.
	B2	The building has circular forms, and the main opening faces in the north-west direction, which gets low wind movement by the door.	Recorded temperature in the building is found in the comfort zone, which may be the orientation of top openings towards high wind movement direction.	The thermal performance of buildings in the north and south orientations is almost similar, even though the north orientation performs better by having a lower average temperature of 0.01 ºC.
	B3	Buildings are oriented in an east-west direction, and the front façade faces north.	In the existing orientation, the building performs relatively well; this may be the effect of the lowest exposed wall surface to the sun rise and sun set directions.	The north orientation has the relatively lowest maximum indoor temperature and lowest fluctuation compared with the altered orientation.

Overhangs	**B1**	A horizontal overhang with 1.08 m length was observed in the north façade of the building.	The building is oriented towards the worst orientation of the area; the openings were slightly shaded by the overhang, but the maximum and minimum indoor temperatures are out of comfort ranges, which is due to the high conductivity of roofing materials.	Optimization of the building's thermal performance was undertaken to identify the effects of overhangs by increasing and reducing the width of overhangs. The results demonstrated that extending the roof overhangs to 1.5 m reduced the indoor temperature slightly. which shows the positive contribution of the shading device for the sample typology.
	B2	The conical forms of the roofs made continuous overhangs on all sides, which measured 0.6 m in width.	The extended overhangs on all sides covered the top openings from exposure to solar radiation, which contributed to the comfortable indoor temperature.	The size of overhangs on existing buildings has better thermal performance than removing and extending overhangs. This is due to removing overhangs, which exposed the vertical envelope of the building (wall and openings) to solar radiation, and adding fixed door fins to block air movement and increase indoor temperature.
	B3	The soil roof building overhang measures 1.06 m and is located in the north orientation, which gets maximum solar radiation.	According to studies, horizontal overhangs are effective in both north and south orientations. The existing overhang width in this typology helps in achieving comfortable indoor temperatures in the daytime.	The thermal performance of the existing building with its 1.06m overhang width is better than the model in which the width extends to 1.5 m and the model in which the overhang is removed. which may be the thermal mass of the overhangs, which store the heat during the day and transfer it to the vertical

				structures of the building (walls). As the width increases, the amount of heat it receives also increases due to the high heat storage properties of the soil covering wooden overhangs.
Forms	**B1**	Rectangular from which has length to width ratio of 1:1.6	The building forms contribute to high solar gain, which makes the indoor environment uncomfortable, especially in the late afternoon and early morning.	The simulation in this typology shows that in addition to the thermal properties of roofing materials, the form of the building also contributes to thermal discomfort in this typology by receiving high solar radiation from its exposed walls and roofs.
	B2	Compact building forms with a length-to-width ratio of 1:1	The compactness of the building forms and other bioclimatic design techniques such as high insulation properties of thatch roofs,high thermal mass of walls, and top openings for stack effect ventilation used in the buildings help in lowering indoor temperatures.	Due to the impact of the forms reccieve lower solar radiation even rotating the building to different orientation has no significant indoor tempereture difference
	B3	The forms of the buildings are rectangular, which somewhat blend into square forms, with a length-to-width ratio of 1:1.5.	In addition to the excellent thermal storage properties of mud walls and soil roofs, the nighttime temperature is slightly uncomfortable due to a lack of air movement.	The soil roofs and mud walls exposed to solar radiation and storing daytime heat and releasing heat at night require night ventilation strategies in such buildings, but the existing buildings have no such system, which makes the night

				temperature for limited periods uncomfortable.
Building height	**B1**	The building is 3 m high, with no provision for a ceiling.	The medium ceiling height and absence of a ceiling made the heat directly enter the room without a barrier, which makes indoor temperatures uncomfortable.	The floor-to-ceiling height affected the indoor environment; as the height became shorter, the hot air from the ground did not escape to the upper part, which made the livable area of the room uncomfortable.
	B2	Due to the high surface-to-volume ratio of the building and the absence of a ceiling in the building, there is a high internal space.	Hot air escapes at the top around the roofs because of their light weight, which makes the indoor temperature and humidity of the roofs stable.	The availability of top openings that ventilate the rooms with stack effect techniques and a high ceiling height help to remove hot air from the room.
	B3	According to interviews, the height of this typology is mostly not more than 2.7 m, which is because of the high thermal mass of soil roofs, which is difficult to support by high walls.	Even though the buildings have a low floor-to-ceiling height, the high thermal mass of the roofs and walls makes the daytime room temperature stable.	The simulation found that even in low ceilings with high thermal mass of roofs and walls, which have low thermal conductivities and have nighttime ventilation techniques such as unovered top openings, this typology has good thermal performance in both day and night.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

Generally, the high day and night temperature fluctuations of the climate of Merti woreda require both heating design strategies such as high thermal mass, compact building forms, and small opening sizes and cooling design strategies such as high ceiling height, ventilation, and shading devices. Accordingly, during observation, it was found that the villagers in the study area had already adapted those strategies without knowledge of climatic analysis, just through trial and error. For instance, the high thermal mass of the walls and roofs, the insulation property of the thatch roofs, which protect the heat loss and gain from the building, the high ceiling heights, the minimum openings, the top openings for stack effect ventilation, and the compactness of its form in B2 all represent the buildings climatically designed On the other hand, the high thermal mass of soil roofs and mud walls, which have low heat conductors, and the position of roof overhangs in the north direction contribute to indoor thermal comfort in B3, and the low ceiling heights and absence of ventilating mechanisms at night affect indoor temperature in B3. The high thermal mass of the walls and the limited opening in B1 have a positive role for the thermal environment. But the low reflective and high heat-conductive properties of CI sheet roofing in this typology affect the indoor environment by causing high heat gain during the day and loss at night. The recorded environmental parameters show the indoor temperature in building B1 was between 20.9 and 30 °C, which shows the maximum and minimum temperatures are outside the upper and lower comfort limits of the area, which is mainly due to the high thermal conductivity of the roofs. The temperature in building B2 was found to be in the range of 21.2 to 28.9 °C, which is in the comfort band, and in building B3, the daytime temperature was also found to be in the comfort band. The porous nature of the roofs and top windows contributes to having comparatively low, uncomfortable wind speeds in B2. The humidity level in all three buildings was within the comfort range.

The existing building orientation in B2 and B3 performed better than the optimized model by having lower maximum indoor temperatures of 26.84 °C and 31.72 °C, respectively. Whereas the south orientation performs better in the B1 model. Existing overhang sizes in B2 and B3 also thermally perform better than optimized cases by having lower average indoor temperatures of 24.02 ºC and 26.78 ºC, respectively. On the other hand, increasing the overhang width to 1.5 m in B1 has a better temperature value. Finally, increasing and reducing wall and roof thickness in the three typologies shows the effect of thermal mass accordingly: changing wall thickness from 20 to 15, and 30 cm in B1 while keeping roof thickness at 2cm in all cases gives indoor temperature fluctuations of 9.55, 9.19, and 9.12 ºC, respectively; altering roof thickness to 15, 20, and 30 cm while keeping wall thickness at 20 cm gives temperature fluctuations of 7.55, 6.75, and 5.34 ºC in B3; and finally, altering wall and roof thickness in B2 has no significant temperature fluctuation difference due to the insulation property of thatch roof beside its thickness.

5.2. Recommendations

Before designing a building in Merti woreda and areas with the same climatic context, the following factors should be considered to achieve climate-responsive design:

- ✓ Applying a minimum opening size of 10–20% of the wall surface helps reduce heat gain and loss in buildings.
- ✓ Using compact building forms to protect the building from high solar radiation during the day and reduce heat loss at night to compensate for the cold night temperature of the area
- ✓ Providing horizontal shading devices such as overhangs, balconies, and verandas in the north and south orientations
- ✓ Incorporate a top opening in the design to maximize night ventilation, stack effect ventilation, and day lighting.
- ✓ Use high ceiling height with good insulation property materials for roofing, which helps in reducing daytime indoor temperature by keeping hot air high, which makes the habitable space near the ground comfortable and protects heat at night from losing
- ✓ Selecting roofing materials with high thermal mass and low heat conductors helps delay both heat gain and loss.
- ✓ The thermal properties of roof materials have a stronger impact than the wall materials in the areas under study in order to respond to the hot air during the day and the cold air at night.
- ✓ Modern buildings in the study area with low heat resistance and high heat conductor properties, like corrugated iron sheet roofing, should be oriented on the east-west axis, with their front facades facing south.
- ✓ A compact courtyard should be incorporated into the design of buildings to use its microclimatic effect of cooling the building.
- ✓ Provide vegetation in the east and west directions, where high wind movement of the area occurs, helps to use the microclimatic effect of the vegetation in the cooling of the building.

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APPENDIX

A. Observation checklist

S/N	Major variables	Sub variables
1	Building envelope and orientation	Using materials that reduce heat gain or loss
		East west orientation
2	Sun shading device	Overhang, verandah, internal shading
3	Passive Design	Natural Ventilation (size and type and position of windows
		Ceiling height
		Zoning of internal spaces
4	Wall construction	wall thickness
		Wall materials
5	Roof construction	Roof thickness
		Roof material
		Roof slope
6	Ventilation	air movement patterns
7	Landscape	Present of shade plant
		Orientation
8	Thermal mass	Use of materials with good thermal mass

B. identified passive design elements and analysis techniques

S/N	Passive design techniques	Methods followed for analyses
1	Building orientation	1. Exposure to sun based on sun path diagram
2	Number and position of opening	1. Prevailing wind direction 2. proportion of building length to floor to ceiling heights which is the width of building =2H for single sided single ventilation which ventilate up to six meters and width of buildings=3H for single sided double opening which ventilate to nine meters

4	Thermal mass	Hight thermal mass materials for higher diurnal temperature swing areas	Materials with low thermal conductivity, high resistivity and high density
		Low thermal mass materials for climates with low diurnal temperature swings (cold climates)	High thermal conductivity materials to quickly store heat.
4	Insulation	Use of locally available insulation materials with its correct position	
		Energy reduction performance of locally available insulation materials.	
5	Form	The shallower the building is the highest length to width ratio and the more the building exposed to solar radiation	

C. Humidity, temperature and wind speed data

i. Relative humidity (%)

Humidity (%) data					
Date	Time	B1	B2	B3	Outdoor
June 1,2022	7:00 AM	43	47	46	52
	9:00 AM	42	46	43	46
	12:00 AM	37	41	38	41
	3:00 PM	33	39	39	36
	6:00PM	41	42	42	39
June 2,2022	7:00 AM	44	46	45	47
	9:00 AM	40	45	43	49
	12:00 AM	39	40	36	39
	3:00 PM	36	37	40	33
	6:00PM	41	42	39	41
June 3,2022	7:00 AM	43	46	43	54

	9:00 AM	42	44	39	43
	12:00 AM	37	41	40	37
	3:00 PM	32	35	39	26
	6:00PM	38	39	40	42
June 4,2022	7:00 AM	43	46	46	51
	9:00 AM	47	42	48	46
	12:00 AM	39	47	36	41
	3:00 PM	38	36	39	29
	6:00PM	37	33	41	38
June 5,2022	7:00 AM	42	45	45	46
	9:00 AM	40	43	47	41
	12:00 AM	40	39	41	39
	3:00 PM	38	41	38	28
	6:00PM	39	46	39	37
June 6,2022	7:00 AM	41	42	43	46
	9:00 AM	43	40	44	42
	12:00 AM	41	39	41	39
	3:00 PM	38	41	38	38
	6:00PM	40	43	39	41
June 7,2022	7:00 AM	41	46	44	52
	9:00 AM	40	41	42	47
	12:00 AM	39	35	40	36
	3:00 PM	41	39	36	33
	6:00PM	36	42	42	41

ii. Air temperature

Temperature (^{O}C) data					
Date	Time	B1	B2	B3	Outdoor
June 1,2022	7:00 AM	21.1	22.3	24.2	20.2
	9:00 AM	26.3	25.6	26.8	25.7
	12:00 AM	28.1	26.5	27.1	28.0
	3:00 PM	29.0	27.2	27.5	32.0
	6:00PM	28.5	28.0	27.9	30.1

June 2,2022	7:00 AM	21.9	21.2	24.5	19.9
	9:00 AM	26.9	25.0	26.2	24.5
	12:00 AM	27.8	26.4	27.5	28.5
	3:00 PM	28.9	28.0	27.2	33.0
	6:00PM	27.9	28.1	28.0	29.0
June 3,2022	7:00 AM	21.1	22.4	23.5	20.5
	9:00 AM	25.5	24.8	24.0	25.3
	12:00 AM	28.5	26.1	27.0	27.5
	3:00 PM	29.2	28.1	27.7	31.2
	6:00PM	28.3	28.9	28.5	28.5
June 4,2022	7:00 AM	22.0	22.5	23.7	21.2
	9:00 AM	25.3	25.0	24.5	26.2
	12:00 AM	27.5	26.3	26.8	27.9
	3:00 PM	29.1	27.5	27.9	32.0
	6:00PM	27.9	27.2	28.1	29.0
June 5,2022	7:00 AM	20.9	23.0	23.9	21.5
	9:00 AM	25.7	24.7	24.1	26.5
	12:00 AM	27.2	25.9	26.2	27.5
	3:00 PM	30.0	28.2	27.5	32.5
	6:00PM	28.2	26.3	28.0	29.5
June 6,2022	7:00 AM	21.5	23.1	23.9	21.1
	9:00 AM	26.1	25.9	26.2	26.0
	12:00 AM	29.3	26.5	27.2	28.4
	3:00 PM	29.3	27.5	27.7	32.2
	6:00PM	28.1	28.0	27.8	29.5
June 7,2022	7:00 AM	22.0	23.5	23.6	20.6
	9:00 AM	26.4	25.7	25.9	26.5
	12:00 AM	28.5	26.0	27.1	28.6
	3:00 PM	29.4	27.5	27.5	34.0
	6:00PM	27.5	28.1	27.9	29.3

iii. Wind speed (m/s)

Wind speed (m/s) data					
Date	Time	B1	B2	B3	Outdoor
June 1,2022	7:00 AM	0.11	0.12	0.06	2.21
	9:00 AM	0.21	0.18	0.19	1.14
	12:00 AM	0.28	0.00	0.15	1.53
	3:00 PM	0.09	0.05	0.00	2.12
	6:00PM	0.22	0.15	0.17	0.75
June 2,2022	7:00 AM	0.12	0.06	0.04	1.01
	9:00 AM	0.28	0.13	0.16	2.52
	12:00 AM	0.11	0.16	0.21	2.16
	3:00 PM	0.31	0.00	0.03	1.43
	6:00PM	0.00	0.03	0.09	0.87
June 3,2022	7:00 AM	0.13	0.02	0.15	1.31
	9:00 AM	0.21	0.18	0.07	2.12
	12:00 AM	0.25	0.27	0.17	0.98
	3:00 PM	0.04	0.01	0.21	1.31
	6:00PM	0.17	0.08	0.00	0.62
June 4,2022	7:00 AM	0.13	0.03	0.32	1.72
	9:00 AM	0.12	0.16	0.18	0.87
	12:00 AM	0.09	0.30	0.03	2.14
	3:00 PM	0.03	0.00	0.07	1.13
	6:00PM	0.15	0.02	0.02	0.91
June 5,2022	7:00 AM	0.21	0.11	0.16	1.23
	9:00 AM	0.18	0.15	0.22	2.51
	12:00 AM	0.29	0.21	0.07	0.75
	3:00 PM	0.03	0.16	0.21	1.56
	6:00PM	0.16	0.01	0.00	2.17
June 6,2022	7:00 AM	0.09	0.17	0.16	0.79
	9:00 AM	0.19	0.13	0.09	1.51
	12:00 AM	0.15	0.08	0.07	2.31
	3:00 PM	0.19	0.05	0.12	1.66

	6:00PM	0.11	0.23	0.17	0.98
June 7,2022	7:00 AM	0.06	0.16	0.13	1.67
	9:00 AM	0.14	0.02	0.12	3.15
	12:00 AM	0.22	0.24	0.11	0.66
	3:00 PM	0.11	0.03	0.04	2.05
	6:00PM	0.17	0.11	0.05	1.22

D. Mahoney table analysis

A Typical Mahoney Table: Data Collection and Analysis Table. (Adapted from Eusebius, 2011)

Location		Year	Longitude		Latitude		Altitude		Highest **DPT:** Lowest **DBT:**		AMT	AMR
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
DBT (ºC) Mean monthly max												
DBT (ºC) Mean monthly min												
Range												
(RH%) Mean monthly max												
(RH%) Mean monthly min												
Average												
Humidity group												
Mean monthly rainfall (mm)												
Day comfort limit **min:**												
Max:												
Night comfort limit **min:**												
Max:												
Thermal stress **day:**												
Night:												
Air movement essential **H1:**												

Air movement desirable **H2:**												
Rain protection **H3:**												
Thermal storage **A1:**												
Outdoor sleeping **A2:**												
Cold season problem **A3:**												

Table 1: data collection
Year 2016-20

location	Dembeka iftu (Merti)
Latitude	39.7580 E
Longitude	8.6370 N
Altitude	1159 m

Air temperature: °C

Air temperature: °C	J	F	M	A	M	J	J	A	S	O	N	D	High	AMT
Monthly mean max.	27.1	29.1	31.4	29.6	29.9	30.8	27.9	27.4	28	28.2	27.5	26.3	31.4	22.3
Monthly mean min.	13.7	15.2	17.5	17.8	18.4	17.9	16.6	16.9	16.7	15.9	14.6	13.2	13.2	18.2
Monthly mean range	13.4	13.9	13.9	11.8	11.5	12.9	11.3	10.5	11.3	12.3	12.9	13.1	Low	AMR

Were, AMT = (Highest + Lowest)/2=22.3, AMR = Highest – Lowest = 18.2

Relative Humidity Monthly (%) and Rainfall (mm):

humidity: %	J	F	M	A	M	J	J	A	S	O	N	D
Average RH	46	43	39	49	49	53	63	64	63	48	48	49
Humidity group	2	2	2	2	2	3	3	3	3	2	2	2

Rainfall mm	7.2	13.5	57.4	151.5	98.2	84.4	152.4	133.3	112.4	42.9	37.3	8.5

Humidity group:

1	If average RH: below 30 %
2	30-50 %
3	50-70%
4	Above 70 %

Comfort limits and Humidity Group:

		AMT over 20 °C		AMT 15-20 °C		AMT below 15 °C	
Comfort limits		Day	Night	Day	Night	Day	Night
Humidity group	**1**	26-34	17-25	23-32	14-23	21-30	12-21
	2	25-31	17-24	22-30	14-22	20-27	12-20
	3	23-29	17-23	21-28	14-21	19-26	12-19
	4	22-27	17-21	20-25	14-20	18-24	12-18

Table 2. Temperature and Humidity Diagnosis. ºC

Temperature	J	F	M	A	M	J	J	A	S	O	N	D
Monthly Mean Max.	27.1	29.1	31.4	29.6	29.9	30.8	27.9	27.4	28	28.2	27.5	26.3
Day Comfort **Upper (ºC)**:	31	31	31	31	31	29	29	29	29	31	31	31
Lower (ºC):	25	25	25	25	25	23	23	23	23	25	25	25
Monthly mean min.	13.7	15.2	17.5	17.8	18.4	17.9	16.6	16.9	16.7	15.9	14.6	13.2
Night Comfort **Upper(ºC):**	24	24	24	24	24	23	23	23	23	24	24	24
Lower(ºC):	17	17	17	17	17	17	17	17	17	17	17	17
Thermal Stress **Day:**	O	H	H	O	O	H	O	O	O	O	O	O
Night:	C	C	O	O	O	O	C	C	C	C	C	C

Were "O" ordinary, "H" hot and "C" is cold

Indicators:

		J	F	M	A	M	J	J	A	S	O	N	D
Humid:	H1(0)	0	0	0	0	0	0	0	0	0	0	0	0
	H2(0)	0	0	0	0	0	0	0	0	0	0	0	0
	H3(0)	0	0	0	0	0	0	0	0	0	0	0	0
Arid:	A1 (12)	1	1	1	1	1	1	1	1	1	1	1	1
	A2 (1)	0	0	1	0	0	0	0	0	0	0	0	0
	A3 (0)	0	0	0	0	0	0	0	0	0	0	0	0

Table 3: Application needed

Application needed	Indicator	Thermal stress		Rainfall	Humidity Group	Monthly mean range
		Day	Night			
Air movement essential	**H1**	**H**			**4**	
		H			**2,3**	Less than 10
Air movement desirable	**H2**	**O**			**4**	
Rain protection necessary	**H3**			**Over 200 mm**		
Thermal capacity necessary	**A1**				**1,2,3**	More than 10
Out-door sleeping desirable	**A2**		**H**		**1,2**	
		H	**O**		**1,2**	More than 10
Protection from cold	**A3**	**C**				

H (Hot): if Mean Is above Comfort Limits.

O (Comfort): If mean within comfort limits.

C (Cold): If means is below comfort limits.

Table 4: Design Recommendation of design guidelines

Indicator Totals from Table 2					
H1	H2	H3	A1	A2	A3
0	0	0	12	0	0

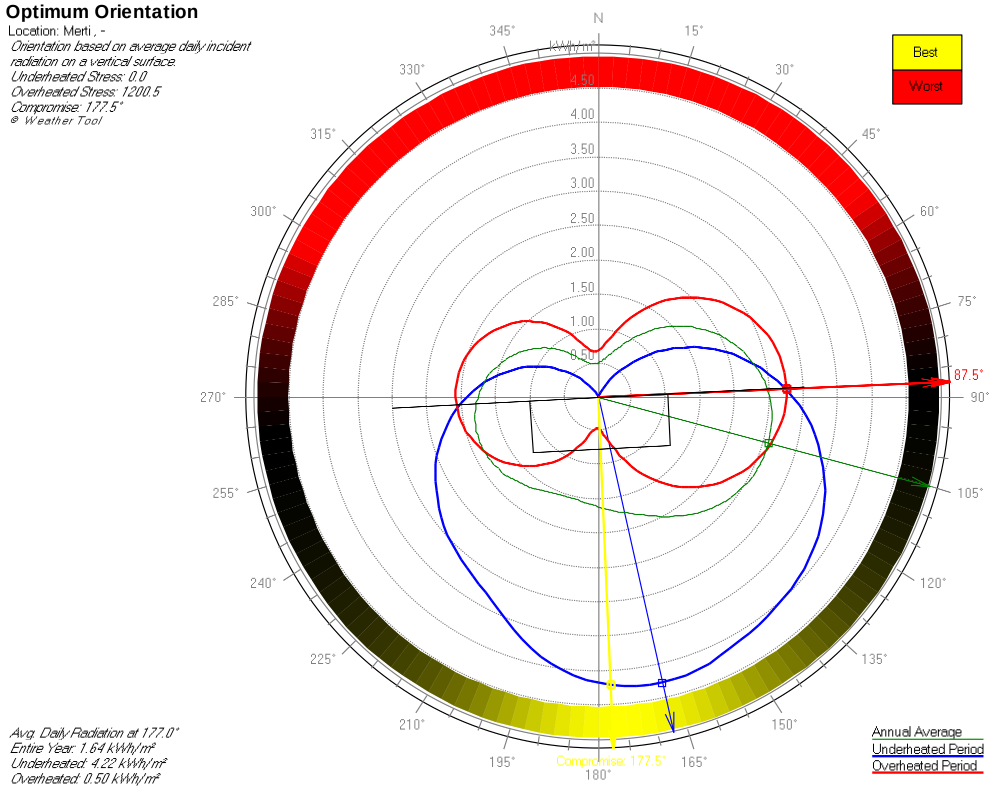
Layout								
			0-10				1	Orientation north and south (long axis east-west)
			11-12		5-12			
					0-4	✓	2	Compact courtyard planning
Spacing								
11,12							3	Open spacing for breeze penetration
2-10							4	As 3, but protection form hot and cold wind
0,1						✓	5	Compact lay-out of estates
Air movement								
3-12							6	Rooms single banked, permanent provision for air movement
1,2			0-5					
			6-12				7	Double banked rooms, temporary provision for air movement
0	2-12							
	0,1					✓	8	No air movement requirement
Openings size								
			0,1		0		9	Large openings, 40-80%
			11-12		0-1	✓	10	Very small openings, 10-20%
			0-1		1-12		11	Medium openings, 20-40%
Protection of openings								
		0-2			0-2	✓	12	Exclude direct sunlight

		3-12					13	Provide protection from rain
		0				✓	14	No protection from heavy rain
Walls								
			0-2				15	Light walls, short time-lag
			3-12			✓	16	Heavy external and internal walls
Roofs								
			0-5				17	Light, insulated roofs
			6-12			✓	18	Heavy roofs, over 8 h time-lag
Out-door sleeping								
			2-12			✓	19	Space for out-door sleeping required
Rain protection								
			3-12				20	Protection from heavy rain necessary

- ✓ In the table is an indication of the appropriate strategies for a building design for Merti woreda)

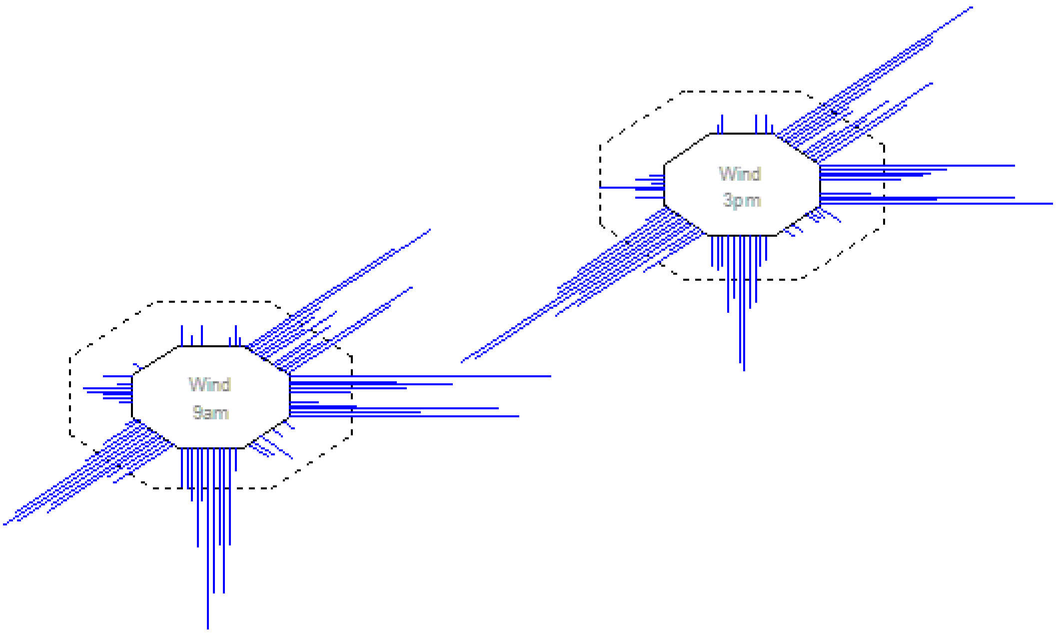
E. Optimum orientation

The weather tool in ECOTECT evaluates solar radiation and establishes the relative best building orientation based on the solar heat received throughout the annual superheated time and underheated period. As a result, the Merti woreda optimum orientation graphs show that a southern orientation is the best for receiving moderate solar radiation in the winter, indicating that the optimum orientation is lies 177.5º, which is slightly inclined from the harsh afternoon sun. And the worst orientation was found to be 87.5º, receiving 2.75 kwh/m^2 solar radiation. The graph shows the need for providing a shading device in the northern direction.



F. Wind analysis

The general wind pattern for different seasons significantly differs; as a result, the wind pattern of the spring seasons in Ethiopia (March, April, and May), which is the hottest season in Merti woreda, was selected to analyze the building ventilation mode with respect to highest wind speed direction in order to receiving a cool breeze.



G. Effect of building orientation

Thermal performance of north orientation (B1)

Time	Air temperature	outside dry bulb temperature
2:00 A.M.	23.86	18.92
4:00 A.M.	22.92	18.23
6:00 A.M.	22.13	18.23
8:00 A.M.	22.89	20.99
10:00 A.M.	25.86	25.13
12:00 A.M.	29.08	28
2:00 P.M.	31.44	29.5
4:00 P.M.	31.72	28.81
6:00 P.M.	29.93	26.74
8:00 P.M.	27.7	23.75
10:00 P.M.	25	21.68
Average	26.59363636	

Thermal performance of South orientation (B1)

time	Air temperature	Outside dry bulb temperature
2:00 A.M.	23.48	18.92
4:00 A.M.	22.59	18.23
6:00 A.M.	21.85	18.23
8:00 A.M.	22.59	20.99
10:00 A.M.	25.55	25.13
12:00 A.M.	28.67	28
2:00 P.M.	30.88	29.5
4:00 P.M.	31.09	28.81
6:00 P.M.	29.32	26.74
8:00 P.M.	27.1	23.75
10:00 P.M.	25	21.68
	26.19272727	

Thermal performance of South west orientation (B1)

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	23.67	18.92
4:00 A.M.	22.76	18.23
6:00 A.M.	22.01	18.23
8:00 A.M.	22.83	20.99
10:00 A.M.	26	25.13
12:00 A.M.	29.07	28
2:00 P.M.	31.19	29.5
4:00 P.M.	31.46	28.81
6:00 P.M.	29.84	26.74
8:00 P.M.	27.51	23.75
10:00 P.M.	25	21.68
	26.48545455	

Thermal performance of north orientation (B2)

time	Air temperature	outside dry bulb temperature
2:00 A.M.	20.65	18.92
4:00 A.M.	19.66	18.23
6:00 A.M.	18.89	18.23
8:00 A.M.	21.3	20.99
10:00 A.M.	26.84	25.13
12:00 A.M.	26.6	28
2:00 P.M.	26.62	29.5
4:00 P.M.	26.65	28.81
6:00 P.M.	26.68	26.74
8:00 P.M.	26.68	23.75
10:00 P.M.	23.92	21.68
	24.04454545	

Thermal performance of South orientation (B2)

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	20.66	18.92
4:00 A.M.	19.67	18.23
6:00 A.M.	18.9	18.23
8:00 A.M.	21.3	20.99
10:00 A.M.	26.85	25.13
12:00 A.M.	26.61	28
2:00 P.M.	26.62	29.5
4:00 P.M.	26.67	28.81
6:00 P.M.	26.72	26.74
8:00 P.M.	26.7	23.75
10:00 P.M.	23.93	21.68
	24.05727273	

Thermal performance of South west orientation (B2)

time	Air temperature	outside dry bulb temperature
2:00 A.M.	20.68	18.92
4:00 A.M.	19.68	18.23
6:00 A.M.	18.91	18.23
8:00 A.M.	21.33	20.99
10:00 A.M.	26.85	25.13
12:00 A.M.	26.6	28
2:00 P.M.	26.63	29.5
4:00 P.M.	26.72	28.81
6:00 P.M.	26.8	26.74
8:00 P.M.	26.87	23.75
10:00 P.M.	23.98	21.68
	24.09545455	

Thermal performance of north orientation (B3)

time	Air temperature	outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	26.49	25.13
12:00 A.M.	26.71	28
2:00 P.M.	27.87	29.5
4:00 P.M.	29.33	28.81
6:00 P.M.	30.74	26.74
8:00 P.M.	31.72	23.75
10:00 P.M.	25	21.68
	27.0781818 2	

Thermal performance of south orientation (B3)

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	26.52	25.13
12:00 A.M.	26.72	28
2:00 P.M.	27.93	29.5
4:00 P.M.	29.43	28.81
6:00 P.M.	30.86	26.74
8:00 P.M.	31.81	23.75
10:00 P.M.	25	21.68
Average	27.1154545 5	

Thermal performance of south west orientation (B3)

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	26.64	25.13
12:00 A.M.	26.89	28
2:00 P.M.	28.13	29.5
4:00 P.M.	29.8	28.81
6:00 P.M.	31.43	26.74
8:00 P.M.	32.34	23.75
10:00 P.M.	25	21.68
	27.29363636	

H. Effect of overhang width on thermal performance of buildings (B2)

Avoiding /removing overhang B1

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	23.86	18.92
4:00 A.M.	22.92	18.23
6:00 A.M.	22.13	18.23
8:00 A.M.	22.89	20.99
10:00 A.M.	25.86	25.13
12:00 A.M.	29.08	28
2:00 P.M.	31.44	29.5
4:00 P.M.	31.72	28.81
6:00 P.M.	29.93	26.74
8:00 P.M.	27.7	23.75
10:00 P.M.	25	21.68
	26.59363636	

Extending overhang B1

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	23.57	18.92
4:00 A.M.	22.67	18.23
6:00 A.M.	22.93	18.23
8:00 A.M.	22.73	20.99
10:00 A.M.	25.75	25.13
12:00 A.M.	28.96	28
2:00 P.M.	31.26	29.5
4:00 P.M.	31.46	28.81
6:00 P.M.	29.62	26.74
8:00 P.M.	27.26	23.75
10:00 P.M.	25	21.68
	26.47363636	

Avoiding /removing overhang B2

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	20.66	18.92
4:00 A.M.	19.67	18.23
6:00 A.M.	18.9	18.23
8:00 A.M.	21.35	20.99
10:00 A.M.	26.85	25.13
12:00 A.M.	26.6	28
2:00 P.M.	26.62	29.5
4:00 P.M.	26.67	28.81
6:00 P.M.	26.74	26.74
8:00 P.M.	26.71	23.75
10:00 P.M.	23.94	21.68
	24.06454545	

Extending overhang B2

time	Air temperature	Outside dry bulb temperature
2:00 A.M.	20.7	18.92
4:00 A.M.	19.71	18.23
6:00 A.M.	18.95	18.23
8:00 A.M.	21.38	20.99
10:00 A.M.	26.86	25.13
12:00 A.M.	26.61	28
2:00 P.M.	26.63	29.5
4:00 P.M.	26.68	28.81
6:00 P.M.	26.72	26.74
8:00 P.M.	26.72	23.75
10:00 P.M.	23.97	21.68
	24.08454545	

Avoiding /removing overhang B3

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	26.59	25.13
12:00 A.M.	26.81	28
2:00 P.M.	28.02	29.5
4:00 P.M.	29.55	28.81
6:00 P.M.	31.04	26.74
8:00 P.M.	32.06	23.75
10:00 P.M.	25	21.68
	27.18818182	

Extending overhang B3

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	26.5	25.13
12:00 A.M.	26.73	28
2:00 P.M.	27.89	29.5
4:00 P.M.	29.36	28.81
6:00 P.M.	30.77	26.74
8:00 P.M.	31.75	23.75
10:00 P.M.	25	21.68
	27.09	

I. Effect of wall and roof thermal mass(thickness) on thermal performance

Thermal performance of (B1) for 15cm wall and 0.2mm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	23.39	18.92
4:00 A.M.	22.31	18.23
6:00 A.M.	21.4	18.23
8:00 A.M.	21.7	20.99
10:00 A.M.	23.9	25.13
12:00 A.M.	27.28	28
2:00 P.M.	29.88	29.5
4:00 P.M.	30.59	28.81
6:00 P.M.	29.33	26.74
8:00 P.M.	27.68	23.75
10:00 P.M.	25	21.68
	25.67818182	

Thermal performance of (B1) in 20cm wall and 0.2mm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	23.62	18.92
4:00 A.M.	22.71	18.23
6:00 A.M.	21.95	18.23
8:00 A.M.	22.74	20.99
10:00 A.M.	25.74	25.13
12:00 A.M.	28.96	28
2:00 P.M.	31.28	29.5
4:00 P.M.	31.5	28.81
6:00 P.M.	29.68	26.74
8:00 P.M.	27.35	23.75
10:00 P.M.	25	21.68
	26.41181818	

Thermal performance of (B1) in 30cm wall and 0.2mm roof thickness

time	Air temperature	outside dry bulb temperature
2:00 A.M.	23.39	18.92
4:00 A.M.	22.74	18.23
6:00 A.M.	22.24	18.23
8:00 A.M.	23.24	20.99
10:00 A.M.	26.32	25.13
12:00 A.M.	29.46	28
2:00 P.M.	31.36	29.5
4:00 P.M.	31.24	28.81
6:00 P.M.	29.16	26.74
8:00 P.M.	22.62	23.75
10:00 P.M.	25	21.68
	26.07	

Thermal performance of (B2) for 20cm wall and 30cm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	20.62	18.92
4:00 A.M.	19.61	18.23
6:00 A.M.	18.84	18.23
8:00 A.M.	21.31	20.99
10:00 A.M.	26.82	25.13
12:00 A.M.	26.55	28
2:00 P.M.	26.55	29.5
4:00 P.M.	26.57	28.81
6:00 P.M.	26.64	26.74
8:00 P.M.	26.82	23.75
10:00 P.M.	23.94	21.68
	24.02454545	

Thermal performance of (B2) for 15cm wall and 20cm roof thickness

time	Air temperature	outside dry bulb temperature
2:00 A.M.	20.62	18.92
4:00 A.M.	19.67	18.23
6:00 A.M.	18.9	18.23
8:00 A.M.	21.35	20.99
10:00 A.M.	26.85	25.13
12:00 A.M.	26.6	28
2:00 P.M.	26.62	29.5
4:00 P.M.	26.67	28.81
6:00 P.M.	26.74	26.74
8:00 P.M.	26.71	23.75
10:00 P.M.	23.94	21.68
	24.06090909	

Thermal performance of (B2) for 20cm wall and 15cm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	20.75	18.92
4:00 A.M.	19.74	18.23
6:00 A.M.	19	18.23
8:00 A.M.	21.42	20.99
10:00 A.M.	26.89	25.13
12:00 A.M.	26.66	28
2:00 P.M.	26.7	29.5
4:00 P.M.	26.77	28.81
6:00 P.M.	26.85	26.74
8:00 P.M.	26.74	23.75
10:00 P.M.	24	21.68
	24.13818182	

Thermal performance of (B2) for 20cm wall and 20cm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	20.66	18.92
4:00 A.M.	19.67	18.23
6:00 A.M.	18.9	18.23
8:00 A.M.	21.35	20.99
10:00 A.M.	26.85	25.13
12:00 A.M.	26.6	28
2:00 P.M.	26.62	29.5
4:00 P.M.	26.67	28.81
6:00 P.M.	26.74	26.74
8:00 P.M.	26.71	23.75
10:00 P.M.	23.94	21.68
	24.06454545	

Thermal performance of (B2) for 30cm wall and 20cm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	20.66	18.92
4:00 A.M.	19.67	18.23
6:00 A.M.	18.9	18.23
8:00 A.M.	21.35	20.99
10:00 A.M.	26.85	25.13
12:00 A.M.	26.6	28
2:00 P.M.	26.62	29.5
4:00 P.M.	26.67	28.81
6:00 P.M.	26.74	26.74
8:00 P.M.	26.71	23.75
10:00 P.M.	23.94	21.68
	24.06454545	

Thermal performance of (B3) for 15cm wall and 20cm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	25.8	25.13
12:00 A.M.	26.74	28
2:00 P.M.	28.6	29.5
4:00 P.M.	30.66	28.81
6:00 P.M.	32.6	26.74
8:00 P.M.	33.85	23.75
10:00 P.M.	25	21.68
	27.56818182	

Thermal performance of (B3) for 20cm wall and 20cm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	26.5	25.13
12:00 A.M.	26.73	28
2:00 P.M.	27.89	29.5
4:00 P.M.	29.36	28.81
6:00 P.M.	30.77	26.74
8:00 P.M.	31.75	23.75
10:00 P.M.	25	21.68
	27.09090909	

Thermal performance of (B3) for 30cm wall and 20cm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	27.03	25.13
12:00 A.M.	27.4	28
2:00 P.M.	28.33	29.5
4:00 P.M.	29.47	28.81
6:00 P.M.	30.47	26.74
8:00 P.M.	31.06	23.75
10:00 P.M.	25	21.68
	27.16	

Thermal performance of (B3) for 20cm wall and 15cm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	26.09	25.13
12:00 A.M.	26.8	28
2:00 P.M.	28.64	29.5
4:00 P.M.	30.55	28.81
6:00 P.M.	31.98	26.74
8:00 P.M.	32.55	23.75
10:00 P.M.	25	21.68
	27.41909091	

Thermal performance of (B3) for 20cm wall and 30cm roof thickness

Time	Air temperature	Outside dry bulb temperature
2:00 A.M.	25	18.92
4:00 A.M.	25	18.23
6:00 A.M.	25	18.23
8:00 A.M.	25	20.99
10:00 A.M.	27.09	25.13
12:00 A.M.	26.99	28
2:00 P.M.	27.55	29.5
4:00 P.M.	28.33	28.81
6:00 P.M.	29.3	26.74
8:00 P.M.	30.34	23.75
10:00 P.M.	25	21.68
	26.78181818	