IMPACT OF CLIMATE CHANGE ON VERNACULAR ARCHITECTURE OF PUNE REGION

Thesis Submitted for the Award of the Degree of

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in

Architecture

By

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DECLARATION

I, hereby declared that the presented work in the thesis entitled “Impact of Climate Change on Vernacular Architecture of Pune Region” in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision Dr. Mahendra Joshi, working as Professor, in the School of Architecture and Design of Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

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CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled "Impact of Climate Change on Vernacular Architecture of Pune Region" submitted in fulfilment of the requirement for the reward of degree of **Doctor of Philosophy (Ph.D.)** in the School of Architecture and Design, is a research work carried out by Mihir Vakharia, 41900119, is bonafide record of his original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

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Name of supervisor: Dr. Raminder Kaur

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ABSTRACT:

The intensifying effects of climate change present critical challenges for building performance and urban environments globally, with rising temperatures threatening both structural stability and occupant comfort (Crawley, 2008). The urgency of global warming calls for building designs that prioritize energy efficiency and renewable resources to achieve sustainable development (Robert & Kummert, 2012). Traditional buildings have historically been adapted to local climates, providing a protective layer that complements biological skin and clothing, working together to regulate human body temperature around 37°C. As buildings respond to various environmental factors, temperature, humidity, solar radiation, and wind patterns, the architectural design must address both micro- and macro-climatic scales to ensure thermal comfort.

Learning from past architectural practices, particularly vernacular forms, offers valuable insights into addressing climate challenges at both the building and urban scales. Studying the architecture of past societies that successfully coped with extreme climates reveals passive design strategies that enable resilience and longevity in urban and building design (Azarbayjani, 2019). This research examines how traditional forms in warm-humid climates specifically the vernacular Wada houses of Pune, India incorporate passive thermal management. These houses demonstrate adaptive methods in response to climate, and this study proposes modern adaptations that integrate these traditional techniques with contemporary technological advances to meet future climatic demands.

India's rapid urbanization intensifies these challenges, as a growing population creates additional pressures on urban infrastructure and energy resources. By 2010, 31% of India's population lived in urban areas, a figure projected to rise to nearly 50% by 2050, adding approximately 441 million urban residents (C. Singh et al., 2021). The energy implications are significant; residential electricity demand is expected to increase sevenfold from 2012 to 2032, with urban areas accounting for 36.5% of national energy demand by 2030 (Ministry of Power, Government of India, 2018). In Maharashtra, climate projections from The Energy Research Institute (TERI, 2014) suggest a temperature increase of 1-1.5°C by 2030. These trends emphasize the need for architecture that not only withstands increasing temperatures but also supports sustainable growth.

The core research question is: How will rising temperatures impact the traditional vernacular house form in Pune? This study specifically examines the Wada, a traditional house type, to assess its ability to maintain thermal comfort in a changing climate. Key research objectives are to analyze the influence of climate change on the thermal performance of Wadas and propose a design model that combines passive and modern technologies to enhance the thermal resilience of these structures for future climates.

Methodologically, this study examines the thermal performance of Pune's Wada houses, which utilize passive design features thick stone walls, large courtyards, and shaded wooden structures—to provide comfort in a warm-humid climate. These elements work to buffer against heat and maintain indoor comfort by allowing natural ventilation and minimizing solar gain. By comparing current thermal performance with future climate projections for 2050 and 2080, the study will identify the limitations of these strategies under higher temperature scenarios. Data from the India Meteorological Department and other sources reveal a 1.0–1.5°C temperature increase over the past decade in Pune, particularly during peak summer months. This rise has resulted in a noticeable decline in comfortable hours within traditional Wadas, projected to decrease by 31% by 2050 and 49% by 2080.

To counter these impacts, the study proposes a combination of passive and active design strategies. Passive interventions include optimizing thermal mass, increasing natural ventilation, and adjusting building orientation. For instance, enhancing shading through projecting balconies or implementing green roofs could reduce heat absorption. Additionally, modifying courtyards to improve air circulation and adjusting room layouts for better ventilation can help maintain lower indoor temperatures. Active strategies, such as energy-efficient cooling and dehumidification, can supplement these passive solutions, reducing dependency on air conditioning and preserving the energy efficiency inherent in vernacular architecture. Although these updates may require some investment, they offer a feasible means to adapt Wada houses to rising temperatures without compromising occupant comfort or environmental sustainability.

The study also highlights the potential of integrating modern technologies such as wall and roof insulation, and ventilated roof for vernacular designs. These additions can improve the thermal performance and resilience of Wada houses without disrupting their architectural integrity or cultural significance. However, implementing these technologies must respect the historical context of Wada architecture, ensuring that modern updates do not detract from the cultural value of these traditional buildings.

This research contributes to the growing field of climate-responsive design, with particular emphasis on vernacular architecture as a sustainable model for the future. As cities like Pune contend with climate change and urban growth, understanding the thermal performance of traditional buildings becomes essential for developing climate-resilient and culturally attuned designs. This study's findings support the creation of energy-efficient buildings that respond to modern urban challenges while preserving cultural heritage. By adapting vernacular architectural principles, architects and planners can construct sustainable, comfortable, and environmentally friendly buildings that meet both contemporary needs and environmental goals.

Furthermore, the study has implications for urban populations vulnerable to climate change, especially low-income communities that often live in poorly insulated structures. These groups face greater health risks from heat stress due to inadequate shelter. Incorporating vernacular design principles into affordable housing can create structures that better adapt to high temperatures and mitigate climate-related health risks. By adapting traditional methods for modern use, this research aims to provide low-energy, thermally comfortable housing solutions that benefit urban populations at large.

In conclusion, the thermal performance of Pune’s Wada houses underscores the potential for vernacular architecture to inform climate adaptation strategies. This study demonstrates the importance of adapting traditional building forms to address the challenges of a warming climate, through both passive and active design interventions that ensure the thermal resilience of Wadas. By merging traditional knowledge with modern technologies, architects can create sustainable, climate-adaptive buildings that respect cultural heritage while addressing global warming. These findings offer valuable insights into sustainable architecture in Pune and beyond, serving as a model for vernacular architecture adaptation. Continuous study of traditional structures amid climate shifts ensures these designs will remain effective in providing comfort and sustainability for future generations.

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I extend my heartfelt gratitude to Dr Mahendra Joshi Sir and Dr. Raminder Kaur ma'am for the unwavering guidance and patience throughout my study. This study would not have been possible without his invaluable advice, supportive comments, and insightful suggestions.

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Mihir Vakharia

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

In recent years, the performance of buildings and human settlements has been severely endangered by the rising temperatures caused by climate change (Crawley, 2008). The threat posed by global warming requires that buildings be planned with energy efficiency and renewable energy in mind to achieve sustainable development (Robert & Kummert, 2012). Buildings are climatically designed to act as the third layer of protection for people, after their biological skin and the second layer of clothes. In the absence of active systems, these three layers work together to maintain the deep body temperature at 37°C. Environmental elements impact both the architectural scale (building scale) and the scale of urban areas. Climate factors such as temperature, humidity, sun path, wind patterns, solar radiation, and others are environmental influences considered in building design. Sustainability is defined as longevity, and researching the architecture and urban patterns of previous societies that overcame harsh climates through time may lead to passive solutions for both building (micro-climate) and urban (macro-climate) scales of design (Azarbayjani, 2019). Given that the urban scale received more attention in the past, this study aims to examine vernacular dwellings to understand how the vernacular house's passive design features have been used to provide thermal comfort and reduce the harshness of the surrounding environment. Then propose contemporary design alternatives by using the advantages of current technological advancements and tools in architectural discourse.

1.1 Vernacular Architecture and Climate Adaptation

Humans have lived in various locations for centuries, adapting local materials and construction techniques to the climate and developing passive solar design strategies (Shastry et al., 2014). Vernacular architecture utilizes building methods and materials that are readily available locally and are influenced by the culture, context, and environment of the people. This architectural design considers energy-saving and climatic features to improve thermal comfort. To mitigate the multiple threats in today's world, including greenhouse gas emissions, resource depletion, deforestation, increasing energy demand, and others, learning from traditional architecture can provide solutions to these issues in the modern world and reduce the impact of globalization on architecture. The so-called modern conventional contemporary design has replaced vernacular architecture, and it is now on the verge of extinction due to the influence of globalization on architecture, highlighting the need to learn from vernacular architecture to achieve greater design resource efficiency. Vernacular architecture evolves by considering design and construction techniques and adopting locally available resources based on the environmental, cultural, and historical background of the people (Shastry et al., 2014). Today, the architectural style of many regions is influenced by globalization, causing traditional designs to be abandoned in favor of modern styles. Climate change poses a severe hazard to building performance and human settlements (Crawley, 2008). The depletion of energy resources and the risk of global warming call for sustainable development in the building sector, emphasizing renewable energies and energy efficiency (Robert & Kummert, 2012). Climate-sensitive shelter design is ingrained in human knowledge (Zhai & Previtali, 2010). India's vast and diverse building traditions have evolved over five millennia in response to the sociocultural, economic, and thermal needs of the population, displaying a remarkably sophisticated thermal adaptation (R. R. Gupta, 2016). Environmental elements significantly influence architectural and urban scales. Sustainability, defined as longevity, involves analyzing the urban pattern and architecture of regional societies and cultural aspects in relation to the environment. Over time, this research may bring passive design solutions to both urban and architectural design (Azarbayjani, 2019).

Need for Sustainable Design in Urban Areas

The study will focus on all the vernacular features that act as passive design features, analyzing their use in summer and winter seasons. It will also investigate the role of the surrounding environment in the vernacular house form in the region. Additionally, the study will examine the socio-cultural aspects and their role in shaping the vernacular-built form of a particular society.

In recent years, the performance of buildings and human settlements has been seriously threatened by temperature rise caused by climate change (Crawley, 2008). The Paris Agreement, agreed upon at COP21 in Paris in 2015, significantly strengthened global efforts to combat climate change. The main objectives of this agreement were to achieve carbon neutrality by the middle of the century and limit global warming to 2°C compared to pre-industrial levels (preferably to 1.5°C) (Campagna & Fiorito, 2022).

Climate-sensitive shelter design is deeply rooted in human experience. Over centuries, people have learned to create shelters that respond to their environment. A building is often described as the third skin, with clothing acting as the second and the biological skin as the first, all working together to maintain the body's internal temperature at 37°C. Due to the depletion of energy resources and the threat posed by global warming, the building industry needs to develop sustainably through renewable energies and energy efficiency (Robert & Kummert, 2012). Climate factors, including wind patterns, sun path, temperature, and others, impact both the scale of a building and the scale of an urban area. If sustainability is defined as long-term viability, studying the architecture and urban patterns of past societies that survived the harshness of the environment over time may offer passive solutions for both architectural and urban design (Azarbayjani, 2019). Even today, issues such as resource depletion, greenhouse gas emissions, increased energy use, deforestation, and others can be mitigated through vernacular architecture.

1.1 About Pune City

Pune, located in the western state of Maharashtra, India, (Figure 1-1) is situated between 18°32' North latitude and 72°51' East longitude in Pune District. It lies 560 meters above mean sea level. Pune is surrounded by several districts: Thane to the northwest, Raigad to the west, Satara to the south, Solapur to the southeast, and Ahmednagar to the north. The city enjoys a moderate tropical wet and dry climate, with distinct seasons. The climate is pleasant during the monsoon (June to September) and winter (November to February) months, with temperatures ranging from 12°C to 32°C. Summers, from March to May, are hotter, with temperatures reaching up to 40°C. Due to its elevation, Pune experiences cooler weather than many other cities in Maharashtra, making it a favoured destination for those seeking relief from the intense heat of other parts of the state.

Culturally, Pune is known as the "Oxford of the East" because of its vibrant academic atmosphere, hosting several renowned educational institutions. The city is steeped in history, having been the seat of the Peshwa rulers during the Maratha Empire. Pune’s culture blends traditional Maharashtrian customs with modern influences, reflected in its festivals, food, and art. Pune's architectural identity is significantly influenced by its history as the capital of the Peshwa rulers. The iconic Shaniwar Wada, a fortified palace built in the 18th century, is an

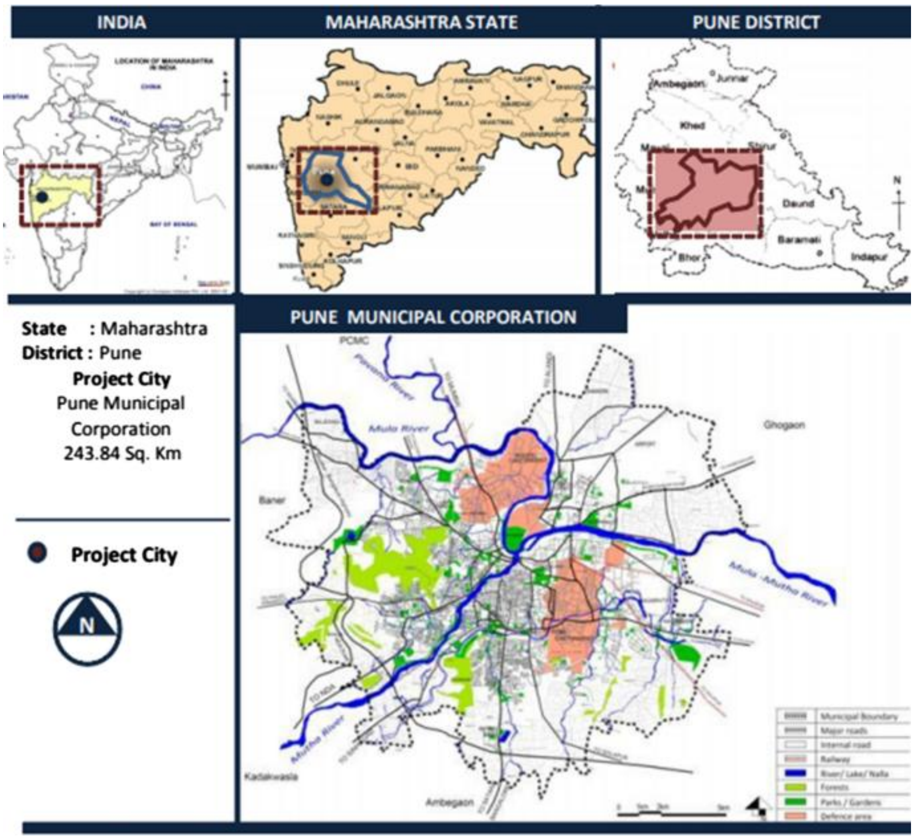


Figure 1-1 Revised City Planning Pune, Maharashtra (Source: JNNURM)

example of Maratha architecture, with intricately designed wooden and stone carvings, grand gates, and courtyards. Other examples of this era's influence include the Aga Khan Palace, which merges British colonial and Indo-Saracenic styles, and the Vishrambaug Wada (Pandya, 2016). These structures often feature decorative arches, ornate wooden windows, and spacious courtyards that encourage natural ventilation, ideal for the region's tropical climate.

1.2 Climate of Pune

Pune, Maharashtra's second-largest city, spans 331.3 km² and falls under Köppen's Tropical Savanna Climate (Aw). This classification is characterized by hot summers, a distinct monsoon season, and mild, dry winters. Due to its inland location, Pune also exhibits semi-arid climatic influences (BSh), which result in lower humidity levels compared to coastal cities like Mumbai. These climatic variations significantly impact Pune's environmental patterns, including temperature fluctuations, rainfall distribution, and seasonal humidity levels. As a rapidly growing urban center, Pune's climate plays a crucial role in architectural design, infrastructure planning, and sustainable development strategies.

1.2.1 Seasonal Climate Variations in Pune

Pune experiences three primary seasons summer (March to May), monsoon (June to September), and winter (November to February) (Gohain et al., 2021). The summer season is characterized by high temperatures ranging from 28.6°C to 31.9°C, with humidity levels between 36% and 50%. While these values indicate relatively low humidity, the heat can be intense, especially in April and May, where the mean maximum temperature reaches 37.3°C. The hottest recorded temperature in Pune was 43.3°C, on April 30, 1897 (Table 1-1). The low humidity during summer makes the heat slightly more tolerable compared to highly humid coastal regions, yet passive cooling techniques and ventilation strategies remain essential to mitigate discomfort.

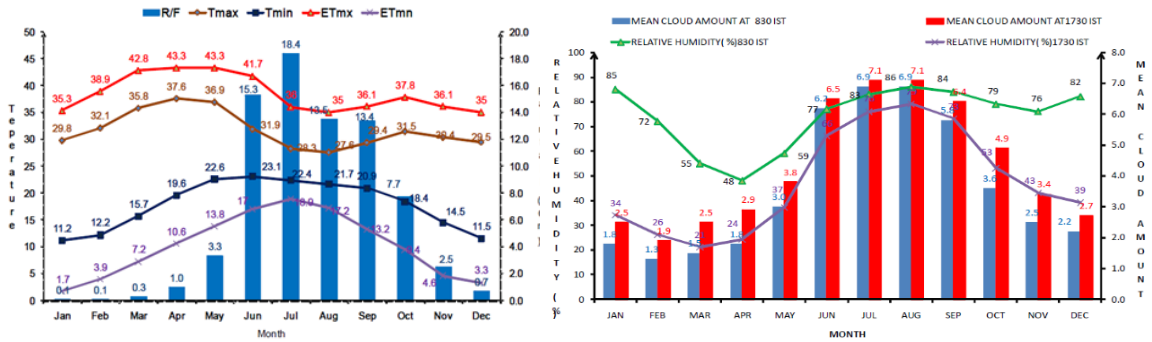
The monsoon season (June to September) brings significant rainfall, cooling temperatures to an average range of 23.9°C to 25.4°C (Figure 1-2). However, humidity levels rise drastically, peaking at 82% in July and August. Pune receives an average annual rainfall of 76.3 cm, with approximately 49 rainy days per year (Climate Research and Services, Pune, 2021). The high relative humidity (RH) in the morning ranges from 77% to 86%, while in the afternoons, it fluctuates between 66% and 79%. This high moisture content in the air increases thermal discomfort, condensation risks, and potential structural damage to buildings. Proper waterproofing, moisture-resistant materials, and effective drainage systems are critical for maintaining infrastructure resilience during the monsoon months.

The post-monsoon transition (October) marks a shift towards drier conditions, with temperatures around 24.9°C and moderate humidity levels at 68% (Figure 1-3). Winter (November to February) is the coldest season, with average temperatures between 21.7°C and 23.8°C and humidity levels ranging from 52% to 58%. The coldest recorded temperature in Pune was 1.7°C on January 17, 1935. Although winters in Pune are mild compared to other parts of India, thermal comfort in buildings can be improved through insulation and passive solar heating techniques (Indraganti, 2018).

1.2.2 Implications for Building Design

The Köppen Climate Classification categorizes climates based on temperature and precipitation, which are crucial factors in urban development and sustainable architecture. Pune’s Tropical Savanna Climate (Aw) results in distinct wet and dry seasons, directly impacting agriculture, water supply, energy consumption, and urban infrastructure. The semi-arid influence (BSh) creates variable rainfall patterns, necessitating efficient water conservation and management strategies to sustain Pune’s growing population. The hot and humid climate during summer and monsoon seasons makes thermal comfort a key challenge for architects and urban planners.

The built environment in Pune must address challenges related to heat, humidity, and rainfall. During summer, shaded facades, cross-ventilation, and reflective roofing materials can help reduce indoor heat buildup. The high solar radiation also makes Pune ideal for solar energy utilization, promoting the integration of solar panels in building designs. In the monsoon season, waterproofing measures, sloped roofs, and elevated foundations prevent water stagnation and structural deterioration. Additionally, permeable surfaces and green spaces aid in rainwater absorption and urban flood mitigation.



Temperature & Rainfall

Cloud cover & RH (%)

Figure 1-2 Temperature, RH (%), Rainfall & Cloud cover for Pune (Source IMD)

Since Pune’s winters are mild, passive solar heating strategies, south-facing windows, and thermal insulation, enhance indoor thermal comfort. With rapid urbanization, Pune requires climate adaptive urban planning that integrates energy efficiency, green infrastructure, and climate-responsive design to ensure sustainability.

Pune's climate presents unique challenges and opportunities for urban planning and architectural design. The combination of hot summers, humid monsoons, and mild winters necessitates innovative building solutions to enhance thermal comfort, energy efficiency, and climate resilience. Strategies such as passive cooling, natural ventilation, rainwater harvesting, and solar energy integration are crucial in mitigating climate related issues.

Table 1-1 Indian Meteorological Data for Pune (Source IMD)

Sr. No.	Parameter	Units	Remarks
1.	Average annual Maximum Temp.	31.7^{0}C	
2.	Average annual Minimum Temp.	17.8^{0}C	
3.	Mean Maximum Temp. of Hottest Months	37.3^{0}C.	April & May
4.	Mean Minimum Temp. of Hottest Months	21.1^{0}C	
5.	Mean Maximum Temp. of Coldest Months	29.7^{0}C	Jan & Dec
6.	Mean Minimum Temp. of Coldest Months	11.3^{0}C	
7.	Recorded Maximum Temp.	43.3^{0}C	30th April 1897.
8.	Recorded Minimum Temp.	1.7^{0}C	17th Jan 1935
9.	RH – Monsoon (Morning)	77% - 86%	
10.	RH – Monsoon (Afternoon)	66% - 79%	
11.	RH - Summer season	27% & 54%	afternoon and morning are about resp.

As Pune continues to expand, sustainable urban development will play a pivotal role in ensuring a balanced and resilient built environment. With effective climate adaptation measures, Pune can enhance environmental sustainability, improve living conditions, and ensure long-term urban resilience. By aligning building designs with climatic conditions, Pune can create energy-efficient, comfortable, and environmentally responsible living spaces for its residents.

1.3 Rise in temperature in Pune City

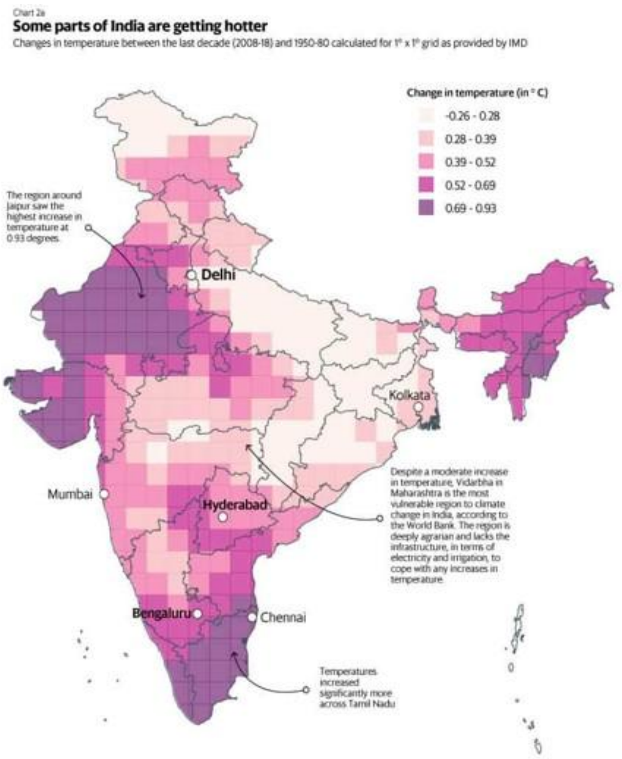


Figure 1-3 Climate change is already making India hotter (The Hindu, 2022)

A map (Figure 1-4) of India illustrating temperature variations between the period from 1950-1990, featured in an article by The Hindu titled "Climate change is already making India hotter," reveals significant temperature increases across many regions. Pune has experienced a significant increase in temperature due to climate change, with a recorded rise of 0.39 to 0.52°C between 1950 and 1990 (The Hindu, 2022). Even slight temperature increases contribute to heat waves, droughts, and floods, making urban centers like Pune increasingly vulnerable. Gohain et al. (2021) used remote sensing and GIS techniques to analyze land surface temperature (LST) and land use land cover (LULC) changes from 1990 to 2019. The study found a 43.1% increase in built-up areas, while agriculture (40.8%), scrubland (-37.1%), and water bodies (-11.1%) declined. These changes, particularly between 2009 and 2019, have contributed to a 5.8% rise in summer temperatures and a 12.4% decrease in winter temperatures(Gohain et al., 2021). Urbanization has led to the conversion of rural land into residential and commercial settlements, accelerating climate-related challenges. Additionally, an urban cool island effect was observed in both summer and winter, particularly in Pune’s core areas, which maintain lower temperatures due to traditional urban planning and natural materials.

The Energy and Resources Institute (TERI) 2014 study projected that Pune's temperature will rise by 2.46-2.74°C by 2070, with monsoon rainfall increasing 10-37.5% (TERI, 2014). These climatic shifts demand adaptive strategies to enhance resilience. (Parishwad & Shinkar, 2017) examined urban heat island effects, revealing that Pune's core areas are cooler than its outskirts, unlike many cities worldwide, due to natural ventilation, the Mula-Mutha rivers, and green cover. Despite localized heat islands, built-up areas are warming faster, signaling a clear impact of climate change. Sustainable development, water conservation, and green infrastructure are crucial to mitigate these risks and ensure Pune's environmental stability.

Pune's climate is undergoing significant transformations due to rising temperatures, land-use changes, and increased urbanization. Studies confirm a warming trend, especially in summer, and the loss of agricultural and natural land to urban development. Future climate projections indicate rising temperatures and increased rainfall, emphasizing the need for adaptation strategies, sustainable urban planning, and climate resilience efforts to safeguard Pune's environment and inhabitants.

1.4 The Role of Wada Architecture in Modern Times

The term "Wada" originates from the Sanskrit word "Vata," meaning "a plot of land intended for a house." These structures, often large residential mansions, were built around a central courtyard and served as homes for both the elite and commoners, with variations in scale and design reflecting socio-economic status (Tambe, 2016). As cultural artifacts, Wadas embody environmental, socio-historical, and aesthetic values, requiring climate-responsive conservation strategies to retain their historical relevance. Their design, influenced by Mughal, Rajasthani, and Gujarati architecture, catered to joint families and ensured ventilation, privacy, and security. The use of local materials such as bricks, limestone, and wood in construction provided durability and insulation, making them suitable for the regional climate (Philokyprou & Michael, 2020) (Dhepe Sushama S., 2017). Wadas commonly featured symmetrical layouts with central courtyards, fountains, lattice windows, and projected balconies, demonstrating the Mughal influence (Alapure et al., 2014).

Flourishing under the Marathas and Peshwas, Wadas played a pivotal role in Maharashtra's architectural and socio-political landscape. Their urban settlements consisted of interconnected two- or three-story structures along road networks, with minimal communal space. Larger

Wadas featured front courtyards for welcoming visitors and conducting commercial and administrative activities, while smaller ones adapted to limited urban space. The spatial organization of Wadas followed a hierarchical structure, with thick walls delineating different functional areas and allowing controlled spatial porosity. Central courtyards (Chawks) served as multi-functional transition spaces surrounded by open verandas (Osari) for daily activities. The number of courtyards varied depending on the house size, reinforcing the introverted architectural character that safeguarded families from external threats (Deshpande & Kotharkar, 2015); (R. R. Gupta, 2016). Wadas remain an essential symbol of Pune's rich cultural heritage, although many have deteriorated due to urbanization (S. Nagapurkar et al., 2020).

The evolution of Pune's housing patterns has been marked by industrialization, British influence, and modern urban expansion. With the British establishment of military headquarters in 1818, bungalow-style housing emerged, along with row houses that combined commercial and residential spaces. Post-World War I industrial growth led to increased housing demand, prompting the subdivision of Wadas and the rise of rental accommodations (A. S. Nagapurkar & Narkhede, 2019). Over time, Pune developed into a modern metropolis characterized by high-rise buildings, apartment complexes, and cooperative housing societies. The introduction of the Urban Land Ceiling and Regulation Act (ULC&R) in 1976 exacerbated land scarcity, limiting bungalow construction and favouring vertical expansion. Consequently, the traditional urban aesthetics of Pune have been altered, with contemporary apartment complexes failing to retain the social and spatial coherence of Wadas. The rapid expansion has also led to a rise in unauthorized settlements and slums, impacting the city's infrastructure and natural heritage sites such as hill slopes, riverbanks, and lakesides (A. S. Nagapurkar & Narkhede, 2019).

As Pune continues to grow, integrating traditional architectural techniques with modern design principles offers a sustainable approach to urban development. Climate-responsive vernacular architecture, incorporating passive design elements, enhances energy efficiency, thermal comfort, and environmental sustainability while preserving the city's cultural identity. The conservation of Wadas through adaptive reuse and sustainable planning strategies can help bridge the gap between heritage preservation and contemporary urbanization, ensuring that Pune's historical legacy remains intact for future generations (Philokyprou & Michael, 2020).

1.5 Statement of Research Problem:

Numerous building traditions in India have evolved in response to the climate, financial socio-cultural, and thermal needs of the population; vernacular buildings demonstrate an extremely intricate thermal adaptation (R. R. Gupta, 2016). The vernacular dwelling, or Wada was designed considering single big family or multiple dwelling family houses. Typically, Wada refers to a courtyard dwelling mansion (Tambe, 2016). These Wada houses belonged to both the governing elite and the general populace. When it refers to historical, cultural, and economic factors, this typology is quite important. Even though there are multiple differences in built form as per financial status, scale and size, all courtyard mansions share several fundamental components and features.

1.5.1 Challenges in India's Urbanization

It is essential to analyze the energy implications of housing development to avoid inefficient dwelling units. India's rapid urbanization presents significant challenges in energy consumption and sustainability. As of 2010, 31% of India's population resided in urban areas, projected to reach nearly 50% by 2050, adding about 441 million urban residents (C. Singh et al., 2021). Residential electricity demand is expected to increase sevenfold from 2012 to 2032, with urban areas accounting for 36.5% of national energy demand by 2030 (Ministry of Power, Government of India, 2018). These factors highlight an urgent need for climate-responsive architecture that can effectively manage increased temperatures and support sustainable urban development.

India, a primarily warm nation with diverse geographical conditions, is home to many vernacular settlements that were developed using local materials and construction techniques based on trial and error with respect to socio-cultural and climatic aspects (Shastry et al., 2014). Vernacular architecture, which includes locally available materials and climate-responsive designs, provides crucial answers for climate change mitigation and adaptation. Vernacular houses were designed passively to maintain comfortable interiors, in contrast to most conventional dwellings that rely on artificial or mechanical energy systems for comfort. Conventional structures tend to be energy-intensive, resulting in significant emissions during their lifetime. In 2014, residential energy usage in India was 50 times higher than in 1971

(Shastry et al., 2014). Vernacular houses, on the other hand, offer a model for sustainable development due to their capacity to survive greater temperature changes with reduced energy-resource intensity.

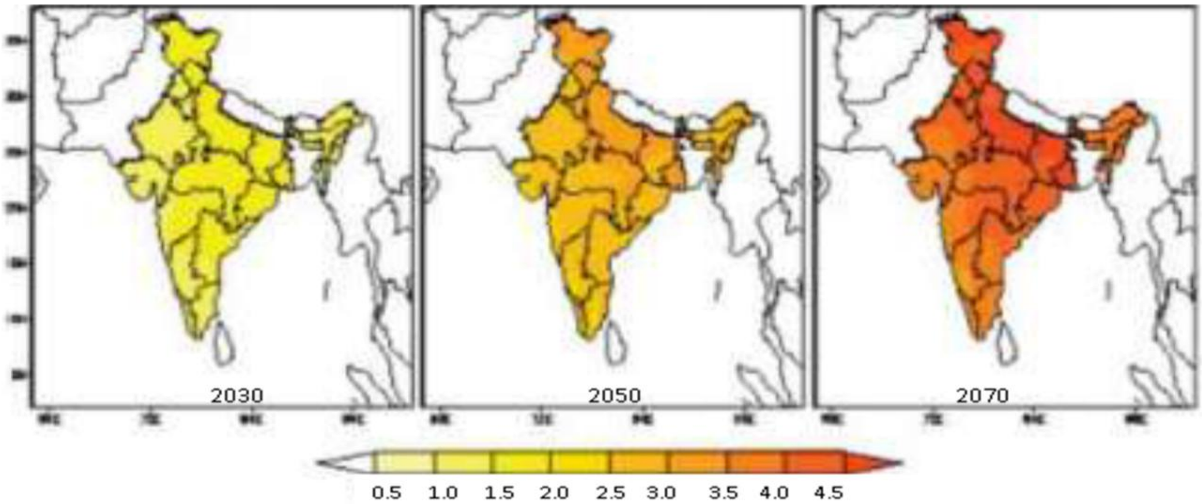


Figure 1-4 Mean Surface Air Temperature Model Projections For 2020s, 2050s, And 2080s With Respect to Baseline Of 1961-1990 (Source: TERI, 2014)

A report published by The Energy Research Institute in 2014 published and report (TERI, 2014) predicted an increase of 1-1.5^{o} C temperature by 2030 across various Maharashtra regions using baseline and IMD data (Figure 1-4).

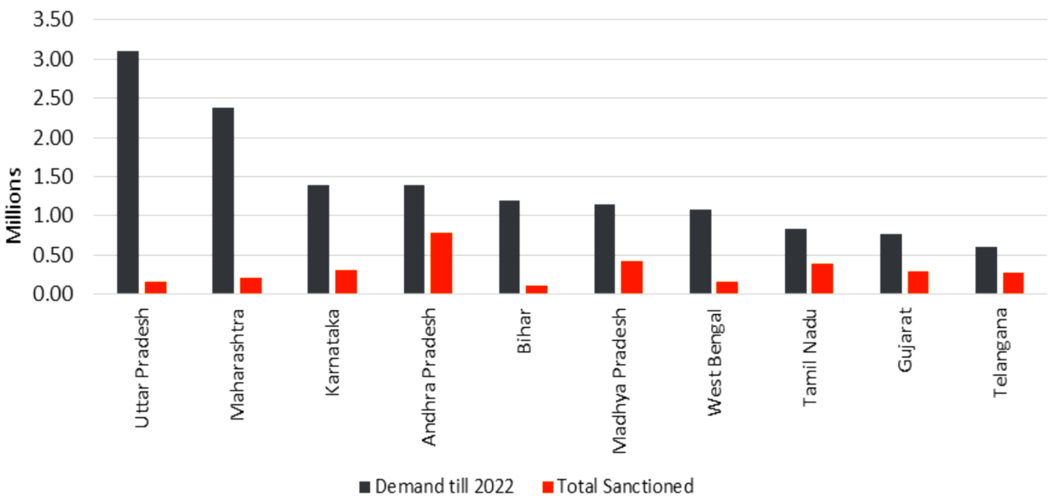


Figure 1-5 States with The Highest Demand for Housing (Source: Kumar, S., et.al.

With increasing residential infrastructure and warm nights more frequent in Pune, the situation will become worse in 2050 and by 2080, there will be a 2.5–3.0 º C increase in Pune's daily average temperature. Figure 1-5 discusses Maharashtra's housing demand amongst the listed states till 2022 totaling 3.5 million units. However, the sanctioned (government approved) falls short indicating a housing deficit. The study focuses on vernacular practices that serve as passive design elements during the summer, monsoon and winter seasons. The study also examines how the built environment will be impacted by the rise in outdoor temperature brought on by climate change.

The study seeks to analyze the effects of climate change on vernacular architecture, focusing on Pune's Wada architecture. The objective is to examine how rising temperatures impact the thermal performance and sustainability of these traditional structures. By studying Pune's Wadas, this study aims to extract design principles that can inform sustainable building practices, providing resilience against the impacts of climate change. This analysis will consider both passive cooling and material selection strategies in the context of future urban planning and sustainable housing solutions (Philokyprou et al., 2013).

Research Question

What are the implications of the rise in temperature on the vernacular house form of the Pune region?

Research Objectives

The primary objective of this research is to analyze the nature of climate change and its impact on the vernacular architecture of Pune, particularly in relation to the rise in temperature. The research aims to explore how traditional building forms, such as the Wada house, respond to the thermal challenges posed by climate change and how these buildings can be adapted to meet future needs. Specifically, the study will focus on the following objectives:

> **Objective 1: To analyze the nature of climate change and its impact on the vernacular architecture for future scenarios considering the rise in temperature in Pune.**

The study will investigate how rising temperatures affect the ability of vernacular houses, particularly the Wada, to maintain thermal comfort. This includes examining the role of passive design strategies such as natural ventilation, thermal mass, and shading in mitigating temperature fluctuations.

The research will explore how the Wada house and similar vernacular forms can adapt to the predicted temperature increases for Pune in 2050 and 2080. This will include assessing the effectiveness of passive design features in maintaining thermal comfort in the face of rising temperatures.

This analysis will provide a foundation for understanding how traditional architectural practices have responded to climatic conditions historically and whether these strategies remain effective or require modification to meet future needs. The findings from this objective will also help identify design elements that contribute most significantly to thermal comfort, offering insights into the adaptability of vernacular architecture in a warming climate.

- **Objective 2: To assess and compare the thermal performance of traditional Wada houses (base case) and their improved climate-responsive strategies through simulations under future climatic scenarios.**

This objective aims to evaluate the thermal performance of traditional Wada houses by analyzing indoor temperature and comfort levels. It involves comparing the original Wada structures (base case) with modified versions that integrate climate-responsive design strategies. Using computer simulations, the study will predict how Wadas will perform under future climate conditions, helping to identify effective ways to enhance thermal comfort and sustainability.

- **Objective 3: To develop practical guidelines for modifying Wadas to improve thermal comfort while preserving their traditional architectural character.**

Based on the findings from thermal performance assessments (objective 2), the study will propose guidelines that integrate traditional passive design elements with modern technologies. These guidelines aim to enhance the climate resilience of Wadas, ensuring thermal comfort in rising temperatures while maintaining their cultural and architectural essence. The recommendations will serve as a framework for sustainable retrofitting of vernacular dwellings in Pune.

Scope & Limitation

This study will focus primarily on the thermal characteristics of the Wada house form, a traditional dwelling typology in Pune. The research will investigate the thermal performance of the Wada envelope, including its passive design features and their effectiveness in providing thermal comfort for the climate of Pune. The study will also explore the impact of rising temperatures on the thermal performance of these buildings in future climate scenarios, specifically for the years 2050 and 2080.

The limitations of the study include a focus on the thermal envelope of the Wada house and the exclusion of other environmental factors such as humidity and wind, which may also influence thermal comfort. Additionally, the study will rely on theoretical climate projections rather than direct field measurements, which may limit the accuracy of the findings. However, the research will provide valuable insights into the potential impact of climate change on vernacular architecture and offer recommendations for enhancing the thermal performance of traditional building forms.

The primary objectives and research techniques are briefly summarised in the Introduction chapter. The primary goal is to carefully analyse the intricate relationships between climate change's rising temperatures and its consequences on Pune's traditional architecture.

The performance of the traditional Wada House envelope and its thermal characteristics are being researched in this study. The investigation casts a wider net, speculating on how these architectural forms would alter because of a rise in temperature in 2050 and 2080. To help stakeholders, such as policymakers and architects, make well-informed decisions about the preservation and change of these important architectural traditions.

Chapter-wise Summary

Chapter 2: Literature Review

This chapter explores the thermal performance and design strategies of vernacular architecture in the different climates. It begins with an analysis of both qualitative and quantitative aspects of vernacular architecture, showing how traditional designs optimize thermal comfort through features like natural ventilation, shading, and thermal mass. The review also explores spatial and cultural aspects, emphasizing how vernacular buildings are tailored to local customs and environmental conditions. The chapter continues by exploring how climate-responsive vernacular architecture acts as a bioclimatic design, offering resilience against climate change. It highlights the passive strategies integrated into these designs, such as utilizing wind and sun, to improve environmental sustainability. The thermal performance of vernacular buildings is examined in relation to future climate scenarios, suggesting that while traditional designs remain effective, modifications may be necessary to address future environmental challenges. The chapter concludes by identifying research gaps, particularly regarding the adaptation of vernacular designs to a rapidly changing climate.

Chapter 3: Vernacular Architecture of Pune

This chapter focuses on the traditional architectural forms of Pune, specifically the Wada houses. It discusses the basic characteristics of these houses, such as courtyards, thick walls, and the use of locally sourced materials that help regulate thermal comfort. The chapter categorizes Wadas based on their size and complexity, with a focus on how the design adapts to the available space. It also explores the typical indoor layout, building materials, and construction methods, which include stone, mud, and wood. Additionally, case studies of well-known Wadas, such as Vishrambaug, Nagarkar, and Chapekar Wadas, provide a better understanding of how these buildings effectively manage temperature and offer insight into the sustainable design strategies employed. A comparative analysis of different Wadas further illustrates the impact of traditional design on thermal comfort and sustainability.

Chapter 4: Research Methodology

This chapter outlines the research methodology used to study the thermal performance of vernacular architecture. It introduces the framework of the study, which includes tools and techniques for data collection and analysis. The chapter examines weather data and its correlation with the rise in temperature in Pune and includes real-time data collection using temperature and humidity sensors, with a focus on calibration procedures to ensure accuracy. A simulation models for the Ranade Wada, Gokhale Wada, & Purandar Wada is developed to predict the thermal performance of the building, and the results are validated using ASHRAE guidelines. The chapter also addresses future climate scenarios and their potential impact on vernacular architecture, employing the IPCC HADCM3 model to generate climate data and formulate an optimistic future scenario for design adaptation.

Chapter 5: Results and Analysis

The results chapter presents the findings from the simulations and data analysis. It provides a detailed description of Pune's climate and the impact of rising temperatures on vernacular buildings. Thermal performance is analyzed in relation to temperature increases, showing how passive design strategies help mitigate the effects of heat. The chapter includes a simulation analysis calibrated to ASHRAE standards, with a focus on how the building performs under different climate conditions. Future weather data is examined through regional climate modeling, and bioclimatic analysis is used to assess the effectiveness of passive design strategies in future scenarios. The chapter concludes with insights into the impact of passive strategies on thermal comfort, providing recommendations for adapting vernacular designs to future climate conditions.

Chapter 6: Conclusion and Recommendations

The final chapter discusses the findings from the previous chapters, emphasizing the importance of vernacular architecture in addressing the challenges posed by climate change and urbanization. It highlights the role of traditional passive strategies in improving thermal comfort and sustainability. The chapter makes recommendations for integrating these principles into modern architectural practice, ensuring that buildings remain resilient to future climate variations. It also calls for further research to optimize vernacular designs for the future, ensuring that they can continue to provide comfortable and sustainable living spaces in a rapidly changing world.

CHAPTER 2: LITERATURE REVIEW

The literature review aims to explore and analyze the impact of climate change, particularly the rise in temperature, on the thermal performance of vernacular house envelopes in warm-humid climates. Vernacular architecture, often shaped by local climate and materials, provides insights into how passive design strategies can mitigate temperature fluctuations and ensure thermal comfort. The review delves into key aspects of vernacular design, focusing on passive features that contribute to energy-efficient buildings, particularly in summer and winter. These passive strategies, such as natural ventilation, thermal mass, and shading, have historically been integral to ensuring the comfort of inhabitants while minimizing reliance on artificial cooling and heating systems.

In addition to thermal performance, the literature review emphasizes the role of surrounding weather conditions, including seasonal temperature variations, in shaping vernacular architecture. It also explores the sociocultural aspects influencing vernacular building forms, such as community practices, traditional knowledge, and regional preferences, which all contribute to the adaptation of architecture to local climates. By examining these aspects, the review aims to uncover the multi-dimensional nature of vernacular architecture and its resilience to climate challenges.

The review covers three primary areas:

a) **Thermal Characteristics of Vernacular Architecture:** Analyzing how traditional designs, materials, and construction techniques contribute to maintaining thermal comfort in hot, humid climates.

b) **Climate-Responsive Vernacular Architecture as a Bioclimatic Design and Its Resilience to Climate Change:** Investigating how vernacular architecture serves as a bioclimatic design solution that responds to environmental conditions while offering resilience to climate change impacts.

c) **Thermal Performance in Future Climate Change Scenarios:** Examining the potential effects of future climate change, particularly the rise in temperature, on the performance of vernacular house envelopes and their ability to maintain thermal comfort.

The objective of this literature review is to identify underexplored areas regarding the intersection of climate change and vernacular architecture, specifically the impact of temperature rise on passive design strategies. While previous studies have explored the general characteristics of vernacular architecture, there is a lack of focus on how these buildings will perform in future scenarios with increased temperatures. This gap provides an opportunity to further investigate the implications of climate change on the thermal comfort and resilience of vernacular buildings, offering new perspectives for sustainable architectural practices.

2.1 Thermal Characteristics of Vernacular Architecture

Vernacular architecture represents a sustainable approach to design, blending local materials, environmental conditions, and cultural practices to create climate-responsive structures. Historically, these traditional building forms have evolved to optimize comfort, resource efficiency, and resilience, particularly in hot, humid, & composite climates where thermal comfort is challenging to maintain. Studies on vernacular architecture across India, such as those on Kerala’s courtyard houses or Nagapattinam's mud-brick homes, reveal effective passive design strategies including courtyards, shaded verandas, and natural ventilation that enhance thermal comfort without mechanical cooling systems. By examining both qualitative aspects, like cultural continuity, and quantitative metrics, like temperature and humidity control, researchers underscore the benefits of vernacular designs for sustainable modern architecture.

In recent decades, climate change and rapid urbanization have posed new challenges for maintaining comfort in contemporary buildings. As global temperatures rise, there is renewed interest in the passive cooling strategies and high thermal mass materials used in vernacular architecture. This literature review synthesizes research on vernacular housing across India and examines how these traditional methods maintain comfort, resist climatic variations, and provide valuable lessons for modern sustainable building practices. By integrating vernacular principles, contemporary architecture can achieve resilience and harmony with the environment, addressing both ecological concerns and occupant well-being.

2.1.1 Qualitative and Quantitative Analysis of Vernacular Architecture

(Dili et al., 2010b) in research discusses the thermal leg between the external and indoor environments while taking temperature, relative humidity, and wind flow into consideration. On the other hand, local vernacular architecture has changed over time because of continuous efforts to seek better, more effective solutions. The qualitative analysis was done for Kerala's vernacular residential architecture and passive environment control system. By logging the thermal comfort parameters of a selected dwelling, a quantitative analysis based on field tests was also completed by using Architectural Evaluation System (AES) instrumentation to continuously record the comfort metrics throughout the period. Temperature sensors were installed in the bedroom adjacent to semi-open spaces, the courtyard surrounding it, and the courtyard, with a verandah outside. The sensor is concealed under the wooden Stevenspns's screen placed to monitor the outdoor temperature. The relative humidity in the bedroom varies almost in real-time with the general semi-open environment. Among the rooms, the courtyard's relative humidity (RH) varies the most, however at night, it only differs from the bedrooms and the adjacent semi-open space by approximately 3%. The relative humidity (RH) in the courtyard drops to its lowest level throughout the day, or about 66%. The building envelope's high level of thermal insulation avoids even a low diurnal variation in internal temperature. The building shell effectively prevents any conductive heat gain. The materials' thermal insulation capabilities and the high level of natural ventilation sustained throughout the structure are demonstrated by the absence of a temporal lag between the temperatures of the internal and exterior air.

(Dili et al., 2010a) The internal courtyard next to living spaces, optimum window sizes for continuous airflow, an insulative built envelope for thermal protection, verandas to shield exterior walls from the sun's rays, a pitched roof to keep out heavy rain, and shading verandas all work together to create Keralan vernacular residential architecture's passive climate control system. This research explores qualitative analysis in detail.

(Zhai & Previtali, 2010), The results of the energy model simulations imply that implementing vernacular architectural traditions improves energy performance, and that performance can be further improved with the use of scientific recommendations. Although there are many traditional dwellings around the world, the study shows that it is difficult (but desirable) for modern building designers to blend vernacular architectural traditions with quantitative design knowledge.

(Radhakrishnan et al., 2011), To find a real-term solution two traditional house forms and two contemporary house forms of the same region were selected to study to compare the thermal performance of contemporary house forms with vernacular houses of the warm-humid climate zone of Nagapparrinam, Tamil Nadu. The measurement tool AES (Architectural Evaluation System) setup is done. To strengthen the study, a thermal comfort and preferences survey of the region was conducted amongst the occupants of the vernacular houses and modern houses of the same region. The Research analyses that in comparison to modern buildings, traditional house form in these regions is more climate responsive.

(Choudhary, 2016) The study examines two vernacular dwelling-built environments in places with diverse climatic, cultural and geographic conditions, considering their resilient features of sociocultural, spatial planning, construction materials with technologies, and factors. The study claims that a detailed understanding of the local vernacular-built environment is necessary to deal with rural transformations. The findings of research on the vernacular-built environments of the two regions, as well as their inherent resilience in terms of sociocultural elements, building methods, and spatial design. These two locations have quite different geographical, social, and environmental circumstances. When dealing with rural areas that are rapidly urbanizing, understanding vernacular built environments is crucial. The use of a traditional strategy of the region will always keep harmony with culture and environment. The capability to develop and enhance the capacity for adaptation is the subject of study. Design-based resilience: Because the traditional building is climate responsive and resilient. Also, vernacular communities harmoniously blend into their surrounding binaural environments. Through the efficient and adaptable use of space, vernacular communities suggest communal living and shared facilities. Using local resources gives buildings the flexibility to adapt to changing climatic factors as they develop over time in response to the environment. Vernacular towns promote independence and self-sufficiency through a variety of design techniques, such as integrating habitations with agricultural regions.

(Dhepe Sushama S., 2017) explored the relevance between two types of architecture with the help of case study analysis done for plan form (Character and geometry), Space (Spatial configuration), Semi-open and Open spaces (Courtyard & and verandah), Structural elements (Wall, roof, Staircase) and façade aspects to understand modification done of traditional architecture for contemporary architecture. This study increases the awareness among contemporary designers to adopt regional design features and integrate traditional architectural styles, characteristics, and elements into conventional designs.

Vishnu et al. (2023.) examine the passive design strategies and thermal performance of traditional Kerala architecture, specifically the Nalukettu houses, which are well-suited for the warm humid climate of Kerala, India. This climate is characterized by high humidity and temperatures ranging from 22°C to 34°C throughout the year.

The study reveals that traditional Kerala houses effectively maintain comfortable indoor temperatures using passive environmental management techniques. The Nalukettu design features a square or rectangular layout with a central courtyard surrounded by four units, promoting natural ventilation and thermal regulation. The courtyard is shaded by a covered verandah, reducing solar heat gain while facilitating airflow. Additionally, the use of locally available materials such as mud, laterite, granite, wood, bamboo, and clay roofing tiles provide good thermal insulation, minimizing heat transmission.

Temperature monitoring showed that, despite a 12°C fluctuation in outdoor temperatures, indoor temperatures remained between 26°C and 30°C, with minimal diurnal variation. The courtyard was observed to be about 5°C cooler than the hottest point outside. The design also maintains stable relative humidity levels indoors, varying only by about 10%, compared to a 40% fluctuation outside. This thermal stability is achieved through effective natural ventilation, strategic orientation, and the use of courtyards and Verandahs.

The study concludes that Kerala's vernacular architecture efficiently utilizes passive cooling strategies, maintaining comfortable indoor climates while minimizing energy consumption. These traditional practices provide valuable insights for contemporary sustainable design in warm humid climates (Vishnu et al., 2023).

Rajapaksha and Kariyawasam (2024) analyzed the thermal and visual comfort of a 17th-century Dutch residential building in Galle, Sri Lanka. The study highlighted thermal behavior through air temperature measurements using Hobo loggers in various spaces, revealing a 3-

hour time lag and a 2.5°C reduction in peak indoor temperatures compared to ambient levels during the day. However, nighttime indoor temperatures were higher due to heat release from the thick walls, which absorb heat during the day and lack proper nocturnal ventilation. Courtyard temperatures were 1.6°C higher than living room temperatures during the day, further contributing to heat gain.

Using Design Builder software (version 6), the building was modeled to evaluate daylighting and thermal performance. Findings indicated the absence of design elements to enable cool night ventilation, with stagnant indoor air at night due to sealed openings. Heat accumulation in the courtyard and insufficient airflow management contributed to elevated indoor temperatures.

Proposed strategies included incorporating openings at upper levels to release hot air and lower-level openings to allow cooler air inflow. These passive design modifications aim to enhance the thermal performance of high thermal mass structures in warm, humid climates. Avoiding daytime ventilation in polluted urban environments and prioritizing nighttime ventilation were recommended to optimize the stack effect and the benefits of thermal mass. This approach preserves the historical integrity of the building while improving comfort and promoting energy-efficient reuse(Rajapaksha & Kariyawasam, 2024).

D’Amato and Kapoor (2024) examine climate-responsive strategies in vernacular architecture in Jaipur, India, which falls within the Hot-Dry climatic zone. The study highlights how traditional design techniques effectively manage the harsh desert climate, ensuring comfortable living conditions while minimizing energy use.

In Jaipur, orientation and layout play a crucial role in climate responsiveness. Buildings are typically oriented north-south to minimize solar exposure on longer sides, reducing heat gain. Courtyards are integral to the layout, promoting cross-ventilation and creating shaded, cooler spaces within the structure. Thick stone walls provide significant thermal mass, absorbing heat during the day and releasing it at night, which stabilizes indoor temperatures. Flat roofs coated with lime plaster reflect sunlight, preventing heat buildup. Traditional Jaali’s (perforated screens) allow for natural light and ventilation while reducing direct solar gain and maintaining privacy. Shading devices such as overhanging eaves, courtyards, and chajjas (projections) protect windows and walls from direct sunlight, maintaining cooler interiors. Additionally, small windows with wooden shutters limit solar exposure while enabling ventilation, especially during cooler nighttime temperatures. Locally available sandstone is extensively used for its thermal insulation and durability in desert climates. This material is applied in both structural and ornamental elements, such as jharokhas (overhanging balconies), which also enhance ventilation.

The study concludes that Jaipur’s vernacular architecture demonstrates an advanced understanding of solar orientation, thermal mass, and natural ventilation. These passive strategies are highly effective in maintaining thermal comfort and reducing energy consumption. Incorporating these traditional methods into modern design can significantly enhance energy efficiency and promote sustainable architecture in hot-dry regions (D’amato & Kapoor, 2024).

This review explores the thermal efficiency and sustainability of vernacular architecture in warm-humid regions of India, emphasizing passive design features that enhance climate responsiveness. Traditional elements such as internal courtyards, shaded verandas, natural ventilation, and high thermal mass materials effectively regulate indoor temperatures and humidity, reducing the need for mechanical cooling.

Studies across Kerala, Tamil Nadu, Maharashtra, and Bengal demonstrate how these passive strategies improve thermal comfort while promoting energy efficiency and resource conservation. For instance, Kerala's Nalukettu houses utilize courtyards and verandas for effective ventilation, whereas Tamil Nadu's traditional homes outperform modern structures in climate adaptability. In Maharashtra and Bengal, high thermal mass walls and natural ventilation maintain indoor comfort despite extreme weather conditions. Additionally, vernacular architecture preserves cultural identity and resilience by harmonizing with local environmental and sociocultural contexts. The review suggests that integrating these traditional principles into contemporary designs offers practical solutions to modern challenges like rising temperatures and urbanization, reinforcing the relevance of passive cooling techniques and sustainable materials.

2.1.2 Spatial and Cultural Analysis in Vernacular Architecture

This section explores spatial and cultural aspects of vernacular architecture, emphasizing how traditional layouts, materials, and passive strategies foster comfort while reflecting regional identities. In hot, humid and composite regions like Nagapattinam's and Divrii, the use of heat-resistant materials such as brick and mud support thermal comfort by regulating interior temperatures. Spatial arrangements like courtyards, verandas, and communal spaces further enhance comfort, allowing for natural cooling and ventilation that adapt to seasonal needs.

These vernacular designs also reflect cultural practices, as seen in Maharashtra's multi-story wada with interior courtyards, which embody community living and shared use. In areas affected by urbanization, like Madhya Pradesh, vernacular homes preserve elements that resist cultural erosion, while integrating essential modernization. This review highlights how vernacular architecture provides not only thermal comfort but also cultural resilience, offering a model for sustainable, climate-responsive design that blends traditional practices with the demands of contemporary life.

(Shanthi Priya et al., 2012) In the study, heat-resistant materials including brick, mud, and mudbrick were discussed. These materials are used in Nagapattinam's, a warm-humid coastal region, and are particularly useful for cooling and heating interior spaces. The spaces were particularly well-organized in the vernacular homes of Nagapattinam's with passive strategies used to create a thermally comfortable space that keeps warm in the winter and cool in the summer.

(Kültür, 2011) in the paper conduct a spatial analysis of Toyhane by comparing it to the culture and house design of Divrii. Toyhane found in various Divrii households will be formally and functionally investigated in this context. The study illustrates the effect of culture and the natural atmosphere on space development, also it will help to raise awareness of Divrii's traditional dwellings and spaces, which are rapidly disappearing.

(Patidat & Raghuwanshi, 2014) The research investigates the evolution of Madhya Pradesh's culture and architecture from vernacular to modern. The two typical BHEL Bhopal dwellings were chosen from the urban community. The result discusses the effects of globalization and urbanization on cultural identity. It ends by appreciating vernacular architecture ideas.

(R Deshpande & R Kotharkar, 2015) Houses surveyed located in villages (Chichkheda), historic town centers (Pauni), and Nagpur's walled city, and comparative research was conducted in terms of neighborhood, spatial organization, kinship structure, cooking practices, and sacred-profane areas. It examines the house form's continuity and evolution by identifying characteristics that resist change and those that have changed because of modernization.

(Rubio-Bellido et al., 2015) in the study analyzes the comfortable temperature of the naturally ventilated built environment using an adaptable approach using field research. The Climate Consultant tool based on the ASHRAE Handbook of Fundamental 2005, which employs weather data (.epw) files to examine outdoor parameters, defines the comfort model chosen. utilized to examine indoor characteristics (HOBO Data Logger: Relative Humidity & Air Temperature) and analyze indoor parameters.

Amol Rathod et al. (2022) examine the climate-responsive design of vernacular architecture in three distinct Indian climate zones: Hot-Dry (Kutch, Gujarat), Warm-Humid (Kerala), and Cold-Sunny (Ladakh, Jammu & Kashmir). Using literature review and case studies, the research explores the interplay between local materials, building forms, and passive strategies that maximize human comfort while minimizing energy usage.

For the Hot-Dry climate (Kutch, Gujarat), the study analyzes the Bhunga House, characterized by circular plan forms, thick mud walls, and conical thatched roofs. These features reduce heat gain and enhance thermal comfort. Small openings with timber Jaali's allow diffused light without glare, optimizing ventilation.

In the Warm-Humid climate (Kerala), the Kerala House is examined. It uses rectangular plan forms, laterite stone, wood, and bamboo for construction. High-pitched roofs with extended overhangs and deep eaves effectively discharge heavy rainfall while enhancing ventilation. Clay roofing tiles and low ceilings made of insulating wood and mud maintain a cooler interior.

For the Cold-Sunny climate (Ladakh), the study explores the Ladakh House, featuring rectangular plans, thick sun-dried earth block walls, and flat roofs with stepped designs to withstand heavy snow loads. Trombe walls and strategically placed large windows optimize solar heat gain, while smaller windows minimize heat loss.

The study concludes that climate-responsive design, utilizing passive sun, wind, and light strategies, significantly enhances human comfort. These vernacular designs showcase effective use of local materials, building techniques, and architectural details tailored to their specific climate zones. The findings underscore the potential of integrating traditional knowledge with modern architecture for sustainable, energy-efficient building designs (Amol Rathod et al., 2022).

(Alapure et al., 2017) did research encompassing fieldwork and surveys to document on-site observations. Coupled with an extensive literature review, the study zeroed in on specific case studies, with a focus on Wada's passive-cooling techniques. These techniques were evaluated for their impact on thermal performance improvement. The study demonstrated the value of using design elements including inside courtyards, verandas, lattice windows, and components like fountains, pools, and arches to improve the indoor microclimate. Notably, the study focused on the importance of materials with high thermal mass in enhancing the resistance of these regional structures to adverse environmental factors.

Vakharia (2017) examines the thermal performance of courtyards in traditional Pol Houses in Ahmedabad, emphasizing passive design strategies for hot-dry and hot-humid climates. These Pol Houses are constructed using wooden posts and beam structures with infill brick walls plastered on both sides, which are not exposed to weather. The buildings share side walls with adjacent houses, maximizing land use and enhancing thermal insulation.

The courtyard, centrally located and open to the sky, serves as a climate regulator by promoting natural ventilation and moderating indoor temperatures. It exhibits high diurnal temperature variations, being warmer during the day and cooler at night, which facilitates passive cooling. By acting as an air shaft, the courtyard enhances airflow and improves humidity levels indoors, ensuring thermal comfort despite rising outdoor temperatures.

Rooms adjacent to the courtyard benefit from this layout. Ground floor rooms, shaded throughout the day, maintain consistent temperatures and are used for daytime activities. Conversely, first-floor rooms without attic insulation experience higher temperatures due to direct solar exposure. The attic space, with its pitched thin roof, acts as a thermal buffer, protecting the first-floor rooms from solar radiation. These attic spaces reach high temperatures during the day but cool rapidly at night, making them ideal for sleeping.

This study demonstrates the effectiveness of courtyard-centric layouts and flexible space usage in achieving year-round thermal comfort in hot climates. The strategic positioning of open spaces and shaded areas, combined with effective ventilation pathways, showcases the ingenuity of vernacular architecture in responding to harsh climatic conditions (Vakharia, 2017).

The study by Maligi et al. (2024) investigates passive design strategies in vernacular architecture to achieve thermal comfort and sustainability in Guledgudda, Bagalkot district, North Karnataka, India, situated in a hot and dry climate zone. Using field studies, observations, interviews, and simulations through DesignBuilder software, the research examines how traditional dwellings effectively prevent heat gain, dissipate heat, and modulate internal temperatures.

The findings highlight several key passive design strategies that contribute to thermal comfort. Shared walls play a crucial role in reducing external heat exposure and promoting thermal stability by minimizing temperature fluctuations. These shared walls significantly decrease internal surface temperatures (by less than 1°C) compared to standalone walls. Additionally, thicker walls with high thermal mass enhance thermal resistance and heat dissipation, effectively reducing indoor heat gain and maintaining stable indoor temperatures even during extreme weather conditions.

Courtyards and open spaces are also instrumental in creating natural ventilation and air circulation, which contribute to heat dissipation and thermal comfort. These spaces facilitate evaporative cooling, enhancing the microclimate within dwellings. The strategic use of fenestration and wall-to-window ratios optimizes cross-ventilation while minimizing direct solar radiation, ensuring adequate natural light without excessive heat gain.

Furthermore, orientation and spatial layout significantly influence thermal comfort. By orienting buildings to minimize solar exposure, particularly on east and west facades, heat gain is substantially reduced. Strategic spatial planning, including the positioning of rooms and courtyards, further optimizes indoor temperatures. Additionally, high parapet walls and traditional roofing systems, such as the Madras Terrace Roof, provide shade and enhance insulation, contributing to better thermal regulation.

The study concludes that these passive design strategies effectively enhance thermal comfort, reduce energy consumption, and promote sustainability in hot and dry climates. It emphasizes the potential of integrating vernacular architectural principles into contemporary building practices for improved energy efficiency and comfort (Maligi et al., 2024).

Gupta et al., (2020) investigates climate-responsive design strategies for rural vernacular dwellings in the composite climate of Ranchi, Jharkhand, India. Using climatic data from the Indian Meteorological Department and tools like Ecotect and Climate Consultant, researchers analyzed temperature, humidity, solar radiation, and wind to propose sustainable solutions for enhancing indoor comfort. The study revealed significant climate shifts from 1986-2013, with hotter summers (peaking above 40°C) and colder winters (as low as 2-3°C), necessitating adjustments in building design.

Findings highlight that compact dwelling units, such as Sample Hut 1 with a perimeter-area (P/A) ratio of 0.3, perform poorly in summer, experiencing higher indoor temperatures and discomfort hours due to heat retention in thick mud walls (450-500 mm). Conversely, Sample Hut 3, with a P/A ratio of 0.65 and moderately spread-out U-shaped planning, exhibited better thermal performance due to improved ventilation and reduced heat gain.

Ventilation: Nighttime flush ventilation with lightweight materials (e.g., 150-200 mm wattle and daub walls) for summer sleeping areas to dissipate heat.

Material Optimization: Insulated 300 mm walls for winter rooms to minimize heat retention.

Layout: Slightly staggered courtyard planning to channel breezes and prevent airflow obstruction between huts.

Orientation: East-west alignment to reduce solar heat gain.

Shading: Sun-shading devices for 10-20% energy savings.

The study concludes that moderately compact layouts with climate-appropriate materials and ventilation strategies outperform compact plans in Ranchi's composite climate. By integrating local climatic, biological, and architectural considerations, the proposed design strategies enhance indoor comfort while preserving cultural and material authenticity (J. Gupta et al., 2020).

(S. Nagapurkar et al., 2020) in study explained that the Marathas introduced this form of planning to protect their family from strangers. The architecture is a mix of Mughal, Rajasthani, and Gujarati styles, as well as local building techniques. These homes are often multi-story buildings with interior courtyards that are surrounded by rooms. These can be used by a single family or several families simultaneously several families at once. The key component of Wada's is the open courtyards known as "Chowks". The number of courtyards in a house is determined by its size. Stone walls, wooden staircases, and open courtyards characterize the architecture.

The spatial and cultural analysis of vernacular architecture explores the deep connection between local traditions, cultural identity, and climate-responsive design. Studies from various regions provide valuable insights into how vernacular architecture evolves to meet both environmental and social needs. Literature suggests the spatial organization in these homes incorporates passive strategies for cooling and heating. The spatial and cultural analysis of vernacular architecture reveals a strong connection between cultural identity, local traditions, and climate-responsive design. Studies from diverse regions illustrate how these traditional homes adapt to environmental and social needs through strategic spatial organization and passive design strategies. In warm-humid regions like Nagapattinam and Divrii, heat-resistant materials such as brick and mud are used to regulate indoor temperatures, while spatial features like courtyards and verandas enhance natural ventilation and cooling. Research on Maharashtra's multi-story wada and Madhya Pradesh's urban homes highlights how vernacular designs preserve cultural identity amidst modernization, incorporating communal spaces and passive cooling techniques that blend tradition with contemporary needs. The review emphasizes the cultural implications of the shift from vernacular to modern architecture, influenced by globalization and urbanization. It concludes that integrating traditional architectural principles with modern design enhances sustainability, thermal efficiency, and cultural continuity, demonstrating the importance of considering cultural, spatial, and climatic factors in contemporary architecture.

2.1.3 Material and Passive Cooling Strategies in Vernacular Architecture

The section on "Material and Passive Cooling Strategies in Vernacular Architecture" examines the key role of traditional building materials and design techniques in achieving thermal comfort and energy efficiency. Through various case studies, this section explores how vernacular architecture, particularly in hot, humid & composite climates, uses local materials and passive strategies such as shaded courtyards, ventilated walls, and semi-enclosed spaces to mitigate heat gains and improve indoor comfort. It emphasizes the importance of climate-responsive design in adapting to changing environmental conditions and mitigating the effects of global warming. The integration of passive cooling techniques offers valuable insights into sustainable and resilient building practices for contemporary architecture.

Subramanian et al. (2016) investigated the performance of a modern residential building in Thanjavur, Tamil Nadu, designed using solar passive architecture (SPA) techniques for a warm-humid climate. The study evaluated thermal comfort during peak summer (May) and winter (December). The building maintained indoor air temperatures between 24.6–30.8°C and relative humidity between 46–74%, aligning with Tropical Summer Index (TSI) and National Building Code (NBC) standards for thermal comfort. Humphreys and Nicol's (2000) thermal comfort model was identified as the best fit for the building's conditions.

SPA strategies incorporated into the design include courtyard and atrium designs (promoting stack and solar chimney effects), heat-reflecting roofing tiles, roof ventilators, high ceilings, shading elements, landscaping for microclimate, light-colored exteriors, and optimized daylight use. These features helped minimize heating, promote ventilation, and reduce artificial lighting requirements, resulting in reduced reliance on electromechanical cooling systems.

During summer, outdoor temperatures ranged from 23–38.2°C with solar radiation levels of 470–1280 W/m^2. Despite this, indoor temperatures remained stable at 27.4–30.8°C with relative humidity at 46–74%, ensuring comfort. Similarly, in winter, outdoor temperatures varied from 20.8–31.6°C, and indoor conditions remained comfortable at 24.6–27.1°C with relative humidity of 61–70.7%.

The study highlights that SPA designs effectively create thermally comfortable environments, reduce energy consumption, and promote sustainability. These results emphasize the need for integrating traditional climate-responsive techniques with modern construction materials to enhance energy efficiency. The findings aim to encourage architects and engineers to adopt SPA principles in contemporary buildings or retrofit existing ones, contributing to sustainable development. The research also underscores the importance of site-specific and climate-specific designs to achieve optimal thermal comfort(Subramanian et al., 2016).

Convertino et al. (2017) analysed the vernacular Mediterranean architecture of Ostuni, Puglia, Italy, focusing on its urban layout and building features, particularly the external coatings. Ostuni's climate experiences extreme temperatures, with the highest dry bulb temperature of 38.2°C in July and the lowest of -2°C in January. The study used dynamic simulations through DesignBuilder v. 4.7 and climatic data from Metronome to assess the impact of building characteristics on microclimatic conditions. The analysis included three renovation scenarios—shallow, intermediate, and deep—to evaluate potential improvements.

The methodology involved a detailed examination of the morphological and typological features of the buildings, followed by implementing materials and stratigraphy into the simulation. The structures are built with semi-hard limestone walls plastered on the interior, clear single-pane wooden windows, and solid wood external doors. The simulations assumed the continuous presence of two relaxed standing occupants, maintaining an indoor temperature of 20°C for heating and 25°C for cooling.

The study highlighted the effectiveness of passive design strategies, particularly the use of high thermal inertia in thick limestone walls, which contribute to stable indoor temperatures by delaying heat transfer. This "heaviness" of the structure enhances thermal comfort in the Mediterranean climate by minimizing temperature fluctuations. The results underscore that the traditional architectural solutions were deliberately designed to optimize thermal performance, proving their relevance in contemporary sustainable building practices. The findings suggest that preserving and adapting these passive strategies can enhance energy efficiency while maintaining cultural heritage (Convertino et al., 2017).

The study by Gupta et al. (2017) analyzed the thermal performance of three types of mud huts with courtyards in Ranchi's composite climate using temperature measurements and Autodesk Ecotect simulations. The huts, constructed with 450 mm thick mud walls and clay-tiled roofs, had internal floor areas of approximately 100 m^2, wall heights of 4 meters, and small openings (0.4 m × 0.4 m) on both north and south walls. Observations were made during the peak summer and winter seasons to evaluate thermal comfort.

The results revealed distinct thermal behaviors among the three hut types:

Sample Hut 1 (Square with central courtyard): Exhibited the highest temperatures during summer and provided the least thermal comfort, recording 5,312 annual discomfort hours due to heat. However, it performed best in winter, maintaining a 2°C higher temperature than the other designs, with only 243 discomfort hours due to the cold.

Sample Hut 2 (Plus shaped with central courtyard): Recorded moderate performance, with 4,584 annual discomfort hours due to heat and 633 discomfort hours due to cold.

Sample Hut 3 (U-shaped with south-facing courtyard): Offered the best summer comfort, with 3,194 discomfort hours due to heat, attributed to better shading and ventilation. However, it performed poorly in winter, registering 1,268 discomfort hours due to cold.

The study highlighted the limitations of current courtyard designs, noting that they do not always enhance thermal comfort in composite climates. Recommendations for improving year-round comfort included reducing wall thickness to 200–300 mm to mitigate heat retention, enhancing nocturnal ventilation with larger wire-meshed voids, and insulating walls and roofs. Vegetation such as bamboo groves and deciduous vines were suggested to lower courtyard temperatures in summer while allowing sunlight in winter.

Overall, the U-shaped dwelling (Sample Hut 3) was identified as the most promising for summer habitation. By addressing its winter performance through insulation and strategic design, it could serve as a model for year-round living while preserving traditional courtyard-style housing. These insights are critical for sustainable rural housing development in composite climatic regions(J. Gupta et al., 2017)

(Manu et al., 2019) Utilizing a combination of construction materials and technology is one of the most efficient ways to lower heat gains through conduction. Gains are reduced while providing thermal mass with lower internal surface temperatures via a removable skin layer shading the outer or vented cavity wall. Another way to limit solar heat gain is to use shaded courtyards and windows.

(Agrawal et al., 2018) in the study discusses the impact of rapidly changing climate due to globalization on the built environment and the exposure to and repercussions of occurrences like floods, drought and heat waves has become a concern. The study offers approaches to include thermal sensation issues. However, if this is taking place outside a person's home, it has a big impact on how comfortable it is inside. A trend in the maximum air temperature (Tmax), minimum air temperature (Tmin), and mean air temperature (Tmean) daily values recorded from 1976 to 2016 for Roorkee, India, addresses the previously described issue. To determine the number of comfort hours on the tropical summer index, the simulation tool Design Builder analyzed weather data files. The study was utilized to simulate several passive design tactics and present the best passive design choices for India's diverse climate. Contemporary construction methods have been published for simulation (RCC structure with infilled brick walls between the column and beam). Each decadal weather file has been simulated, and the findings for the indoor air temperature, radiant temperature, relative humidity, and air velocity have been used to determine the number of indoor comfort hours using the Tropical Summer Index. By installing exhaust fans, a staircase can be used as a ventilation shaft to cut the number of hours (1687–19%) spent feeling chilly and increase the number of hours (28–30%) spent in thermal comfort (251–2653). Measurements and strategies demonstrate that passive-design solutions, such as highly thermally efficient wall and roof assemblies, operate as a design strategy with only small modifications in terms of the need for space.

Tungnung, (2020) in the paper focuses on optimizing the design process for galvanized iron roof two-story houses in North-East India, which falls under the Cool-Humid climatic zone. The goal is to reduce energy consumption by predicting thermal performance at diurnal time scales and adapting space functions accordingly. The study introduces a novel parametric strategy that explores the mutual affordances of space forms, materials, climate, and lifestyles, emphasizing the potential of passive solar technologies in retrofitting existing buildings for enhanced energy efficiency.

The research adopts a multi-method approach comprising

(1) Affordance theory criticism,

(2) Climate, architecture, and lifestyle survey,

(3) Parametric simulations, and

(4) Synergy analysis. It classifies passive design affordances into three novel categories:

Climate-Architecture-Affordances (CAA) – examining climate's influence on space design.

Lifestyle-Architecture-Affordances (LAA) – considering lifestyle needs in space utilization.

Parametric-Architecture-Affordances (PAA) – using parametric tools to optimize design.

The study reveals that flexible ventilation significantly influences indoor temperatures. For instance, in the living-dining space, the optimum temperature ranges are: 20–28°C in autumn, suitable for multi-functional use like bedroom, kitchen, and social space. 17–22°C in winter and 20–31°C in summer, supporting diverse space functions. Conversely, the attic-space experiences high peak temperatures due to low thermal mass and high thermal conductivity. However, adaptive ventilation strategies like 30 air changes per hour (ACR) in autumn and combined day and night ACRs in summer effectively reduce temperatures to ≤35°C in autumn and ≤41°C in summer. This space can function as a day space in winter and a bedroom on summer nights due to its high heat emissivity. The shaded veranda maintains comfortable temperatures (18–28°C) during summer evenings, serving as a semi-outdoor space for light work and leisure activities. The findings highlight the effectiveness of parametric passive design strategies in optimizing space functions while enhancing thermal comfort and energy efficiency. The study concludes that affordance theory—integrated with parametric design tools—provides a robust framework for adaptive space utilization, paving the way for economical low-energy architecture in North-East India (Tungnung, 2020).

The study by Naik and Oswal (2020) examines passive design strategies derived from vernacular factors to create energy-efficient housing solutions for Bangalore, a city in the temperate climate zone of southern India. The research highlights how rapid urbanization, changing social dynamics, and evolving occupant requirements have impacted housing designs, necessitating passive strategies for sustainable development. Bangalore's moderate climate, characterized by temperatures ranging from 15°C to 35°C, distinguished wet and dry seasons, and natural ventilation potential, makes it an ideal setting for exploring passive architectural solutions. However, climate change and urbanization have led to more extreme temperatures, increasing the importance of adaptive design.

The study identifies five key components influencing vernacular housing designs: sun, wind, topography, local materials, and spatial distribution. These components guide passive design strategies, including orientation, transitional spaces, building envelopes, shading devices, and natural ventilation. Specific strategies include orienting shorter sides of buildings to the North and South to minimize solar heat gain, incorporating verandas or courtyards as semi-private transitional spaces to diffuse light and reduce direct heat exposure, and using low heat-gain materials and sloped roofs to reflect sunlight. Facades with multiple angles are recommended to minimize heat absorption, and openings are strategically positioned to optimize wind flow and reduce glare.

The research also emphasizes the importance of material selection, advocating for the use of locally available materials like red clay, bamboo, and terracotta due to their low heat gain and high reflectivity. The study suggests avoiding high heat-absorbing materials like RCC and encourages traditional construction techniques to promote sustainability and local employment. Additionally, the research underscores the need for functional spatial zoning, placing heat-generating areas like kitchens with appropriate ventilation and using transition spaces on sun-exposed sides to diffuse heat. By integrating social hierarchies positively within housing designs, the study suggests enhancing community interaction and energy efficiency.

Overall, the study provides comprehensive guidelines for future residential developments in Bangalore, balancing vernacular wisdom with contemporary requirements to achieve energy-efficient and thermally comfortable living environments(Naik & Oswal, 2020)

The study of materials and passive cooling strategies in vernacular architecture demonstrates how traditional buildings in warm-humid climates achieve thermal comfort and energy efficiency. By utilizing locally sourced, heat-resistant materials like brick and mud, these structures effectively regulate indoor temperatures, reducing reliance on mechanical cooling systems. Passive design techniques such as shaded courtyards, ventilated walls, and semi-enclosed spaces enhance comfort while minimizing energy consumption. Case studies reveal how features like high thermal inertia walls in Mediterranean architecture and strategic courtyard designs in Indian homes optimize thermal performance. These findings highlight the relevance of climate-responsive design, rooted in cultural and environmental contexts, in addressing modern challenges like global warming. The research underscores the potential of integrating traditional passive cooling strategies with contemporary construction practices to create sustainable and resilient built environments, emphasizing the importance of site-specific and culturally adaptive architectural solutions for achieving energy efficiency and thermal comfort.

2.2 Climate-responsive Vernacular Architecture as a Bioclimatic Design and Climate Change Resilience

Climate-responsive vernacular architecture plays a crucial role in designing buildings that align with their natural environment, particularly in the face of climate change challenges. Rooted in traditional building practices, vernacular architecture incorporates regional climate knowledge, optimizing energy use, enhancing thermal comfort, and reducing reliance on mechanical systems. This approach is fundamentally based on bioclimatic design principles, which focus on adapting the built environment to local weather conditions through passive strategies such as natural ventilation, shading, and the use of locally sourced materials.

The integration of these principles offers a pathway for resilient and sustainable architecture, as it minimizes environmental impact while improving occupant comfort. As climate change intensifies, the need to revisit and incorporate these time-tested strategies becomes increasingly urgent. Research on climate-responsive vernacular architecture highlights how traditional building forms and techniques, such as strategic window placement, thermal mass, and roof designs, can be leveraged to mitigate the effects of temperature fluctuations and extreme weather events.

(Keskin & Erbay, 2016) The Features investigated Settlement Characteristics and examined over the same province as their architectures were explored in the research. The results of this study demonstrate that traditional homes are built in harmony with the regional climate, landforms, and the natural environment, minimizing environmental impact by lowering energy requirements through efficient use of energy sources.

(M. K. Singh et al., 2010) researched to explore the vernacular homes placed in the climatic zones in the northeastern state of India and their comfort levels. The thermal performance was done for selected vernacular homes in the region by employing adaptive models proposed by Humphreys and Auliciems. The study predicted comfortable temperatures and the percentage of thermally comfortable time within these homes. Additionally, the research incorporated survey data to conduct comprehensive comfort analysis. Through these analyses, the study delineated an average temperature range conducive to an optimal indoor environment. Moreover, the researchers leveraged the "adaptive technique," which evolved from field studies and was eventually integrated into ASHRAE Standard 55/2004, to estimate the comfortable temperature ranges specific to vernacular structures endowed with natural ventilation.

Alapure et al. (2014) developed a sustainability assessment model for traditional built forms using a combination of the Delphi group decision-making method, Analytical Hierarchy Process (AHP), and Fuzzy Logic (FL). The study assessed the relevance of traditional architecture through thermal analysis of mud and stone masonry houses in South-West Bengal and Western Maharashtra. Climatic data and physical measurements were recorded alongside an interview-based questionnaire survey to understand user perceptions. Case studies included the Swapan Adhikari House in South-West Bengal and the Raghoba Salunkhe Wada in Western Maharashtra, both naturally ventilated buildings utilizing locally available materials like mud, stone, and thatch.

Methodologically, the study used AHP for Multi-Criteria Decision-Making (MCDM) to determine the relative importance of sustainability criteria, while Fuzzy Logic quantified complex factors into understandable ratios. Thermal analysis was conducted on three types of buildings with different materials (mud, stone, and modern materials), revealing that mud walls with thatch roofs significantly reduced energy consumption compared to contemporary building materials.

The findings highlighted the effectiveness of passive design strategies, such as high thermal mass walls and natural ventilation, in maintaining indoor comfort. In warm-humid climates, the mass effect of heavy constructions provided stable temperatures. Night ventilation further enhanced cooling by dissipating stored heat. The study emphasizes the relevance of traditional wisdom in sustainable architecture, advocating for the integration of high thermal mass walls, internal courtyards, and ventilated attic spaces to optimize indoor comfort while minimizing energy use(Alapure et al., 2014).

(Beccali et al., 2018) in research discusses models that use adaptive comfort techniques to assess thermohydrometer comfort in naturally ventilated buildings. The study validates and has a solid scientific framework of the thermal comfort models discussed, but considering the results, significant effort still must be made to integrate and transform them into appropriate standards. It must be emphasized that good energy efficiency can be achieved while using fewer HVAC systems by applying unified Standards (UNI EN 15251:2008 and ASHRAE 55,) for evaluating building technology design options in a naturally ventilated built environment. The best approach could be to apply vernacular and bioclimatic concepts; this is also helpful in developed nations.

The study by Choudhury and Chettry (2023) investigates bioclimatic features in the vernacular architecture of Northeast India, focusing on two housing typologies: Assam-type houses and Stilt houses (Chang Ghar). These typologies are prevalent in Assam, which lies in a humid subtropical climate zone characterized by high humidity, heavy rainfall, and susceptibility to flooding. The study examines how these houses effectively respond to local climatic conditions through passive design strategies, contributing to energy efficiency and sustainability.

Through qualitative analysis based on site surveys, the study evaluates bioclimatic features using ten parameters: construction materials and methods, spatial arrangement, orientation, wall thickness, open spaces, vegetation, ventilation, window-to-wall ratio, plinth height, shading devices, ceiling design, and special features. The findings reveal that both typologies utilize locally available materials such as bamboo, Sal wood, teak, and mud due to their climate resilience and earthquake resistance. Assam-type houses use wattle and daub walls with elevated brick plinths to prevent moisture ingress, while Stilt houses are raised on bamboo stilts (130-160 cm or more) to protect against flooding and enhance air circulation through perforated bamboo floors.

Both typologies incorporate high ceilings (240 cm to 350 cm) for natural ventilation and lighting. Attics and voids between walls and roofs allow warm air movement and temperature regulation, with perforated bamboo or timber screens maintaining airflow while allowing light penetration. Additionally, openings are oriented to align with prevailing wind directions to maximize ventilation. The lightweight materials used contribute to earthquake resilience, while the strategic use of stilts effectively addresses flood risks.

The study concludes that these vernacular designs are highly responsive to local climatic conditions, reflecting socio-cultural and economic influences. The integration of bioclimatic features enhances thermal comfort, energy efficiency, and disaster resilience. The findings provide valuable guidelines for sustainable architectural practices in humid subtropical regions, supporting the United Nations Sustainable Development Goal 11 for sustainable cities and communities(Choudhury & Chettry, 2023).

(Bodach et al., 2014) in the research discussed Nepal - Bioclimatic analysis suggests vernacular building design also optimized to use natural resources in cold winter by using solar passive heating strategies, in summer by designing medium-sized windows with shading to enhance air movement and high thermal mass which reduces the impact of rain and cold of with medium-sized windows high thermal mass protects from the cold and rain.

Indraganti (2018) explores bio-climatic vernacular architecture in India, focusing on warm-humid climates while also addressing hot-dry, composite, and cold climates. The study highlights how traditional designs harmonize with local climates, ensuring thermal comfort and energy efficiency. It examines various strategies, climate zones, methodologies, and tools to optimize thermal comfort.

Climate Zones and Strategies:

Warm-Humid Climate: Characterized by high humidity, minimal temperature variation, and heavy rain. Strategies include perforated structures with courtyards, spread-out layouts, deep eaves for rain protection, high plinths to prevent flooding, and high-level ventilators for hot air exit. Lightweight wooden roofs with clay tiles offer low capacitive insulation, ensuring ventilation without significant thermal lag.

Warm-Humid Maritime Climate: High temperature, humidity, and solar radiation necessitate increased ventilation. Lightweight, close-knit shelters provide sun protection while allowing airflow.

Hot-Dry Climate: Requires insulation against intense heat and hot breezes. Designs incorporate compact layouts with thick walls for thermal mass and shaded courtyards for passive cooling.

Composite Climate: Adapts to seasonal extremes using semi-open built forms. Examples include Sevagram, which employs heavy mud brick walls for summer insulation and clear story openings for monsoon ventilation.

Cold Climate: Emphasizes heat retention with compact planning, timber-framed walls, and stone masonry for insulation and seismic resistance.

The study uses a descriptive-analytical approach, examining traditional architectural forms across climatic zones. It evaluates thermal comfort by analyzing building envelopes, ventilation techniques, and material properties. The research relies on climate data, historical case studies, and examples of modern vernacular adaptations to provide design guidelines that integrate indigenous materials with contemporary needs (Indraganti, 2018)

The above research highlights the importance of climate-responsive vernacular architecture in mitigating the challenges posed by climate change. It emphasizes how traditional building practices, rooted in regional climate knowledge, optimize energy use, enhance thermal comfort, and reduce reliance on mechanical systems. Studies show that integrating bioclimatic principles such as natural ventilation, shading, and locally sourced materials can lead to more resilient and sustainable buildings. Research also underscores the effectiveness of passive strategies like solar heating and thermal mass in regulating indoor temperatures. Additionally, adaptive comfort models for vernacular homes, especially those in diverse climatic zones, offer insights into improving energy efficiency and indoor comfort without heavy reliance on HVAC systems.

2.2.1 Vernacular Architecture's Role in Climate Change Resilience

The objectives of the reviewed studies are to examine the impact of vernacular architecture on modern sustainable building practices. These studies explore how traditional design methods and passive strategies such as natural ventilation, thermal mass, and climate-responsive layouts improve energy efficiency and indoor comfort. The aim is to bridge the knowledge gap between historical building practices and current technological advancements, showing how these age-old solutions can inform and enhance modern architectural design. The studies also investigate how vernacular methods contribute to urban planning, regional adaptation, and climate resilience, offering a blueprint for future architectural developments.

(Y. Wang et al., 2016) investigated how traditional Chinese architecture, which has a comprehensive understanding of ecological design, relates to green building research and nature. This article demonstrates a green building method and an integrated ecosystem approach using the Xijie neo-vernacular architecture. The article provides references for upcoming studies that will be relevant to modern design while summarizing green techniques for cold winter and hot summer places.

(Zhai & Previtali, 2010) The study indicates that the vernacular architectural traditions and knowledge of quantitative design will aid architects in maximizing the energy efficiency of contemporary structures. (Michael et al., 2017) The different ventilation strategies, including afternoon, full-day, and night ventilation, were examined. Additionally, several window opening patterns for cross-ventilation at night were investigated. The investigation illustrates that, during the hot summer, night ventilation improves more comfortable circumstances than other solutions in the houses. The ventilation at night also helps maintain comfortable indoor temperatures when the outside temperature is at its highest in the daytime.

(Azarbayjani, 2019) To analyze the impact of urban elements (vegetation, water bodies, courtyard streetscapes, street shades and wind catchers, on urban comfort, the analysis was done using simulations in the ENVI-MET software. The city of Yazd, which has a hot, arid climate, was selected to study the various architectural components such as wind captures, courtyards, and other features that assist the city in adapting to its desert-like climate. The context was modelled in Envi-Met (the simulation software), and each environmental category was added to investigate them individually and together to learn lessons for future urban planning.

(Nie et al., 2019) in their paper investigate the possibility of enhancing interior thermal comfort and conclude field research for indoor settings in the Tibetan area. It talks about the documenting of houses with materials and construction highlighted. Kham's climate design strategies for responsive climate design satisfy regional financial levels and contemporary living requirements are the combination of Town location and town layout aspects of the environment, cultural values, considering the optimization of space, materials, seismic design for structures and implementing passive solar energy strategies. The test parameters for the Pekong dwelling include indoor air temperature, relative humidity, and wall-windows surface temperature, whereas the test parameters for the Kangba residence only include air temperature. Examining Tibetan habitation locations and layout designs is the first step in design that considers both the natural environment and culture. Building settlements on mountain slopes is particularly advantageous since buildings on south-facing slopes absorb more direct sunlight compared to flat villages, while those on north-facing slopes rely on the mountain to protect them from the brisk plateau wind in the winter.

(Shastry et al., 2014) This study examines the impact of passive solar components on the thermal comfort of indoor space using cutting-edge climate-responsive design methodologies. The effects of switching from conventional to modern material combinations were investigated using dynamic simulation models backed by quantifiable data. The vernacular strategies were found to be in line with current knowledge of bio-climatic analysis and climate resilience, while the average was observed to be increasing concerning contemporary transitions. Analysis of the adoption of modern design and building materials raises the temperature by 7 to 10ºC in the summer, which increases the requirement for HVAC systems to maintain indoor comfort. The presence envelope features like a roof overhang keep the room 3.5ºC cooler. According to the survey, the typical inhabitants of traditional homes would fall beyond Givoni's Bio-Climatic chart's extended thermal comfort zone.

(Baghaei Daemei et al., 2018) Wind CFD simulation analysis is done for existing wind patterns and little change in the planning of houses to understand why people need modification in their house form in the present scenario considering ventilation aspects. (Santy et al., 2017) Form analysis is done by using bio-climatic charts, Mahony tables, and Energy Simulation to analyze the need for natural ventilation. The research proposed improvement in natural ventilation to deal with high Rh and high temperature. The study also recommended shading devices for solar radiation.

(Takebayashi, 2019) focuses on the appropriate selection and arrangement of buildings, trees, and covering materials through the investigation of redevelopment buildings to understand microclimatic components and their impact on thermal environmental design in outdoor space.

(Tandon & Sehgal, 2017) study investigates the character of one of the commercial streets Vishram Bazaar of Mathura's. This study aims to identify the spatial physical characteristics of the street in terms of physical attributes including enclosure, imageability, transparency, human scale, and complexity, as well as to ascertain the applicability of these characteristics in Indian holy streets.

Sheng et al. (2021) conducted in-situ monitoring campaigns in Cambridge (UK), Hong Kong, and Shanghai to assess the energy performance of residential building envelopes across distinct climatic zones. The study examined thermal transmittance (U-value), a key indicator of energy efficiency, and analyzed how climate and policy influence building performance. By employing the single thermal mass (STM) model with Bayesian prediction, the researchers achieved precise U-value estimations from measured data, demonstrating that in-situ monitoring provides more reliable results than conventional tabulated data.

The findings revealed significant regional variations in building envelope performance due to differing energy policies and climate conditions. Cambridge's building exhibited superior insulation due to stringent net-zero energy policies, whereas Hong Kong's building was more vulnerable to temperature fluctuations due to less robust insulation regulations. Shanghai fell between the two, reflecting its transitional climate and evolving policy framework. The study underscores the necessity of climate-sensitive and region-specific energy efficiency policies. Coordinated policy frameworks and inter-regional collaboration are recommended to enhance building resilience against climate change and energy demand growth. For example, Hong Kong could benefit from adopting stricter insulation standards modeled after the UK's net-zero initiatives.

While the research highlights the effectiveness of tailored policies, it also acknowledges limitations, including the small sample size (one case per climatic zone) and the focus on unoccupied buildings. Future studies should expand the sample size and examine a broader range of building types to provide more comprehensive insights. Overall, pioneering cross-regional analysis emphasizes the need for localized energy-saving policies that account for climatic conditions and building characteristics. Their findings provide a foundation for developing sustainable energy standards that balance regional needs with global climate goals(Sheng et al., 2021).

(Remali et al., 2016), in the study looks at the growth of housing typologies in four significant Gulf cities: Abu Dhabi, Doha, Manama and Dubai. The study explores the creation of the region and historical occurrences that have significantly influenced modern social and economic realities in addition to changing types of dwellings across the past two centuries.

(Shabahang et al., 2019) A study describes how the layout of Iranian cities has changed because of a desire for modernity and the quick urbanization that followed, resulting in them being both manufacturers and consumers of greenhouse emissions and energy. The study investigates how Iran's urban planning and design processes now neglect adaptation and mitigation measures, even though they are crucial remedies to urban warming.

(Chandel et al., 2016) In order to adapt modern architecture to contemporary lifestyles, the study aims to explore vernacular architecture's aspects for energy-efficiencies that improve thermal comfort conditions of indoor. Investigated are vernacular architectural components of different climatic regions of the Himalayan state of Himachal Pradesh in India. There is also a case study on Hamirpur's composite climate zone. The relationship between vernacular architectural elements and thermal comfort levels is established by this study. According to the study, a new architectural style is developing in this Himalayan location that combines energy-efficient elements with modern design and building methods with passive solar characteristics to provide thermal comfort. The research recommended the thermal comfort of traditional homes, strengthening and extending the earth's durability as a building material, and the expansion of this architectural form. The study is relevant for enhancing thermal comfort in modern constructions across the world by utilizing locally accessible building materials and architectural components. The primary characteristics noted are constructed mass design, space planning, sun direction, supply of sunspace, apertures, construction methods, and building and roof and wall materials. Due to its natural thermal insulation, the earth is a widely utilized vernacular building material despite its low compressive strength and durability.

Hegde (2023) explores passive design strategies in vernacular architecture suitable for the warm humid climatic zone of South Kanara, located along the Konkan coast in Karnataka, India. This region experiences high temperatures (30–38°C) and heavy rainfall (around 3000 mm/year) with high humidity throughout the year, necessitating effective passive cooling techniques for thermal comfort. The study investigates traditional manor houses in South Kanara, which are isolated within farmlands surrounded by coconut and areca nut trees with high canopies that allow uninterrupted wind movement. These houses utilize climate-responsive architecture that incorporates passive design strategies such as optimal building orientation, lightweight materials, enhanced cross ventilation, and shading techniques. Specifically, the buildings are oriented with shorter sides facing east and west to minimize solar heat gain, and windows are positioned to catch prevailing winds for effective ventilation. Linear plans and open sections promote daylight and stack ventilation, while courtyards and verandas provide rain and sun protection, reduce glare, and improve air circulation. Light-colored roofs reflect solar radiation, and landscape features offer shade while maintaining airflow.

This research highlights the effectiveness of passive cooling strategies in reducing energy costs and dependence on active cooling systems. It advocates for integrating traditional design principles with modern techniques to achieve sustainable and energy-efficient architecture in warm humid climates (Hegde, 2023).

Saifudeen and Mani (2024) explore climate-responsive building adaptation strategies to enhance thermal comfort and resilience against climate change impacts, focusing on passive adaptation mechanisms. The study emphasizes temperature regulation as a critical factor due to the increasing frequency of extreme heat events. It examines adaptation strategies at both building and occupant levels, highlighting innovative approaches to thermal management.

At the building level, the study identifies several effective strategies. Designing building envelopes with double-skin facades, proper insulation, and shading devices help minimize cooling loads. Natural ventilation is another key strategy, achieved through adaptive use of openings such as windows, doors, and balconies, as well as flexible interior layouts that promote airflow. Landscaping plays a significant role in mitigating the urban heat island effect by incorporating increased vegetation, green roofs, and cool pavement materials. To enhance flood resilience, the study suggests designing flexible ground floors, supporting buildings on pillars, and implementing open stormwater systems to manage flooding. At the occupant level, the study highlights behavioral thermoregulation as an effective adaptation strategy. This includes adjusting clothing, modifying metabolic rates, and optimizing the use of blinds, curtains, and shades. Adaptive behaviors, such as changing locations within a building or using passive cooling methods, are also recommended to maintain comfort in varying thermal conditions.

The study underscores the importance of region-specific designs and recommends adapting simulation models to account for future climate scenarios. It also identifies research gaps, including the need for localized climate-change vulnerability assessments, a deeper understanding of vernacular architecture's adaptive capacities, and frameworks for evaluating building adaptation.

In conclusion, the paper emphasizes that sustainable building adaptation requires a holistic approach that integrates passive design principles, occupant behavior, and urban planning. These strategies are crucial for maintaining indoor environmental quality and reducing energy consumption in the face of climate change (Saifudeen & Mani, 2024).

Thapa et al., (2021) This article presents the results of the online thermal comfort survey that was carried out in India during the COVID-19 shutdown. The poll was conducted to find out more about the challenges and limitations people in lockdown encounter when staying home in India's various climate zones. The data show that changes in fan speed and window opening were observed together with changes in the mean temperature of the outside air. Contrary to what a quadratic relationship between the number of open windows and the outdoor mean air temperature suggested, the logistic regression between preference for outdoor air temperature and the use of fans suggested that participants preferred to use fans at much lower temperatures than those found in the previous study. In the afternoon when temperatures are high, individuals like to close their windows. The research also establishes the standards for thermal comfort in the built environment that are suitable (Thapa et al., 2021).

(Ray & Shaw, 2018) generalized a study without a survey structure, providing only the most basic information. The objective of this article is to trace the development of the built environment in a tiny West Bengali hamlet and the resulting loss of spaces that respond to the climate and are socially active. The perspective of the inhabitants who favor modernization of constructed form is based on primary data. Moreover, field trips were made to the research area near Malancha Road. Based on in-depth field observations, the traditional constructed form was examined, paying particular attention to the spaces that are incorporated into it that are socially engaged and climate responsive. A rise in the number of homes with contemporary architectural styles, the elimination of passive cooling systems and places for social interaction, and a rise in the usage of artificial climate control systems were also noted.

The research emphasizes the importance of integrating vernacular architectural strategies into contemporary design to enhance energy efficiency and indoor comfort. Studies on Chinese architecture (Wang et al., 2016) demonstrate how ecological design principles from traditional architecture can inform modern green building techniques, especially in regions with extreme weather. The use of passive ventilation, such as night ventilation, was shown to improve comfort during hot summers (Michael et al., 2017). Additionally, the impact of local climate factors on urban comfort, including vegetation and water bodies (Azarbayjani, 2019), highlights the role of urban planning in promoting climate adaptability. Investigations into Tibetan architecture (Nie et al., 2019) and the use of materials such as earth in Himachal Pradesh (Chandel et al., 2016) show how traditional methods can meet modern living requirements while Hegde (2023) showcased passive cooling in humid climates. These studies underscore the effectiveness of integrating vernacular techniques with modern technologies for sustainable urban planning, enhancing thermal comfort and energy efficiency in the face of climate change. These findings underscore the value of combining bioclimatic analysis with modern design to address current environmental and social needs.

2.3 Thermal performance against future climate change scenarios

The rapid urbanization of cities has led to significant changes in their land use and surface characteristics, contributing to alterations in microclimates and environmental conditions. Pune, a growing city in India, has witnessed a considerable increase in its built-up area, with a 43.1% rise from 1990 to 2019 (Gohain et al., 2021). This urban expansion has had a noticeable impact on the Land Surface Temperature (LST), which has generally increased in the summer and decreased in winter. The rise in LST, particularly in the urban areas compared to surrounding rural regions, suggests the emergence of urban heat islands. The study of such climatic changes is critical, as these shifts influence building performance, energy consumption, and overall urban sustainability. Additionally, the impact of climate change on buildings, including extreme weather events such as heavy rains, floods, and heatwaves, necessitates the incorporation of adaptive design solutions in construction. Traditional and passive building strategies, especially in regions with extreme climatic conditions, are vital in mitigating the effects of these changes.

(Gohain et al., 2021)The statistics show that Pune's built-up area rose by 43.1% from 116.6 square kilometers in 1990 to 166.9 square kilometers in 2019. 1990 through 2019 The mean LST (land surface temperature) across the city increased generally in the summer (5.8%) and decreased overall in the winter (12.4%). In contrast to the winter season's negative and dropping trend, the change in mean LST across various LULC (land use land cover) classes exhibits a large increasing and positive trend throughout the summer. Between 1990 and 2019, the mean LST on agricultural, shrub, aquatic, and fallow land has risen in comparison to the urban area throughout both the summer and winter seasons. The analysis revealed a 1.4 °C LST difference between the city and the neighboring rural area, pointing to the potential presence of an urban cool island above the metropolis.

Zięba et al., (2020) The study includes a quantitative examination of statistical data on building catastrophes in Poland, as well as a review of reports and publications that explain the reasons and effects of specific failures. The research was conducted using data from 2006 to 2018 and found that construction calamities are mostly caused by random occurrences, with human mistakes in the design and execution stages contributing to disasters to a lesser extent. Strong winds, floods, heavy rains, and floods are becoming more common due to global warming and climate change. They are not only a direct destructor, but they also induce landslides and tree flipping. Lightning, high temperatures, and dryness are all factors that contribute to wildfires. The structural elements are subjected to higher pressures, severe temperatures, powerful winds, whirlwinds, floods, and landslides, all are affected due to climate change (Zięba et al., 2020).

Stagrum et al., (2020) Adaptation procedures are necessary to ensure the built environment's long-term integrity and effective operation. This study analyses the literature on creating climate adaptation strategies through a broad literature review. The majority of the information focuses on how buildings in warm climates are affected by climate change, with overheating being the most important problem (Stagrum et al., 2020).

Parishwad & Shinkar, (2017) The constructed area of Pune has experienced diurnal temperature fluctuations as a result of increasing urbanization and population increase. The study investigated this premise by estimating the impact of climate change on the Pune Municipal Corporation area through remote sensing technology data (Parishwad & Shinkar, 2017).

Rawal et al., (2022) India Model for Adaptive Comfort-Residence, or IMAC-R. According to a given outdoor reference temperature, the model indicates the operating temperature bands for 80% and 90% thermal desirability for naturally ventilated (NV) and mixed-mode (MM) dwellings, respectively. The neutral temperature recommended by IMAC-R was, on average, 2.9 °C and 2.1 °C warmer than the neutral temperatures recommended by IMAC (Indian model for adaptive comfort for commercial building) NV and MM. Furthermore, it exceeded the neutral temperatures suggested by the current models of EN 16798-1 and ASHRAE-55 increase by 3 °C and 2 °C, respectively. IMAC-R has the capacity to address the country's thermal comfort demands while establishing the framework for sustained energy savings and the mitigation of climate change (Rawal et al., 2022).

Bano & Sehgal, (2019) This study identified the demands and shortcomings in India's office building envelope optimization. Additionally evaluated were the design concerns for the building envelope, modern simulation and optimization approaches, criteria for selecting simulations, and optimization tools. Over 100 studies were examined, with a focus on work conducted in India on relevant subjects. Based on statistical graphs created from the reviews, the results are presented. The approach for the research and creation of a base case model, the choice of building design variables, and simulation and optimization tools are some of the outcomes. One of the results the most common construction materials used for building energy optimization (BEO) are siding, roofing, and glass (Bano & Sehgal, 2019).

X. Wang et al., (2019) Passive solar solutions have long been thought to be a cost-effective way to heat a building. Traditional passive solar buildings, on the other hand, fall short of creating a somewhat steady and comfortable indoor temperature environment. This research suggests that without requiring extra energy for heating, the hybrid heat collecting facade (HHCF) proposed in this study can raise the air temperature of the interior spaces(X. Wang et al., 2019).

Chen et al., (2015) By analyzing the thermal performance of a case study building, particularly lifecycle energy usage, under multiple climate change scenarios and climate zones, the authors investigate the durability of passive design strategies through time. Initially, the solar heat gain coefficient (SGHC) was altered. To assess the building's performance in the 2020s, 2050s, and 2080s, three future climatic conditions (for mild, moderate, and severe climate change) were constructed for three climate zones (Chen et al., 2015).

Khadeeja et al. (2019) investigate the climate responsiveness and thermal performance of vernacular dwellings in Suggenahalli village, India, focusing on their adaptability to climate change. The study emphasizes the resilience of traditional building designs, which evolved to regulate comfortable indoor conditions in response to external climates. It also examines the impact of transitioning from vernacular to modern construction materials on thermal comfort, highlighting the growing reliance on electro-mechanical appliances for space conditioning as occupants' lifestyles evolve.

The research focuses on Suggenahalli, located in a warm-humid climate zone, with temperatures ranging from 14°C to 36°C. Vernacular dwellings in this region are constructed using local materials such as stone, mud plaster, timber, bamboo, and clay tiles. A representative dwelling, characterized by thick rubble masonry walls, a courtyard layout, and a combination of mud and Mangalore tiled roofs, was selected for in-depth study. The thermal performance of this dwelling was evaluated under three climatic scenarios: warm-humid (current), hot-dry (possible future if temperatures increase), and temperate (possible future if temperatures decrease). Weather files from Sholapur (hot-dry) and Bangalore (temperate) were used for dynamic simulation modeling to assess the dwelling's adaptability to changing climates. The study employed a mixed-methods approach, including real-time monitoring and dynamic simulation modeling using DesignBuilder integrated with EnergyPlus. Indoor and outdoor temperatures, relative humidity, and dew point were recorded every 30 minutes using calibrated data loggers over a period from June to July 2010. The simulation model incorporated the thermal properties of traditional materials and included neighboring houses to provide a realistic representation of the built environment.

Results revealed that the vernacular dwelling maintained comfortable indoor temperatures across all climate scenarios. In the current warm-humid climate, indoor temperatures ranged from 23°C to 31°C, effectively buffering against outdoor temperatures of 21°C to 34°C. In the hot-dry scenario, indoor temperatures were slightly higher but still within a comfortable range, while in the temperate scenario, indoor temperatures consistently exceeded outdoor temperatures, maintaining comfort. The study attributed this thermal resilience to the physical characteristics of the building envelope, including thick masonry walls, strategic ventilation, and a courtyard layout that enhanced passive cooling. In contrast, the modernized dwelling, which replaced traditional thick masonry with thinner brick walls and RCC roofs, performed poorly in all scenarios, particularly in warm-humid and hot-dry climates. The study concluded that vernacular designs offer superior climatic resilience and thermal comfort compared to modern constructions, underscoring the value of traditional wisdom in building design amidst climate change (Khadeeja et al., 2019).

Alhindawi & Jimenez-Bescos, (2020) The impact of high and medium-high emission scenarios on thermal comfort range, passive zone potential, and heating/cooling periods for the 2050s and 2080s future timelines is tested in this paper with Energy Plus software and EPW weather files for dynamic simulations. Simulation findings show a significant impact on the size of daily cooling hours and monthly coverage for the high GHG emission scenario, resulting in a 60% increase in their range, during summer peak 3 months/year and daily 6 hours, with a 33.3% yearly decrease in heating period (Alhindawi & Jimenez-Bescos, 2020).

Andric & Al-Ghamdi, (2020) research quantifies the consequences using a case study of Qatar's residential sector. The energy consumption of a structure from the national building portfolio was predicted for current and future weather conditions. The results indicate that heat waves will happen more often in the future, and they will also be longer and more intense. Up to 30% more energy is anticipated to be used in buildings. A rise in energy consumption would lead to increased water levels, quicker fossil fuel depletion, and a greater effect on the marine environment in the area. To mitigate the consequences on the environment, regional environmental legislation should be adopted for major renovations of existing structures including the installation of energy from renewable sources (Andric & Al-Ghamdi, 2020).

Mahadevia et al., (2020) Official state and city rules, particularly in the case of vulnerable populations, do not specifically mention heatproofing for new or existing homes to reduce indoor heat exposure. In 26 settlements in Ahmedabad, India, during the height of summer (formal and informal), the authors monitored the temperatures for three different housing typologies inside and outdoors of 860 low-income living inhabitants. As an aspect of a long-term urban development strategy to address the impact of interior temperature, researchers contend that deliberate efforts towards heatproofing currently existing informal housing are crucial, especially for households with low incomes and residents of informal housing. The relocation of residents from informal housing to official housing is one of the strategies under investigation right now (Mahadevia et al., 2020).

Liu et al., (2020) Examine the dynamic efficacy of passive design techniques for residential buildings in Hong Kong in light of the anticipated climate change. simulation-based sensitivity analyses and Givoni building bioclimatic charts (BBCC) have been utilised to track the efficacy of workable and residential buildings for the time in 21st century by placing strategies for passive design. The data is drawn from newly created hourly weather data and an adaptive comfort standard model. The results demonstrate that sun protection measures remain the most critical ones for a building's energy efficiency. By the end of the century, the airtightness of external windows is predicted to improve by 329%, while the cooling potential of ventilation use will prominently decline. Up to 56.7% and 64.5%, respectively, can be taken off the yearly and peak cooling loads of a residential building model when multiple combinations of sensitive passive design components are introduced for varying temperature scenarios. The yearly and peak cooling loads may be decreased by up to 56.7 and 64.5 per cent, respectively, when various combinations of exact passive design components are introduced to the fundamental residential building model for various climate situations (Liu et al., 2020).

Wright & Venskunas, (2022) the study discusses modern houses (row houses with terraces semi-detached and detached) and their comfort performance. Overheating is measured by using established parameters, such as a bedroom's temperature at night reaching 26 ^{o}C, and overheating is measured. Simulations are done for future weather years for the present, 2030s, 2050s, and 2080s using media under medium and high-emission scenarios for 14 locations in the UK. The results indicate that overheating will significantly increase in all 14 locations by the 2080s. Sunshade and natural ventilation greatly reduce overheating, providing comfort in the northern locations most by 2050s but few locations by 2080 (Wright & Venskunas, 2022).

Huang & Hwang, (2016) This work employed the morphing approach to model hourly weather data for future years while creating simulations based on projected values from a GCM. In order to calculate cooling energy consumption, the adaptive comfort model has been used to identify cooling hours required in the mixed-mode residential building during the occupancy period. The yearly cooling energy consumption for the past and three-time slices into the future—the 2020s, 2050s, and 2080s—was dynamically estimated using Energy Plus. The simulations showed rises in cooling energy of 31%, 59%, and 82% in the three time slices. We look at five passive design ideas that could be used to redesign buildings and reduce the amount of energy needed for cooling. The results demonstrate that a variety of passive techniques can help to lessen the effects of rising cooling energy use, even though no single strategy can totally counteract such effects (Huang & Hwang, 2016).

Kishore, (2022) the article looks at the effects of bioclimatic passive cooling and heating strategies for climate change scenarios in five locations across India. IPCC (Intergovernmental Panel on Climate Change) A2 (medium-high) scenario, weather data were created using climate change world weather tool using TMY (Typical Meteorological Year), for four time slices, namely TMY, 2020, 2050, and 2080. Residential buildings were selected as a case and logger data was used to calibrate energy plus simulation to check the potential of bioclimatic strategies. Assuming residential buildings do not implement passive design solutions, the rise in annual demand for cooling energy beyond the base scenario varies among the five cities from 18 to 89 percent in 2020, 32 to 132 percent in 2050, and 58 to 184 percent in 2080. Karimpour et al., (2015) The modern house form analysis is discussed in the paper while considering housing categories. Change in combinations of insulation in an exterior wall, in interior wall, in roof, and thermally reflecting roofing with various floor covering and their cooling and heating demand has been investigated in this research using a robust future TMY for 2070. Researchers investigated several design factors that primarily affect this energy usage. Each variable was subjected to the main alternatives usually used in structures. Changing the weather year has been the method of choice for evaluating the consequences of climate change in a range of climatic settings by using the software tool to adjust for them when constructing models (Kishore, 2022).

Campagna & Fiorito, (2022) The research employed statistical techniques to map the quantitative effects of climate change on building energy use and explore possible correlations between energy variation and a range of variables, such as the reference period, IPCC emission scenarios, future time slices, as well as cooling and heating and degree-days (CDDs & HDDs). The range of data obtained emphasizes the importance of doing more focused impact analyses to find effective adaptation approaches (Campagna & Fiorito, 2022).

Henna et al., (2021) The study assesses the climate-resilience of traditional homes as well as those in transition (structured economic growth and adoption of clean and resource-efficient technologies) in response to three climate change scenarios, A1B, A2 & B1 (A1B- rapid economic expansion supported by balanced energy consumption, A2- regionally sensitive economic development, and B1-rapid changes towards a service and information economy). The study, which looks at dwellings in three rural Indian towns that represent three significant climate zones, uses both real-time monitoring and simulation-based research. The study stands out because it contrasts how climatic change affects indoor thermal comfort in rural dwellings employing both traditional and modern materials. According to the study, traditional homes are better able to withstand climatic change (Henna et al., 2021).

Zune et al., (2020) research examines the vernacular dwellings of Myanmar to analyze the thermal performance of passive design strategies. Simulation studies were conducted using an experimental design method to examine the thermal performance of dwellings and the impact of passive strategies of three different climate zones of Myanmar. The two dwellings' passive design concepts were investigated in more depth. With typical weather and predicted future climatic circumstances, a thermal performance test produced fifteen models. The findings demonstrate that, under the projected future climatic conditions, conventional passive design methodologies will not be sufficient to guarantee thermal comfort. To cope with the changing environment, the authors advised that Myanmar vernacular housing's passive design practices be upgraded, including new solutions (Zune et al., 2020).

Leo Samuel et al., (2017) Cover sensor-only research but provide a better grasp of traditional materials versus passive techniques. In July 2014, the thermal comfort of eight traditional structures that incorporate contemporary building components to increase structural durability was observed. The buildings having various passive cooling strategies such as high thermal mass, and induced ventilation and air chamber situated in Hyderabad, India selected for the study. Between the summer and monsoon seasons, research was conducted on traditional architecture utilizing contemporary materials. The interior spaces of six buildings are uniformly comfortable when considering the 80% adaptive comfort standards. Each passive cooling technique that was looked at was found to have a considerable effect on the interior space's thermal comfort. The roof's ventilated air gaps helped to lower the inner surface's average temperature by 1.2°C. A structure with a higher thermal mass had a 0.9 °C lower diurnal temperature change of the inside air than a building with a thin roof and a thin wall. Most of the time, all eight buildings some of them in the morning, others at night—were thought to be outstanding (Leo Samuel et al., 2017).

Andrić et al., (2019) discussed climate change's impression on the built environment and how such effects might be reduced by using appropriate passive methods in conjunction with materials selection and insulation. The main goal of this study is to provide comprehensive, multidisciplinary insights into the potential effects of climate change on the energy efficiency of the built environment, as well as associated effects, potential mitigation strategies, and associated barriers to their implementation in both developed and developing countries. Priority was given to peer-reviewed journal articles written in English and released up until April 2018. A total of 169 articles were evaluated for the final selection. According to research, structures in hot-humid climates are more susceptible to the effects of climate change. While cooling needs could increase by up to 150%, heating needs could decrease by up to 264%. (depending on the location and the building's qualities that have been observed) (Andrić et al., 2019).

Gohain et al., (2021) The major goal of this study (1990-1999, 1999-2009, and 2009-2019) is to determine how changes in the city's land use, land cover, and seasonal variations in LST have altered over the past three decades. According to the findings, the built-up area increased overall from 116.6 km2 in 1990 to 166.9 km2 in 2019, an increase of 43.1% over the course of the research period. Between 1990 and 2019, the city's mean land surface temperature increased in the summer (5.8%) and decreased in the winter (12.4%). In contrast to the downward and falling trend throughout the winter, the change in mean LST across different LULC classes exhibits a considerable upward and positive tendency throughout the summer. The change in mean LST across different LULC classes shows a significant upward and positive tendency throughout the summer, in contrast to the negative and decreasing trend during the winter (Gohain et al., 2021).

Palme et al., (2013) examine how the energy consumption of recently constructed residential structures would alter as a result of climate change in the years 2040 and 2070 under three different scenarios. To mimic the energy performance of buildings, several scientists have created a wide range of models during the past 30 years. The "sensitive" and "robust" building typologies differ slightly according to the climatic location. Yet, the broad definition of "sensitive" and "robust" building procedures yields two universal characteristics of the samples: Thermal mass values for robust buildings are high, compared to those for sensitive buildings, which are either medium or low. Up to 10% of the façades of robust buildings are made of glass, compared to up to 50% for sensitive buildings (Palme et al., 2013).

Rapid urbanization in Pune, India, has significantly impacted land use and Land Surface

Temperature (LST), with built-up areas increasing by 43.1% from 1990 to 2019. This urban expansion has led to a rise in summer LST by 5.8% and a decrease in winter LST by 12.4%, contributing to urban heat island effects. These climatic changes influence building performance, energy consumption, and urban sustainability, necessitating adaptive design solutions. Traditional and passive building strategies are crucial for mitigating the adverse effects of extreme weather events like heatwaves and floods. Vernacular architecture demonstrates resilience against climate change, particularly in regions with harsh climates. Studies in Suggenahalli, India, highlight that traditional dwelling, built with local materials and designed with passive cooling features, maintain thermal comfort across different climate scenarios. Conversely, modern constructions with thinner walls and RCC roofs perform poorly, increasing dependence on energy-intensive cooling systems.

Climate change is further implicated in the increasing frequency of extreme weather events such as strong winds, floods, and heavy rains, which, in turn, contribute to structural failures in buildings. Literature underscores the necessity of climate adaptation measures to ensure the sustainability and resilience of built environments. Passive design strategies, including vernacular architecture, are identified as key solutions for mitigating temperature fluctuations and reducing energy consumption. Traditional dwellings in regions such as India and Myanmar demonstrate superior thermal performance compared to modern constructions, reinforcing the importance of integrating indigenous knowledge with contemporary design principles.

Additionally, studies emphasize the role of adaptive comfort models, such as IMAC-R (Indian Model for Adaptive Comfort – Residential) for naturally ventilated building, in optimizing indoor temperatures and reducing reliance on mechanical cooling systems. Passive solar solutions, insulation improvements, and optimized building envelopes emerge as cost-effective strategies to address climate-induced thermal stress. Energy simulations predict a significant increase in cooling energy demand across different climatic scenarios, necessitating the adoption of bioclimatic strategies and energy-efficient building practices.

Overall, the research highlights the urgent need for sustainable urban planning, regulatory interventions, and resilient building designs to mitigate the adverse effects of climate change on the built environment. Implementing energy-efficient and climate-responsive architecture will be crucial in reducing environmental impact and ensuring long-term livability.

2.3.1 Review of Vernacular architecture for different Climatic Zone of India.

Table 2-1 Review of Vernacular architecture for different Climatic Zone of India

	Author	Climatic	Methodology	Passive Strategies of the Structure	Results and Observations
1.	M. K. Singh et al., 2010	Northeastern India; Vernacular homes	Thermal performance analysis using adaptive models by Humphreys and Auliciems	Natural ventilation and adaptive comfort techniques	Defined comfortable temperature ranges and percentage of thermally comfortable time, validating adaptive comfort models in vernacular structures
2.	Dili et al., 2010	Tropical climate; Keralan vernacular residential architecture	Qualitative analysis	Internal courtyards, optimum window sizes, insulative built envelope, verandas for shading, pitched roof for rain protection	Effective passive climate control system combining architectural elements for thermal comfort and protection against climatic conditions
3.	Alapure et al., 2014	Hot and arid; Vernacular-traditional houses	Observational study	Deep plan with narrow street frontage, densely crowded around narrow streets to provide mutual shading	Shaded streets contribute to cooler microclimates, maintaining thermal comfort in hot and arid environments

	Author	Climatic	Methodology	Passive Strategies of the Structure	Results and Observations
4.	Subramanian et al. (2016)	Warm-Humid Climate *Modern Residential Building, Thanjavur, Tamil Nadu, India*	- Field temperature and humidity measurements - Tropical Summer Index (TSI) and NBC standards for thermal comfort	- Courtyard and atrium design for stack and chimney effects - Heat-reflecting roofing tiles - Roof ventilators and high ceilings - Shading elements and light-coloured exteriors	- Indoor temperatures were maintained at 27.4–30.8°C during summer and 24.6–27.1°C during winter - SPA designs effectively enhanced thermal comfort and reduced energy consumption
5.	Gupta et al. (2017)	Composite Climate *Mud Huts with Courtyards, Ranchi, India*	- Field temperature measurements - Autodesk Ecotect simulations	- Courtyard shading and ventilation - Reduced wall thickness for heat dissipation - Insulated walls and roofs - Vegetation for shading and cooling	- U-shaped courtyards provided better summer comfort but were less effective in winter - square courtyard designs retained the most heat during summer - Suggested design modifications enhanced year-round comfort
6.	Alapure et al., 2017	Hot and dry; Wada architecture	Fieldwork, surveys, literature review	Internal courtyards, verandas, lattice windows, fountains, pools, arches, and high thermal mass materials	Passive cooling techniques improve indoor microclimate; high thermal mass materials enhance resistance to environmental factors

	Author	Climatic	Methodology	Passive Strategies of the Structure	Results and Observations
7.	Vakharia (2017)	Hot-Dry, Pol House, Ahmedabad, Gujarat	Field temperature and humidity measurements	Courtyard-centric layouts, flexible space usage, and attic buffers.	Monitored dry bulb temperature and humidity over three months; courtyards showed high diurnal variation and enhanced ventilation.
8.	Beccali et al., 2018	Mediterranean climate; Naturally ventilated buildings	Adaptive comfort models and thermal comfort standards	Adaptive comfort techniques, bioclimatic design, minimized HVAC use	Demonstrated potential for energy efficiency with unified standards and bioclimatic concepts, relevant for both developing and developed nations
9.	Indraganti (2018)	Warm Humid, Hot Dry, Composite, Cold India (Multiple Regions)	Descriptive-analytical approach	Perforated structures, courtyards, thick walls, shaded courtyards, compact planning, semi-open built forms	Thermal comfort, energy efficiency, climate adaptability, vernacular wisdom integration
10.	Khadeeja et al. (2019)	Warm Humid Suggenahalli, India	Real-time monitoring, dynamic simulation modelling	Thick rubble masonry walls, courtyard layout, strategic ventilation, use of local materials	Thermal resilience, effective passive cooling, energy efficiency, climatic adaptability

	Author	Climatic	Methodology	Passive Strategies of the Structure	Results and Observations
11.	Gupta et al. (2020)	Composite Climate *Vernacular Rural Dwellings, Ranchi, Jharkhand, India*	- Indian Meteorological Department Data - Ecotect and Climate Consultant for climate analysis	- Nighttime flush ventilation with lightweight materials - Insulated walls for winter rooms - Courtyard planning for airflow - East-west orientation - Sun-shading devices	- Compact units retained more heat, causing discomfort in summer - Moderately spread-out U-shaped layouts performed better thermally due to enhanced ventilation - Shading devices contributed to 10-20% energy savings
12.	S. Nagapurkar et al., 2020	Composite climate; Maratha Wada architecture	Historical and cultural analysis	Multi-story buildings with interior courtyards ("Chowks"), stone walls, wooden staircases, open courtyards	Courtyards enhance thermal comfort and cultural continuity; architectural style integrates Mughal, Rajasthani, Gujarati, and local techniques
13.	Tungnung (2020)	Cool-Humid Climate *Two-Storey Houses, North-East India*	- Parametric simulations - Affordance theory and synergy analysis	- Flexible ventilation strategies - Adaptive space utilization based on diurnal temperature variations	- Ventilation significantly improved indoor thermal comfort - Parametric strategies optimized space functionality and energy efficiency
14.	Naik and Oswal (2020)	Temperate Bangalore, India	Analytical study on urbanization impact	Building orientation, transitional spaces, shading devices, use of low heat-gain materials, strategic wind flow optimization, spatial zoning	Energy-efficient housing, reduced solar heat gain, natural ventilation, enhanced community interaction, sustainability

	Author	Climatic	Methodology	Passive Strategies of the Structure	Results and Observations
15.	Callejas et al. (2020)	Tropical Savanna Climate (Aw) *Courtyard Houses, Cuiabá, Brazil*	- Microclimatic monitoring - Thermal comfort questionnaires	- Passive cooling and heating through courtyard designs - Shading structures and vegetation for solar control	Courtyards reduced thermal sensation by up to 5°C on hot days - Enhanced comfort through strategic courtyard designs, including shading and vegetation
16.	Amol Rathod et al. (2022)	Hot-Dry (Kutch), Warm-Humid (Kerala), Cold-Sunny (Ladakh)	- Literature review - Case studies of vernacular architecture	- Thick mud walls and circular plans for thermal comfort (Kutch) - High-pitched roofs and cross-ventilation (Kerala) - Trombe walls and strategic solar gain (Ladakh)	- Local materials and traditional layouts significantly enhanced thermal comfort - Climate-responsive designs minimized energy usage and preserved cultural authenticity
17.	Choudhury and Chettry (2023)	Humid Subtropical Northeast India	Qualitative analysis (site surveys)	Locally available materials, elevated plinths, stilt construction, high ceilings, perforated screens, strategic ventilation	Thermal comfort, energy efficiency, disaster resilience, flood protection, earthquake resistance
18.	Vishnu et al. (2023)	Warm Humid Kerala, India	Temperature monitoring, architectural analysis	Central courtyard, shaded Verandah, natural ventilation, locally available materials	Stable indoor temperatures, minimal diurnal variation, energy efficiency, thermal comfort
19.	Hegde (2023)	Warm Humid South Kanara, Karnataka, India	Analytical study	Optimal building orientation, lightweight materials, cross ventilation, shading techniques, landscape integration	Reduced energy costs, effective passive cooling, enhanced air circulation, sustainable architecture

	Author	Climatic	Methodology	Passive Strategies of the Structure	Results and Observations
20.	Tyagi et al. (2024)	Diverse (Region-specific) Uttar Pradesh, India	Descriptive-analytical approach	Traditional roofing (rat trap bond), hollow interlocking CSEB, strategic wall and roof materials	Superior thermal performance, energy efficiency, integration of traditional and modern materials
21.	Maligi et al. (2024)	Hot and Dry Guledgudda, Bagalkot, North Karnataka, India	Field studies, interviews, simulations (DesignBuilder)	Shared walls, thick walls with high thermal mass, courtyards, strategic fenestration, building orientation, Madras Terrace Roof	Effective heat prevention, temperature modulation, reduced internal surface temperatures, natural ventilation, enhanced insulation, energy efficiency
22.	Baghel et al. (2024)	Hot-Dry Climate *Traditional Urban Design, Jodhpur, India*	- Morphological analysis of traditional urban design - Case study approach	- Narrow alleys for shading and ventilation - Courtyards for light and ventilation - Raised platforms for social engagement and thermal comfort - Clustered house formations for improved thermal regulation	- Narrow alleys enhanced social interaction and protected from harsh weather - Courtyards provided passive cooling and multifunctional spaces - Cluster formations reduced exposed surfaces and improved thermal comfort
23.	D'Amato and Kapoor (2024)	Hot-Dry Climate *Vernacular Architecture, Jaipur, India*	- Field observations - Qualitative analysis of traditional design elements	- North-south orientation for solar control - thick stone walls for thermal mass - Jaali for ventilation and reduced solar gain - Shading devices like chajjas and courtyards	- Passive strategies effectively maintained thermal comfort and reduced energy use - Demonstrated potential for modern integration to enhance energy efficiency

	Author	Climatic	Methodology	Passive Strategies of the Structure	Results and Observations
24.	Saifudeen and Mani (2024)	Varies (Climate Change Focus on thermal adaptation	Analytical review	Double-skin facades, natural ventilation, flexible interiors, landscaping, behavioural thermoregulation	Enhanced thermal comfort, flood resilience, energy efficiency, occupant behaviour adaptation
25.	Rajapaksha and Kariyawasam (2024)	Warm-Humid Climate *17th-century Dutch Residential Building, Galle, Sri Lanka*	- Field measurements using Hobo loggers for air temperature - Design Builder (v6) for daylighting and thermal performance modelling	High thermal mass walls with time lag in heat transfer. Proposed upper-level openings for hot air release and lower-level openings for cooler air inflow Avoided daytime ventilation in polluted urban areas, emphasized nighttime ventilation	Indoor temperatures were 2.5°C lower than ambient during the day but higher at night due to heat release from thick walls - Courtyard temperatures were 1.6°C higher than living room temperatures during the day. Proposed ventilation strategies enhanced thermal comfort while preserving historical integrity

This literature summary examines studies on vernacular and modern architectural strategies across diverse climatic zones, emphasizing passive design approaches to achieve thermal comfort and energy efficiency.

In Northeastern India, Singh et al. (2010) utilized adaptive comfort models to analyze vernacular homes, demonstrating that natural ventilation and adaptive comfort techniques effectively maintained comfortable temperature ranges. Similarly, Kerala's tropical climate was studied by Dili et al. (2010), highlighting internal courtyards, insulative envelopes, and verandas as effective passive climate control systems. Alapure et al. (2014, 2017) observed that densely built houses and shaded streets in hot and arid regions maintained cooler microclimates, while high thermal mass materials in Wada architecture improved indoor comfort.

For warm-humid climates, Subramanian et al. (2016) analyzed modern residential buildings in Tamil Nadu, demonstrating the effectiveness of courtyards, roof ventilators, and light-colored exteriors in maintaining indoor temperatures. Vishnu et al. (2023) and Hegde (2023) found that central courtyards, natural ventilation, and landscape integration achieved stable indoor temperatures and energy efficiency in Kerala and South Kanara, respectively.

Studies in composite climates emphasized courtyard-centric designs for thermal comfort. Gupta et al. (2017, 2020) showed that U-shaped courtyards and nighttime ventilation enhanced thermal performance, while compact units trapped heat. S. Nagapurkar et al. (2020) noted that Maratha Wada architecture’s courtyards preserved cultural continuity and thermal comfort.

In hot-dry climates, courtyard designs were particularly effective. Vakharia (2017) observed high diurnal variations and enhanced ventilation in Pol Houses of Ahmedabad. Beccali et al. (2018) and D’Amato and Kapoor (2024) demonstrated that adaptive comfort strategies and bioclimatic designs reduced HVAC use and maintained thermal comfort. Baghel et al. (2024) highlighted the role of narrow alleys and courtyards in Jodhpur's traditional urban design for passive cooling.

Further, studies in temperate and diverse climates explored adaptive strategies. Naik and Oswal (2020) and Tyagi et al. (2024) emphasized building orientation, shading devices, and hybrid materials for energy efficiency. Choudhury and Chettry (2023) highlighted thermal comfort and disaster resilience in humid subtropical regions through stilt construction and strategic ventilation.

Lastly, climate-responsive designs were explored by Amol Rathod et al. (2022) and Saifudeen and Mani (2024), showcasing the integration of local materials, flexible interiors, and landscaping for thermal adaptation. Rajapaksha and Kariyawasam (2024) proposed innovative ventilation strategies in warm-humid Sri Lanka, balancing historical preservation and thermal comfort.

Overall, these studies underscore the effectiveness of passive design strategies, adaptive comfort techniques, and climate-responsive architecture in enhancing thermal comfort and energy efficiency while preserving cultural heritage across varied climatic contexts.

2.4 Conclusion and Research Gap:

The existing body of literature on energy optimization, thermal comfort, and climate-responsive strategies in vernacular architecture underscores the significant role design plays in reducing energy demands and enhancing the thermal comfort of buildings. The strategies, deeply rooted in traditional knowledge and the use of local materials, have long been effective in creating sustainable, energy-efficient environments. Vernacular architecture, particularly in warm-humid climates, has evolved to utilize passive cooling techniques, natural ventilation, and thermal mass, which contribute to maintaining comfortable indoor temperatures with minimal energy input. These characteristics make vernacular buildings particularly relevant as a model for sustainable, climate-responsive design in the context of global warming.

Furthermore, the resilience of vernacular architecture is a critical factor in addressing climate change, especially for vulnerable populations such as the urban poor. These groups are particularly susceptible to the adverse effects of climate change, including increased temperatures and urban heat islands. The lack of adequate housing and basic amenities in these areas exacerbates their vulnerability. As such, there is an urgent need to design housing that is climate-resilient, capable of adapting to temperature fluctuations, and reducing the associated health risks, while simultaneously reducing energy consumption.

While the literature offers valuable insights into the thermal, bioclimatic, and energy aspects of vernacular architecture in warm-humid climates, there is a notable gap in studies that explore how the vernacular building forms in Pune, specifically Wada houses will perform in future climate scenarios. Research on vernacular houses in the region often focuses on present-day thermal performance and sustainability but does not fully address the implications of future climate change, particularly the predicted rise in temperature. Pune, as a rapidly urbanizing city, faces the challenge of increasing land surface temperatures and growing urban heat islands, which can further exacerbate the thermal discomfort in buildings, especially those constructed with traditional techniques.

This research gap presents an opportunity to explore the future viability of vernacular house forms in Pune, particularly in the context of climate change. By analyzing the nature of climate change and its impact on the thermal performance of vernacular architecture, this study will explore how traditional design solutions can be adapted to meet the challenges posed by rising temperatures. Specifically, the study will focus on two future scenarios 2050 and 2080 and assess the thermal performance of the Wada house form under these conditions. This analysis will consider how the rise in temperature may affect the overall thermal comfort within the house envelope, highlighting potential vulnerabilities and areas for improvement.

The key objective of this study is to recommend a model for enhancing thermal performance of vernacular dwellings in Pune, taking into account the predicted temperature rise and the broader impacts of climate change. By examining the thermal characteristics of the Wada house, the research will identify strategies for mitigating the impact of increased temperatures on indoor comfort. These recommendations could inform contemporary architectural practice by suggesting how traditional vernacular forms can be adapted or modified to meet the demands of modern environmental conditions. This approach can provide valuable insights for architects, urban planners, and policymakers working to create sustainable, climate-resilient housing solutions.

The scope of this study is limited to analyzing the thermal characteristics of the vernacular house form, with a particular focus on the Wada house, a traditional typology in Pune. The study will explore the performance of the Wada house envelope in relation to the projected rise in temperature for two future timeframes 2050 and 2080. By examining these future scenarios, the research will provide insights into how vernacular designs, specifically the Wada house form, may need to evolve to adapt to future climate conditions. This study will also assess the potential for integrating modern technologies and materials with traditional design to enhance thermal performance and resilience to climate change.

In conclusion, while much of the existing literature provides valuable information on the thermal performance and sustainability of vernacular architecture, there is a clear gap in studies addressing the future impacts of climate change, particularly the rise in temperatures, on vernacular houses in Pune. This research aims to fill that gap by analyzing the thermal performance of traditional Wada houses in Pune under future climate scenarios, thereby contributing to the development of a model for climate-resilient, energy-efficient housing. By considering the future implications of climate change, this study will offer valuable recommendations for adapting vernacular architecture to the challenges of a warming world, ensuring that these traditional forms continue to provide sustainable and thermally comfortable living environments.

CHAPTER 3: VERNACULAR ARCHITECTURE OF PUNE

As a part of cultural heritage, vernacular architecture encompasses a range of tangible and intangible characteristics (such as environmental, socio-historical and aesthetic), as well as other regional sustainable and climate responsive strategies that must be taken into account during conservation (Philokyprou & Michael, 2020). The traditional home has been transformed, adapted to fit the region's needs, and endured as a symbol of former cultures and civilizations, offering tangible connections to the past.

A Wada is a style of dwelling that was popular among Marathas in India under the Peshwas' rule. These were constructed across the Maharashtra region to cater to the special requirements of large joint families. On the other hand, Wadas from the Maratha and Peshwa eras portray the challenges and customs of the period. (R. R. Gupta, 2016). Some are impressive, while others are private, isolated structures along riverbanks. The architectural style of Wada was a mix of Mughal, Rajasthani, and Gujarati elements, as well as native building skills. Because of the outside of the structure, this form of dwelling design deals with air and light, resulting in excellent ventilation for both and also addresses security and privacy problems (Dhepe Sushama S., 2017).

The Vernacular architecture of Wadas shows a noteworthy Mughal influence in their design through Symmetry in plan form, central courtyards with fountains, lattice windows, and projected balconies (S. Nagapurkar et al., 2020). Due to a lack of space, Wadas have only two to three levels and smaller courtyards. Bigger dwellings, however, include a courtyard in the front to greet visitors and perform the family's commercial and administrative tasks. The settlement's urban form is a network of two or three-story structures with interior courtyards, situated alongside the road network and with a small community space. (Alapure et al., 2017).

The houses were constructed with local resources and had strong composite walls made of bricks or limestone inlaid with wood. Thick walls also aid in noise reduction by insulating the space. Wadas are occupied by one or two families, with one or two households sharing washing facilities. The ground level of the front facade used to be used for commercial functions, but nowadays most Wadas are purely residential (S. Nagapurkar et al., 2020).

3.1 Architecture of Traditional Houses in Pune

India boasts a truly splendid architectural legacy, where each architectural element draws its inspiration from profound abstract beliefs. With numerous states steeped in their own unique cultures, every nook and cranny of the country captivates global attention due to its varied architectural marvels. Astonishingly, even the smallest villages have safeguarded treasures that vividly showcase their time-honored architectural heritage. A prime example lies in Pune's "Wadas," a living testament to how dwellings from centuries past have shaped the very fabric of the city's neighborhoods. These are the traditional houses of Maharashtra, known as "Wadas," a term derived from "Vata," signifying a plot of land designated for housing. Despite the towering presence of modern skyscrapers, these Wadas proudly stand, adorned with distinctive features of immense significance (R. R. Gupta, 2016). Originating during the Peshwa rule, these traditional residential structures in Pune were profoundly influenced by the prevailing political, social, and cultural dynamics of the era.

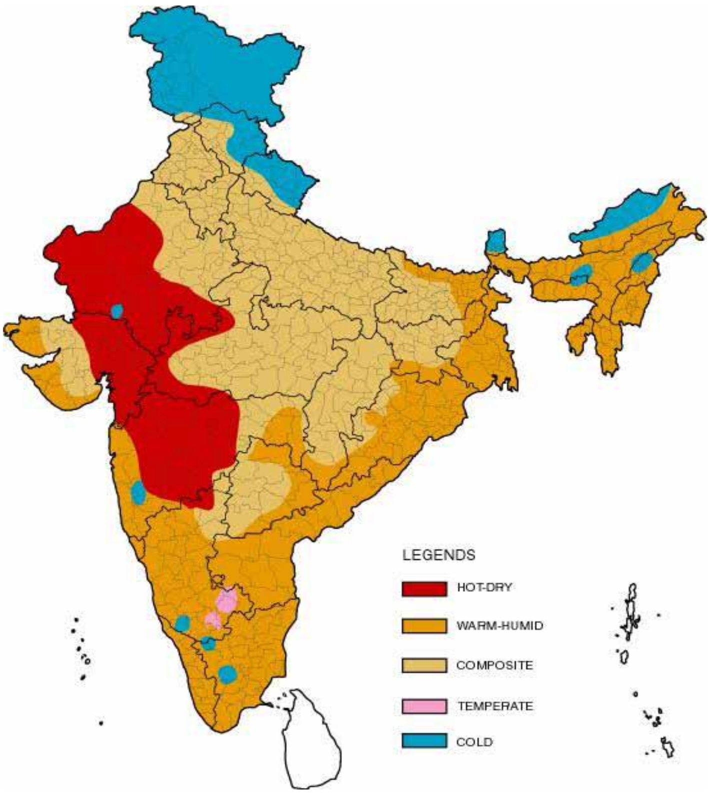


Figure 3-1 Map of India showing Different climatic zones (Source: ECBC 2018)

3.2 Passive features in the vernacular architecture of Pune

Pune being warm-humid with dry weather in winter climate (Energy Conservation Building Code for Residential Buildings India, 2018) (Figure 3-1) effective passive cooling involves integrated systems and developing approaches to minimize the effect of heat gain from all sources. Due to the difference in air temperatures within and outside, solar heat gains occur through façade apertures or glass as well as through opaque surfaces such external walls and roofs (Al-Sallal & Rahmani, 2019). Building equipment, lighting fixtures, and internal heat gains produced by occupants of the building all contribute to internal heat gains.

According to current studies, bioclimatism is a fundamental characteristic of vernacular architecture and a key factor in achieving sustainability (Shanthi Priya et al., 2012). Solar heat gain may be decreased by using low-absorbance materials for walls and roofing. Reduce the transfer of heat via the building's exterior surfaces to achieve lowest transmission through the building envelope (Al-Sallal & Rahmani, 2019).

The constructed area of Pune has seen diurnal temperature fluctuations as a result of rapid urbanization and population increase caused urban Heat Island effect (Parishwad & Shinkar, 2017). Wadas are created with the meteorological parameters of the location or region in mind. The rectangular linear plan with two or three floors has a central courtyard with surrounding verandah and rooms. Wada controls solar gains by taking into account the opening widths, timber windows, and high thermal mass of the outside wall to minimize solar heat gain transmitted via the building envelope (Alapure et al., 2017). Wada contains two or three courtyards that are surrounded by various rooms. The first courtyard is designated as a public space for social gatherings, while the second courtyard is reserved for female-only rooms. The courtyard design is a long-term design plan that may meet a variety of functional, social, and bioclimatic needs. In Wada architecture, the courtyard is an integral part. Within one of the courtyards of the Wada, there is also a well and Tree which modifies the microclimate of the built environment (Alapure et al., 2014). The courtyard design is a long-term design plan that may meet a variety of needs, including practical, social, and bioclimatic considerations.

3.3 Types of Wada – Size Based

Garhis were essentially fortified versions of wadas, characterized by bastions and defensive ramparts strategically positioned at the heart of the village. Wada housing clusters would naturally develop on the Garhi's perimeter as the pattern of the village or town evolved around it. These Wadas had an inward-looking design with a series of courtyards inside its boundaries. They were made of brick and stone. Examples include the Shaniwar Wada in Pune, Chandwad’s Hilkar Wada, and the Vishrambagh Wada.

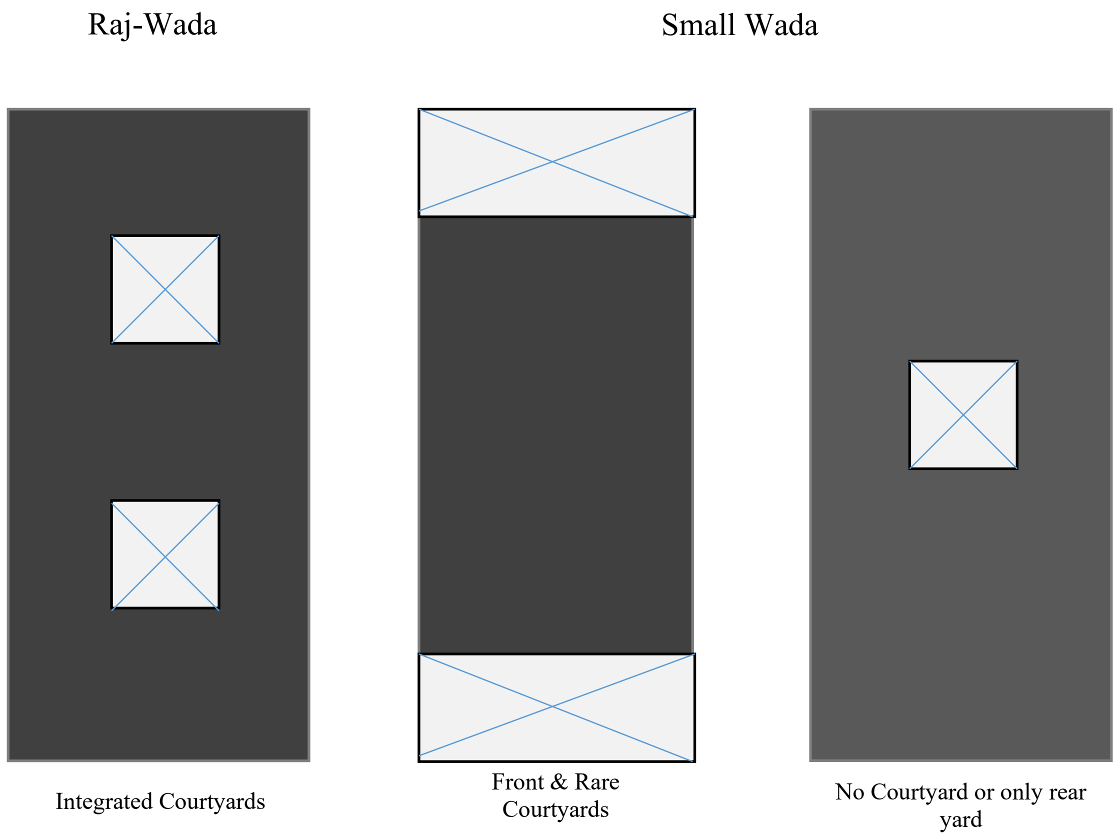


Figure 3-2 Type of Wada Source :(Gupta, 2016)

However, Rajwadas or Palace Wada dwellings stood out since they lacked bastions and walls while playing a prominent role in the town's layout. The Satara Rajwada with two courtyards and Bhor Rajwada with single courtyard.

Smaller Wada (Figure 3-2) dwellings were arranged together in the area surrounding the town's center, which might be a Garhis or a Rajwada. In contrast to the isolated Garhis and Rajwadas (Figure 3-2), these houses were clustered closely together along roadways, sharing longer walls and having their thin sides facing the street.

Another category of buildings existed, referred to as "wadi," typically representing the modest rural dwellings. These wadi structures contrasted by having an outward-facing design, often marked by temporary boundaries that merely indicated the property lines. The central area within these structures wasn't as defined as in the other types of houses.

3.4 Building indoor layout

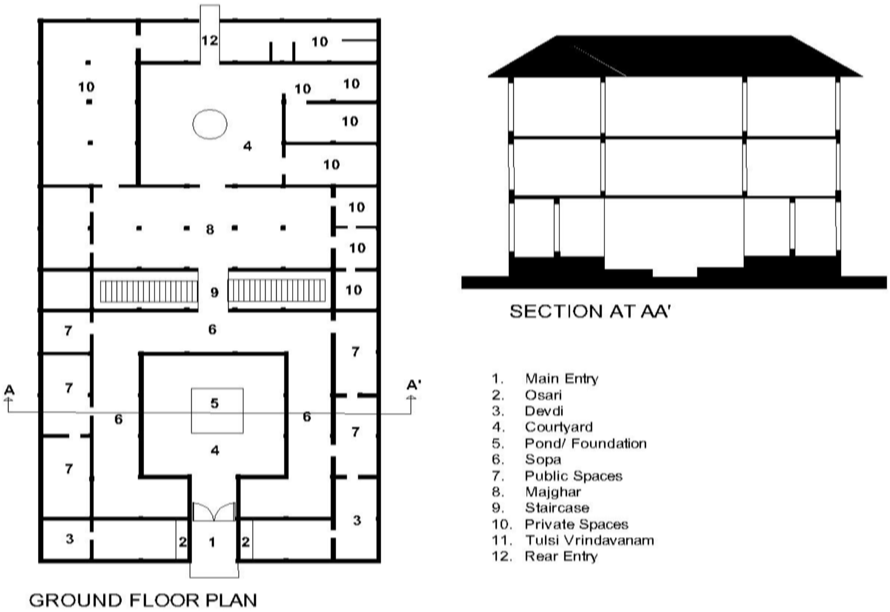


Figure 3-3 Typical Wada plan and section (Source: (Gupta, 2016)

Table 3-1 Vernacular Vocabulary for Wada

Sr. No.	Vernacular terminology	Type of Space	Purpose of the Space
	Osari	Semi-open Space	Verandah or transition space. a passage or spill-out space for activities
	Sadrecha Sopa	Semi-open Space	Verandah space is placed at the first or central courtyard for administrative purposes.
	Chowk	Courtyard	The first courtyard is for public meetings and the Second is a private space for house ladies
	Diwankhana	Living room	Huge hall for formal gatherings.

	Majghar	Middle room	It's a private space. The private and public areas are separated in this section. It is mostly used by women and family members.
	Devghar	Prayer Room	space for performing rituals.
	Tijory	Enclosed	Private and secured space for Treasury.
	Gotha	Semi-open Space	Cow-pen in the backyard of a Wada
	Swayampak Ghar	Enclosed Space	Kitchen.
	Kothar	Enclosed Space	Storeroom

3.4.1 Typical Wada plan and section

Wada is a house that is inwardly centered, with the courtyard taking center stage and acting as the orchestrator for all the spaces and activities that are centered around it (Dengle, 1998). Thresholds, which can be physical or perceived, are used to construct a precise spatial hierarchy that is scrupulously upheld.

The table 3-1 discuss about various terminology like the Platforms called as 'otlas' or 'osari' first interactive public spaces located at plinth level on either side of the entrance staircase (Indraganti, 2018). Devdis or little rooms that resemble vestibules, flank the entryway. To access the front courtyard (chowk), enterance for Wada. Closer to the entryway, the outermost rooms were used for office work (kacheri and daphtar), managing other communal business (kalbatkhana), and keeping weapons and manuscripts (shahastraghar and pothichi kholi). If there was a second courtyard, it would have been reserved for women's use and would have included a maternity room (balantinichi kholi), medical room (aushadhi bhandar), places of worship (deoghar), kitchen (swaipak ghar), dining area (pangaticha sopa), and treasury (tijory).

Near the rear entrance were separate sections for grain storage (kothar), cowsheds (goshala), and restrooms (hound). The cowshed and water wells would be located in the third courtyard, if there were one. This structure came after a changeover to private spaces from public space (R. R. Gupta, 2016).

All these rooms had a semi-open space (sopa) surrounded by pillars that led to the open courtyards. The rooms and courtyard may be reached through this area. A potted herb (tulsi vrindavan) would frequently be in the courtyard's core, especially in the inner courtyard if there were many courtyards. This middle area might house a fountain or pond in the exterior courtyard.

In the mornings, public and semi-private events took place on the ground floor near the entrance. The first story was more private, with bedrooms, sitting rooms, and gathering spaces (diwarkhana) that looked out onto the courtyard. The second floor was characterized by a single expansive space, devoid of divisions. Primarily used for additional storage, this floor remained unutilized in daily activities. However, during festivals, it transformed into guest quarters.

3.4.2 Building materials and construction

The arrangement of spaces within the architectural framework was closely tied to the available timber lengths. These internal spaces were typically designed as multiples of a standardized bay unit called "khaan" (Pandya, 2016).

The foundation of these structures was constructed using basalt or granite stone, making use of the abundant resources of these materials throughout the state. Coastal areas, in particular, offered a wealth of granite. Meanwhile, regions in the east were characterized by limestone deposits. Solid load-bearing walls either having brick masonry or a mix of brick and timber frames were used to construct the walls. The structure was constructed from sandstone and saangwan (teak wood), adhered to with lime mortar (Alapure et al., 2014). "Pushpak Vit" or book bricks were burned in a kiln and composed of sand, clay, and cow dung, with or without lime. These bricks measured 10 x 6 x 2, or roughly the size of a book. The mortar, which was composed of different proportions of lime, jaggery, sand, wheat chaff, plus water, kept the structure together (R. R. Gupta, 2016). They utilised most of native wood species such as agar, khejri, and peepal. These plants' gum, jaggery, cactus juice, black gramme, and bananas were used to make the plaster.

Moving higher, lateral load distribution was accomplished using timber beams supported by walls or columns. A supplementary grid of timber beams served as bracing. A composite slab with a base tray composed of stone or wood planks was covered with a dry mixture of husk or brick and sand. Stone slabs were used for the flooring. No matter how the lower floor was set up, the top story still had a timber frame. Wall panels came in a variety of materials, including husk boards, timber planks, and brick coursing continuation. The lattice timber railing that encircled the balcony slab and was occasionally broken up by thin timber posts that reached the roof level was a striking aesthetic element. Terracotta tiles were often supported by bamboo rafters and purlins, which were in turn supported by trusses. often, roofs had a pitched shape. Arched alcoves on exterior and interior walls, intended to house lamps or serve as storage areas, were notable architectural features. The levels were joined by thick mud-mortared brick walls that included narrow straight-flight wooden staircases. Sloped roofs in warm-humid coastal climate regions and forms more appropriate for searing, arid eastern regions are examples of location-specific variances in roof styles.

3.4.3 Environmentally conscious architectural features of Wada

The vernacular style of architecture represents one of the most effective examples of maximizing limited resources through the use of regionally appropriate building materials and climate responsive passive design. It's a result of a blend of geographic, economic, and socio-political influences, not just providing shelter, but also reflecting the owner's identity and ambitions. These structures are ingeniously attuned to the climate, incorporating natural cooling techniques.

In the context of Wada houses, the courtyard assumes the role of a convective thermostat. It shields inhabitants from extreme weather conditions, smoothing out daily temperature fluctuations. Essentially, courtyards function as micro-climate regulators, simultaneously serving as crucial sources of light and ventilation. The open court and the windows and doors of the rooms facing the courtyard allow for horizontal cross-ventilation. Walking vertically is made easier by narrow staircases. Front courtyards are typically oriented northward to reduce direct sun exposure, and they are generously sized to provide shelter in the summer and enough light in the winter. When air passes over them and enters the rooms, the small ponds or fountains placed in the first courtyard even help in evaporative cooling.

Heat transfer is delayed for a considerable amount of time when walls and roofing are constructed using locally sourced, high-thermal mass materials. This reduces the amount of heat that builds up inside and acts as an insulator against sound and dust. To lessen the absorption of solar heat, outside walls are coated with light-colored paint, which is often stained with a distinctive light blue color created by mixing indigo with lime mortar. Even at ground level, tall and narrow windows have little apertures at the top for airflow. To avoid direct sunlight exposure, jutting, slanted roofs were designed; they slope north and south to block the sun's rays and to make it easier for rainwater to drain. The terracotta-tiled pitch absorbs a lot of heat during the course of the day, but by separating the roof from the inner rooms below, the vacant top floor acts as a kind of thermal buffer, thereby improving energy efficiency.

3.5 Case Studies of Wada

3.5.1 Vishrambaug Wada

Constructed in 1807, this palace served as the dwelling for Baji Rao II, the ultimate ruler of the Peshwa dynasty. Today, it accommodates a museum, library, post office, and a local crafts store. Situated in Sadashiv Peth, Vishrambaug Wada is a historic mansion dating back 200 years, established in 1807. The construction spanned six years and incurred a cost of approximately Rs 2 lakhs. Peshwa Baji Rao II, the final Peshwa of the Maratha realm, is said to have inhabited this mansion for roughly 11 years during the early 17th century. Curiously, he opted for this residence over Shaniwar Wada, the customary Peshwa seat, believing the latter to be inauspicious. Tradition claims the wada once embraced a splendid baug (garden), from which it derives its name, honoring the gardener, Vishram.

Unfortunately, a fire swept through the Wada on October 31, 1880, leading to significant structural damage. While only the facade remained intact, subsequent efforts resulted in the reconstruction of the building to its original layout. Since 2001, a permanent exhibition curated by historian Babasaheb Purandare, titled ‘Punawadi te Punyanagari,’ has found a home within the wada. This exhibition hall celebrates artefacts from the Maratha Empire and narrates the city's history.

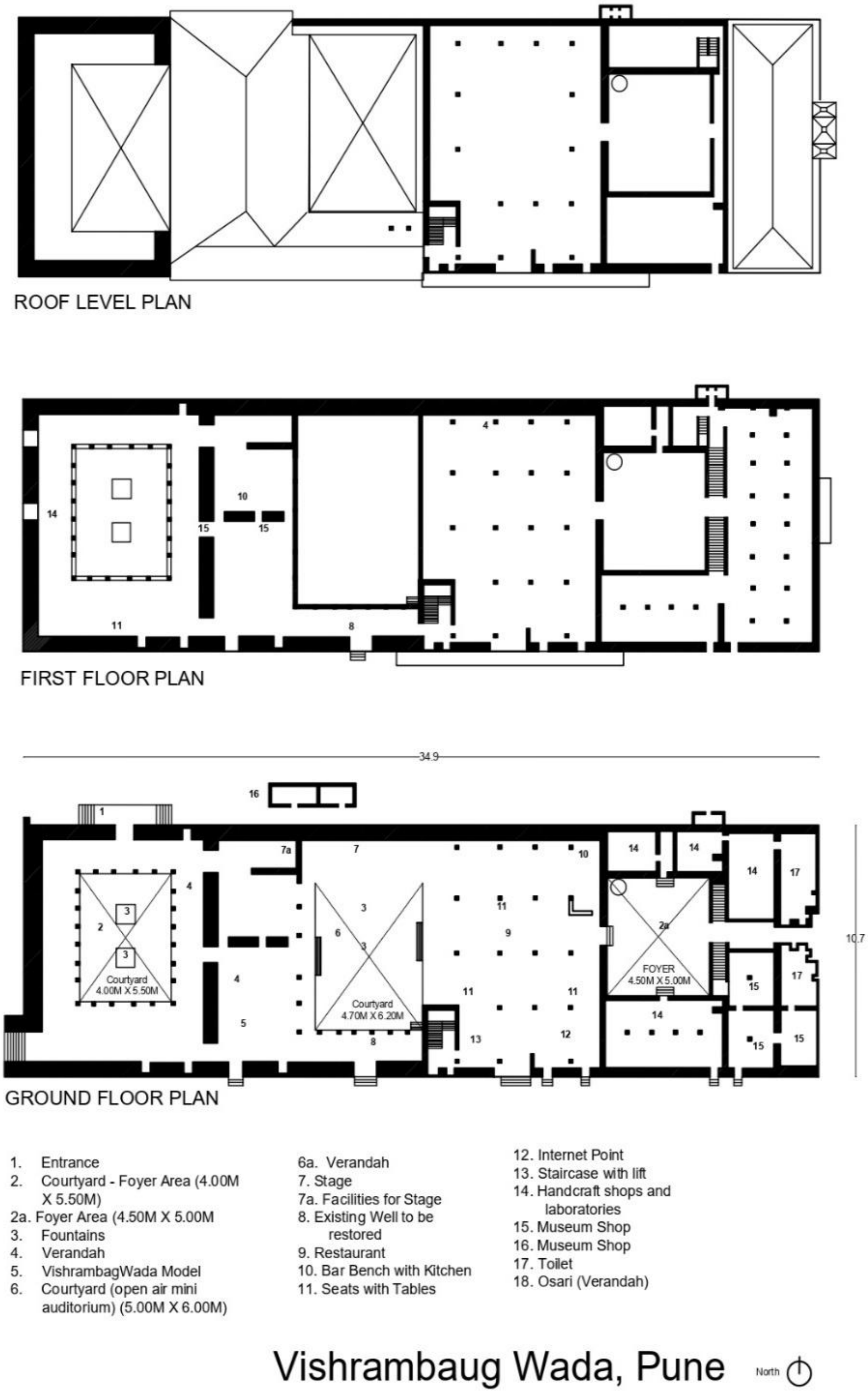


Figure 3-4 Vishrambagh Wada Plans

The Wada (Figure 3-4) is aligned east west and follows a rectangular plan, with a G+2 floor structure. The design incorporates several passive architectural strategies, including three courtyards that enhance stack ventilation and promote cross ventilation. Additionally, the attic floor helps reduce the impact of heat radiation on the lower levels. Lattice windows, fitted with ventilators, are placed on the north and south walls and within the courtyards, ensuring adequate airflow. The roof is constructed with an RCC slab, and the front elevation is characterized by minimal openings and a projected balcony.

Despite its architectural brilliance, the Wada's maintenance is subpar, with broken tiles and rods scattered across the premises. Nonetheless, Vishrambaug Wada remains an important symbol of Pune's heritage and the Maratha legacy, serving as a key cultural and historical site. The structure is equipped with basic amenities such as a compound wall and animal shelter, highlighting its functional aspects.

3.5.2 Nagarkar Wada

Constructed in 1890 by the influential social reformer Raghunath Nagarkar, affectionately known as Daji, this 130-year-old mansion, nestled within the electronics market at Tapkir Galli, Budhwar Peth, carries the moniker Nagarkar Wada or Dagdi Wada. Spanning 4,000 square feet, this wada (traditional mansion) is an embodiment of Peshwa-style architecture (Figure 3-5). Beyond being an architectural gem, it has housed the Pune Nagar Vachan Mandir library and the socio-political organization Poona Sarvajanik Sabha over the years.

Nagakar Wada, over 100 years old, is a rectangular structure with a load-bearing construction system. It has a G+1 layout and is oriented in the north-south direction. The Wada is designed with one central courtyard and a rear yard, which contributes to its passive design strategy, allowing for natural cross ventilation. Lattice windows are placed on the east and west walls, and the courtyard also has lattice windows with ventilators to promote airflow. Indo-Western ornamentation adds to the architectural uniqueness of the Wada, while the raised plinth enhances ventilation. The roof is flat, and the front elevation is characterized by minimal openings and a projected balcony. The structure was renovated and now functions as a museum. The courtyard is rectangular in shape and constitutes 9% of the total built form. The Wada is finished with mud plaster, and there is no compound wall or animal shelter.

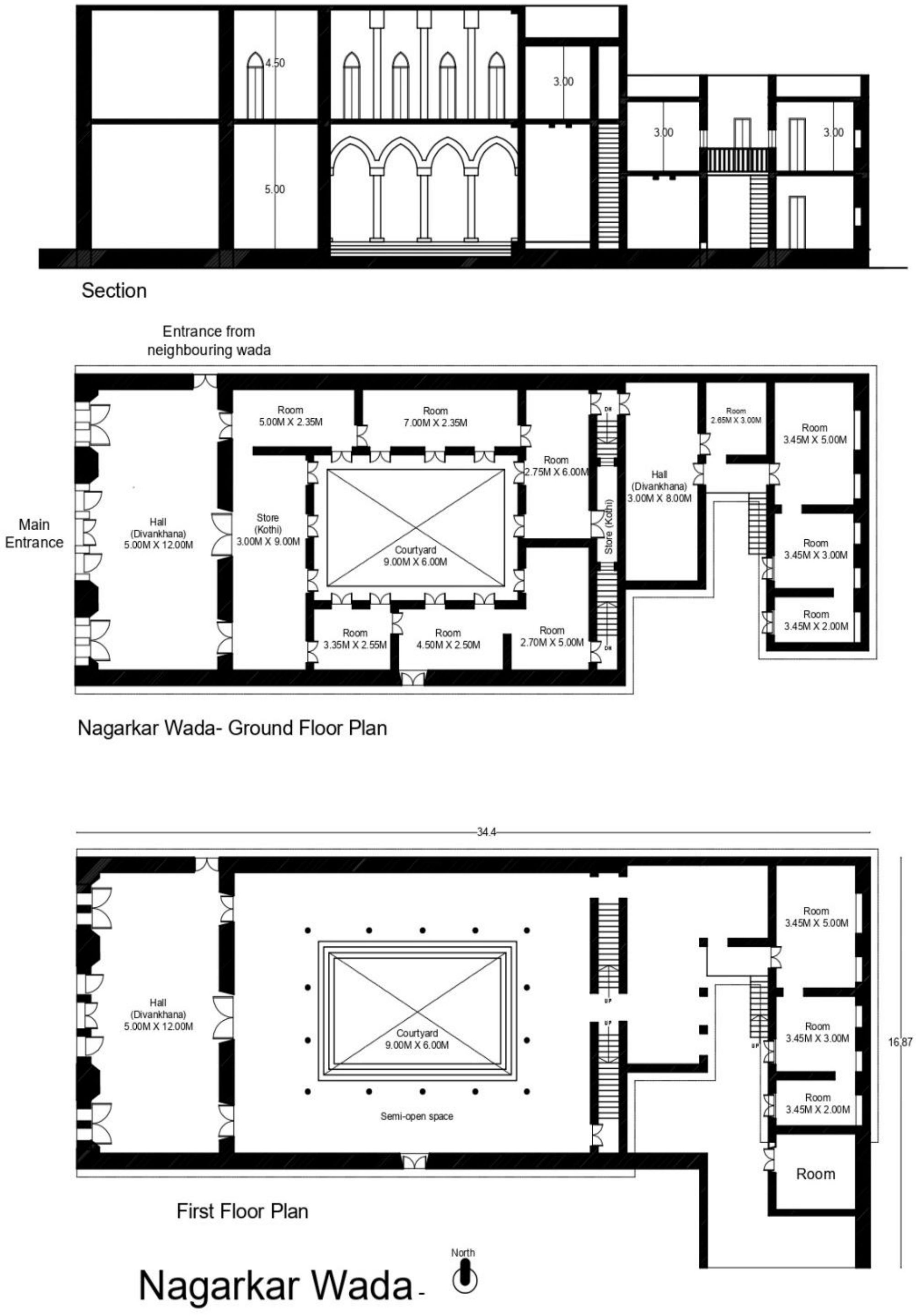


Figure 3-5 Nagarkar Wada Plans & Sections

3.5.3 Chapekar Wada

Chapekar Wada, the Chapekar Museum weaves a narrative of Maharashtrian freedom fighters, with a dedicated focus on the remarkable lives of the Chapekar brothers. Damodar Hari, Balkrishna Hari, and Vasudev Hari Chapekar, who arrived in Chinchwad in 1830 with their family, take center stage. This museum features an array of captivating maps, informative graphics, photographs, and statues commemorating legendary figures from India's freedom struggle.

Originally a wada (Figure 3-6) the building was transformed into a museum to counter its deteriorating state. The collaborative effort of the Pimpri Chinchwad Municipal Corporation and the Chapekar Smarak Samiti brought this endeavor to fruition. Inside the museum, an intriguing assortment of artefacts utilized by the freedom fighters, including swords and guns, are on display. Additionally, the museum houses a devghar (temple) crafted by the skilled hands of the Chapekar Brothers.

Chapekar Wada, a rectangular, load-bearing structure with two courtyards, is oriented east-west and was renovated in 2018. It has a G+2 layout and incorporates several passive design strategies. The front courtyard, attic floor, and front staircase create a buffer for the indoor spaces, while the projected balcony serves as a shading element. Lattice windows with ventilators are placed on the north and south walls, as well as in the courtyards, promoting natural ventilation. The roof features a sloping attic floor oriented towards the north-south direction. The front elevation has minimal openings and a projected balcony. The Wada, which is finished with mud plaster, is now used as a museum. The square-shaped courtyard accounts for 14% of the built form, and while there is no compound wall, the structure includes an animal shelter.

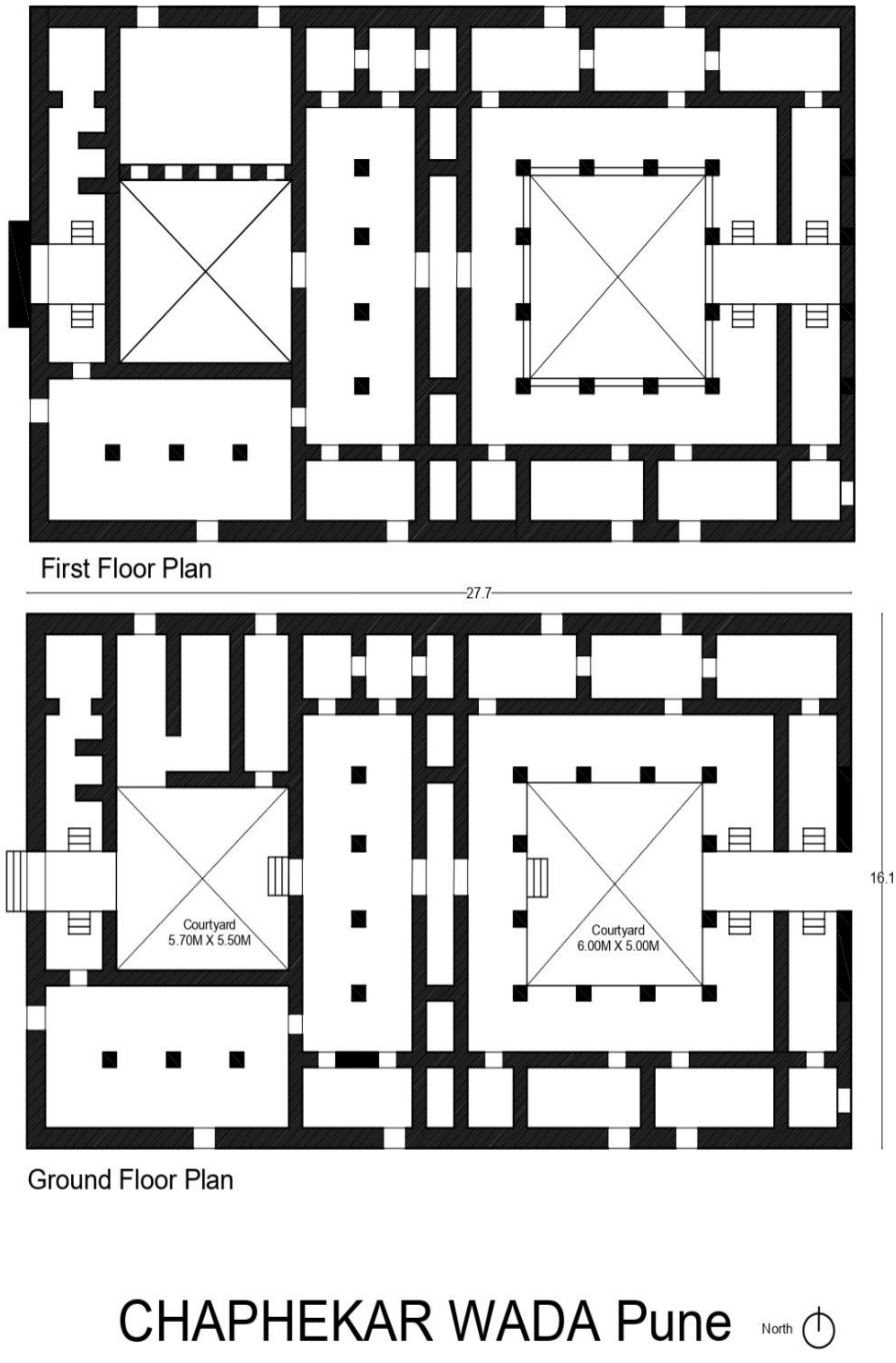


Figure 3-6 Chaphekar Wada

3.5.4 Ranade (Kiwale) Wada at Kiwale Area Pune

Human consciousness is ingrained with regard to designing climate-sensitive shelters. A person's third skin is typically referred to as a structure, with clothing acting as the second and hiding the first (biological) skin. These three elements combine to keep the deep body temperature at 37^{o}C in the absence of active systems (Indraganti, 2018). Over the past few decades, traditional courtyard dwellings in India have become less popular for a variety of reasons. People are turning away from opaque walls and doors and becoming more focused on their look than on spatial harmony. The courtyard alternative has been constrained by the development ordinances because both front and rear setbacks are required for smaller parcels. due to the transition from nuclear to joint families. Due to the need for better ground covering and F.A.R., the family lounge has replaced the courtyard residences. People choose air-conditioned areas and shorter distances over crossing wide open regions for comfort (Gangwar & Kaur, 2020).

Facades in Ranade Wada (Figure 3-7) have a minimum of openings, whereas highly ornamented facades have apertures in every structural bay. Using appropriate customs to adapt to the climate: Throughout history, indigenous peoples have learned to adjust their lifestyles to changing climatic circumstances and cycles(Al-Sallal & Rahmani, 2019). During the hot outside temperature in the summer, people like to sleep in their courtyards. When it gets too hot outside during the day, they move inside into enclosed rooms to feel more comfortable.

The most crucial factor in producing interior thermal comfort in traditional structures in hot, humid climates in the summer is natural ventilation. Wind-induced ventilation brought on by cross ventilation was the main factor causing wind circulation inside the homes under investigation (Shaeri et al., 2018).

To increase the performance of the courtyard in the summer season, evaporative cooling such as basins and fountains were installed on the courtyard floor. It is easy to reduce temperature by coloring the outside of buildings in a bright color, which also helps to lower the temperature of the interior air. In the house two staircases were placed one at the entrance for administrative purposes while the next set was placed adjacent to Living (Diwankhana) for family, the staircase was hidden between walls. The kitchen and storage room were located in the second court, which was reserved for exclusive use by the ladies of the house. The tulsi-vrindavan plant was also included for prayer reasons.

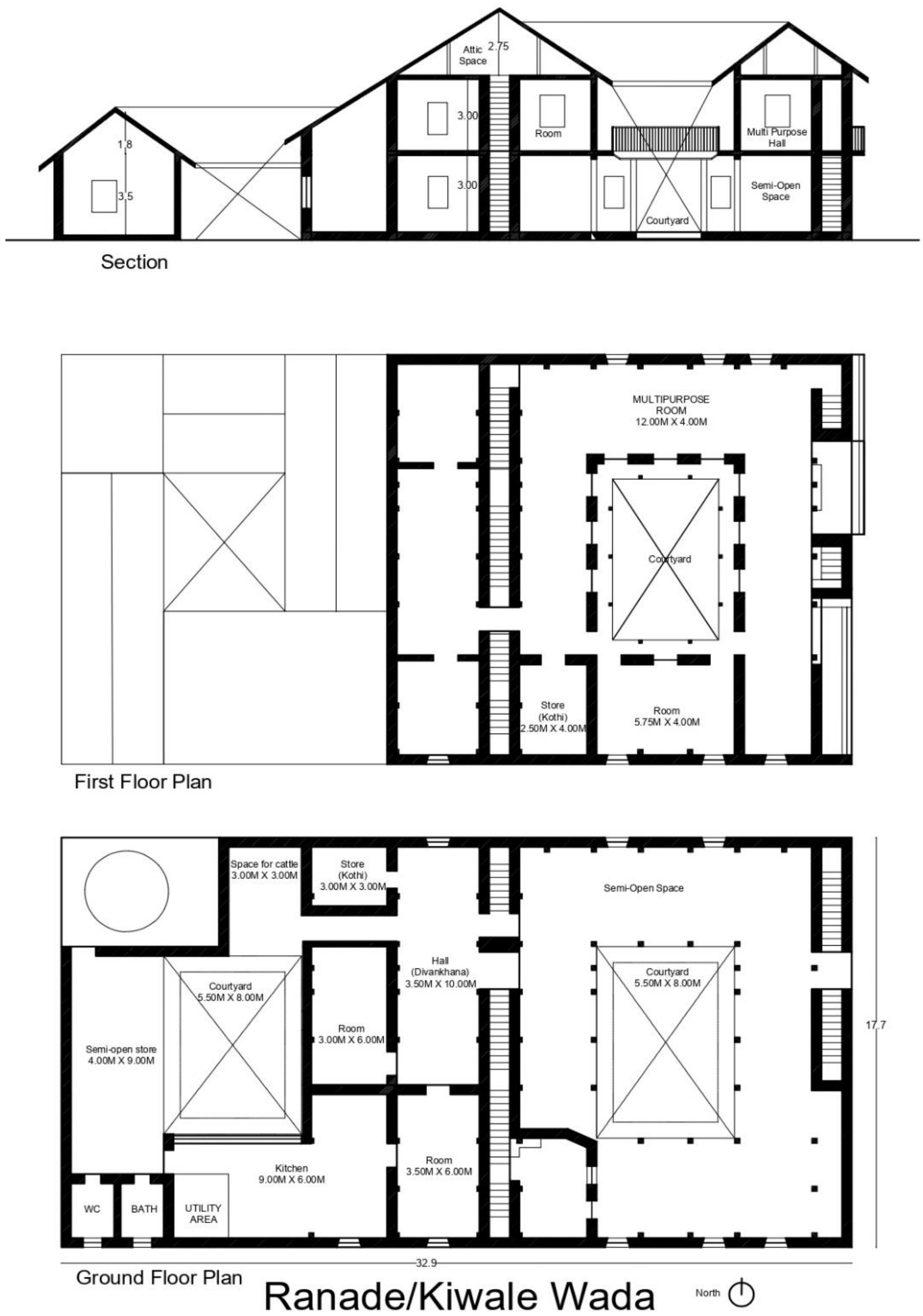


Figure 3-7 Ranade Wada Plan & Section

In the table below, the vernacular vocabulary is given along with their purpose and functions.

Ranade Wada (Figure 3-7), a historic building with a East-West orientation, is over 100 years old. It has a rectangular plan with load-bearing construction and two courtyards, one formal and one private, with a tree planted in the latter. The building has a G+1 configuration and incorporates passive design strategies such as an attic floor and a front staircase that acts as a cavity wall. A projected balcony on the front elevation helps with shading. The building features lattice windows on the east and west walls, as well as in the courtyards, promoting natural ventilation. The roof is sloped and constructed with timber trusses, covered with GI sheets. The front elevation has minimal openings and a projected balcony. The Wada is currently used for residential purposes and has not undergone any renovations. It is finished with mud plaster, and the square-shaped courtyards cover 15% of the built form. While the structure does not have a compound wall, it includes an animal shelter.

3.5.5 Thakore Wada Nashik

Thakore Wada in Nashik is a significant example of traditional Maratha residential architecture that flourished during the Peshwa era. These wadas, an integral part of Nasik's rich architectural heritage, are distinguished by their strategic zoning, with separate entrances for guests, domestic help, visitors to the durbar, and a dedicated entry to the cattle shed. The architectural layout features elements like a Devdi (guard house), cattle shed, multiple courtyards, darbar, sitting and family rooms, hauds (underground water storage), and internal staircases. Climate-responsive design is evident through thick walls, courtyard-centric planning, layered windows, and sloping roofs, all of which enhance ventilation and natural light.

The structure (Figure 3-8), a G+2 load-bearing construction, is oriented north-south, with lattice windows on the east and west sides and ventilators in the courtyard. Although the wada is no longer in use, its passive design strategies, such as contour levels for airflow and a central courtyard for ventilation and lighting, reflect its thoughtful planning. The building's mud and lime plaster and its attic floor with a sloping roof add to its historic character, even though it currently remains unused and unrenovated. The rectangular courtyard proportion remains an important feature of the plan form.

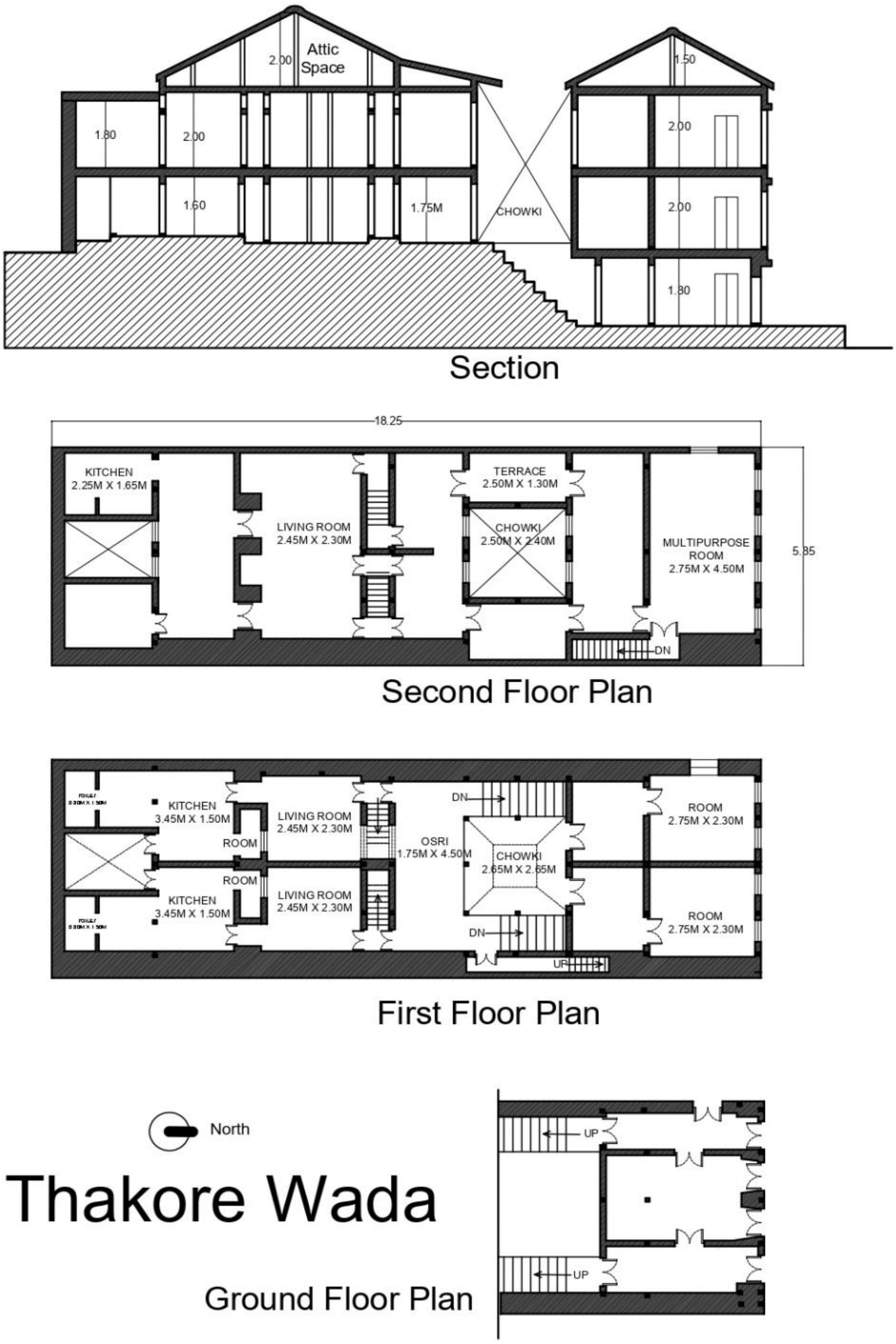


Figure 3-8 Thakore Wada Nashik

3.5.6 Comparative Analysis of Raj -Wada Houses

Table 3-2 Comparative analysis of Wada houses

	Items /Particulars	Vishrambagh Wada	Ranade Wada	Chapekar Wada	Nagakar Wada	Thakore Wada
1.	Orientation	East-West	East-west	North -South	East-West	North -South
2.	Structure Age	Renovated in 2008	Above 100	Renovated in 2018	Above 100	Structure not in used
3.	Plan Form and Character	Rectangular	Rectangular	Rectangular	Rectangular	Rectangular
4.	Construction Type	RCC after renovation	Load-bearing Construction with two courtyards.	Load-bearing Construction with two courtyards.	Load-bearing Construction with one courtyard and Rear yard	Load-bearing Construction with one courtyard and Rear yard
5.	No. of Floors	G+2	G+1	G+2	G+1	G+2
6.	Passive Design Strategies	Three courtyard helps in stack ventilation and improve cross	Formal & Private courtyard with tree, Attic Floor Front Staircase	front courtyard attic floor, and front staircase acting as buffer for indoor	Volume with a ventilator above the door and windows plays an important role in	Contour level helps the air ventilation also central courtyard improves the light and

Table 3-2 Comparative analysis of Wada houses

	Items /Particulars	Vishrambagh Wada	Ranade Wada	Chapekar Wada	Nagakar Wada	Thakore Wada
		ventilation, attic floor reduces the impact of radiation on lower floors	acting as a cavity wall. Projected balcony on the front elevation	spaces. The projected balcony also acts as the shading element.	cross ventilation, into western ornamentation makes this Wada unique with a courtyard and raised plinth	ventilation of indoor adjacent spaces.
7.	Door & Windows	Lattice windows: the north & south wall	Lattice windows: east & west wall	Lattice windows: north & south wall	Lattice windows: east & west wall	Lattice windows: east & west wall
		Lattice windows with ventilators are placed in the courtyard	Lattice windows with ventilators are placed in the courtyard	Lattice windows with ventilators are placed in the courtyard	Lattice windows with ventilators are placed in the courtyard	Lattice windows with ventilators are placed in the courtyard
8.	Roof form	RCC slab	Only sloping with GI sheets. Sloping roof constructed with timber trusses.	Attic floor with sloping roof oriented towards north-south	Flat roof	Attic floor with sloping roof oriented towards north-south
9.	Front Elevation	Minimum opening and projected balcony	Minimum opening and projected balcony	Minimum opening and projected balcony	Minimum opening and projected balcony	Minimum opening and projected balcony

Table 3-2 Comparative analysis of Wada houses

	Items /Particulars	Vishrambagh Wada	Ranade Wada	Chapekar Wada	Nagakar Wada	Thakore Wada
10.	Renovation Done	Done	Not Done	Done	Done	Not in use
11.	Present use	Museum	Residential	Museum	Museum	Not in use
12.	Plaster	Cement plaster	Mud plaster	Mud plaster	Mud plaster	
13.	shape of Courtyard	square	square	square	rectangular	rectangular
14.	Courtyard ratio with Built form	20% of built form	15% of built form	14% of built form	09% of built form	07% of built form
15.	Compound Wall	yes	no	no	no	no
16.	Animal Shelter	yes	yes	yes	no	yes

3.5.7 Case Study Selection and Sample Size Justification

Ranade Wada was chosen as a primary case study due to its historical authenticity, unique architectural features, and continued residential use, which align with the research objectives of assessing the thermal performance of vernacular dwellings in Pune (Table 3-2). The selection is based on the following criteria:

Preservation of Original Architectural Features: Unlike Vishrambagh and Chapekar Wadas, which have undergone modern renovations, Ranade Wada retains its traditional load-bearing construction, mud plaster, and sloping roof with timber trusses. This authenticity allows for an accurate analysis of traditional thermal performance without the influence of modern materials.

Effective Passive Design Strategies: The Wada incorporates strategic passive cooling features, including formal and private courtyards, an attic floor, projected balconies, and lattice windows. These elements provide a comprehensive basis for studying traditional climate-responsive design techniques.

Distinct Orientation and Spatial Configuration: With its East-West orientation and dual courtyard layout, Ranade Wada offers a contrasting thermal environment compared to North-South oriented Wadas. This allows for comparative analysis of different orientations' impact on thermal comfort. Residential Functionality and Cultural Relevance: As Ranade Wada continues to serve as a residential dwelling, it provides realistic insights into the thermal comfort needs of occupants, enhancing the study’s applicability to contemporary living conditions.

Comparative Analysis Potential: The architectural elements of Ranade Wada are comparable to other selected Wadas (e.g., Nagarkar and Vishramabgh Wadas), enabling a systematic comparative analysis of thermal performance across different construction types and passive design strategies.

3.5.8 2. Sample Size Justification:

Qualitative Approach with Comparative Analysis: Given the study's focus on thermal performance evaluation through simulations and field measurements, a comparative case study approach is adopted. This approach allows for an in-depth exploration of variations in thermal behavior across different Wada designs and orientations.

Selection of Five Raj-Wadas: The research includes a total of five Raj-Wadas: Vishrambagh, Ranade, Chapekar, Nagarkar, and Thakore. This sample size was chosen to ensure diversity in construction type, orientation, passive design features, and current usage. This diversity enhances the generalizability of findings while maintaining cultural and architectural relevance.

- Comparative Framework: The sample size supports a comparative framework that examines:
- Traditional vs. modern construction (e.g., RCC in Vishrambagh vs. load bearing in Ranade)
- Varied orientations (East-West vs. North-South)
- Different passive design strategies (e.g., single vs. dual courtyards)

3.5.9 Validity and Reliability:

By analyzing multiple case studies with similar yet distinct features, the research ensures triangulation, enhancing the validity and reliability of findings. The sample size is also justified by the need to evaluate both existing base cases and improved climate-responsive versions for a holistic assessment. The selection of Ranade Wada, along with four other Wadas, is strategically justified based on architectural authenticity, passive design effectiveness, and comparative analysis potential. The chosen sample size ensures sufficient diversity while maintaining thematic saturation, supporting a robust and comprehensive examination of thermal performance in Pune's vernacular architecture.

3.5.10 Selected Wada for further analysis

This study focuses on a comparative analysis of five Rajwada structures out of a total of seven documented Wada. These five structures Vishrambagh Wada, Ranade Wada, Chapekar Wada, Nagakar Wada, and Thakore Wada were selected based on their architectural characteristics, passive design strategies, and current use. Table 3.3 provides a detailed comparison of these

Wadas based on factors such as orientation, structure age, construction type, number of floors, and more. Key differences in the Wadas include their passive design strategies, such as courtyards for ventilation, attic floors, and the use of projected balconies for shading.

To provide a comprehensive analysis of vernacular Wada architecture, two smaller Wadas, Purandar Wada and Gokhale Wada, were selected based on their architectural diversity and distinct passive design strategies. Purandar Wada, characterized by its front yard and rear Wada layout, was chosen for its effective use of open spaces in ventilation and passive cooling. Its North-South orientation, rectangular plan, and traditional load-bearing construction make it a valuable case for understanding the role of spatial organization in thermal regulation. Additionally, its cavity wall staircase enhances airflow, reducing heat accumulation within the structure. It features a combination of sloping and flat roofs, constructed with timber and stone tiles, adding another dimension to the comparative analysis of roof types.

Gokhale Wada, featuring an open front space and a rear Wada, presents another perspective on vernacular thermal strategies. It incorporates an attic designed for ventilation and a wooden staircase cavity wall that facilitates stack ventilation, making it an essential case for studying airflow dynamics in traditional dwellings. Unlike Purandar Wada, Gokhale Wada has a ventilator in the second-floor sloping roof, which enhances its passive cooling efficiency. Its North-South alignment and load-bearing construction with both mud and lime plaster ensure that it remains a valuable case for studying thermal performance in different spatial configurations. The courtyard ratio of Gokhale Wada (7.64%) is notably smaller than Purandar Wada (15.64%) and Ranade Wada (10.98%), allowing for a comparative study of how courtyard proportions influence ventilation and thermal comfort.

3.6 Purande Wada

Purandar Wada (Figure 3-9), a traditional structure oriented along the North-South axis, showcasing a classic load-bearing construction style with both front and rear yards. This architectural approach emphasizes stability and spatial organization, characteristic of historical Indian residences. The flooring predominantly features stone and slate, offering durability and a rustic aesthetic. The walls of Purandar Wada are crafted from mud, reflecting traditional building practices. These walls vary in thickness from 350 to 450 mm, providing excellent insulation. To enhance structural integrity, intermediate wooden columns are strategically placed at intervals of 1.5 to 1.8 meters. Internally, the walls are coated with mud plaster, maintaining a natural, earthy finish, while the exteriors are reinforced with cement plaster for added durability against weathering.

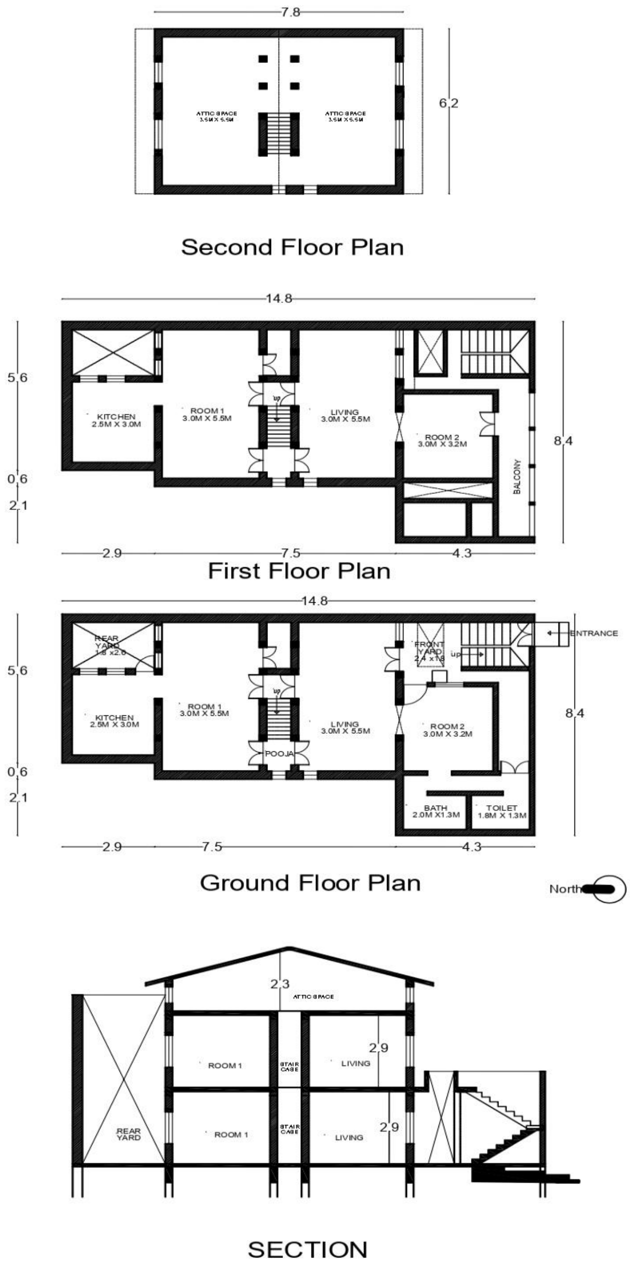


Figure 3-9 Purande Wada Plan & Section

Passive design strategies are thoughtfully integrated into the structure. The presence of front and back yards facilitates natural ventilation and daylight penetration. An attic floor and a front staircase function as cavity walls, enhancing thermal comfort by moderating indoor temperatures. The doors in Purandar Wada are wooden double shutters complemented by ventilators, allowing for adequate airflow and natural lighting. Windows are strategically positioned, with smaller openings on the east and west walls to minimize heat gain, while larger windows are placed in the front and rear yards to maximize ventilation. The roof system is a blend of sloping and flat designs. Sloping roofs, constructed with timber and stone tiles, efficiently drain rainwater, whereas the flat roofs utilize a combination of mud, brick, timber, and cement for structural support. Additionally, GI sheets and tiles contribute to the roofing materials, ensuring durability. The compound wall, made of stone, stands at a height of 2.4 meters, offering security and privacy. Notably, no animal shelter is present within the premises.

3.7 Gokhale Wada Plan & Section

Gokhale Wada (Figure 3-10), a traditional architectural structure oriented along the North-South axis, a strategic design choice that optimizes natural light and ventilation while adhering to cultural norms. The construction follows a load-bearing pattern with thoughtfully designed front and rear yards, enhancing airflow and providing functional outdoor spaces for various activities. The flooring of Gokhale Wada is crafted from stone and slate, chosen for their durability and natural cooling properties, which help maintain comfortable indoor temperatures even during hot weather. The walls are constructed from mud, reflecting age-old building techniques known for their excellent insulation properties. These walls vary in thickness from 350 mm to 450 mm, ensuring structural stability and thermal efficiency. To further strengthen the structure, intermediate wooden columns are placed at intervals of 1.5 to 1.8 meters, adding both support and an element of traditional design. Both internal and external walls are finished with cement plaster, providing a uniform appearance while enhancing durability and resistance to environmental elements.

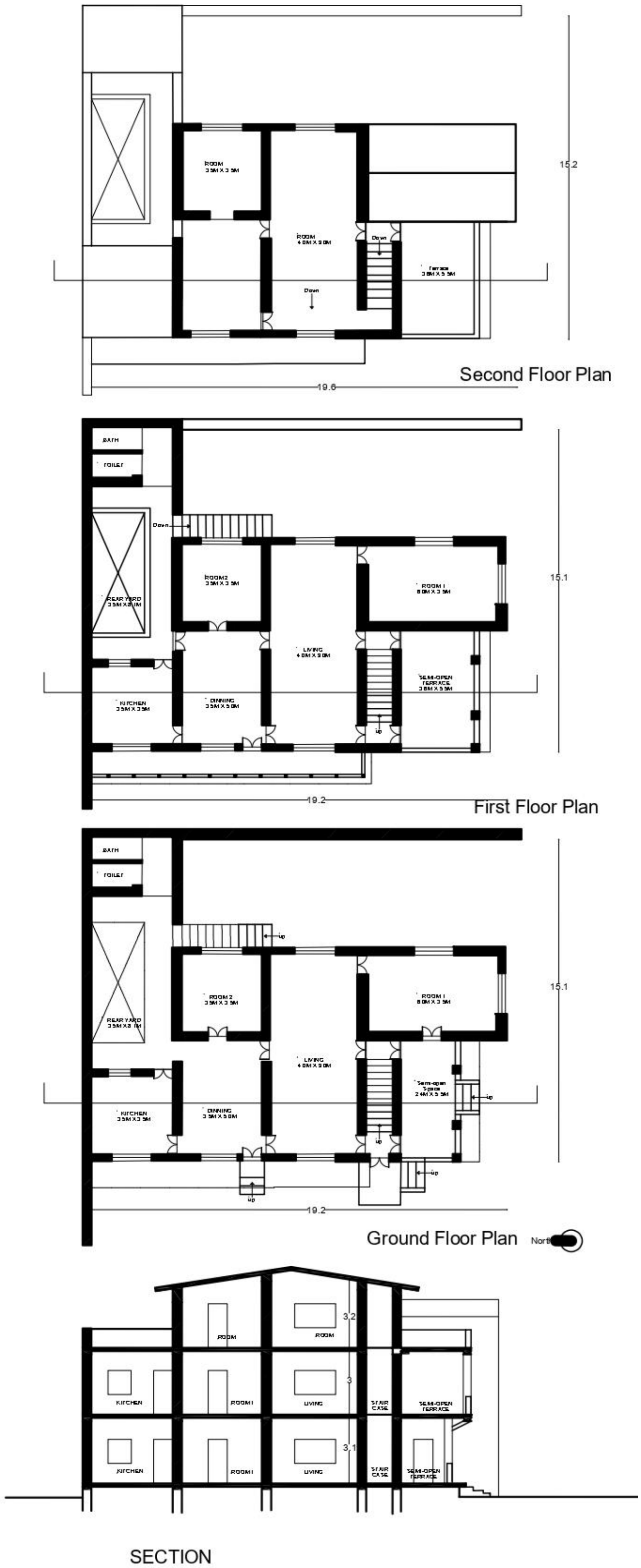


Figure 3-10 Gokhale Wada Plan & Section

The design of Gokhale Wada incorporates several passive design strategies, ensuring optimal thermal comfort and energy efficiency. The front and back yards facilitate cross-ventilation, while an attic floor and a front wooden staircase act as cavity walls, reducing heat transfer. Additionally, a ventilator on the sloping roof of the second floor supports stack ventilation, allowing warm air to escape while promoting continuous airflow. The doors in Gokhale Wada are crafted as wooden double shutters with ventilators, allowing ample light and ventilation while maintaining privacy. Windows are strategically positioned to enhance airflow and lighting. Smaller windows are located on the east and west walls to minimize direct sunlight, while larger windows are placed in the front and rear yards for enhanced ventilation and a connection to outdoor spaces. The roof design is a combination of sloping and flat styles. The sloping roof, made of timber and stone tiles, ensures effective rainwater drainage, while the flat roof is constructed using mud, brick, timber, and cement, providing stability and usability. GI sheets and tiles are also used, ensuring durability and weather resistance. The compound wall, built of stone and standing at 2.4 meters, provides security and privacy. Notably, Gokhale Wada does not include an animal shelter, emphasizing its residential purpose.

The selection of these Wadas was guided by the need for a systematic evaluation of traditional versus modern construction techniques, diverse orientations, and varied passive design strategies. The different courtyard configurations, wall thicknesses, and ventilation strategies across these Wadas offer a nuanced understanding of thermal performance in vernacular architecture. This methodology ensures a holistic assessment of how different architectural elements contribute to passive cooling while preserving cultural and architectural relevance. Comparative analysis not only aids in understanding vernacular thermal behavior but also informs sustainable architectural recommendations. By integrating traditional passive cooling methods with modern enhancements such as hybrid ventilation systems, thermally efficient materials, and adaptive shading solutions, this study aims to develop climate-responsive design strategies that enhance the resilience of vernacular Wada architecture against future climatic challenges.

CHAPTER 4: RESEARCH METHODOLOGY

The introduction of the bioclimatic analysis and the creation of the bioclimatic analysis tool open the chapter. The next section elaborates on the strategy used to create a modified comfort zone for the bioclimatic instrument. The assessment and validation of the bioclimatic analysis outcomes are undertaken through a case study of the Wada building, employing simulation techniques facilitated by the Design-Builder (Energy Plus) tool across eight distinct locations. The simulation employs mesoscale (TMY) climatic data of these eight locations, thus exempting the site-specific microclimate data from consideration in this evaluation. The ensuing figure (Figure 4-1) illustrates the flow chart delineating the research methodology.

4.1 Methodology Framework

Research framework for studying vernacular architecture in the Pune region under changing climatic conditions. The key components of the framework include literature review, climate analysis, vernacular architecture study, simulation, and validation (Figure 4-1).

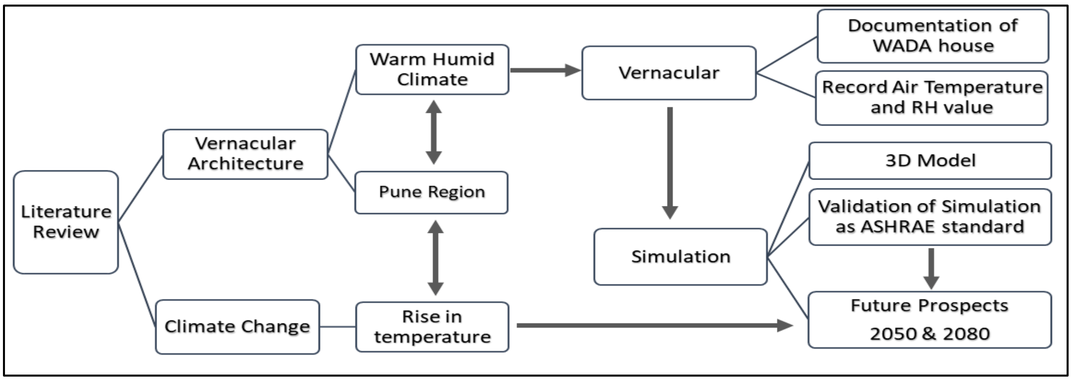


Figure 4-1 Methodology Flow Chart

Literature Review and Climate Change

The study begins with a literature review, which serves as the foundation for understanding vernacular architecture and climate change. The rising temperatures due to climate change are particularly and its implication. The increase in temperature affects the thermal comfort and passive cooling efficiency of traditional Wada architecture.

Vernacular Architecture and Climate Considerations

The framework highlights the strong connection between vernacular architecture and climatic conditions. The Pune region's traditional Wadas were designed to provide thermal comfort using passive design strategies. The study examines how these structures respond to temperature variations over time.

Case Study Selection: Three Different Wada Typologies

The research focuses on three Wadas; Ranade Wada (Raj Wada), Purandar Wada, and Gokhale Wada each representing different typologies based on their spatial organization, construction materials, and passive cooling strategies. These Wadas have been selected based on their orientation, architectural authenticity, materiality, courtyard-to-built-form ratio, and renovation status.

Simulation and Data Collection

The study involves documentation of selected Wadas, including recording air temperature and relative humidity (RH) values. A 3D model of the structures is created to simulate their thermal performance. The simulation is validated against ASHRAE standards to ensure accuracy in predicting future climate impacts.

Future Prospects and Adaptation

Once validated, the simulation results are used to project thermal performance for future climate scenarios, specifically for the years 2050 and 2080. This helps in understanding how traditional Wada architecture will cope with climate change and informs potential adaptation strategies for preserving vernacular heritage while enhancing thermal comfort.

This structured approach integrates historical knowledge with modern simulation techniques, providing insights into sustainable architectural solutions for future climatic challenges.

Table 4-1 Comparative literature study to analyse different tools used and major finding

Author & year	Building Typology &Country	Tool Used & Parameters	Major Finding
(Palme et al., 2013)	Residential buildings recently constructed. Rome, Osaka, Caracas	Tool: UKCIP used for future climate data and Trnsys tool Simulations (multizone building) used	Design strategies on the long-term performance of buildings used to analyse the energy demand. Fuel typology, system effectiveness, and emerging electrical supply trends will be the deciding factors in this situation when setting up a broad judgement.
(Chen et al., 2015)	ASHRAE office (Prototype) California	Tool: world climate change weather file generation tool by University of Southampton. Energy Plus for simulation. Parameters: Three locations were examined with regard to lifecycle energy use and SHGC values.	To find the starting settings that produced the best long-term outcome, the SHGC values were changed. Although only SHGC has been evaluated thus far, this research offers architects and engineers an approach that they may utilise in the preliminary stages of design to prevent the negative effects that climate change might have over the building's lifetime.
(Kikumoto et al., 2015)	Detached house. Tokyo	Tool: Future (2031–2035) weather data predicted by a GCM and TRNSYS software for Simulation.	The outdoor temperature by 2034, expected to rise (1.52 °C) from 26.23 °C to 27.75 °C and the detached house's sensible heat load would rise by 15%.
(Huang & Hwang, 2016)	Residential apartment Taiwan	Tools: Energy-Plus to simulate the natural ventilation performance with A1B future climate change scenario. Parameters: 1) Design: Base case, Low, Medium, and High 2) Insulation: External Wall Roof, Window	2020s, 2050s, and 2080s, annual increases in cooling energy of 31%, 59%, and 82% over current levels were noted. It is discovered that while no one technique can keep cooling energy use at the existing levels, a combination can work.

		& Overhang	
(Moazami et al., 2019)	Commercial Building Geneva,	Tool: Future weather data generated using the GCM method as proposed by the ASHRAE standard 90.1, was simulated using Energy Plus to study performance of building energy using future weather data sets.	In the near future, the range of relative change in peak load for cooling demand under extreme circumstances may increase by 2-28.5%. Under difficult circumstances at urban and city scale, the neighbourhood's peak energy usage might increase by 4.0% (in short term), 7.6% (in medium term), and 16.8% (in long-terms).
(Alhindawi & Jimenez-Bescos, 2020)	Typical Building Chelmsford, England	Tools: Climate change tool used for study A2 and the A1FI. Scenarios & Energy Plus software for simulations Parameters: Sets (Effective Temperature) processed through the "Nomogram for the Effective Temperature index,"	GHG emissions shows the cooling hours and monthly coverage would be increased by 60%, summer peak days with 6 hours, as well as a 33.3% yearly drop in the heating period.
(Andric & Al-Ghamdi, 2020)	Residential building Qatar	Tool: CCWorldWeatherGen tool, Design Builder (v.5.4) Parameters: Impact interpretation- ReCiPe approach Mitigation scenario based on the long-term perspectives considering social and economical	Future Climate change may result in a rise in the temperature difference between interior and outdoor air and increase Qatar's energy demand for cooling.
(Liu et al., 2020)	Residential building Hongkong	Tool: Representative Concentration Pathways (RCPs) and Energy Plus for simulation	The airtightness of external windows will be up to 329% more effective, although ventilation use's cooling potential will gradually decline. The yearly and peak cooling demand can be lowered by up to 56.7% and 64.5%, respectively, by using combinations of sensitive passive design.

(Summa et al., 2020)	residential apartment (nearly net zero) Rome	Tool: TRNSYS for simulation with RCP8.5 and RCP4.5 future projections.	The hours of adaptive comfort are reduced by 6.2% and 5.1%, respectively, under the RCP4.5 (2050) and RCP8.5 (2050) scenarios, in absence of cooling devices due to temperature increase and solar gains.
(Zune et al., 2020)	Residential House form Myanmar	Tool: ApacheSim for simulation and Macroflo programs, and IESVE software. for future weather data files. "shift" of a TMY hourly weather data parameter used.	air temperature used as a threshold of 30 °C and 36 °C to compare the effects of three climate settings and passive design methods on the inside thermal conditions of Myanmar dwellings.
(Henna et al., 2021)	Residential India	Tool: Resistance Temperature Detector (RTD) data loggers and design builder (v 3.4) simulations for Calibrated of the vernacular residences. And Meteonorm used to generate future climate scenarios.	As a result of climate change, increases yearly temperatures outdoors have an impact on inside climate as well. Suggenahalli, in a warm-humid climate, the effects of climate change making the indoor environment warmer than usual and necessitating the usage of cooling appliances.
(Kishore, 2022)	Residential India	Tools: CCWorldWeatherGen to study A2 Scenarios & Design Builder Simulation Parameters: Adaptive Thermal Comfort consider for NVP (natural Ventilation Potential); PSHP (Passive solar heating potential); DECP (Direct evaporative cooling potential).	warm humid climate of Chennai - increase in uncomfortable summertime hours: 42%. & for NVP: 28%. Paper also suggests for summer alternate active strategy.

(Wright & Venskunas, 2022)	no. of House forms, UK	Tool: Three decades climate change scenarios and IES-VE software (2018 version) Parameters: Base case scenario, solar radiation and or with window ventilation.	Warming due to climate change in all regions of the UK, three future decades up to the 2080s. Significance of solar shade and ventilation as preventative measures.
(Thapa et al., 2023)	Residential Building India	Tools: CCWorldWeatherGen to study A2 Scenarios & Design Builder Simulation Parameters: Orientation, Material like AAC bricks, infiltration, and lower window-to-wall ratio for optimal thermal performance and proposes a method for assessing under-cooling.	The parametric study revealed that west-facing buildings performed the worst under global warming, while south-facing orientations had the lowest annual cooling demands, guiding future designs. Among four wall designs, overheating reduced until the wall U-value reached 1.0 $W/m^2°C$, after which it increased due to insufficient heat dissipation. Additionally, reducing air infiltration from 5 to 2 ACH decreased both annual overheating and under-cooling hours across current and future climate scenarios (2050 and 2080).

4.1.1 Tools used for analysis

Table 4-1 reviews various research efforts focused on building performance under future climate change scenarios across different locations, building types, and simulation tools. Key findings include the influence of building orientation, material choices, and passive design strategies on long-term energy performance. Adaptive strategies were explored, such as insulation, shading, and reduced window-to-wall ratios to optimize cooling and mitigate overheating across diverse climates.

A summary of key studies examining the impact of climate change on building performance reveals diverse findings across various building typologies and climates. Palme et al. (2013) studied residential buildings in Rome, Osaka, and Caracas, using the UKCIP tool and Trnsys software. They highlighted the long-term importance of fuel typology, system effectiveness, and electricity trends for energy demand. Chen et al. (2015) focused on ASHRAE office prototypes in California, using Energy Plus and weather files to explore lifecycle energy and SHGC values. The study emphasized early design decisions to mitigate climate change impacts. In Tokyo, Kikumoto et al. (2015) predicted a 1.52°C rise in outdoor temperature by 2034, increasing heat loads by 15% for detached houses. Similarly, Huang and Hwang (2016) found that cooling energy demand in Taiwan's residential apartments could increase by up to 82% by the 2080s, stressing a combination of strategies to manage energy consumption.

Moazami et al. (2019) analyzed commercial buildings in Geneva, predicting a 2-28.5% rise in cooling demand under extreme conditions. Alhindawi and Jimenez-Bescos (2020) showed a 60% rise in cooling hours in Chelmsford, England, under future scenarios. Studies in Qatar by Andric and Al-Ghamdi (2020) and Hong Kong by Liu et al. (2020) pointed to increasing cooling demands driven by temperature differentials and passive design strategies. Summa et al. (2020) and Zune et al. (2020) explored adaptive comfort and passive design impacts in Rome and Myanmar, respectively. Recent research by Thapa et al. (2023) on residential buildings in India found that south-facing orientations performed best, and reducing air infiltration helped mitigate overheating and under-cooling.

While the specific tools used can vary depending on the research objectives and available resources, here are some of the maximum tools commonly utilized for analysis in this field:

Energy Plus: U.S. Department of Energy created the widely used energy efficiency simulation programme called EnergyPlus. It enables researchers to simulate and examine the energy usage and thermal efficiency of buildings under various climatic conditions. It is especially helpful for determining how climate change may affect energy demand.

Design Builder: Design Builder is another building energy modelling tool that integrates with EnergyPlus. It provides a user-friendly interface for creating and simulating building energy models, making it accessible for architects and engineers.

TRNSYS: The TRNSYS software suite is renowned for its versatility in simulating dynamic energy systems. It can be used to model the interaction between buildings and their surrounding environments under varying climate conditions.

Climate Data Generators: Tools like CCWorldWeatherGen and Weather Morph are used to generate future climate data based on climate change scenarios. Researchers can input this data into energy simulation software to evaluate building performance under changing climate conditions.

ASHRAE Standard 90.1: Standards published by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) are frequently used in building energy analyses. Commonly used as a standard for energy performance is ASHRAE Standard 90.1.

CIBSE Weather Files: Weather data files are made available by CIBSE (Chartered Institution of Building Services Engineers) for use in energy simulations and climate impact analyses.

Climate Models: To make predictions about the future climate, researchers frequently use data and climate models from IPCC (Intergovernmental Panel on Climate Change). Building designers can use these models to learn about anticipated changes in humidity, temperature, and other climate variables.

GIS (Geographic Information Systems): GIS tools enable researchers to integrate spatial data, such as building locations and topography, with climate data. This spatial analysis can provide insights into localized climate impacts on buildings.

Statistical Software: To analyse huge datasets, spot trends in climate data, and do regression analysis to comprehend the connections between environmental factors and building performance measures, statistical analytic tools like R or Python can be employed.

Passive Design Software: Passive design modules are frequently included in programmes like DesignBuilder to assist in evaluating how well passive measures like, daylighting, shading and natural ventilation work to cut down on energy use and improve comfort.

Building Information Modeling (BIM) Software: BIM tools like Autodesk Revit can be used to create detailed 3D building models, which can then be linked to energy simulation software for more accurate performance analysis.

Weather Data Repositories: Many research initiatives use publicly accessible repositories like NCEI (National Centers for Environmental Information) by United States, to obtain past weather data and future climate estimates.

Machine Learning and Data Analytics Tools: Advanced data analytics tools and machine learning algorithms can be applied to climate and building performance data to uncover complex relationships and make predictions about future climate impacts.

Geospatial Analysis Tools: Geographic Information System (GIS) software and geospatial analysis tools are crucial for incorporating geographic and spatial factors into climate impact assessments for buildings.

Comfort and Thermal Analysis Software: Specialized software, such as Ladybug Tools for Grasshopper in the context of Building Information Modeling (BIM), can assess thermal comfort and analyze daylighting strategies.

Life Cycle Assessment (LCA) Tools: For a holistic view of the environmental impact of buildings, LCA tools like SimaPro or Open LCA are used to assess a building's ecological footprint throughout its life cycle.

Researchers often integrate several of these tools and methodologies to conduct comprehensive climate change impact assessments on buildings. The choice of tools depends on the specific research objectives, available data, and the complexity of the analysis required. This multidisciplinary approach helps to gain deeper insights into the interactions between climate change, building design, and energy performance. Advanced modelling, simulation, and data analysis must be integrated to create resilient data, comprehend building performance under climate change future scenarios for temperature rise, and develop resilient and sustainable building solutions that address the challenges posed by a changing climate. The next Table discusses the tools used considering other objectives and methodologies for the research.

Table 4-2 Tools and Instruments Used

Objective	**Analysis to be undertaken**	**Instruments/ Processes/Software to be used**	**Organization/Institute (where the facility is available)**
Objective 1: To analyse the nature of climate change and its impact on the vernacular architecture for future scenarios considering the rise in temperature in	Literature Review: Understand passive design strategies for vernacular house forms in warm-humid regions and thermal performance.	Books, Research papers, Articles	Library: Lovely Professional University, 2Symbiosis Skills & Professional University, Websites: Journal Publications, E-Books, Articles & Conference Proceedings

Pune.	Case Study Documentation: Analyse vernacular architecture Wadas for passive design strategies and construction techniques.	Physical site visits (Quantitative Analysis): Architectural Documentation, Photography, Survey Forms	INTACH Pune Chapter, People Residing in Old City, Research Scholars, and Architects working on vernacular settlements.
	Analyse rise in temperature trends: Peak Summer Temperature historical data (1990-2023) from IMD to assess temperature rise over the last few decades.	IMD Weather Data	Indian Meteorological Department (IMD)
	Bioclimatic Chart Analysis: Air & Radiant Temperature, Relative Humidity, Wind Speed, Wind Direction.	Climate Consultant Software	Climate Consultant, Developed by Department of Energy, USA
	Monitoring Indoor Conditions: Record half-hourly temperature and RH using data loggers during peak summer.	HTC Data Logger	Data loggers purchased and placed at selected Wada houses based on the literature Study
	Building Simulation: Create and validate a model based on logged data.	Design Builder	Design Builder Software for building simulation

	Validation of observed data with Simulation data	Linear Regression, Mean Biased Error & Coefficient of Root mean Square Error	MS: Excel
	Generate Future Weather Data: Use	CCWorldWeather Gen Tool	CCWorldWeatherGen Tool for generating climate change scenarios (2050 & 2080).
	Simulation with Future Weather Data: Analyse the thermal performance of Wada architecture under future weather scenarios using .epw files.	Design Builder Software	Design Builder Software for simulating building performance under future climate scenarios.
To assess and compare the thermal performance of traditional Wada houses (base case) and their improved climate-responsive strategies through simulations	It involves comparing the original Wada structures (base case) with modified versions that integrate climate-responsive design strategies. Using computer simulations, the study will predict how Wadas will perform under future climate conditions, helping to identify effective ways to enhance thermal comfort	Design Builder Software	Literature Study, Simulation Results. Design Builder Software for simulating building performance under future climate scenarios. With improved case using bioclimatic strategies observed from climate consultant tool

under future climatic scenarios	and sustainability.		
To develop practical guidelines for modifying Wadas to improve thermal comfort while preserving their traditional architectural character.	Based on the findings from thermal performance assessments (objective 2), the study will propose guidelines that integrate traditional passive design elements with modern technologies. These guidelines aim to enhance the climate resilience of Wadas, ensuring thermal comfort in rising temperatures while maintaining their cultural and architectural essence. The recommendations will serve as a framework for sustainable retrofitting of vernacular dwellings in Pune.		
Results & Analysis			
Conclusion & Future Recommendations			

The research methodology outlined in the table (Table 4-2) presents a systematic and multidisciplinary approach to understanding the impact of rising temperatures on vernacular house forms in warm-humid regions (Figure 4-1). It begins with a comprehensive literature review, drawing from books, research papers, articles, and online publications available in reputed institutions and libraries. Although in-house resources are limited, collaboration with esteemed educational institutions and libraries ensures access to valuable theoretical foundations. The subsequent phase involves in-depth case studies, necessitating physical site visits and engagement with residents, scholars, and architects. This hands-on exploration allows for qualitative insights into passive design strategies and construction techniques

To comprehend the temperature rise, IMD weather data analysis is conducted, supplemented using Climate Consultant software for bioclimatic comfort chart creation. The online availability of resources further supplements the analysis, showcasing adaptability in the face of limited in-house tools.

Monitoring indoor temperature and humidity using HTC Data Loggers provides essential on-site data, particularly during peak summer conditions. The proactive approach of procuring loggers exemplifies dedication to robust data collection.

The research advances into simulation modelling using Design Builder software, with validation through logger data. Synthetic weather data files for future scenarios are generated, anticipating temperature rises in 2050 and 2070, demonstrating forward-looking research.

The final experimental phase involves the analysis of changing weather data files using Design Builder. This stage examines the impact of temperature rise on vernacular house forms in Pune's warm-humid climate, considering passive design strategies. The comprehensive nature of this stage, incorporating data from literature, case studies, interviews, and field analysis, signifies a holistic approach to achieving research objectives.

Research methodology is a meticulously planned and resourceful strategy for investigating temperature rise effects on vernacular house forms. It combines various research approaches, demonstrating adaptability and proactivity in using available resources and external collaborations to fulfil research objectives.

4.2 Weather Data and Temperature Increase Analysis for Pune:

To comprehend the escalation in temperature within the Pune region, a meticulous analysis of the last three decades' maximum temperature records was performed utilizing meteorological data from the Indian Meteorological Department (IMD).

4.3 **Correlation Between Temperature Rise and Vernacular Architectural Form:**

A comprehensive review of the literature was undertaken to glean insights into the thermal attributes intrinsic to vernacular architecture in warm-humid contexts. This scrutiny aims to identify pertinent parameters for integration into the simulation model.

4.4 Real-time Data Collection and Documentation of Relative Humidity and Air Temperature

Real-time relative humidity and air temperature data were regularly logged using data loggers throughout the entire year for a sample vernacular dwelling shape. This data accrual facilitates a nuanced understanding of the fluctuation in these environmental parameters

4.4.1 Data Loggers for Monitoring period and procedure

All four seasons—Summer, Monsoon, and Winter were covered throughout the 12-month monitoring period, which ran from April 10, 2022, to March 31, 2023. The HTC-Easy log data recorder was used for both inside areas and the courtyard to measure the indoor air temperature. The loggers were thoroughly calibrated prior to the collection of dry-bulb temperature data. Both the first-floor balcony and the ground-floor living room were secured for observation. These spaces were selected due to their direct exposure to the outdoor environment through their roofs, rendering them more sensitive to climate fluctuations.

The loggers were positioned at the spatial center and elevated above 2 meters from the floor level to mitigate measurement discrepancies arising from radiation emitted by the floor and adjacent surfaces (see figure). While the ground floor's monitored room featured west-facing windows with wire mesh to prevent insect intrusion while facilitating natural airflow, the courtyard-facing door remained open throughout the day, enhancing thermal efficiency.

The outdoor data logger placement aimed to avoid direct solar radiation exposure. Instrument specifications are outlined in the table provided. The house was occupied by a couple for the entirety of the survey period, including heat gains associated with human tenancy in the simulation framework. HTC was used to fully understand indoor thermal characteristics including Rh & air temp.

4.4.2 Input data for Validation

The places were set up with indoor and outside air temperature sensors and a relative monitoring logger for half-hourly data.

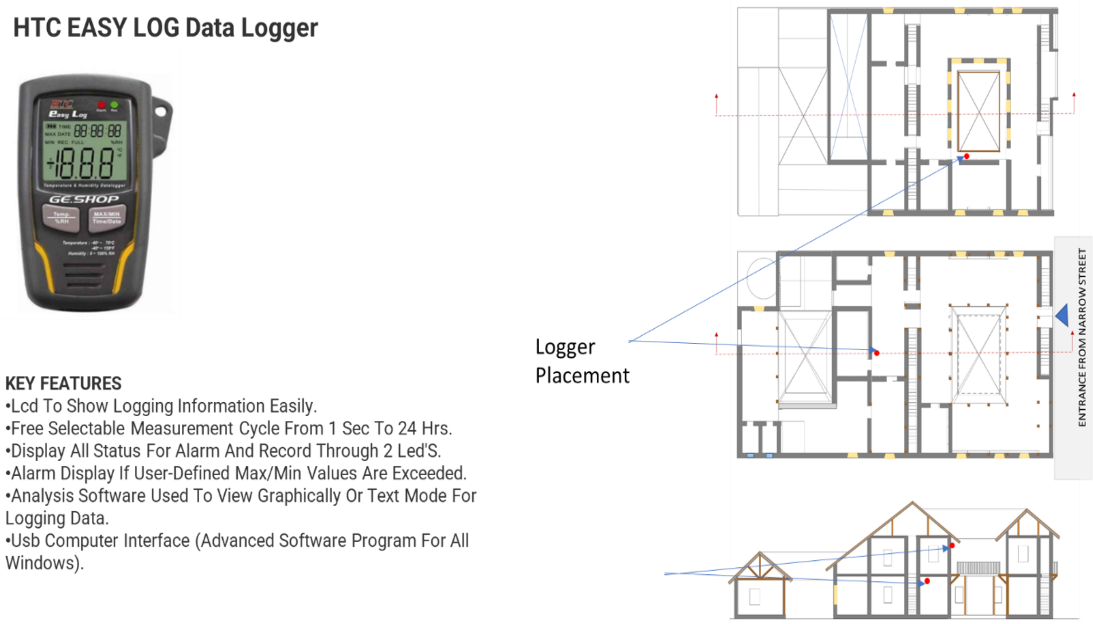


Figure 4-2 Logger Details & Location of Loggers in Ranade Wada

As per the literature review to take onsite measurements two loggers were installed at the given location (Fig 4-2) for Air Temp. & RH. These data loggers were installed for peak summer to understand the resilience of house forms in extreme outdoor weather conditions. According to weather data, the exterior temperature logger recorded a low temperature of 18 °C and a maximum temperature of 42 °C.

4.5 Ranade Wada at Kiwale area Pune Region

Climate-responsive shelter design is embedded in social consciousness. The structure is usually referred to as a person's third skin, with clothes serving as the second, concealing the first (biological) skin. Ranade Wada was once occupied by big joint families, but with the shifting socioeconomic landscape, they are now occupied by several tenants and subtenants. They typically feature several bedrooms, as well as a shared living room, storage area, kitchen, and toilet block. In the house two sets of staircases were placed one at the entrance for administrative purposes while the next set was placed adjacent to Living (Diwankhana) for family, the staircase was hidden between walls. The kitchen and storage room were in the second court, which was reserved for exclusive use by the ladies of the house. The tulsi-vrindavan plant was also included for prayer reasons. In the table below,

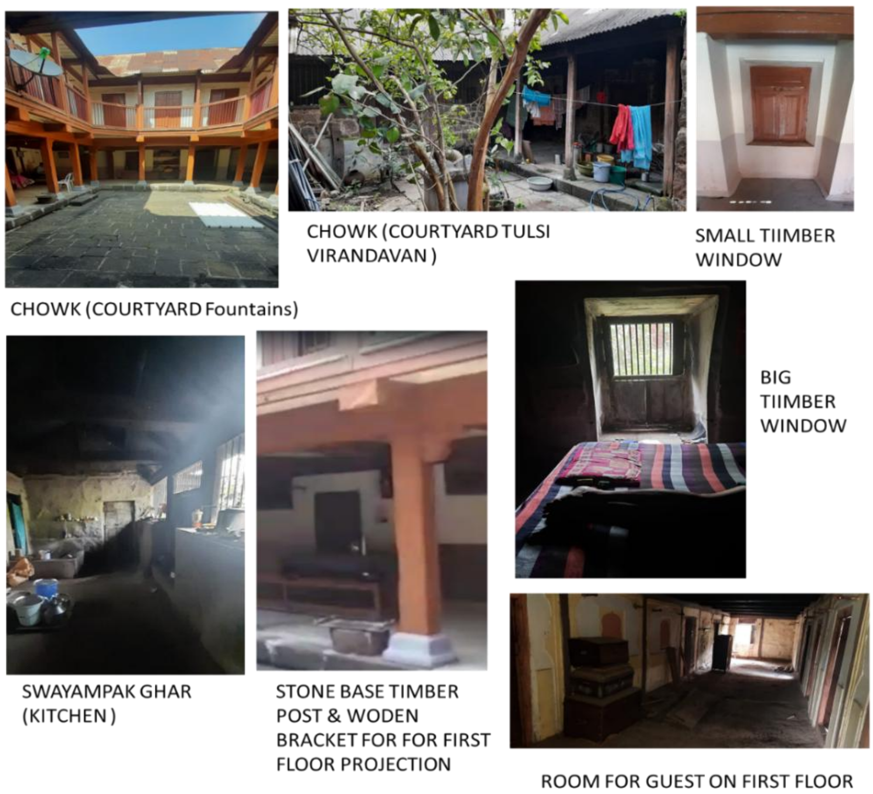


Figure 4-3 Interior Details of Ranade Wada

the vernacular vocabulary is given along with their purpose and functions.

4.5.1 <u>Thermal Characteristics for each space High thermal mass (Wall) made locally –</u>

Enables a longer time lag, inhibits heat buildup inside, and serves as sound and dust insulation walls, providing thermal mass for roofs with thermal reversal.

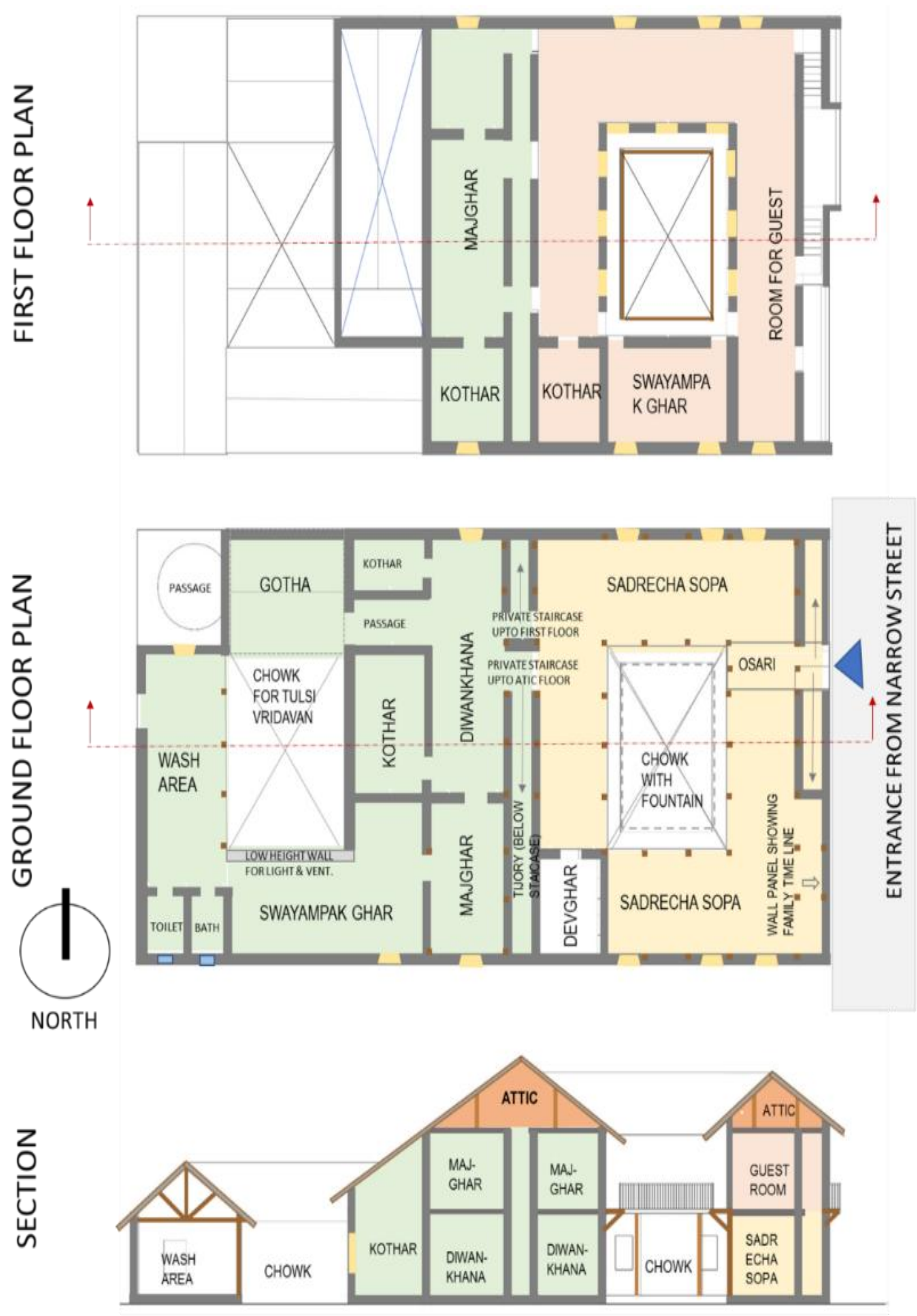


Figure 4-4 Ranade Wada at Kiwale Area Pune Region

4.5.2 Building Orientation

The long side of Ranade Wada faces north-south (Figure 4-3 & 4), while the main facade faces east along a small roadway. Wada's planning and layouts were based on the notion of a courtyard. Wada's basic planning was introverted and chowk based. Introvert planning gives the dwellers of the house a sensation of containment and privacy. The shape and design evolved from their everyday activities and the spaces required to carry out those tasks. Stone walls, wooden stairs, and open chowks characterize the architecture, ventilation making desired wind to achieve thermal comfort.

4.5.3 Socio - Activities areas

Vernacular architecture creates harmony with nature, climate, and social aspects of people. Every Wada has at least one hall for entertaining visitors and holding private events.

Diwankhana was the name given to it (Figure 4-6). All the Diwankhana had free-standing wooden columns. The most common type of column was a column with a stone base. The ceiling was decorated with exquisite carvings, chandeliers, and hanging lanterns. Frequently, wooden planks were used for the ceilings, and they were then adorned with floral patterns of geometry.

The Ranade Wada Diwankhana exhibits evidence of the more polite Peshwas period. In addition to full-height windows fronting the court, the smaller passageways on both sides of the great central hall also contained smaller square windows.

4.6 Thermal Characteristics of Purandar Wada

Purandar Wada, located in the Sawad area of Pune, is a traditional vernacular house that follows a rectangular plan form. With an age exceeding 100 years, the Wada embodies the essence of historical architecture designed to suit Pune's warm-humid climate. The layout comprises a front yard, rear yard, and an attic, all contributing to its ability to regulate indoor temperatures passively (Figure 4-5 & 6). The load-bearing construction method, coupled with the strategic arrangement of spaces, enhances its thermal comfort while preserving cultural aesthetics.

GROUND & FIRST FLOOR LIVING ROOM CONNECTED TO FRONT YARD

FRONT YARD

VENTILATED ATTIC SPACE

FRONT & SIDE ELEVATION OF WADA

Figure 4-5 Details of Purandar Wada

4.6.1 <u>Building Orientation:</u>

The Wada follows a north-south orientation, a strategic approach to minimize direct solar heat gain, especially during peak summer months. This alignment ensures that longer facades receive indirect sunlight, reducing excessive heating of the interiors. The positioning of courtyards and ventilated attic spaces further aids in maintaining comfortable indoor temperatures.

4.6.2 Thermal Characteristics for Each Space

Purandar Wada is constructed with 350mm thick brick masonry walls, plastered with mud on both sides. These walls exhibit high thermal mass, allowing them to absorb heat during the day and release it gradually at night, stabilizing indoor temperatures. The roof consists of a combination of sloping and flat surfaces, with sloping roofs made from timber and stone tiles, providing excellent insulation. The attic space contributes to stack ventilation, enhancing airflow and minimizing heat buildup.

4.6.3 Symmetry

The house follows a symmetrical layout in terms of structural design and space distribution. The rectangular form ensures uniform distribution of air and light,

Figure 4-6 Purande Wada Plan & Section

reducing temperature variations between different sections. The front and rear yards are symmetrically aligned, ensuring cross-ventilation across the indoor spaces.

4.6.4 Solar Radiation

Purandar Wada mitigates solar radiation impact through various passive design strategies. The north-south orientation ensures minimal direct sun exposure, while the combination of sloping and flat roofs, along with strategically placed openings, regulates solar heat gain. Front and rear yards introduce shading and further reduce the heat load on the interiors.

4.6.5 Internal Space Design, Openings with Shading, and Natural Ventilation.

The design incorporates wooden double-shutter windows with ventilators. Small windows on the east and west walls limit heat entry, while larger openings in the front and rear yards promote ventilation. The staircase acts as a ventilated cavity wall, improving air flow and enhancing stack ventilation. Additionally, the attic space allows warm air to escape, maintaining a cooler indoor environment.

4.6.6 Socio-Activity Areas

The presence of a front yard and rear yard enables community interactions and household activities, reflecting the socio-cultural importance of shared spaces in traditional Wada architecture. The shaded yards serve as comfortable outdoor areas, reducing dependency on indoor cooling during hot weather.

4.7 Thermal Characteristics of Gokhale Wada

Gokhale Wada (Figure 4-8 & 9), situated in Shivaji Nagar, Pune, shares similarities with Purandar Wada but has distinct architectural adaptations. Following a rectangular layout, the Wada is built using a load-bearing construction technique with an open front space and a rear yard. With a history of over 100 years, this house exemplifies climate-responsive design by integrating passive cooling strategies adapted to Pune’s climatic conditions.

4.7.1 Thermal Characteristics for Each Space

The Wada consists of 350mm thick-brick masonry walls, finished with mud and lime plaster. These materials contribute to thermal stability by moderating heat absorption and dissipation. The roof integrates sloping and flat surfaces, constructed from timber and stone

STAIRCASE WITH VENTILATION

ROOM ADJECENT TO REAR YARD

FIRST FLOOR PROJECTED CORRIDOR

FIRST FLOOR SEMI-OPEN TERRACE

FIRST FLOOR KITCHEN

FIRST FLOOR DINNING

ROOFING WITH SMALL VENTILATORS

FRONT ELEVATION

4-7 Interior Details of Gokhale Wada

tiles, ensuring insulation and minimizing heat penetration. The attic serves as a key ventilation element, preventing overheating of upper floors.

4.7.2 Building Orientation

Like Purandar Wada, Gokhale Wada follows a north-south orientation, reducing excessive heat gain from direct sunlight. This alignment ensures optimal shading, preventing prolonged exposure to solar radiation while enabling efficient cross-ventilation.

4.7.3 Symmetry

Gokhale Wada exhibits a symmetrical design, maintaining a balanced distribution of indoor and outdoor spaces. The rear yard, attic, and strategically placed ventilators ensure uniform airflow, promoting passive cooling across the structure. The rectangular rear yard supports air circulation, complementing the symmetry in thermal performance.

4.7.4 Solar Radiation

Solar heat gain is managed through shaded openings, courtyard positioning, and ventilated attic spaces. The ventilator on the second-floor sloping roof aids in stack ventilation, drawing warm air upward and releasing it, preventing heat buildup within living spaces. The extended balconies on the front elevation provide additional shading, further reducing indoor temperatures.

Figure 4-8 Gokhale Wada Plan & Section

4.7.5 Internal Space Design, Openings with Shading, and Natural Ventilation

The Wada features wooden double-shutter windows with ventilators, like

Purandar Wada. Small windows on the east and west walls limit direct solar heat entry, while large windows on the front and rear sides enhance ventilation. The front wooden staircase acts as a ventilated cavity wall, improving airflow and aiding in temperature regulation. The attic space, combined with ventilators in the sloping roof, enables effective natural cooling through the stack effect.

4.7.6 Socio-Activity Areas

The rectangular rear yard serves as a communal and functional space, supporting household activities while fostering social interactions. The integration of shaded spaces allows for outdoor usage without excessive heat exposure, reinforcing the role of vernacular architecture in sustaining community-oriented living environments.

4.8 Simulation Model Construction of Purandar, Gokhale and Ranade Wada House Form:

A sophisticated simulation model was crafted for in-depth investigation. This model, developed through Design Builder version 7.0.2.004 (Table 4-4), serves as a pivotal tool for subsequent analyses. Table 4-3 discusses the Construction Parameter for Simulation Model.

Table 4-3 Construction Parameter for Simulation Model

	Building element	**Thermal Characteristics**	**U -value (/(m2·K)**
1	Wall	External & Internal Wall: walls are covered in 350 mm brick masonry walls with inside mud plaster.	3.91
2	Window	20 mm Timber panelled shutter	2.22
3	Floor	Terrazzo(10mm), Vermiculite aggregate (75 mm) & Wooden battens (100mm)	0.673

Table 4-3 Construction Parameter for Simulation Model			
	Building element	**Thermal Characteristics**	**U -value (/(m2·K)**
4	Flat Roof	Roof Tiles (20mm), Bitumen water proofing layer (5mm), Vermiculite aggregate (100 mm) & Vermiculite Plaster (20mm)	1.143
		30 mm Maalige Roof with 15 mm air gap on wood rafters	0.742
		Semi expose floor Roof Tiles (20mm), Vermiculite aggregate (100 mm) & Vermiculite Plaster (20mm)	1.044
5	Air Change per hour	2.00 ACH	
6	HVAC	No mechanical ventilation	

4.8.1 Simulation model & working

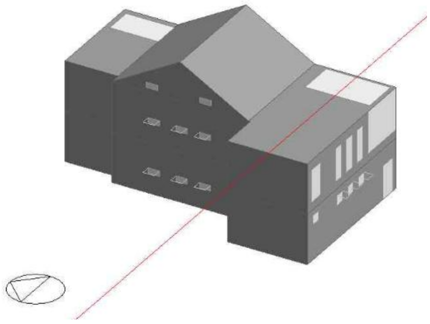
A simulation Model was created for further Investigation using Design Builder – v7.0.2.004. Design Builder uses the energy plus simulation engine and generates the graphical results for better interpretations of results.

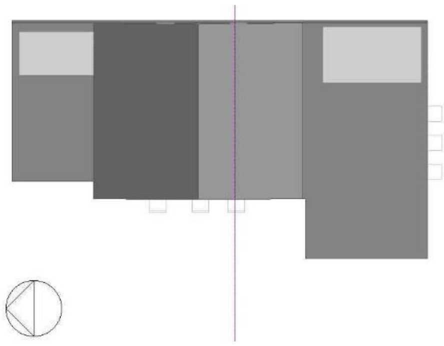
4.9 Validation of Steps c & d and Temperature Variation Utilizing ASHRAE Guidelines**:**

The observed temperature fluctuations and the simulation results are validated using the ASHRAE standards. MBE (Mean Bias Error), regression analysis, and CVRSME (Coefficient of Variance of Root Mean Squared Error) are used to evaluate the consistency of the results.

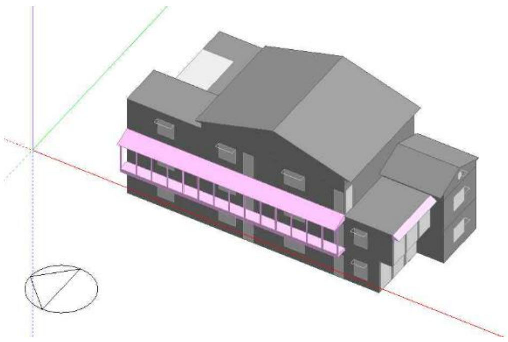
Table 4-4 Simulation Model for Purandar, Gokhale & Ranade Wada

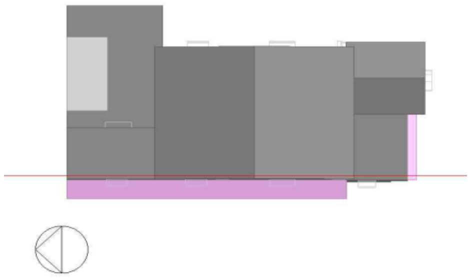
Design Builder Model for Purandar Wada



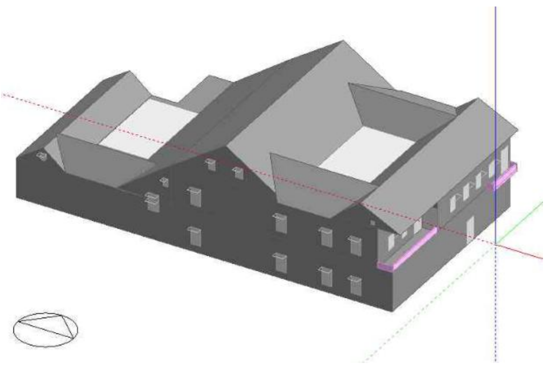


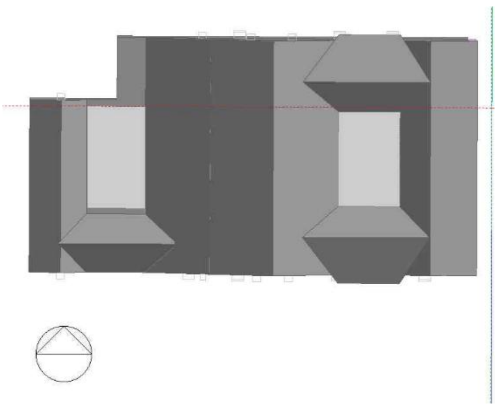
Design Builder Model for Gokhale Wada





Design Builder Model for Ranade Wada





4.10 Projection and Examination of Future Climate Scenarios:

Anticipating future climate alterations, weather data files for 2050 and 2080 were formulated. This was accomplished by harnessing the IPCC HADCM3 model, it was transformed using the World Weather File Generator tool (Figure 4-10) to produce artificial future climate data files appropriate for use with simulation software for building

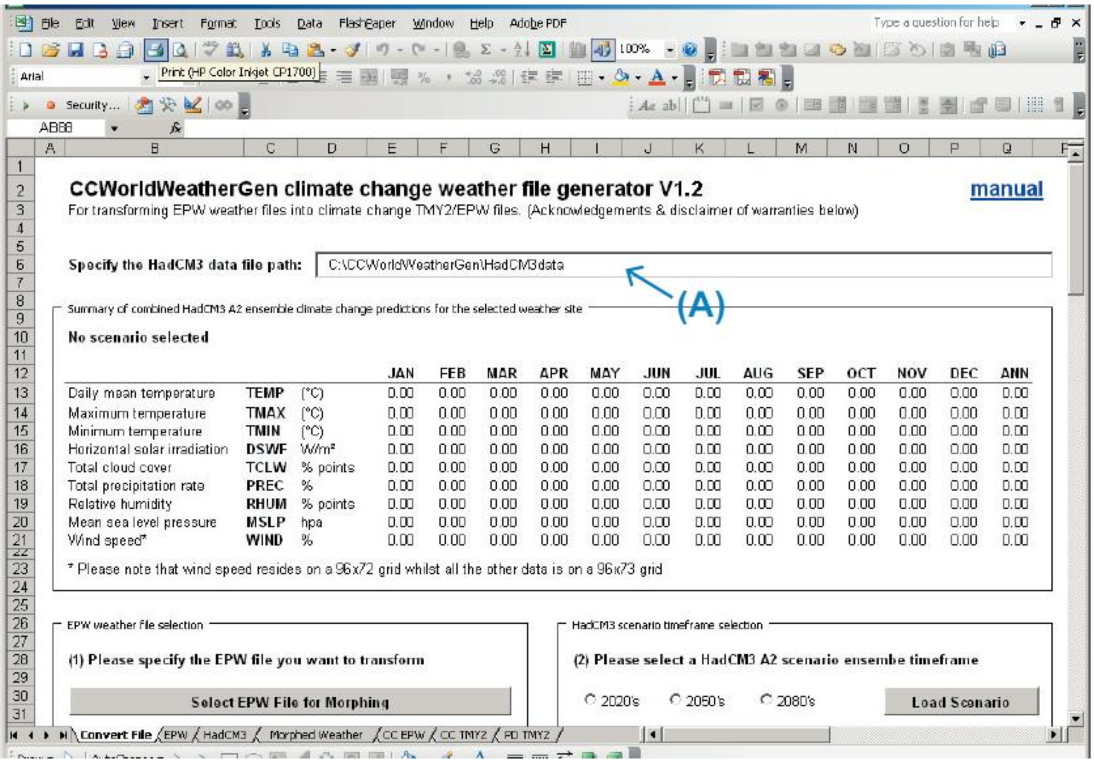


Figure 4-9 CCWorldWeatherGen Tool

performance.

4.11 Utilization of IPCC HADCM3 Model for Climate Data Generation:

The IPCC TAR model data summary of the HADCM3 A2 experiment ensemble served as the foundation for the World Weather File Generator for Climate Change, which was used to create meteorological data files for the years 2020, 2050, and 2080. This utility uses Microsoft® Excel and a "morphing" process created by Powell, Belcher, and Hacker to convert current EPW weather data into TMY2 or EPW files that have been modified to account for climate change.

4.12 Formulation of an Optimistic Future Scenario**:**

Envisioning favorable climate change scenarios, the study incorporates variables such as wall and roofing materials, U-value, Solar Heat Gain Coefficient and Window-to-Wall Ratio (WWR), (SHGC). By considering these factors, the research endeavors to outline a best-case future scenario.

The chapter covers the approach and numerous methods that were utilised for the research of vernacular homes' thermal performance using techniques from passive design to address future scenarios and a rise in temperature brought on by climate change. In the next chapter Wada Structure, passive design strategies and case studies will be discussed in detail.

CHAPTER 5: RESULT AND ANALYSIS

Numerous researchers have examined and studied various variables related to vernacular architecture's performance in diverse temperature zones, bioclimatic architecture, climate change resilience, sustainability, and energy concerns. Additionally, numerous research studies have been conducted on the local vernacular architecture of the Pune region, but none of them address climate change. Here there is a Research gap on the change in temperature and its impact on vernacular houses and that is the motive to go for the research and understand the implications of the rise in temperature on vernacular house form.

Society is already facing Climate change and its implications i.e., the temperature rise, by understanding passive design strategies in vernacular architecture will not only promote regional design and material understating but also help architects and Interior Designers to develop concepts of vernacular architecture in contemporary architectural design to tackle global issues (rise in temperature). The research will need pieces of evidence to draw conclusions and findings which can be obtained from case studies, Weather analysis and

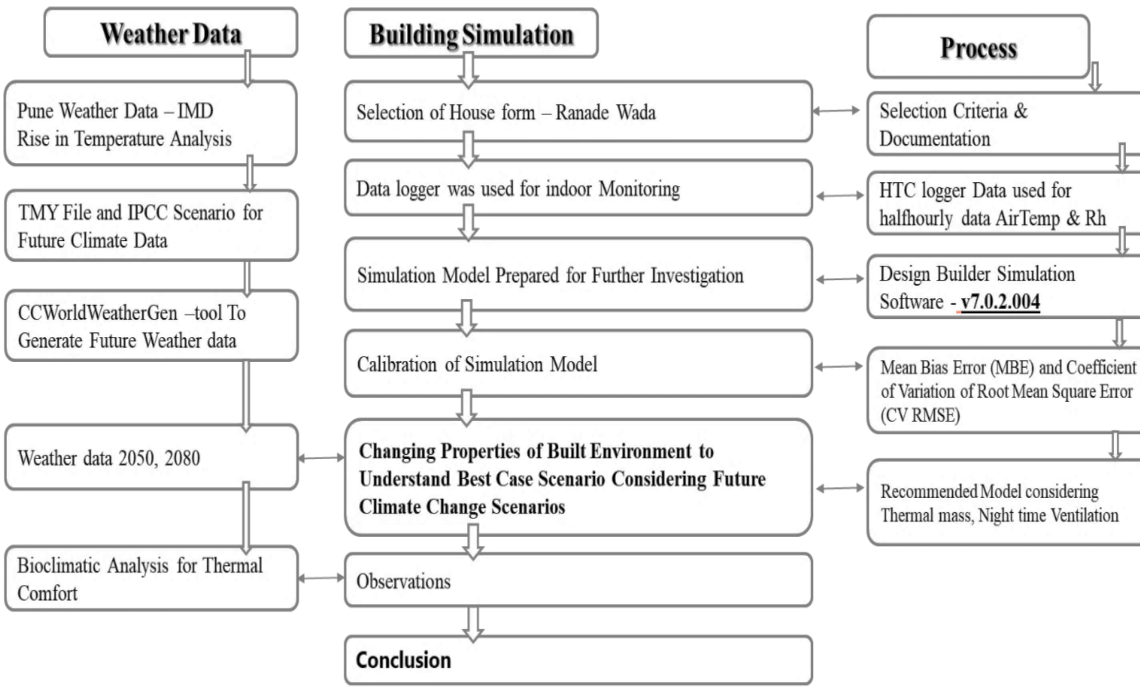


Figure 5-1 Analysis Flow Chart

studies to understand the following chart demonstrating strategies considered for analysis. northeast of the city (Figure 5-1).

5.1 Climate of Pune

Passive design strategies involve the thermal comfort of the region and people's adaptation i.e., according Köppen's climate classification Pune is Tropical Savanna Climate (Aw). This classification is characterized by hot summers, a distinct monsoon season, and mild, dry winters. Due to its inland location, Pune also exhibits semi-arid climatic influences (BSh), which result in lower humidity levels compared to coastal cities like Mumbai. These climatic variations significantly impact Pune's environmental patterns, including temperature fluctuations, rainfall distribution, and seasonal humidity levels. As a rapidly growing urban center, Pune's climate plays a crucial role in architectural design, infrastructure planning, and sustainable development strategies.

Adaptive thermal comfort from the above Figure 5-2 around 40% comfort be achieved the in-summer season, 30% in Monsoon and around 50% comfort can be achieved in winter considering standard data file. Here there is a lot of scope to understand the implication of the rise in temperature of vernacular passive design strategies. With this study, we can evaluate what will be the best passive design strategies to consider when designing

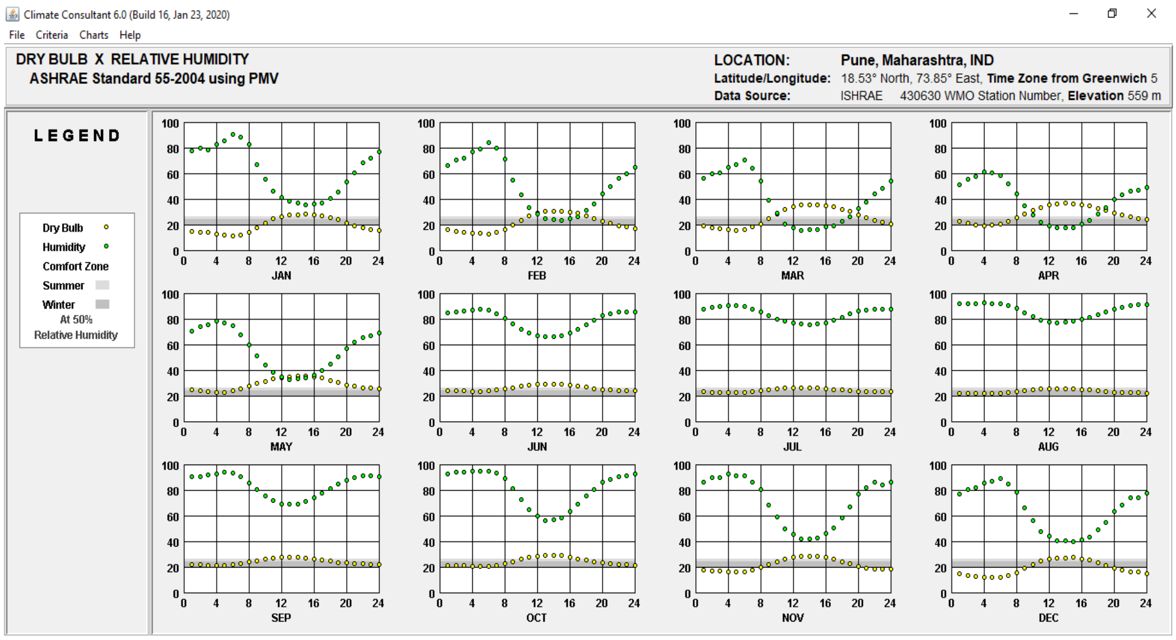


Figure 5-2 Monthly Graph for Rh &temp Using Climate Consultant software using TMY weather data

buildings in the near future.

5.1.1 Rise in temperature in Pune City

A map (Figure 5-3) of India illustrating temperature variations between the period from 1950-1990, featured in an article by The Hindu titled "Climate change is already making India hotter," reveals significant temperature increases across many regions. Pune, located in Maharashtra, witnessed a temperature rise ranging from 0.39 to 0.52 degrees Celsius. Although these shifts might appear minor, even slight temperature increases can have

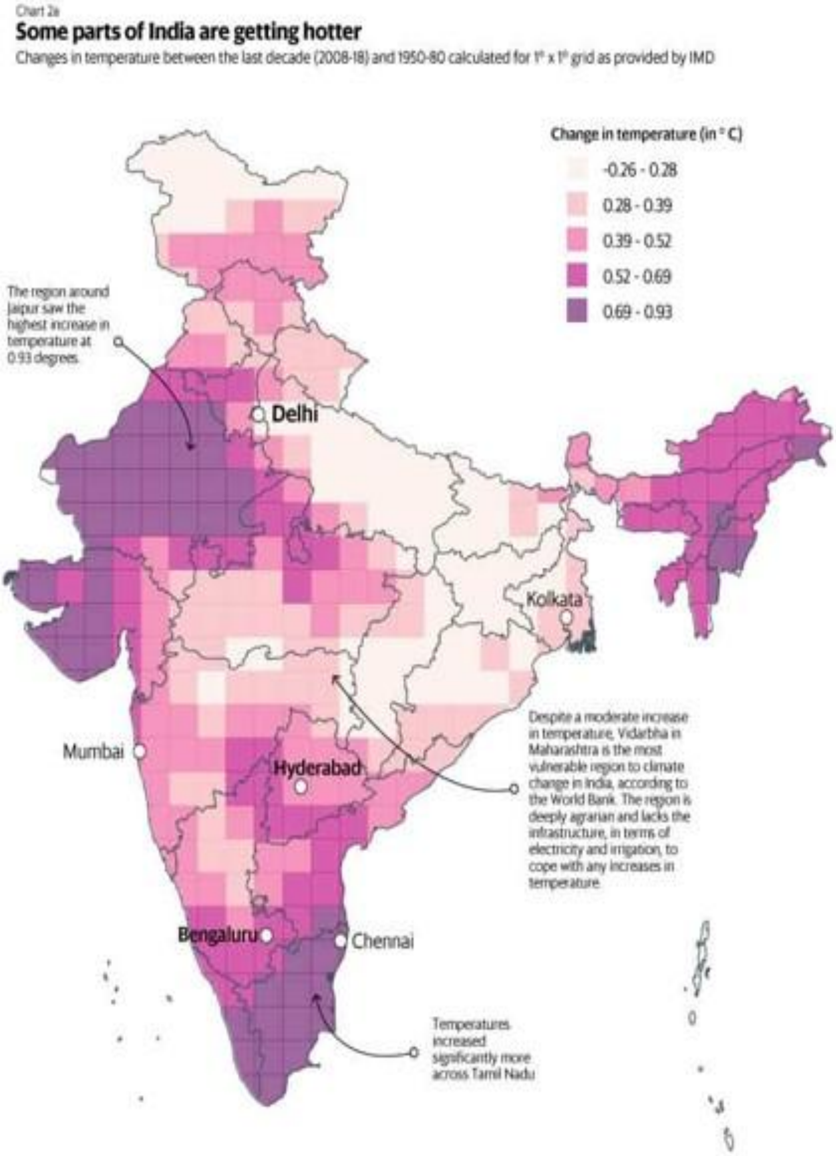


Figure 5-3 Climate change is already making India hotter (The Hindu, 2022)

substantial effects on urban centers like Pune, leading to more frequent and intense heat waves, droughts, and floods. Pune is a large and developed city; it remains vulnerable to these changes. Urgent actions, such as adopting renewable energy, strengthening water infrastructure, and developing heat resilience strategies, are critical. Climate change involves more than just temperature increases; it also includes changes in precipitation patterns and an increase in extreme weather events. Although the map presents historical data, the potential for more severe climate impacts emphasizes the need for proactive adaptation efforts (The Hindu 2022).

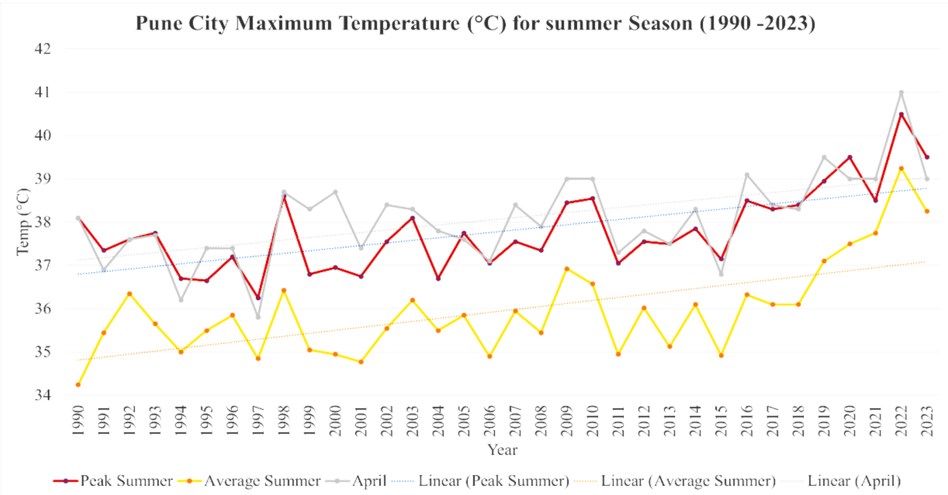


Figure 5-4 Graphs Are Plotted as Per Weather Data From IMD

To understand the Rise in temperature in the Pune region weather data analysis has been 30 years of weather data using India Meteorological Data for Monthly Minimum and Max Temperatures from 1990 to 2023 (Fig 5-4).

Based on the annual variation in summertime temperatures for the hottest month, April, peak summer (April–May), and summer average (March–June), Pune city is shown to be experiencing an increasing trend in the graph above. The average decadal temperatures show a 1.00–1.5 °C increase from 1990–2000 to 2009–2024. The influence of the temperature rise brought on by climate change is likely demonstrated by this maximum temperature increase throughout the hottest summer months in Pune. Whereas minimum temperature also shows study consider the coldest month – January, Peak winter (Dec-Jan) and winter average (Nov-Dec-Jan-Feb) The minimum temperature graph h shows a slightly increasing trend rise in temperate nature for winter months. The trend in report published by Times of India using IMD date 2013-2024 for April month shows 1.8ºC increase in maximum temperature and 1.5 ºC in minimum temperature(Madan Neha, 2024).

The world weather file generator for climate change and the IPCC's hadcm3 file are used to create synthetic weather data files for the years 2020, 2050, and 2080, as well as Figure 13. The HadCM3 (Hadley Centre Coupled Model, version 3) A2 experiment ensemble's IPCC TAR model summary data, which may be obtained from the IPCC DDC, is used by the climate change global weather file generator (CCWorldWeatherGen). The tool, ready for integration into building performance modelling programmes.

Its conversion of "present-day" TMY weather data into climate change TMY2 weather data, which works with most building performance modelling programmes, is based on Microsoft® Excel. The weather file generation algorithms of this programme depend on the designated "morphing" methodology developed by Belcher, Hacker, & Powell to alter meteorological data to adjust for climate change. demonstrates a discernible annual increase in temperature for the mean lowest, mean average, and mean maximum temperatures.

5.1.2 Thermal Performance due to rise in temperature

Minimum temperature is 21 ºC. (Fig.5-6) outside logger data shows a maximum temperature e 34.5 ºC & a minimum temperature. Accordingly, the thermal mass of the vernacular is resisting harsh outdoor environmental conditions throughout the alignment with alignment environmental conditions considering adaptive thermal comfort parameters. Weather data for the given shows a maximum Rh 80 % & minimum temperature and minimum temperature Rh 15 %. (Fig.5-5). Outside logger data shows maximum Rh and 60 % & minimum temperature and minimum temperature Rh 20 %. Outside logger data shows maximum and Rh 60% & minimum temperature and minimum temperature Rh 25 %.

Accordingly, Ranade Wada's indoor environment maintains the indoor humidity level and that is the reason for higher temperature with optimum Rh levels the people living in the house is achieving thermal comfort without any other means of which requires mechanical energy conditions throughout the day and night in alignment with indoor environmental conditions considering the Simulation Model and analysis for the Piolet project.

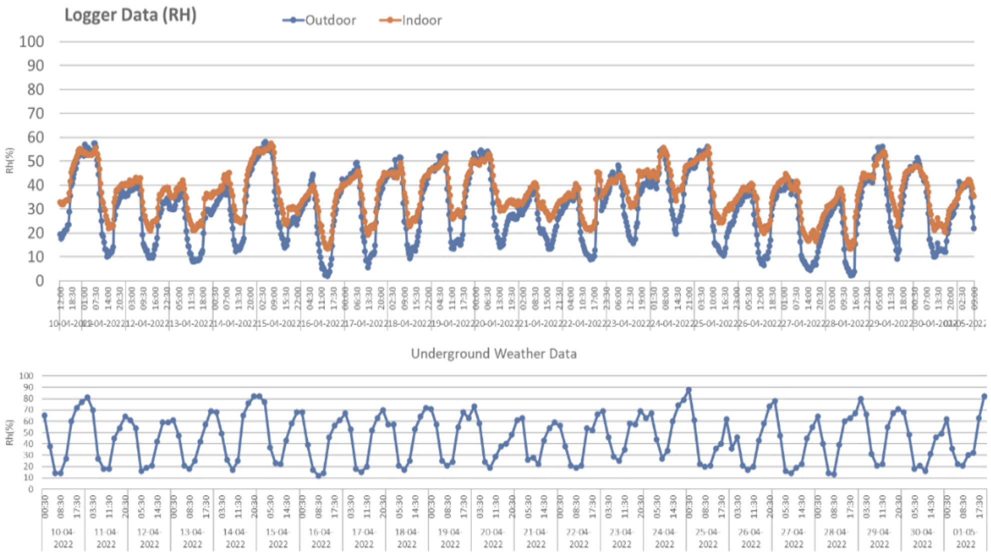


Figure 5-5 Logger Data for RH inside & outside the Ranade Wada with Weather data (Underground weather data)

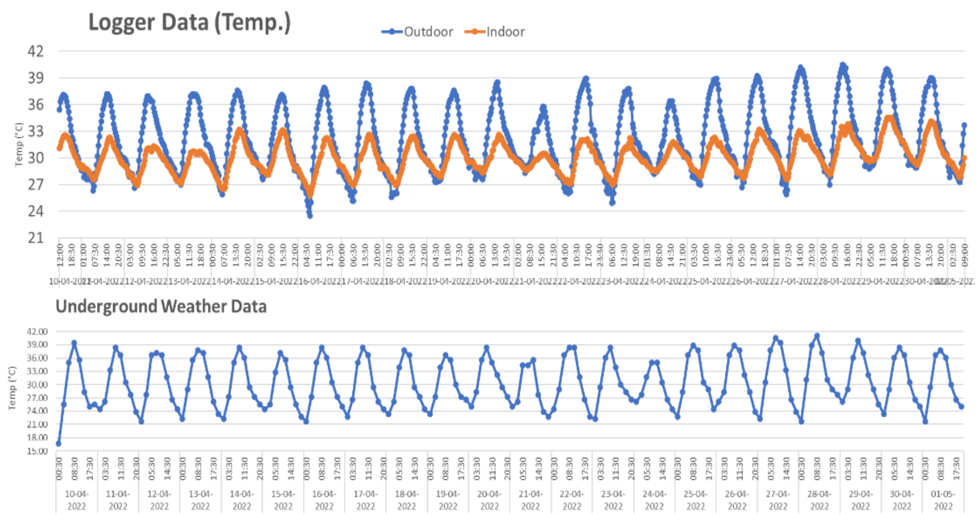


Figure 5-6 Logger Data for Temp inside & outside the Ranade Wada with Weather data (Underground weather data)

5.1.3 Simulation Analysis

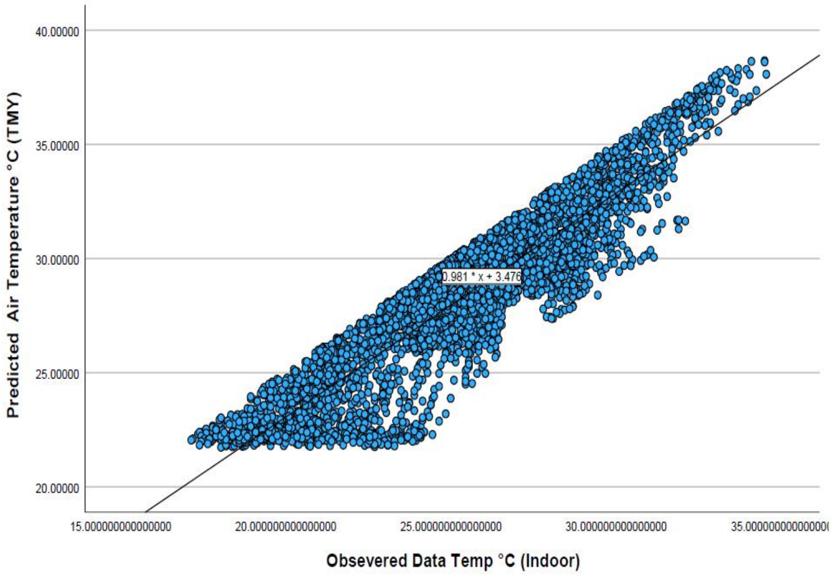


Figure 5-7 Linear Regression Analysis for Ranade Wada

The linear regression graph (Figure 5-7) presents an R-value of 0.84, demonstrating a strong correlation between observed and predicted indoor temperatures. The temperature variations between the observed and predicted values are minimal, indicating a high level of accuracy in the model's predictions.

5.2 Statistical standards for validation for Ranade Wada in accordance with Guideline 14 of ASHRAE

$$MBE\ (\%) = \frac{\sum_{i=1}^{N}(mi - si)}{\sum_{i=1}^{N}(n)}$$

Equation 5-1 Mean Biased Error

$$CVRSME\ (\%) = \frac{\sqrt{(\sum_{i=1}^{N}(mi - si)^2\ /N}}{m}$$

Equation 5-2 Coefficient of variation of the Root Mean Squared Error

where N is the total number of data points,
m is the average of the measured data points, and
si and mi are the simulated and measured data points during the i^{th} hour.

Statistical indices	Monthly calibration	Hourly calibration
MBE (in %)	±5	±10
CVRMSE (in %)	15	30

CVRMSE: coefficient of variance of root mean square error; MBE: mean bias error.

Figure 5-8 Calibration error limit as per ASHRAE Guideline 14

ASHRAE Guideline 14 sets statistical standards (Figure 5-9) for validating building energy models, specifically for Mean Bias Error (MBE) (Equation 5.1) and Coefficient of Variance of Root Mean Squared Error (CVRMSE) (Equation 5.2). For monthly data, MBE should be within ±5% and CVRMSE within 15%, while for hourly data, MBE should be within ±10% and CVRMSE within 30% (Figure 5-8). These thresholds ensure model accuracy in representing actual energy consumption, supporting reliable building performance simulations and comparisons to observed data.

RMSE. The solid blue bar represents MBE, and the orange bar represents CV RMSE. The Wada's MBE and CV RMSE fall within the ASHRAE 14 guideline's acceptable bounds. According to ASHRAE 14 rules, the MBE and CV RMSE Summer, Winter, and Annual (Table 5-1) are also within the limit.

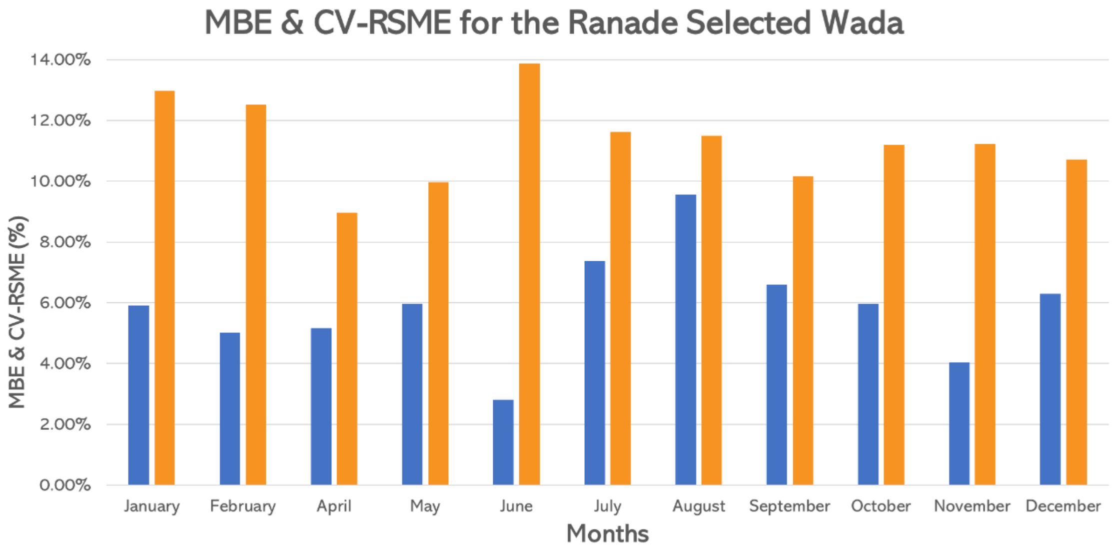


Figure 5-9 MBE & CV-RSME for the Selected Wada

Table 5-1 MBE & RCV-RSME Value for Summer, Winter & Annual for Ranade Wada

	MBE	CVRMSE
SUMMER	4.65%	10.94%
WINTER	5.32%	11.86%
ANNUAL	4.99%	11.40%

5.3 Gokhale Wada Observation on Simulated vs. Measured Air Temperature Data

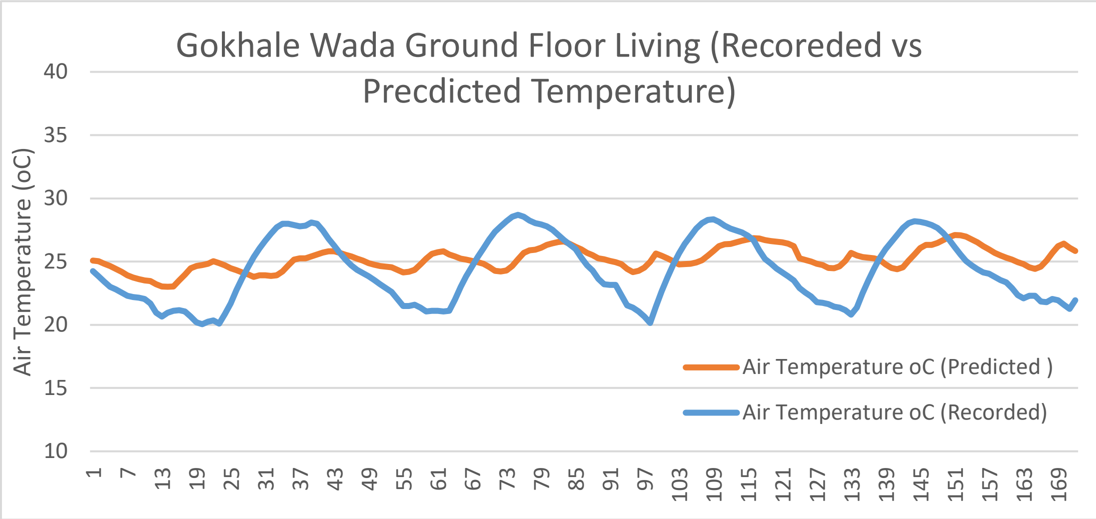


Figure 5-10 Gokhale Wada Ground Floor Living (Recorded vs Predicted Temperature)

Data loggers have been placed in Gokhale wada from 25 Jan – 2 Feb 2025 to record half hourly Air Temperature & Relative humidity. The comparison (Figure 5-10) between recorded and predicted (Simulated) air temperatures show a consistent pattern, with some variations between the two datasets. While the predicted values tend to be slightly higher or lower than the actual recorded temperatures, the overall trend remains concurrent with real-time conditions. The recorded air temperature ranges from 20.65°C to 28.7°C, whereas the predicted values fall within 23.01°C to 26.94°C. This indicates that the simulation smooths out temperature fluctuations but still maintains alignment with observed values.

Error Analysis: Mean Bias Error (MBE) and CVRMSE

To assess the accuracy of the simulated data, Mean Bias Error (MBE) and Coefficient of Variation of Root Mean Square Error (CVRMSE) were calculated. The MBE value of 3.76% indicates a slight overprediction in the simulated temperature data. However, this percentage remains relatively low, suggesting minimal systematic bias. The CVRMSE of 10.56% further confirms that the variations between measured and simulated values are within an acceptable range, ensuring the reliability of the model.

Validation Against ASHRAE Guideline 14

According to ASHRAE Guideline 14, the acceptable error limits for model calibration are MBE ≤ ±10% for hourly data and ≤ ±5% for monthly data, while the CVRMSE thresholds are ≤ 30% for hourly data and ≤ 15% for monthly data. Since the calculated MBE (3.76%) and CVRMSE (10.56%) fall within these limits, the simulation model is deemed accurately calibrated and suitable for further thermal performance assessments.

The analysis confirms that the simulated temperature data closely follows the real-time recorded values, with only minor deviations. The calculated error metrics validate the model's accuracy as per industry standards. Given its alignment with ASHRAE guidelines, the simulation can be confidently used for evaluating the thermal performance of Gokhale Wada.

5.4 Purandar Wada Observation on Simulated vs. Measured Air Temperature

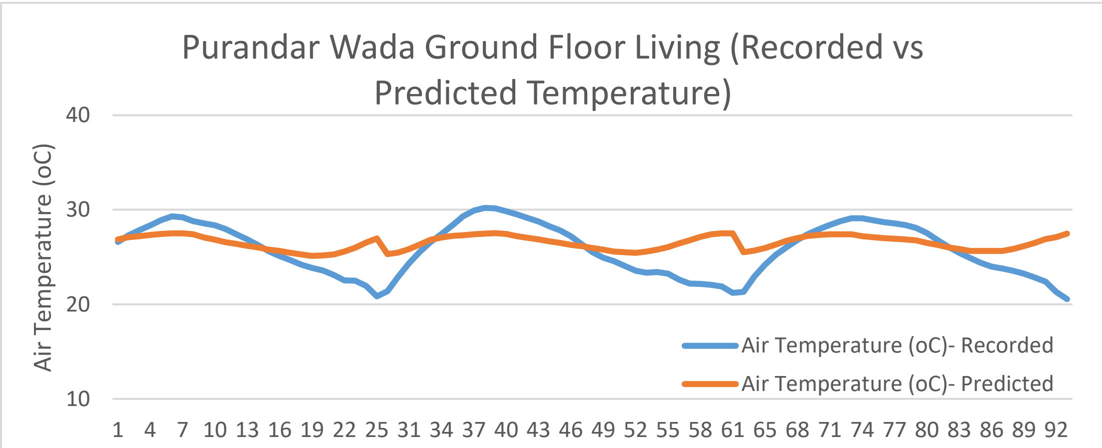


Figure 5-11 Purandar Wada Ground Floor Living (Recorded vs Predicted Temperature)

Data loggers have been placed in Purandar wada from 5–14 Feb 2025 to record half hourly Air Temperature & Relative humidity. The comparison (Figure 5-11) between recorded and predicted (Simulated) air temperatures show a consistent pattern, with some variations between the two datasets. The comparison between the recorded and predicted air temperatures for Purandar Wada reveals a close correlation, with the predicted values following the overall trend of the recorded temperatures. However, slight discrepancies are observed, particularly during temperature peaks and troughs. The recorded air temperature ranges from 20.45°C to 30.03°C, whereas the predicted temperatures range from 25.21°C to 28.58°C. This suggests that while the simulation effectively captures temperature variations, it slightly underestimates higher temperatures and overestimates lower temperatures.

Error Analysis: Mean Bias Error (MBE) and CVRMSE

The accuracy of the simulated air temperatures is evaluated using the Mean Bias Error (MBE) and Coefficient of Variation of Root Mean Square Error (CVRMSE). The calculated MBE of 4.29% indicates a slight systematic overestimation of air temperature. Meanwhile, the CVRMSE value of 11.76% suggests that the variation between simulated and recorded temperatures is within an acceptable range for predictive modelling. While these errors are slightly higher than those observed in other studies, they remain within reasonable limits for thermal simulation validation.

Validation Against ASHRAE Guideline 14

According to ASHRAE Guideline 14, the acceptable limits for model calibration are MBE ≤ ±10% for hourly data and ≤ ±5% for monthly data, while the CVRMSE thresholds are ≤ 30% for hourly data and ≤ 15% for monthly data. Given that the calculated MBE (4.29%) and CVRMSE (11.76%) fall well within these prescribed limits, the simulation model for Purandar Wada meets the required accuracy standards.

The simulation model successfully predicts air temperature variations at Purandar Wada, with minor deviations that are within acceptable limits per ASHRAE Guideline 14. The calculated MBE and CVRMSE values confirm the reliability of the model, making it suitable for further thermal analysis and performance assessments of the building.

5.5 Future Weather Data File

The constructed area of Pune has seen diurnal temperature fluctuations as a result of rapid urbanization and population increase caused urban Heat Island effect (Parishwad &

Shinkar, 2017). Wadas are created with the meteorological parameters of the location or region in mind. The rectangular linear plan with two or three floors has a central courtyard with surrounding verandah and rooms. Wada controls solar gains by considering timber windows and opening widths in addition to the outside wall's high thermal mass. This helps to minimize heat gain from solar gain that enters the interior through the building envelope (Alapure et al., 2017). The transitions change the indoor climate from a zone that might need active air conditioning to a psychrometric zone of airflow and evaporative cooling. The inability to utilise these sophisticated ventilation systems causes the inhabitants' discomfort to worsen (Shastry et al., 2014). Cooling performance effectiveness of the various ventilation techniques under investigation is assessed using cooling degree-hours (CDH), a quantitative metric (Michael et al., 2017). Low-tech techniques found in traditional building styles can be applied to construct structures and surroundings that are compatible with the climate and culture of the area (Nguyen et al., 2019).

The climate consultant tool has been used, and the latest handbook of fundamental models of ASHRAE Standard 55 has been taken into consideration as part of further research. Thermal comfort is determined by several elements, including mean radiant temperature, air velocity, humidity, metabolic activity, dry bulb temperature, and clothing level. Compared to buildings with centralized HVAC systems, residential settings provide a wider range of comfort since residents can dress for the weather and tolerate higher air velocity.

5.5.1 Regional climate modelling

The CCWorldWeatherGen (Figure 4-10) programme, originally created by the University of Southampton research group, has been used to forecast prospective weather data for Pune, India. The programme needs two primary inputs: output simulation files for the A2 family of IPCC scenarios derived from the coupled HadCM3 Atmosphere–Ocean Global Circulation Model (AOGCM), created at the Hadley Centre (London, United Kingdom), and the Typical Meteorological Year (TMY) in epw format as reference weather data.

5.6 Bioclimatic Analysis for Future Scenarios

Climate change A2(A2a, A2b & A2c) scenario generated using CCWorldWeatherGen tool for the year 2080 using climate consultant Comfortable hrs. without using active strategy shows 9 % (788 hrs.). Adaptive thermal comfort graphs using ASHRAE 50 guidelines psychometric chart prepared using climate consultants show that there will be a drop in comfort from 13% to 11% in 2050 and 9% in 2080. Due to the rise in temp. months (April, May, June, Sept & Oct) it reduces the maximum comfort hours. by 2080 (fig-4) and the building will require more cooling.

Due to this energy consumption increases drastically. In comparison to the TMY climate scenario, all passive design criteria will be considerably less important in the future for reducing energy usage. This is because the denominator for the climatic predictions of the future is the much higher energy demand in construction (Liu et al., 2020).

5.7 Observations:

5.7.1 Analysis of temperature using a data file for future weather scenarios

The impacts of climate change for the location considering IPCC scenarios A2 (A2a, A2b, & A2c) for the years 2050 and 2080 generated using the CCWorldWeatherGen programme. Year-round increases in outside temperatures brought about by climate change also had an impact on the interior environment. In Pune the warm- humid climate caused indoor temperatures to rise above average and demanded the use of cooling appliances, the implications of climate change were more evident. Climate change is causing winter outdoor temperatures to decrease and summer temperatures are increasing (fig. 5-12 & 5-13). It is anticipated that summer temperatures would rise in the second half of the century. Due to the need for cooling in homes, increased interior temperatures brought on by climate change will result in higher energy use.

Pune desperately needs climate-responsively designed buildings, especially in view of impending climate change events. The consequences of climate change would be somewhat mitigated by the employment of passive approaches. The potential savings (%) in yearly energy use and discomfort hours would decrease as the atmosphere warmed up. This fact indicates that the current passive approaches will eventually lose their efficiency as yearly average global solar radiation and annual mean temperature grow. Both present and future climatic circumstances must be considered when designing new residential buildings, and existing buildings must be modified with appropriate envelope materials in anticipation of potential climate change in the future. Climate change A2(A2a, A2b & A2c) scenario generated using CCWorldWeatherGen tool for the year 2080 using climate consultant Comfortable hrs. without using active strategy shows 9 % (788 hrs.).

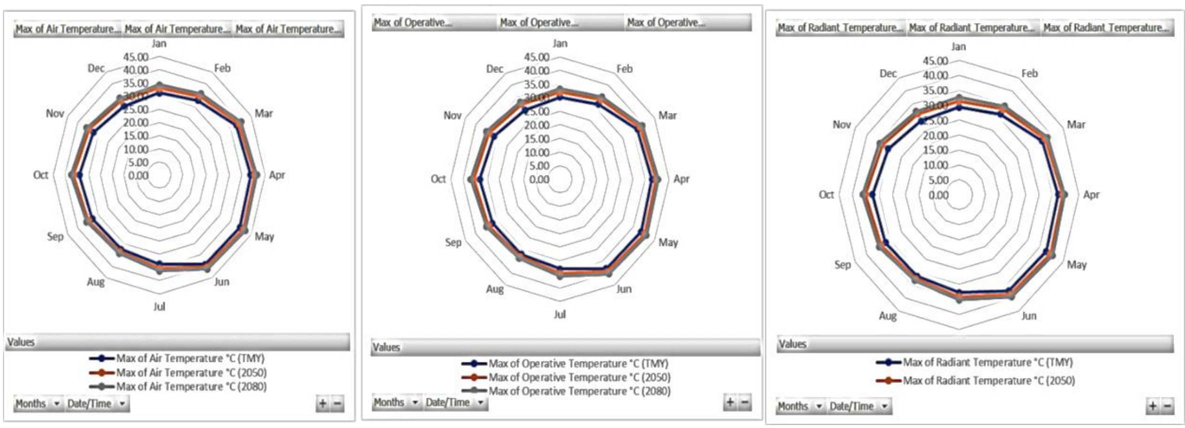


Figure 5-12 Mean (Max) Monthly Temperature Analysis

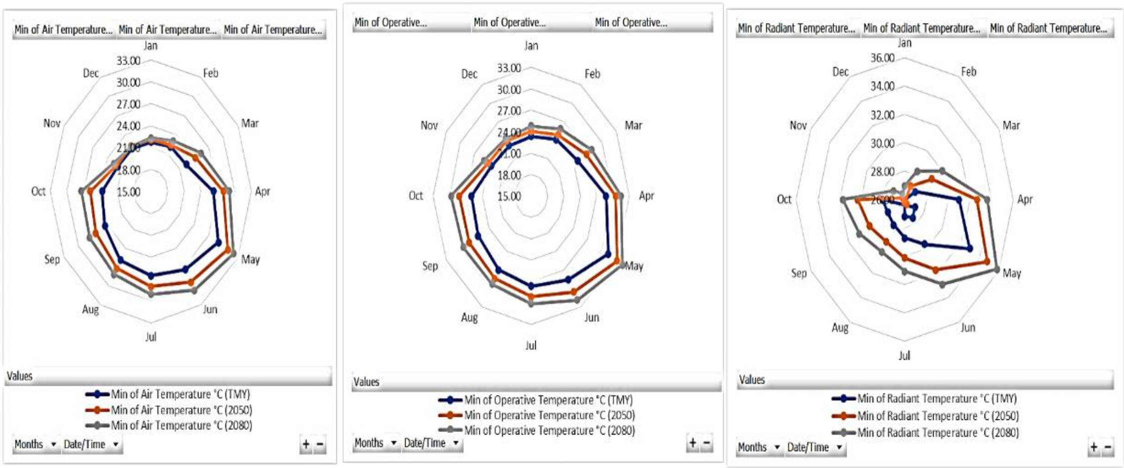


Figure 5-13 Mean (Min) Monthly Temperature Analysis

5.7.2 Impact of Passive Strategies Using Bioclimatic Analysis Using Climate Consultant

Through the combination of active design strategies (dehumidification) and passive design strategies like passive solar direct gain high mass, high thermal mass for walls and roofing with night flush, and internal heat gain. TMY file (Fig- 5-14) shows almost 81% Comfortable hours and the remaining 19% can be achieved with the help of HVAC systems. The year 2050 file (Fig-5-15) shows almost 69 % (12% less than TMY) Comfortable hours and the remaining 31% can be achieved with the help of TMY) Comfortable hours and the remaining 49% can be achieved with the help of (38% less than. Adaptive thermal comfort graphs using ASHRAE 50 guidelines psychometric chart prepared using climate consultants show that there will be a drop in comfort from 13% to 11% in 2050 and 9% in 2080 (Fig-5-16).

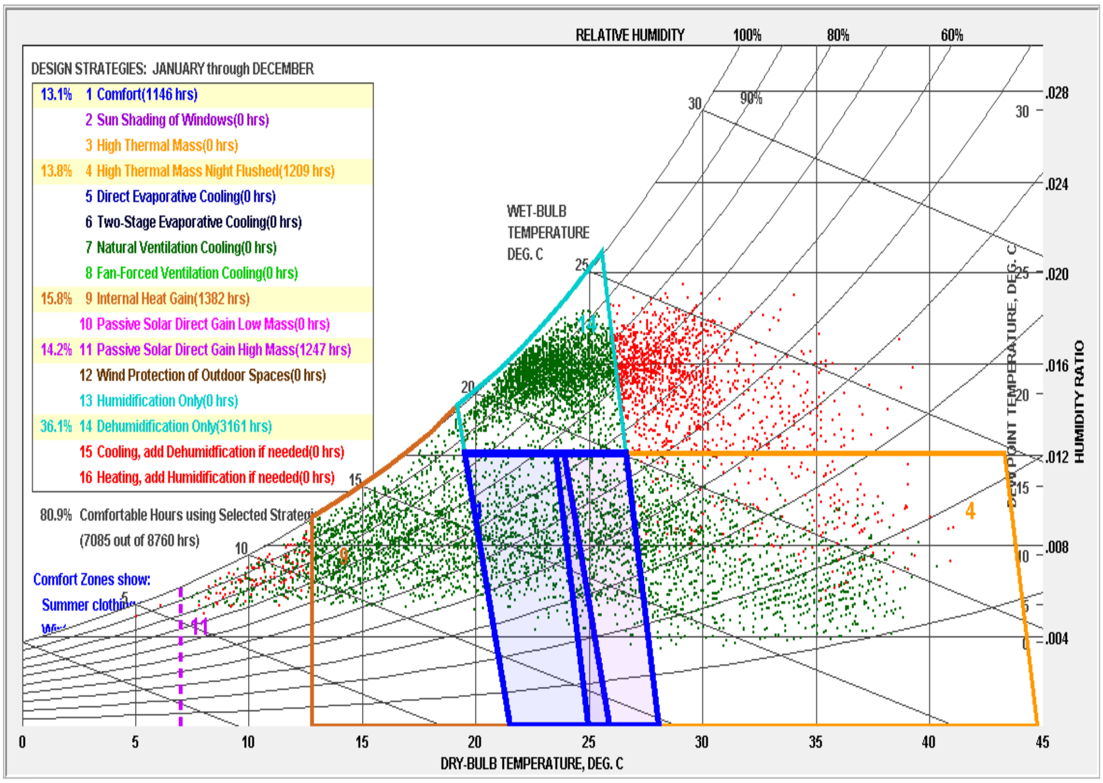


Figure 5-14 Bioclimatic Analysis Using Tmy Weather Data

HVAC systems. HVAC systems. The year 2080 file (Fig- 5-16) shows almost 51 % Due to the rise in temp. summer months (April, May & and June) reduce the maximum comfort hours. By 2080 and the building will require more cooling. Due to this energy consumption increases drastically

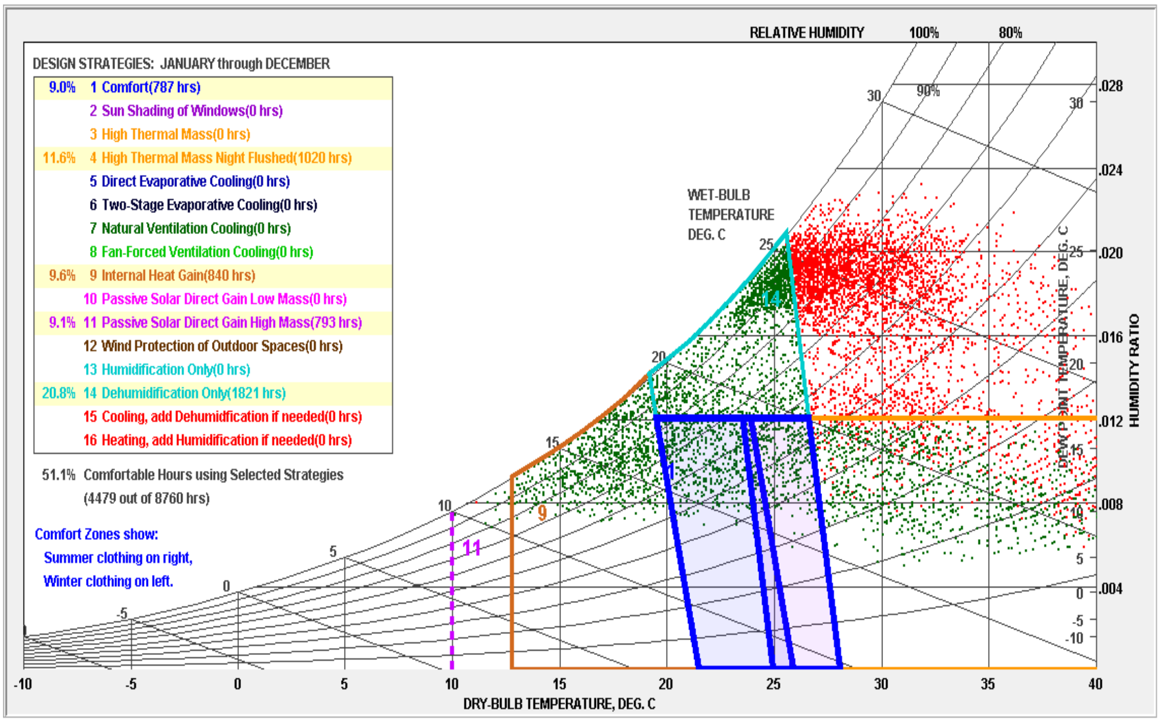


Figure 5-16 Bioclimatic Analysis Using 2080 Weather Data

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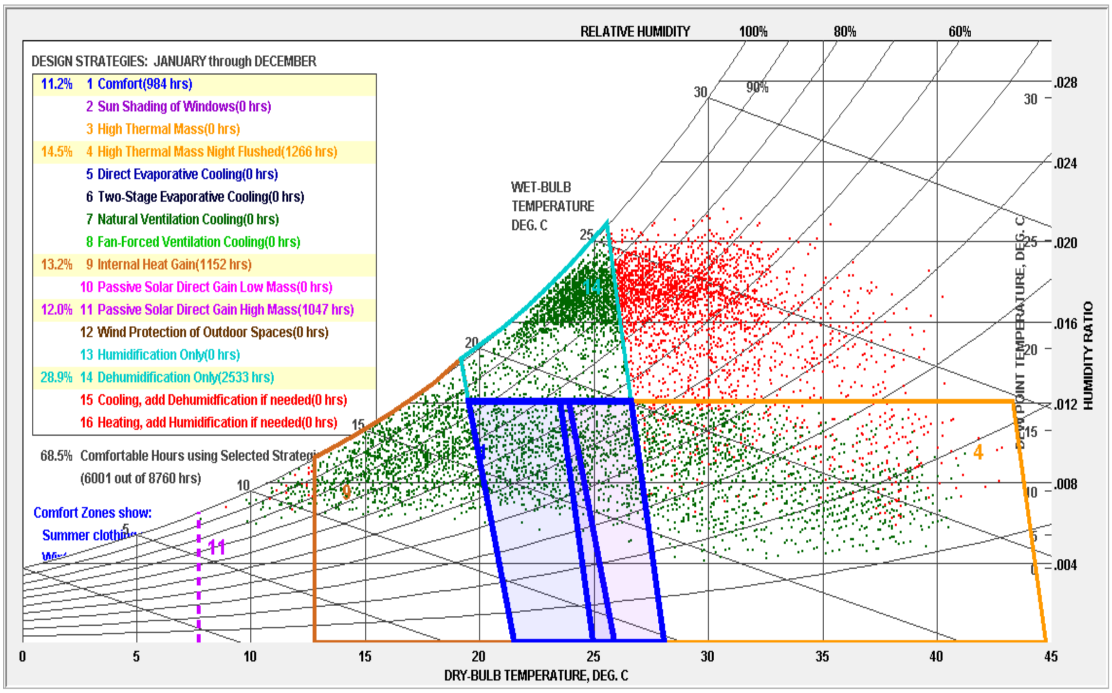


Figure 5-15 Bioclimatic Analysis Using 2050 Weather Data

5.8 Simulation Analysis for Future Scenarios Considering Comfort Hours

The primary objective of this research is to analyse the impact of climate change on vernacular architecture in Pune, with a specific focus on the rise in temperature and its implications for thermal comfort in traditional Wada houses. The study investigates how passive design strategies such as natural ventilation, thermal mass, and shading influence the thermal performance of Wadas under projected climate conditions for 2050 and 2080. To achieve this, a structured methodology was adopted, beginning with the development of a simulation model using Design Builder v7.0.2.004, which operates on the EnergyPlus simulation engine. This model was used to assess the thermal performance of Ranade Wada, Purandar Wada, and Gokhale Wada, ensuring accuracy in the comparative evaluation of their adaptability to future climate scenarios.

To quantify thermal comfort potential, the research applied the adaptive comfort equation developed by R. Rawal et al. (2022) for residential buildings in India. This approach evaluates adaptive comfort hours under three climate scenarios: the Typical Meteorological Year (TMY), 2050 Climate Projection, and 2080 Climate Projection. The study considers 80% and 90% wooden battens, resulting in a U-value of 0.673 W/m²K.

For the roof, multiple configurations were considered. The flat roof consisted of 20 mm roof tiles, a 5 mm bitumen waterproofing layer, 100 mm vermiculite aggregate, and 20 mm vermiculite plaster, achieving a U-value of 1.143 W/m²K. An alternative Maalige roof, comprising 30 mm wooden panels with a 15 mm air gap supported on wooden rafters, had a U-value of 0.742 W/m²K. Additionally, a semi-exposed floor configuration was modelled with 20 mm roof tiles, 100 mm vermiculite aggregate, and 20 mm vermiculite plaster, resulting in a U-value of 1.044 W/m²K.

The air change rate per hour (ACH) was set at 2.00 ACH, indicating moderate ventilation through passive means. Mechanical ventilation was not incorporated, aligning with the traditional natural ventilation strategies typical of Wada architecture. This simulation setup ensures that thermal characteristics and passive cooling effects of these vernacular structures are accurately represented for further analysis.

acceptability ranges in accordance with the IMAC-R Adaptive Comfort Model, providing insights into comfort variations due to climate change.

Further, the research assesses the thermal performance of the selected Wadas by analyzing adaptive comfort hours and identifying key vernacular design elements that contribute to thermal comfort. Elements such as central courtyards (front, center, and back), thick stone walls, ventilated attics, and shaded verandas were examined for their effectiveness in mitigating temperature fluctuations. To support this analysis, an Excel-based tool was developed to quantify the thermal comfort potential of Wada houses. The tool integrates TMY weather data for Pune along with climate projections for 2050 and 2080, defining boundary conditions for thermal comfort and passive design strategies. The assessment involved applying IF-AND logic to calculate the number of data points within the comfort zone and utilizing general equations to determine monthly and yearly comfort potential, ensuring a precise representation of climate impacts.

The results of this study provide a quantified understanding of the effectiveness of vernacular architectural strategies in addressing climate change. By comparing the thermal comfort hours across the three Wadas, the study identifies the most resilient design strategies and highlights necessary adaptations to maintain comfort levels under future temperature scenarios. This analysis serves as a foundation for future research on climate-responsive architectural adaptations in vernacular buildings.

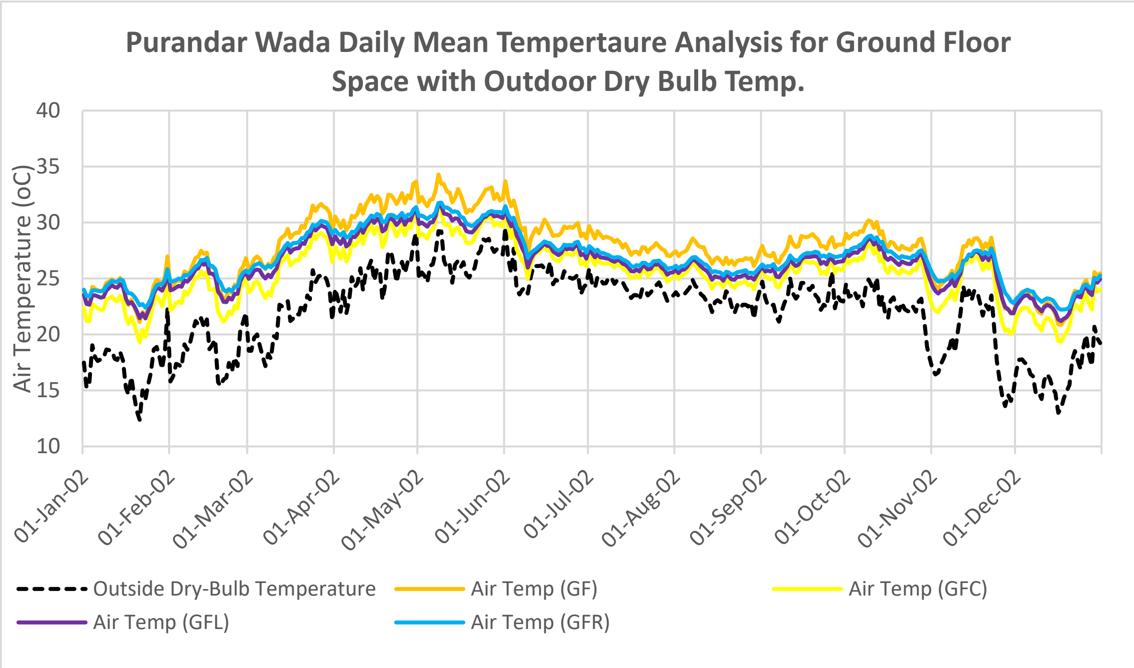
5.9 Simulation Analysis of Wada

A simulation model was developed using Design Builder – v7.0.2.004 (Table 4-4) to further investigate the thermal performance of the three Wadas. Design Builder utilizes the EnergyPlus simulation engine, generating graphical outputs that enhance result interpretation. For accurate analysis, several key parameters were considered in developing the simulation model, particularly focusing on the base case scenario (Table 4-3).

The building elements and their corresponding thermal characteristics were defined with specific U-values. The external and internal walls on the ground floor were modelled using 350 mm brick masonry with interior mud plaster, both having a U-value of 3.91 W/m²K. Windows were assumed to have 20 mm timber-paneled shutters, with a U-value of 2.22 W/m²K. The floor composition included 10 mm terrazzo, 75 mm vermiculite aggregate, and 100 mm

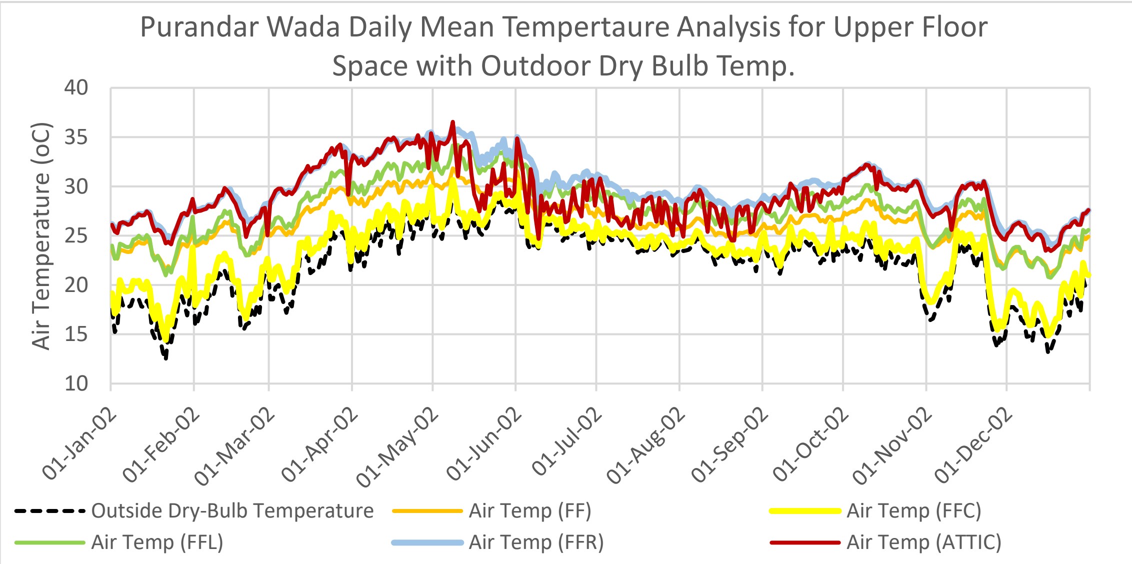
5.9.1 Simulation Observation for Purandar Wada (Table 5-2 & 3)

Table 5-2 Purandar Wada Ground Flor Spaces analysis & observation for Air Temperature and outdoor dry bulb Temperature



Observations: The ground floor space at Purandar Wada shows minimum temperature variations throughout the year, with noticeable moderation due to the presence of the front and rear yards. The maximum temperature on the ground floor reaches around 35-37°C during peak summer months (May and June), while the minimum temperature drops to 15-17°C in winter (December and January). The average temperature remains in the 22-28°C range, making the ground floor relatively comfortable. The presence of front and rear yards plays a crucial role in regulating indoor temperatures by improving natural ventilation and promoting convective cooling, especially during summer. The open-to-sky front-yard & rear-yard allows heat dissipation at night, reducing indoor temperatures. Additionally, the thermal mass of surrounding walls helps in buffering temperature fluctuations, ensuring a more stable and comfortable environment on the ground floor compared to upper levels.

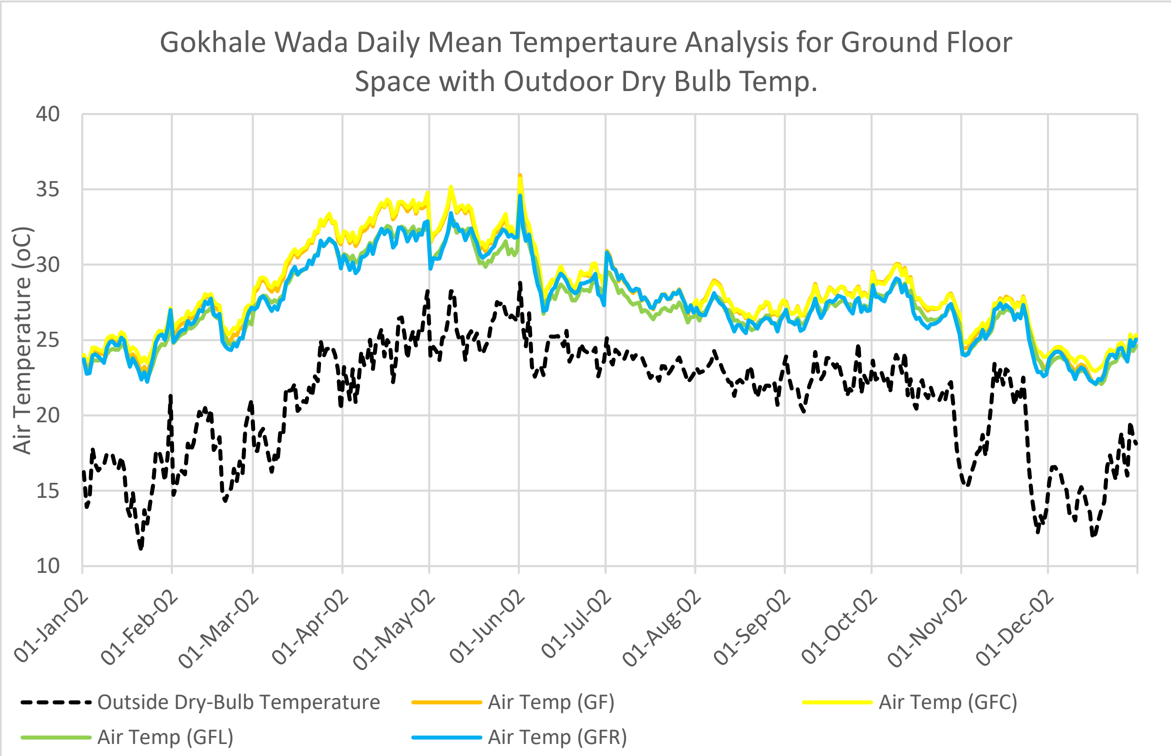
Table 5-3 Purandar Wada Observations for upper Floor spaces analysis & observation for Air Temperature and outdoor dry bulb Temperature



Observations: The upper floor experiences more significant temperature fluctuations due to its direct exposure to solar radiation. The maximum temperature on the upper floor, particularly in the attic, reaches 37-39°C in peak summer months, while other rooms experience slightly lower temperatures in the 34-37°C range. In winter, the minimum temperature drops to 16-18°C in attic spaces and 17-20°C in other upper-floor rooms. The average temperature on this level ranges between 24-30°C, with attic spaces being on the higher end. The front & rear yard effect plays a mixed role in regulating the thermal performance of the upper floor. On one hand, it enhances cross-ventilation, reducing heat buildup in some spaces by allowing hot air to escape and fresh air to circulate. However, due to increased exposure to solar radiation, rooms adjacent to the front & rear yard experience higher daytime temperatures, especially in summer, when reflected heat from front & rear yard surfaces contributes to warming the interior. The attic, being the most exposed space, undergoes extreme temperature variations, emphasizing the need for additional insulation or passive cooling techniques such as shading elements or ventilated roofing. While the front & rear yards help in night-time cooling, the effectiveness were more on the lower levels, whereas the upper floor remains vulnerable to heat gain, requiring additional cooling strategies.

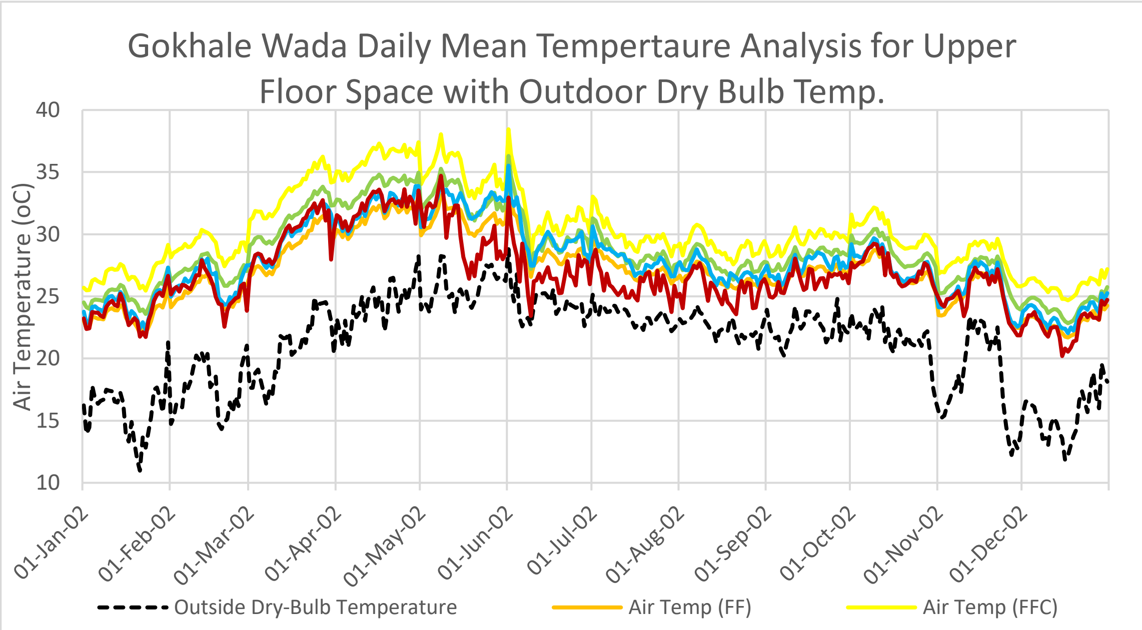
5.9.2 Simulation Observation for Gokhale Wada (Table 5-4 & 5)

Table 5-4 Gokhale Wada Ground Floor spaces analysis & observation for Air Temperature and outdoor dry bulb Temperature

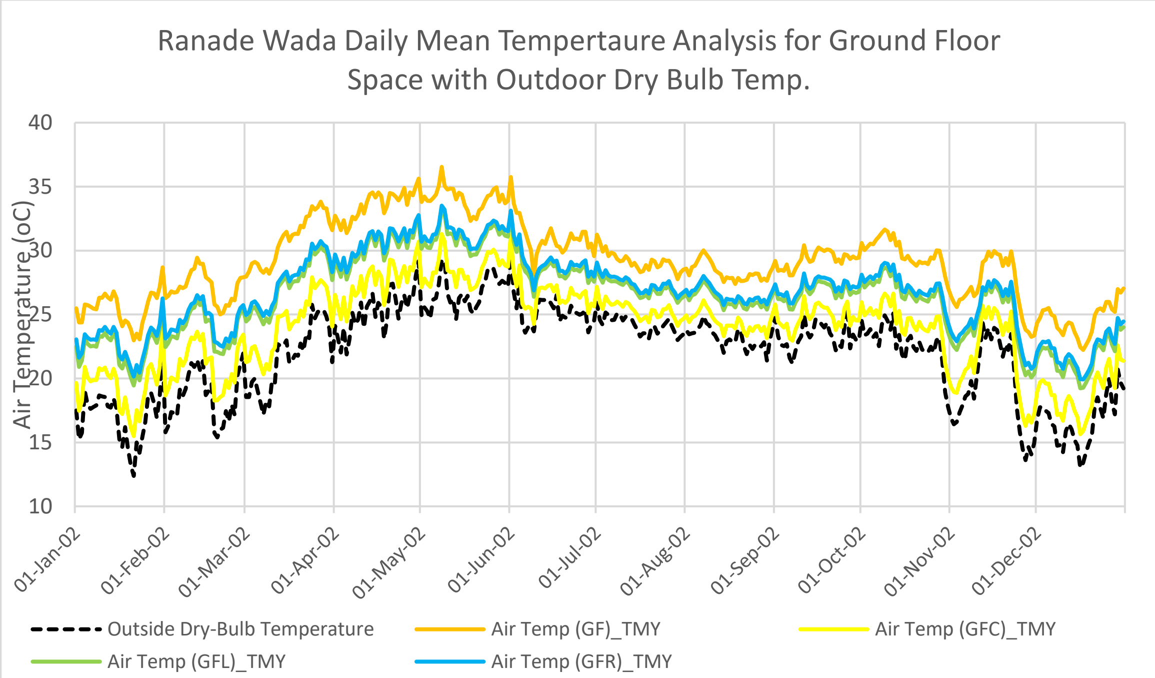


Observations: The temperature variations in the ground floor space of Gokhale Wada are more thermally stable environment compared to the upper floors. The maximum temperature on the ground floor reaches approximately 34-36°C during the summer months (May and June), while the minimum temperature drops to around 15-17°C during the colder months (December and January). The average temperature remains within the range of 22-28°C, creating relatively comfortable indoor conditions. The rear-yard significantly influences the thermal performance of the ground floor by promoting natural ventilation and heat dissipation. During the daytime, the rear-yard enables passive cooling by channelling breezes into the surrounding rooms, helping in reducing peak indoor temperatures. At night, it enhances heat loss through radiation, contributing to a cooler indoor environment. The thermal mass of surrounding walls further helps in absorbing heat during the day and

releasing it gradually at night, moderating indoor temperature fluctuations. As a result, the ground floor remains cooler in summer and warmer in winter compared to outdoor conditions.

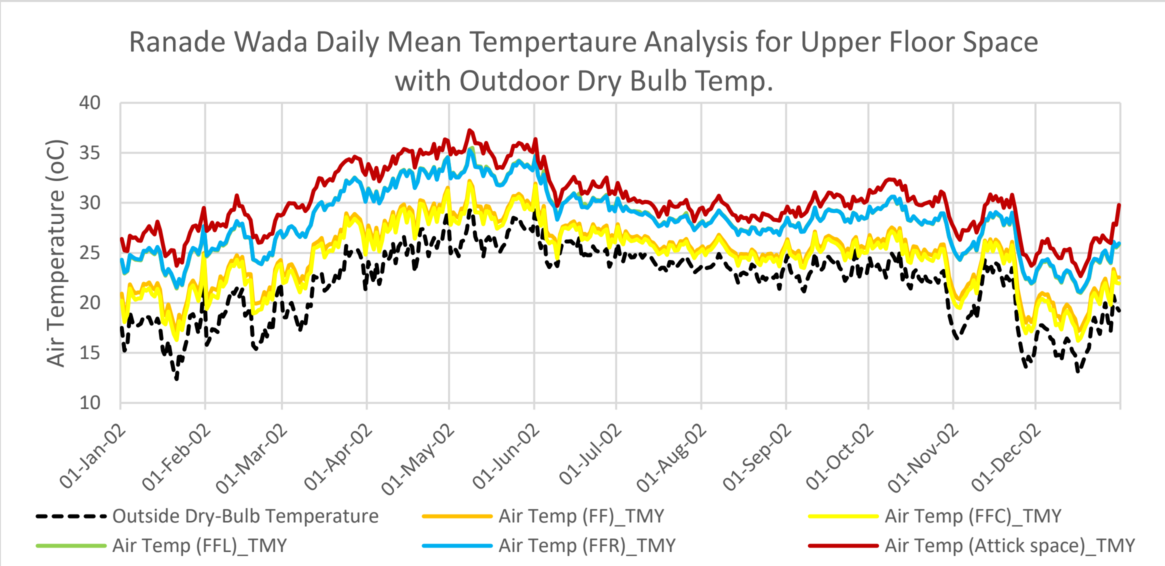
Table 5-5 Gokhale Wada Upper Floor spaces analysis & observation for Air Temperature and outdoor dry bulb Temperature

Observations: The upper (first & Attic) floor spaces of Gokhale Wada demonstrate higher temperature variations due to greater exposure to direct solar radiation. The maximum temperature on the upper floor reaches approximately 36-38°C, particularly in attic spaces, while the other rooms experience 34-37°C in peak summer months. During winter, the minimum temperature drops to 16-18°C in the attic and 17-20°C in other upper-floor rooms. The average temperature across these spaces ranges from 24-30°C, with attic spaces experiencing more extreme fluctuations. The rear-yard with cross-ventilation, helping in heat dissipation, the upper floor rooms still experience higher temperatures due to their proximity to the roof and external walls, which absorb and retain more heat. The attic space is the most affected, experiencing the highest temperature variations due to its direct exposure to solar radiation. During the daytime, attic temperatures soar, making it the warmest part of the house,

while at night, heat loss is rapid, leading to significant temperature drops. Though the rear-yard aids in ventilation, the upper-floor spaces, especially the attic, require additional passive cooling strategies, such as shading devices, ventilated roofing, and thermal insulation, to mitigate excessive heat gain.

Table 5-6 Ranade Wada Ground Floor spaces analysis & observation for Air Temperature and outdoor dry bulb Temperature

Observations: The ground floor space of Ranade Wada demonstrates a more stable thermal environment due to the influence of two courtyards, which promote passive cooling and ventilation. The maximum temperature on the ground floor reaches approximately 35-37°C during peak summer months (May and June), while the minimum temperature drops to around 15-17°C in winter (December and January). The average temperature remains in the range of 22-28°C, indicating a relatively comfortable indoor climate throughout the year. The two courtyards play a significant role in regulating the temperature by facilitating air circulation and heat dissipation. The presence of open-to-sky spaces allows hot air to escape, reducing heat buildup within enclosed rooms. During the daytime, the courtyards help in cooling the ground floor spaces through shaded areas, while at night, they enhance heat loss, maintaining

a lower indoor temperature. The thick walls and thermal mass of the structure further aid in temperature balance by absorbing heat during the day and gradually releasing it at night, ensuring thermal comfort for occupants.

Table 5-7 Ranade Wada Upper Floor spaces analysis & observation for Air Temperature and outdoor dry bulb Temperature



Observations: The upper floor spaces of Ranade Wada exhibit significant temperature fluctuations due to direct solar exposure and heat retention by the roof. Summer temperatures peak at 36-39°C, with the attic space experiencing the highest temperatures, followed by peripheral rooms (FFR). Other upper-floor spaces, including living areas (FFL) and courtyards (FFC), range from 34-37°C. In winter, temperatures drop to around 16-18°C in the attic and 18-20°C in rooms, while the annual average fluctuates between 24-30°C.

The two courtyards aid in cross-ventilation, moderating temperatures in shaded areas. However, the upper floors remain warmer than the ground floor due to heat absorption from the roof and reflected radiation from courtyard surfaces. The attic experiences extreme fluctuations, with rapid heating during the day and heat loss at night. While the courtyard effect improves airflow, it is insufficient to prevent overheating in upper spaces. Additional strategies such as ventilated roofing, shading devices, and reflective surfaces could further improve thermal comfort, especially for attic spaces and rooms with high solar exposure.

5.9.3 Comparative Observation of Purandar Wada, Gokhale Wada, and Ranade Wada

Table 5-8 Comparative Analysis of Three Wadas

Parameter	Purandar Wada	Gokhale Wada	Ranade Wada
Ground Floor – Max Temp (°C)	35–37°C (May–June)	34–36°C (May–June)	35–37°C (May–June)
Ground Floor – Min Temp (°C)	15–17°C (Dec–Jan)	15–17°C (Dec–Jan)	15–17°C (Dec–Jan)
Ground Floor – Remarks	Moderate variation due to passive design	Thermally stable; ground floor better than upper floors	More stable due to two courtyards and effective ventilation
Upper Floor – Avg Temp (°C)	24–30°C (attic on higher end)	24–30°C (attic slightly moderated)	24–30°C (attic warmer due to roof exposure)
Upper Floor – Remarks	Significant fluctuation; attic most affected	Moderate to high variation; slightly more stable than others	High fluctuation: roof heat retention affects attic the most

The thermal performance of Purandar Wada, Gokhale Wada, and Ranade Wada varies due to differences in spatial configuration and courtyard effects (Table 5-9). Ground floor spaces in all three Wadas maintain lower temperature fluctuations than outdoor conditions due to thermal mass and shaded areas. The maximum air temperature on the ground floor ranges between 34-36°C, which is 2-4°C lower than the outdoor dry bulb temperature (38-40°C). The minimum temperature is 14-16°C, aligning with outdoor winter temperatures, while the average temperature remains 22-28°C. Ranade Wada, with two courtyards, has the best cooling effect, keeping ground-floor temperatures consistently lower than outdoor levels.

Upper floor spaces experience greater temperature fluctuations due to direct solar exposure and heat retention. The maximum temperature varies between 36-38°C, with attic spaces reaching 38-39°C, making them 1-3°C higher than the ground floor and often matching or exceeding outdoor temperatures. The minimum temperature ranges from 16-20°C, and the average temperature is 24-30°C. Purandar Wada and Gokhale Wada have similar temperature trends, but Gokhale Wada exhibits slightly higher upper-floor temperatures due to reduced courtyard ventilation.

The courtyard effect is significant, particularly in Ranade Wada, where two courtyards enhance air circulation, reducing indoor temperatures by 3-4°C. Purandar wada with front & rear yard and Gokhale Wada with rear yard, show moderate cooling benefits, mainly for ground-floor spaces, while upper floors retain heat. Attic spaces in all Wadas remain the warmest, indicating a need for better ventilation, insulation, and shading mechanisms. Overall, Ranade Wada performs best in thermal comfort, followed by Purandar Wada, with Gokhale Wada showing slightly higher temperatures across spaces.

5.10 Simulation Analysis for Future Scenarios Considering Comfort Hours

The adaptive comfort equation developed by R. Rawal et al. (2022) for residential buildings consider calculating comfort hours for the TMY, 2050& and 2080 years using the following to study 80% and 90 % acceptability (Figure 5-17).

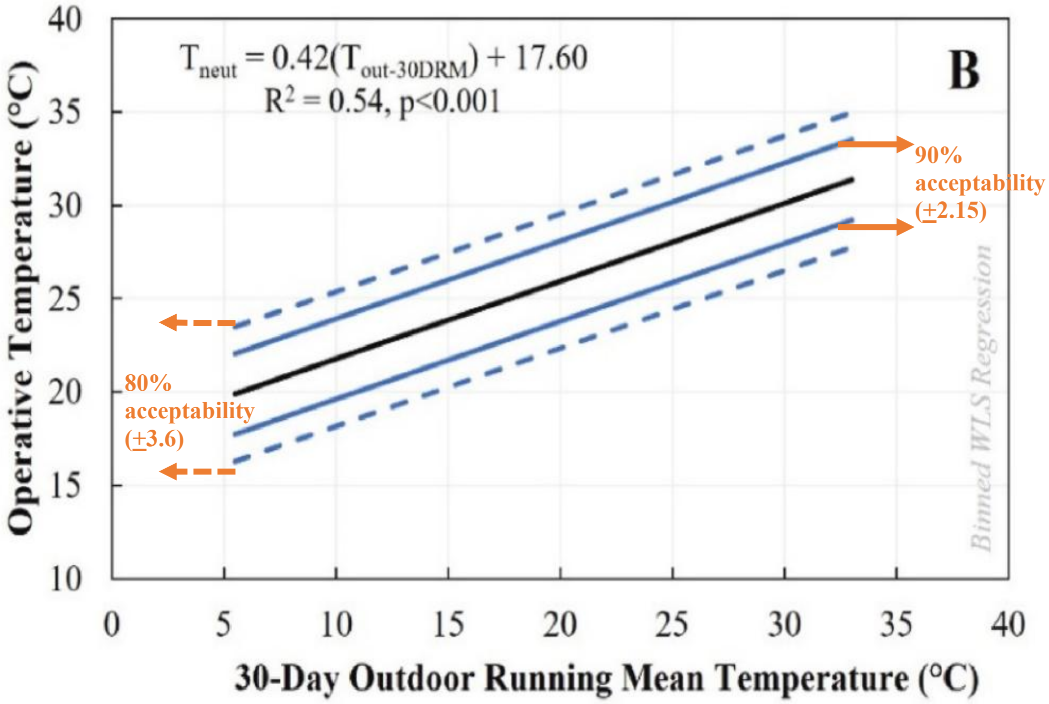


Figure 5-17 Adaptive Thermal Comfort Model Having for Indian Residences (Source R. Rawal 2022)

$$T_{neut} = 0.42(T_{out-30DRM}) + 17.60 \quad (1)$$

Where T_{neut} is Neutral temperature in °C

$T_{out-30DRM}$ - Is The 30 -Day Outdoor Running Mean Air Temperature Ranging From 19.4 to 29.2

With ±2.15 °C as a 90% Acceptability Are & ±3.6 °C as an 80% Acceptability

Table (5-9) shows month wise adaptive temperature for Pune Maharashtra India have been calculated using IMAC-R Adaptive model

Based on the 30-day running mean calculation the monthly acceptability range is calculated, and the above table shows the monthly range considering 80% & 90% acceptability above the monthly range (Figure 5-17). The potential frequency of the hours lies within the base comfort temperature period or the number of comfortable hours out of the total duration (hours) calculated for the vernacular house.

Table 5-9 Adaptive Thermal Comfort Range						
	Outdoor Running Mean Temperature	Minimum Temp (80% acceptability)	Minimum Temp (90% acceptability)	Operative Temp.	Max Temperature (90% acceptability)	Max Temperature (80% acceptability)
Jan	19.4	22.1	23.6	25.7	27.9	29.3
Feb	19.8	22.3	23.8	25.9	28.1	29.5
Mar	21.6	23.1	24.5	26.7	28.8	30.3
Apr	22.8	23.6	25.0	27.2	29.3	30.8
May	24.0	24.1	25.5	27.7	29.8	31.3
Jun	24.6	24.3	25.8	27.9	30.1	31.5
Jul	24.7	24.4	25.8	28.0	30.1	31.6
Aug	25.1	24.5	26.0	28.2	30.3	31.7
Sep	25.9	24.9	26.3	28.5	30.6	32.1
Oct	26.6	25.2	26.6	28.8	30.9	32.4
Nov	28.2	25.8	27.3	29.5	31.6	33.0
Dec	29.2	26.3	27.7	29.9	32.0	33.5

Weather Data file considering Climate change A2(A2a, A2b & A2c) scenario generated using CCWorldWeatherGen tool for TMY 2050 & 2080 year. Simulations are run by Design Builder Software with the above weather data files and calculated the Total comfort hours for TMY, 2050, & and 2080 considering ASHRAE standard 55 for naturally ventilated buildings. Data shows (Figure 5-18) that comparative climate consultant analysis vernacular-built form shows much better results TMY 4344 (50%), in 2050 decrease 1921 (22%) but we can observe of maximum 2080 945 (11%).

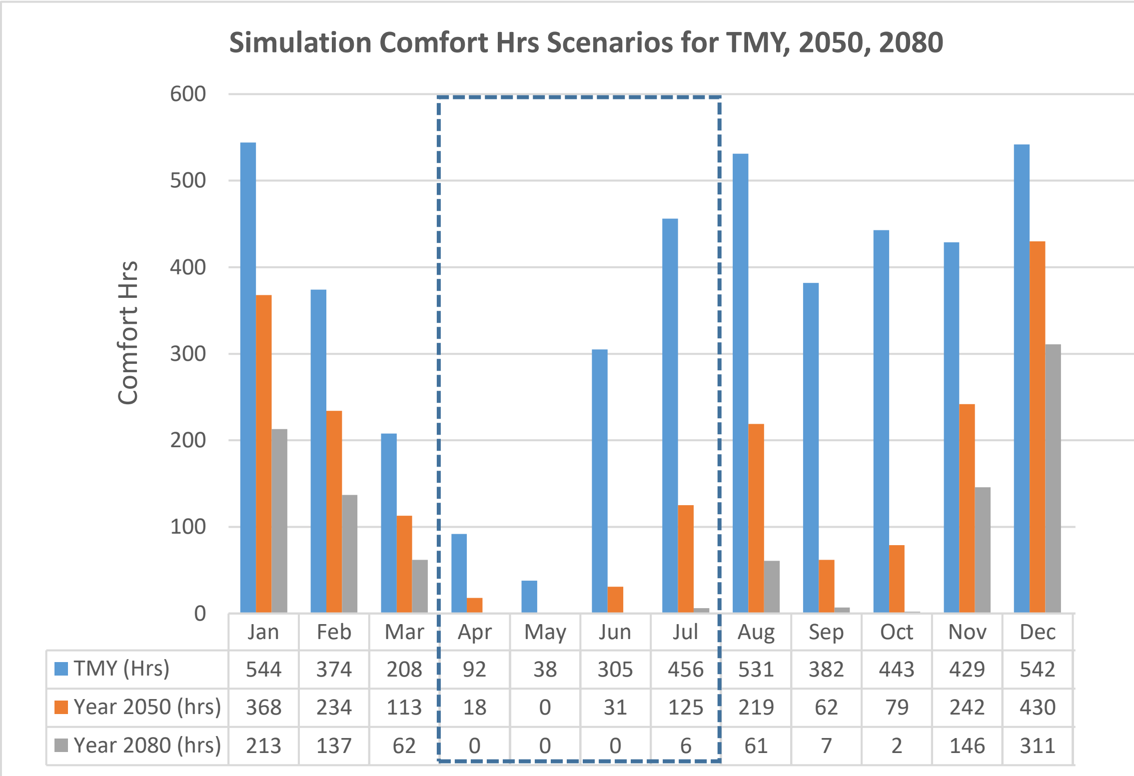


Figure 5-18 Total Comfort Hours For Tmy, 2050, & 2080 Considering Ashrae Standard 55 For Natural Ventilated Building

5.11 Adaptive Thermal Comfort (considering base case Scenarios)

The thermal performance analysis was done for Ranade Wada, Purandar Wada, and Gokhale Wada by evaluating adaptive comfort hours under Typical Meteorological Year (TMY), 2050, and 2080 climate scenarios considering IMAC-R Adaptive Comfort model with 80% acceptability. The vernacular design elements of these Wadas such as yards (Front, Centre & Back), thick walls, ventilated attics, and shaded verandas, play a crucial role in maintaining indoor comfort.

An Excel spreadsheet was used to analyze comfort potential, designed to quantify thermal comfort and passive design potential for three selected wada house form of Pune region India. The tool utilizes climatic data from the Typical Meteorological Year (TMY) weather file for Pune.

The boundary definitions for the comfort zone and passive design strategies were established based on previous discussions. Comfort potential was calculated using the IMAC-R (Rawal et al. 2022) range for hourly condition for a typical meteorological year, as well as projections for 2050 and 2080 in Pune. The number of data points within each boundary was determined using IF-AND logic in the Excel spreadsheet. General equations for calculating monthly (2) and yearly (3) comfort potential is provided below, followed by a table (Table 11) describing the variables used in these equations. The study, conducted using hourly data points, offers a more precise representation of the climate.

$$C_m = \left(\frac{P_m}{\sum_{i=1}^{n} T_i}\right) x100 \qquad (2)$$

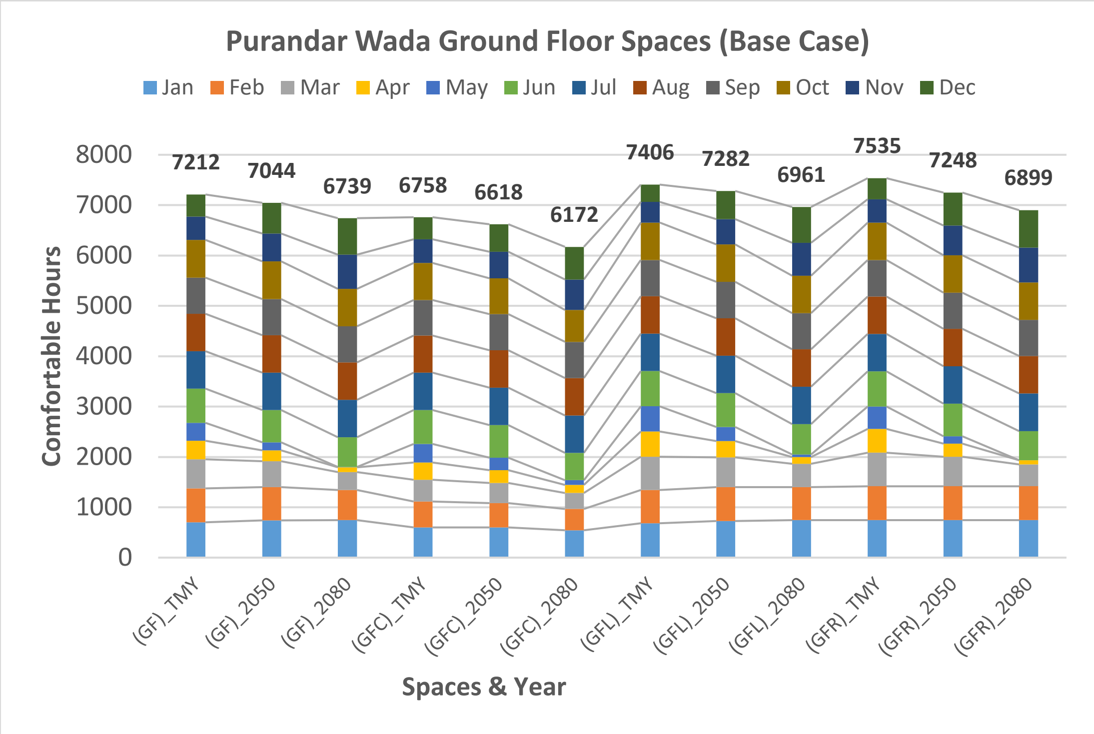
$$C_y = \left(\frac{P_y}{8760}\right) x100 \qquad (3)$$

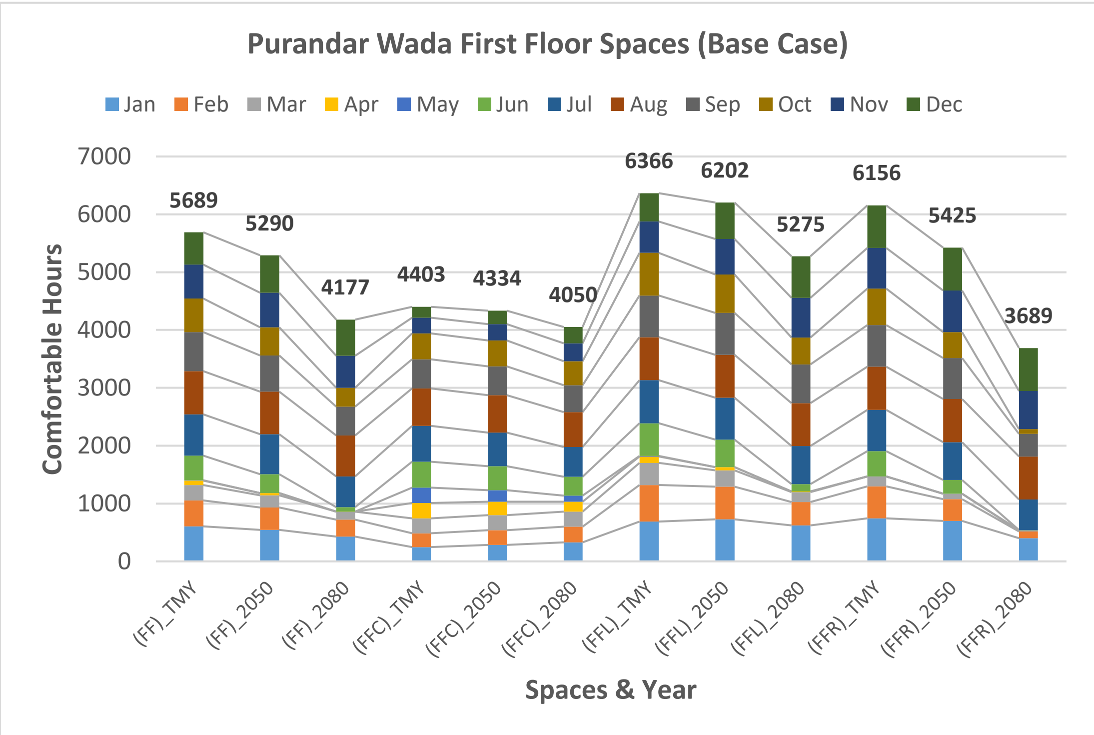
By comparing adaptive comfort hours across seasons, this study highlights how future climate scenarios impact indoor thermal environments. Findings indicate that while courtyard-based cooling and passive ventilation strategies provide resilience, summer months (April-May) in 2050 and 2080 show a decline in comfort, particularly on the first floors. This analysis emphasizes the need for adaptive retrofitting.

5.11.1 Observation for Purandar Wada

The adaptive comfort hours for Purandar Wada exhibit significant seasonal variations across summer, monsoon, and winter months, reflecting the thermal response of different spaces to changing climatic conditions. The analysis incorporates Typical Meteorological Year (TMY) data along with future projections for 2050 and 2080, highlighting long-term trends in thermal comfort due to rise in temperature and climate change.

Figure 5-19 Purandar Wada Comfort Hour Analysis for Ground & First Floor Spaces





The study (Figure 5-19) of adaptive comfort hours for Purandar Wada across different spaces and future years reveals a significant decline in comfort levels due to climate change. Analyzing three-time Years: Typical Meteorological Year (TMY), 2050, and 2080 and across various spaces such as Ground Floor (GF), First Floor (FF), front and rear yards (GFC, FFC), Living Areas.

During the summer months, adaptive comfort hours decline sharply due to high outdoor temperatures, significantly affecting indoor spaces. In March, comfort hours remain relatively higher in the ground floor front and rear yards (GFC) and ground floor living (GFL) shows 664 hours in TMY, which reduces to 592 hours in 2050 and further to 460 hours in 2080. The first-floor courtyard (FFC) and first floor living (FFL) show minimal comfort, decreasing from 382 hours in TMY to 282 in 2050 and only 171 in 2080. April and May show extreme conditions, with almost no comfort in first-floor spaces and a sharp drop in ground-floor spaces. By May 2080, comfort is nearly absent across all spaces, with the ground floor room (GFR) reducing from 444 hours in TMY to 147 in 2050 and completely disappearing in 2080. This highlights worsening thermal discomfort due to rising temperatures.

The monsoon months provide the highest adaptive comfort, particularly in July and August, were rainfall moderates temperatures. In June, comfort hours on the ground floor (GF) drop from 680 in TMY to 640 in 2050 and 586 in 2080, showing a progressive decline. July and August exhibit full-day comfort, with 744 hours recorded in GF and GFR during TMY, though a slight reduction occurs in future projections. First-floor spaces (FFC, FFL, and FFR) show a steady decline, particularly in 2080, due to heat retention in exposed areas. September follows a similar pattern, with comfort declining more on the upper floors than in ground-floor spaces.

The winter season generally maintains higher comfort levels, though future climate projections indicate some decline. In January, the ground floor (GF) registers 704 comfort hours in TMY, increasing slightly to 738 in 2050 and 744 in 2080. Enclosed spaces like GFR and GFL retain high comfort levels, even in 2080, suggesting better thermal stability. However, first-floor spaces (FFL and FFR) see a decline, with FFL shows 691 hours in TMY to 726 in 2050 but decreasing to 622 in 2080. February shows a sharper decline, especially in upper floors, where heat accumulation causes discomfort.

Among all spaces, the most affected areas in 2050 and 2080 are the first-floor room (FFR), first-floor courtyard (FFC), and first floor living (FFL). FFR experiences a drastic reduction in comfort hours, dropping from 6156 hours (TMY) to only 3689 by 2080, making it one of the least livable spaces. Similarly, FFC declines from 4403 hours (TMY) to 4050 in 2080, while FFL sees a major drop from 6366 (TMY) to 5275 hours in 2080, indicating severe overheating in future climate conditions.

The least affected spaces observed are the ground-floor room (GFR), ground-floor courtyard (GFC), and ground-floor living (GFL). GFR maintains the highest comfort levels, with 7535 hours in TMY, slightly reducing to 6899 by 2080, proving its strong thermal stability. GFC and GFL also perform well, retaining over 6000 comfort hours even in 2080, benefiting from thick masonry walls, shading, and better ventilation.

Overall, the analysis reveals that ground-floor spaces provide the most consistent thermal comfort, while first floor and courtyard spaces experience severe reductions in comfort hours due to rising temperatures. Summer months pose the highest thermal stress, with nearly zero adaptive comfort hours in April and May for upper floors. Monsoon months offer the best conditions, but comfort hours decline significantly by 2080, particularly for exposed spaces. Winter remains the most stable season, though upper-floor spaces show a decline in comfort over time. These findings highlight the urgent need for passive cooling strategies, increased shading, and improved ventilation for first-floor spaces and courtyards to mitigate the impact of rising temperatures in future climate scenarios.

5.11.2 Observations for Gokhale Wada

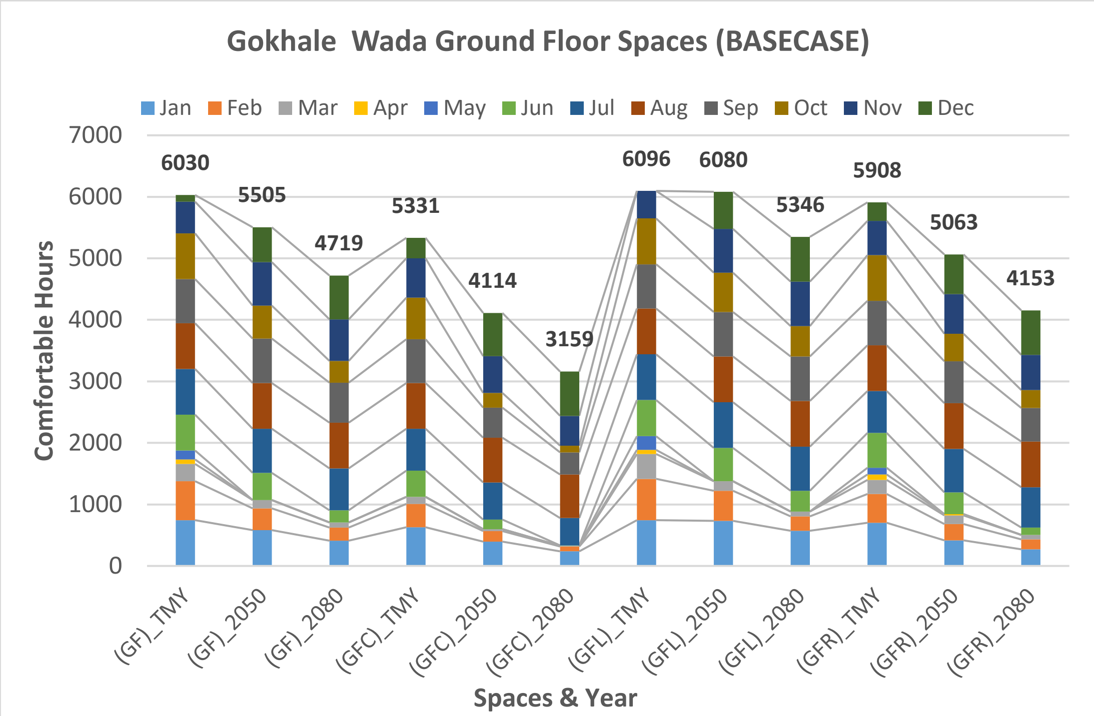
The adaptive comfort hours for Gokhale Wada exhibit significant variations across the summer, monsoon, and winter months, highlighting the thermal performance of different spaces in response to changing climate conditions. The analysis considers Typical Meteorological Year (TMY), future projections for 2050, and 2080 to understand long-term trends in thermal comfort.

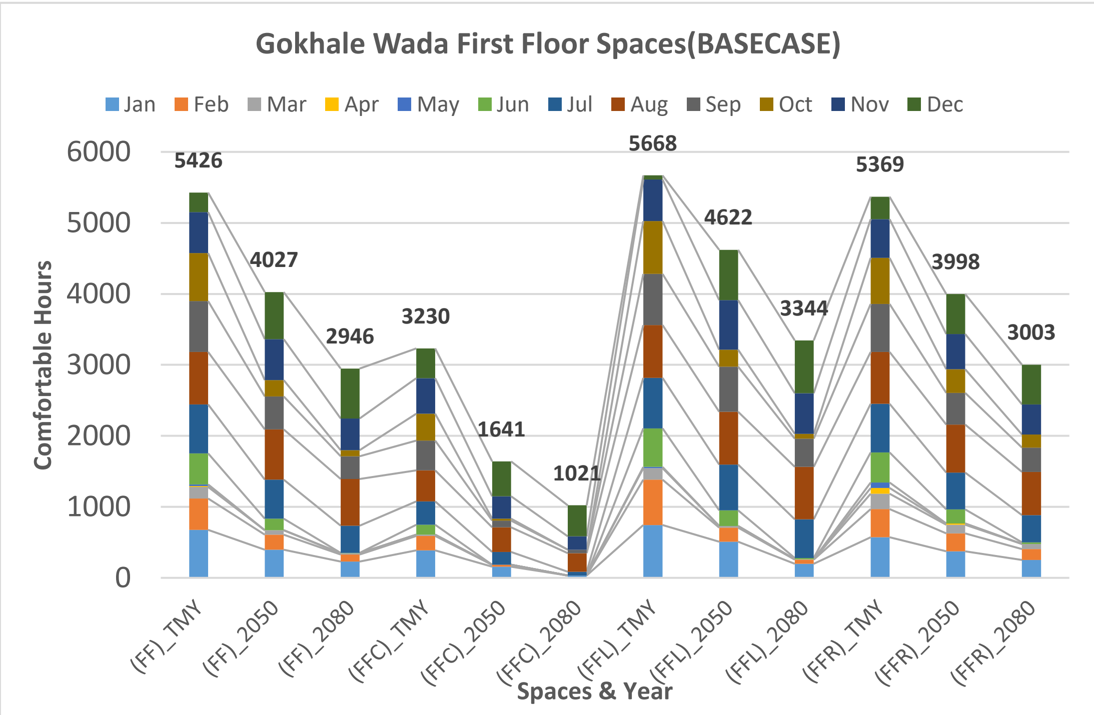
The adaptive comfort analysis for Gokhale Wada (Figure 5-20) reveals significant variations in comfort hours across the summer, monsoon, and winter months, emphasizing the thermal performance of different spaces under changing climate conditions. The study considers Typical Meteorological Year (TMY), future projections for 2050, and 2080, highlighting long-term trends in thermal comfort across ground floor (GF), first floor (FF), rear-yard courtyards. (GFC, FFC), living areas (GFL, FFL), and rooms (GFR, FFR). The results indicate a notable decline in comfort hours due to rising temperatures, with first-floor spaces experiencing severe discomfort in future projections.

Summer months show the lowest adaptive comfort hours across all spaces, with a significant decline in future years due to rising temperatures. March sees relatively higher comfort levels on the ground floor, where GFL records 212 hours and GFR 148 hours in TMY, but these drop sharply by 2080, with GFL at only 74 hours and GFR at 72 hours. The first-floor spaces (FF, FFC) have almost no comfort hours, indicating extreme heat accumulation. April and May present the most extreme discomfort, with comfort hours nearly disappearing across all spaces. By May, only 3 hours of adaptive comfort remain on the ground floor (GF), and the first-floor spaces record zero comfort hours, making it the most uncomfortable period. Future projections show this trend worsening, indicating severe thermal stress by 2080.

Monsoon months provide the highest adaptive comfort hours, though future projections indicate a steady decline. In June, GF and GFL register 465 and 549 comfort hours in TMY, but these dropped to 199 and 341 hours in 2080, respectively. First-floor spaces (FF, FFC, FFL) experience more heat retention and reduced ventilation, leading to a decline in comfort hours. July and August offer the best comfort conditions, with GF recording 740 hours in TMY, reducing slightly in 2050 and 2080. GFR and FFL maintain over 700 comfort hours in July and August, indicating relatively good thermal stability. However, by 2080, first-floor spaces (FFC, FFL, FFR) show substantial declines, reinforcing that ground-floor spaces remain more thermally stable over time. Monsoon months provide the highest adaptive comfort hours, though future projections indicate a steady decline. In June, GF and GFL register 465 and 549 comfort hours in TMY, but these dropped to 199 and 341 hours in 2080, respectively. First-floor spaces (FF, FFC, FFL) experience more heat retention and reduced ventilation, leading to a decline in comfort hours.

Figure 5-20 Gokhale Wada Comfort Hour Analysis for Ground & First Floor Spaces





July and August offer the best comfort conditions, with GF recording 740 hours in TMY, reducing slightly in 2050 and 2080. GFR and FFL maintain over 700 comfort hours in July and August, indicating relatively good thermal stability. However, by 2080, first-floor spaces (FFC, FFL, FFR) show substantial declines, reinforcing that ground-floor spaces remain more thermally stable over time.

Winter months offer the most stable adaptive comfort hours, though future projections show an increasing decline, particularly in exposed areas such as GFC and FFC. In January, GF, GFC, GFL, and GFR record over 500 comfort hours in TMY, but these decline in 2050 and 2080, with the greatest losses seen in first-floor spaces. FFC drops from 387 comfort hours (TMY) to just 33 in 2080, and FFR declines from 572 to 252 hours. In December, GFL and FFL maintain over 700 hours in TMY but decline sharply in 2080, indicating increasing winter discomfort due to shifting climate conditions.

Among all spaces, the most affected and worst-performing areas in 2050 and 2080 are the first-floor room (FFR), first-floor courtyard (FFC), and first floor living (FFL). FFR sees a drastic drop in comfort hours from 5369 (TMY) to 3003 in 2080, indicating severe overheating. Similarly, FFC declines from 3230 hours (TMY) to only 1021 in 2080, while FFL drops from 5668 (TMY) to 3344 in 2080, demonstrating extreme thermal stress.

Conversely, the least affected and best-performing spaces are the ground-floor room (GFR), ground-floor courtyard (GFC), and ground-floor living room (GFL). GFR remains the most thermally stable, with comfort hours reducing only slightly from 5908 (TMY) to 4153 in 2080. GFC and GFL also maintain relatively high comfort levels, recording over 5000 comfort hours even in 2080, benefiting from thicker masonry walls, shading, and better ventilation strategies.

The overall adaptive comfort hours for Gokhale Wada decline significantly across future projections. Total comfort hours for all spaces combined drop from 6030 hours in TMY to 5505 in 2050 and further to 4719 in 2080. This steady decline highlights worsening thermal discomfort, particularly in first floor and courtyard spaces. Summer months present the most extreme heat stress, with nearly zero comfort hours in April and May on the upper floors.

Monsoon months remain the most comfortable, though future projections show a decline in first-floor adaptability. Winter months, despite providing the best conditions, also exhibit comfort loss over time, especially in exposed areas.

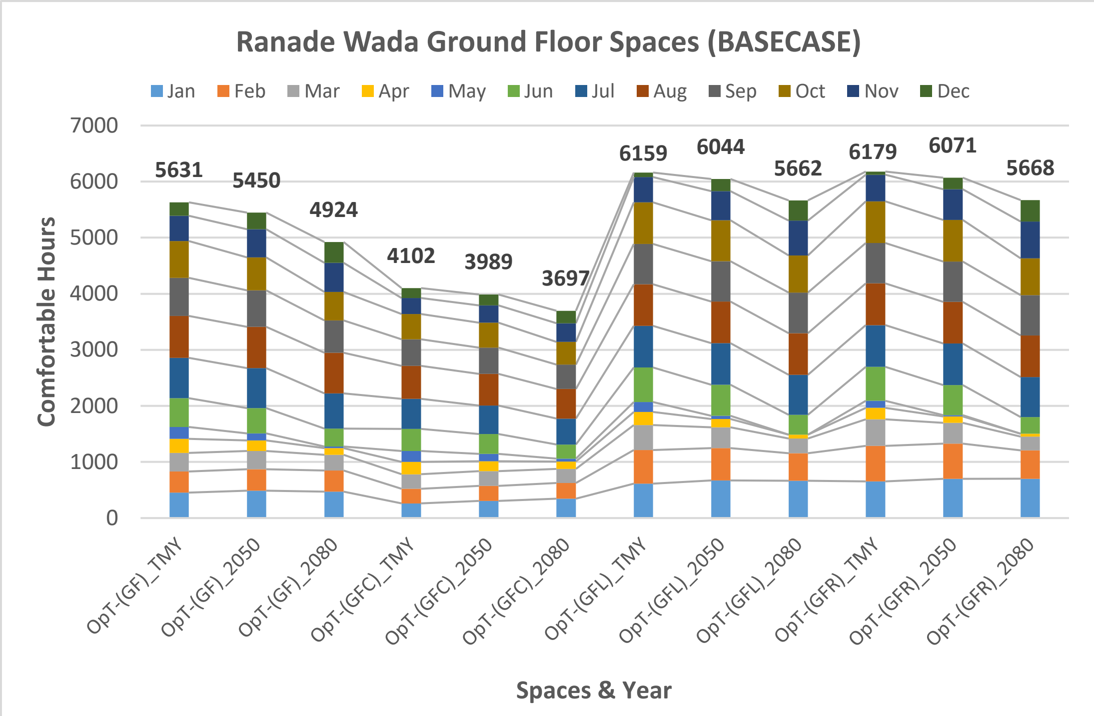
The analysis underscores the urgent need for passive cooling strategies, improved ventilation, and shading mechanisms to mitigate the impact of climate change and preserve indoor thermal comfort, particularly in first floor and courtyard spaces.

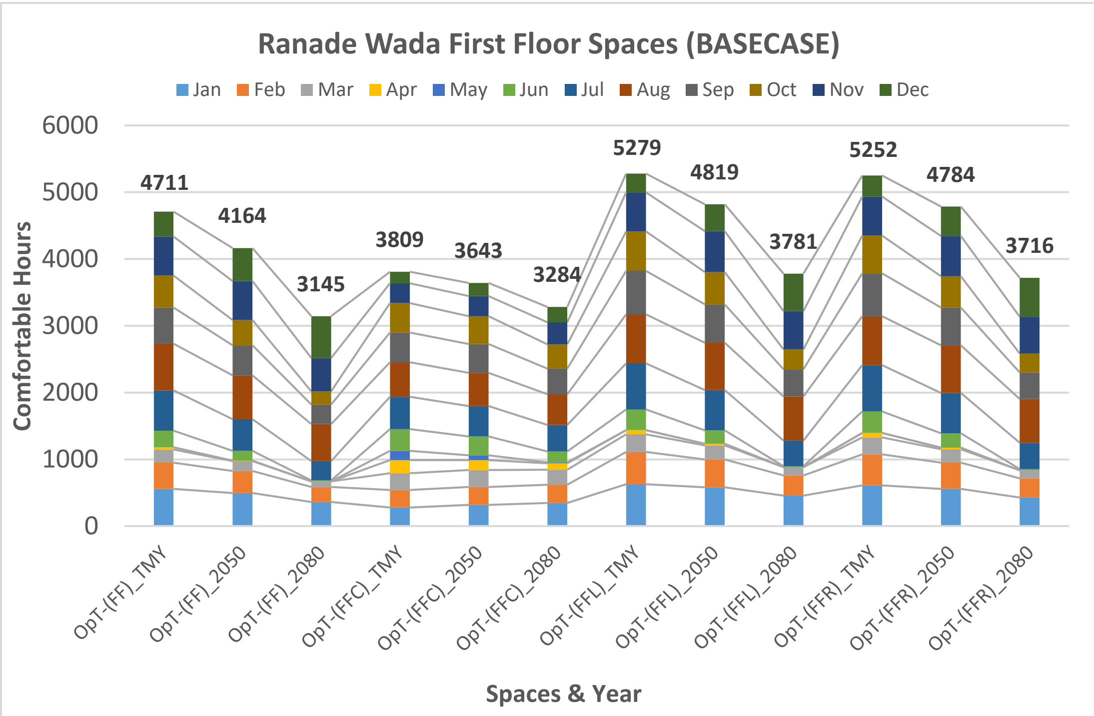
5.11.3 Observation for Ranade Wada

The adaptive comfort hours for Ranade (Figure 5-21) Wada exhibit significant variations across summer, monsoon, and winter months, emphasizing the impact of seasonal climate changes on different spaces. Analysing comfort levels based on the Typical Meteorological Year (TMY) and future projections for 2050 and 2080 reveals a steady decline due to rising temperatures and changing climatic conditions. The trends observed across spatial zones Ground Floor (GF), First Floor (FF), Courtyards (GFC, FFC), Living Areas (GFL, FFL), and Rooms (GFR, FFR) indicate increasing thermal discomfort over time, with first-floor spaces being the most affected.

During the summer months, adaptive comfort hours are at their lowest, with April and May experiencing extreme discomfort. In March, ground floor living (GFL) and room (GFR) spaces offer relatively better comfort, recording 444 and 474 hours in TMY, but these decline significantly to 265 and 249 hours by 2080. The first-floor spaces, particularly FFL and FFR, see even sharper reductions, from 264 and 258 hours in TMY to just 127 and 119 hours in 2080. April marks a severe drop, with GFL comfort hours decreasing from 234 in TMY to just 67 in 2080, while GFR declines from 204 to 49 hours. First-floor spaces become nearly uninhabitable, with FFL and FFR dropping from 63 hours to 0. By May, comfort levels are almost non-existent in most spaces, with GFL declining from 175 hours in TMY to zero by 2080, and GFR following a similar pattern. The first-floor spaces face complete thermal discomfort, underscoring the critical need for passive cooling strategies such as shading, ventilation, and material modifications.

Figure 5-21 Ranade Wada Comfort Hour Analysis for Ground & First Floor Spaces





The monsoon season offers significant relief, particularly in July and August, when most spaces maintain high comfort levels. In June, ground floor spaces perform relatively well, with GFL and GFR recording 616 and 606 comfort hours in TMY, though these decline to 352 and 298 hours in 2080. First-floor spaces experience more severe reductions, with FFL and FFR dropping from 310 and 321 hours in TMY to just 14 and 18 hours, respectively, due to heat retention. July emerges as the most comfortable month, with GFL and GFR maintaining 744 hours in TMY, which remain stable through 2080. However, first-floor spaces still show a declining trend, with FFL reducing from 690 to 384 hours and FFR from 695 to 394 hours. August continues to provide high comfort, with minimal reduction across all spaces. GFL and GFR retain 744 hours, while FFL and FFR experience slight declines from 734 and 733 hours in TMY to 657 and 655 hours in 2080. By September, as the monsoon transitions into drier conditions, comfort levels begin to decrease. Ground floor spaces remain stable at 720 hours, while first-floor areas decline, with FFL and FFR dropping from 651 and 641 hours in TMY to 408 and 399 hours in 2080.

Winter months maintain relatively stable adaptive comfort, with the ground floor continuing to outperform the first floor. In January, GFL and GFR sustain high comfort hours at 614 and 654 in TMY, with minor reductions to 668 and 702 hours in 2080. However, first-floor spaces show a significant decline, with FFL reducing from 627 hours in TMY to 454 in 2080 and FFR from 612 to 428 hours. December follows a distinct trend, where GFL comfort hours increase from 76 in TMY to 356 in 2080, indicating the effect of rising winter temperatures. FFL also sees an increase from 282 to 562 hours in the same period. In contrast, November shows a declining trend, with first-floor spaces experiencing a drop in comfort levels over time, suggesting that heat retention in these areas worsens discomfort even in cooler months.

Overall, ground floor living (GFL) and ground floor room (GFR) consistently provide better adaptive comfort across all seasons and future projections, maintaining higher comfort hours even under extreme warming scenarios. GFL remains the best-performing space, with total annual comfort hours decreasing from 7024 in TMY to 6280 in 2080. In contrast, first-floor spaces (FF, FFL, FFR) exhibit substantial declines, particularly in summer months, due to heat accumulation. Total annual comfort for first-floor spaces drops from 5281 in TMY to just 3854 in 2080, rendering them increasingly uninhabitable without interventions. Courtyards (GFC, FFC) help improve airflow but are insufficient in preventing heat buildup on upper floors. The overall decrease in comfort hours highlights an urgent need for passive cooling strategies, improved ventilation, and architectural modifications, such as ventilated roofing, shading devices, and reflective surfaces, to mitigate future climate impacts.

5.11.4 Comparative Analysis of Thermal Performance in Vernacular Wadas (Base Case)

The adaptive comfort hours for the ground and first-floor spaces of Gokhale Wada, Purandar Wada, and Ranade Wada show (Table 5-10) significant seasonal variations, with monsoon months providing the highest comfort and summer months experiencing the sharpest decline. Analysing these traditional structures across different time frames (TMY, 2050, and 2080) highlights a gradual decrease in comfort over time due to rising temperatures, with first-floor spaces being the most affected.

Table 5-10 Comparative Analysis of Thermal Performance in Vernacular Wadas (Base Case)

Wada	Season	TMY (hrs)	2050 (hrs)	2080 (hrs)	Reduction (TMY–2050)	Reduction (TMY–2080)
Purandar	Summer	1956	1868	1773	4.5%	9.4%
	Monsoon	2952	2891	2856	2.1%	3.3%
	Winter	1948	1914	1881	1.7%	3.4%
Gokhale	Summer	1442	1327	1212	8.0%	16.0%
	Monsoon	2962	2944	2933	0.6%	1.0%
	Winter	1857	1826	1801	1.7%	3.0%
Ranade	Summer	1212	1155	1108	4.7%	8.6%
	Monsoon	2734	2674	2648	2.2%	3.1%
	Winter	1708	1663	1602	2.6%	6.2%

During summer adaptive comfort hours decline sharply due to increasing temperatures, with first-floor spaces suffering greater discomfort from direct solar exposure and heat retention. In Gokhale Wada, the ground floor maintains 1442 comfortable hours in TMY, but this drops to 1212 by 2080, while the first floor declines more significantly from 1085 hours in TMY to just 762 in 2080. A similar trend is observed in Purandar Wada, where ground-floor comfort hours decrease from 1956 in TMY to 1773 in 2080, while the first-floor hours drop from 1421 to 977. Ranade Wada performs slightly better, with ground-floor comfort hours reducing from 1212 in TMY to 1108 in 2080, whereas the first floor declines from 1056 to 889 hours. Overall, summer results in a 10-30% reduction in comfort hours, making first-floor spaces significantly uncomfortable by 2080.

The monsoon season provides the most comfortable conditions due to lower ambient temperatures and improved ventilation. In Gokhale Wada, the ground floor retains 2962 comfort hours in TMY, dropping only slightly to 2933 in 2080, while the first floor remains relatively stable at 2276 hours in TMY, reducing to 1893 in 2080. Purandar Wada outperforms the others, with ground-floor spaces achieving 2952 hours in TMY and sustaining 2856 by 2080, while the first floor remains around 2500 hours. Ranade Wada follows a similar pattern, with ground-floor spaces maintaining 2734 hours in TMY, decreasing to 2648 in 2080, while first-floor spaces decline from 2268 to 1852 hours. Monsoon conditions remain the most thermally comfortable, with only a 5-10% reduction in adaptive comfort hours by 2080.

During winter thermal comfort remains moderate, although future climate projections indicate a gradual decline due to rising temperatures. In Gokhale Wada, the ground floor maintains 1857 comfort hours in TMY, decreasing slightly to 1801 in 2080, while the first-floor spaces decline from 1525 to 1343 hours. Purandar Wada remains the best performer, with the ground floor sustaining 1948 hours in TMY, reducing to 1881 in 2080, while the first floor drops from 1608 to 1421 hours. Ranade Wada experiences a similar reduction, with ground-floor spaces decreasing from 1708 (TMY) to 1602 (2080), and first-floor spaces reducing from 1382 to 1206 hours. Overall, winter sees a 5-15% reduction in comfort hours, with first-floor spaces being more affected.

Across all three Wadas, the ground floors consistently perform better due to reduced solar exposure and better passive cooling strategies. The best-performing spaces include Purandar Wada's ground floor, which exhibits the highest thermal resilience, maintaining over 7200 comfort hours even in 2050. Gokhale Wada and Ranade Wada also perform relatively well, maintaining comfort levels above 6000 hours under future climate projections. Monsoon conditions provide the most favorable indoor temperatures, minimizing heat stress and maintaining adaptive comfort levels. In contrast, the worst-performing spaces are first-floor areas, which suffer from overheating and inadequate ventilation, particularly during summer and late winter. In Purandar Wada, first-floor comfort hours drop drastically to 3689 in 2080, while Gokhale Wada's first floor declines from 5334 (TMY) to 3998 (2080), showing a significant loss of comfort over time. Similarly, Ranade Wada's first floor follows this downward trend, emphasizing the vulnerability of upper-level spaces to climate change.

In conclusion, adaptive comfort hours are significantly influenced by seasonal variations, building orientation, and ventilation strategies. While ground floors remain relatively thermally stable, first-floor spaces require urgent interventions to mitigate future heat stress. The monsoon season ensures the highest comfort, while summer poses the most significant challenge due to increasing temperatures. Without passive cooling measures, improved cross-ventilation, and shading strategies, first-floor spaces in these traditional Wadas will become increasingly uninhabitable under future climate conditions.

5.12 Improved Case Simulation and Passive Design Strategies

- **Objective 2: To assess and compare the thermal performance of traditional Wada houses (base case) and their improved climate-responsive strategies through simulations under future climatic scenarios**

The second objective of this research is to comparatively assess the thermal performance of existing Wada base cases and their improved versions, modified for better climate responsiveness. This involves evaluating the thermal efficiency of traditional Wada structures and comparing them with optimized designs incorporating climate-responsive features. By integrating passive design strategies informed by Climate Consultant's bioclimate analysis, the improved cases are assessed across TMY, 2050, and 2080 weather scenarios to determine their effectiveness in maintaining indoor comfort.

To enhance the thermal performance of Wadas, key passive design strategies were implemented, focusing on heat gain reduction, thermal mass stabilization, and ventilation efficiency. The improved case simulations align with bioclimatic analysis findings, ensuring an optimal indoor environment under projected climate conditions.

The thermal performance of the improved Wada cases was analyzed by evaluating adaptive comfort hours and identifying key vernacular design elements that contribute to indoor thermal comfort. To quantify these improvements, an Excel-based tool was used to calculate thermal comfort potential, integrating TMY weather data along with climate projections for 2050 and 2080. The tool defines boundary conditions for thermal comfort and passive design strategies, applying IF-AND logic to determine the number of data points within the comfort zone. General equations were used to calculate monthly and yearly comfort potential, ensuring a precise representation of climate impacts.

Finally, a comparative analysis was conducted between the base and improved cases to quantify the impact of these modifications. The results demonstrate that improved Wada designs consistently outperform base cases in terms of thermal comfort, particularly in hotter months. The integration of bioclimatic strategies led to a substantial increase in adaptive comfort hours, showcasing the effectiveness of passive cooling techniques in mitigating future climate stress. This comparative assessment highlights the importance of optimizing vernacular architecture to enhance thermal resilience and maintain comfortable indoor environments amid rising temperatures.

5.12.1 Building Envelope and Thermal Characteristics for Improved Case Simulation Model

Table 5-11 Simulation parameters for Improved Model

Building Element	**Material**	**U-Value ($W/(m^2 \cdot K)$)**
External Wall	External plaster – Vermiculite plaster (20mm), Insulation – XPS Extruded Polystyrene (75mm),	0.297

Table 5-11 Simulation parameters for Improved Model		
Building Element	**Material**	**U-Value (W/(m²·K))**
	AAC block wall (200mm), Internal plaster – Vermiculite plaster (15mm)	
Internal Wall	External plaster – Vermiculite plaster (20mm), AAC block wall (200mm), Internal plaster – Vermiculite plaster (20mm)	0.617
Windows	Optimized fenestration to balance solar gain and ventilation	
Floor	Terrazzo (10mm), Aerated concrete slab (100mm), Plaster (15mm)	0.599
Flat Roof	Ceramic Tiles (20mm), Bitumen layer (5mm), Polyurethane Board (100mm), Aerated concrete slab (100mm), Vermiculite plaster (20mm)	0.264
Pitched Roof	Clay Tile roofing (30mm), Ventilated air cavity (15mm), Insulation – XPS Extruded Polystyrene (75mm), Aerated concrete slab (100mm), Internal Vermiculite plaster (20mm)	0.306
Semi Expose roof	Vermiculite plaster (20mm), XPS Extruded Polystyrene (75mm), Aerated concrete slab (100mm), Vermiculite plaster (13mm)	0.316
Air Change Per Hour	Natural ventilation efficiency	5.00 ACH
Mechanical Ventilation	Enhanced air circulation with dehumidification (no active cooling/heating)	5.00 ACH

Simulation Parameters Against Bioclimatic Analysis

The improved case simulation aligns with bioclimatic analysis findings for **TMY, 2050, and 2080** to enhance passive thermal comfort. The following parameters were considered:

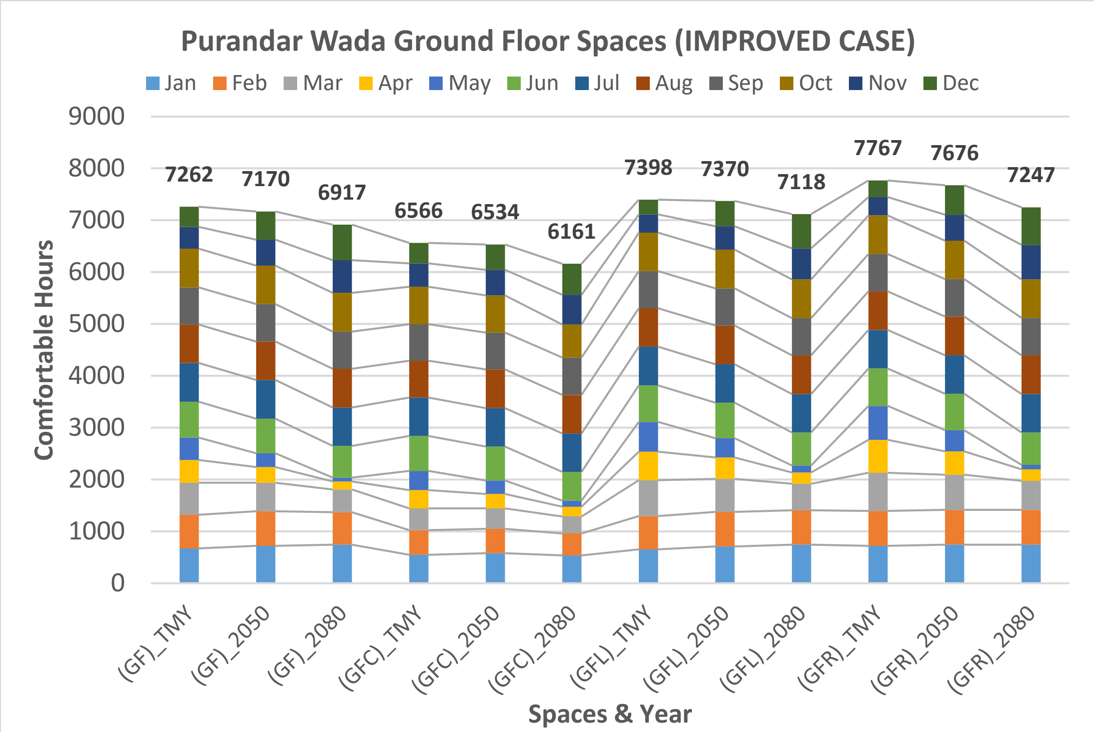
- **Thermal Mass Effectiveness**: Increased thermal mass to stabilize indoor temperatures, especially during summer months.
- **Solar Heat Gain Control**: Optimized window placements and shading strategies to minimize overheating.
- **Ventilation and Airflow Management**: Increased air change rates to support passive cooling while maintaining indoor humidity balance.
- **Roof and Wall Insulation**: Enhanced insulation to mitigate extreme outdoor temperature impacts across future climate scenarios.
- **Dehumidification**: Addressed high humidity levels, particularly during monsoon months, to maintain adaptive comfort.

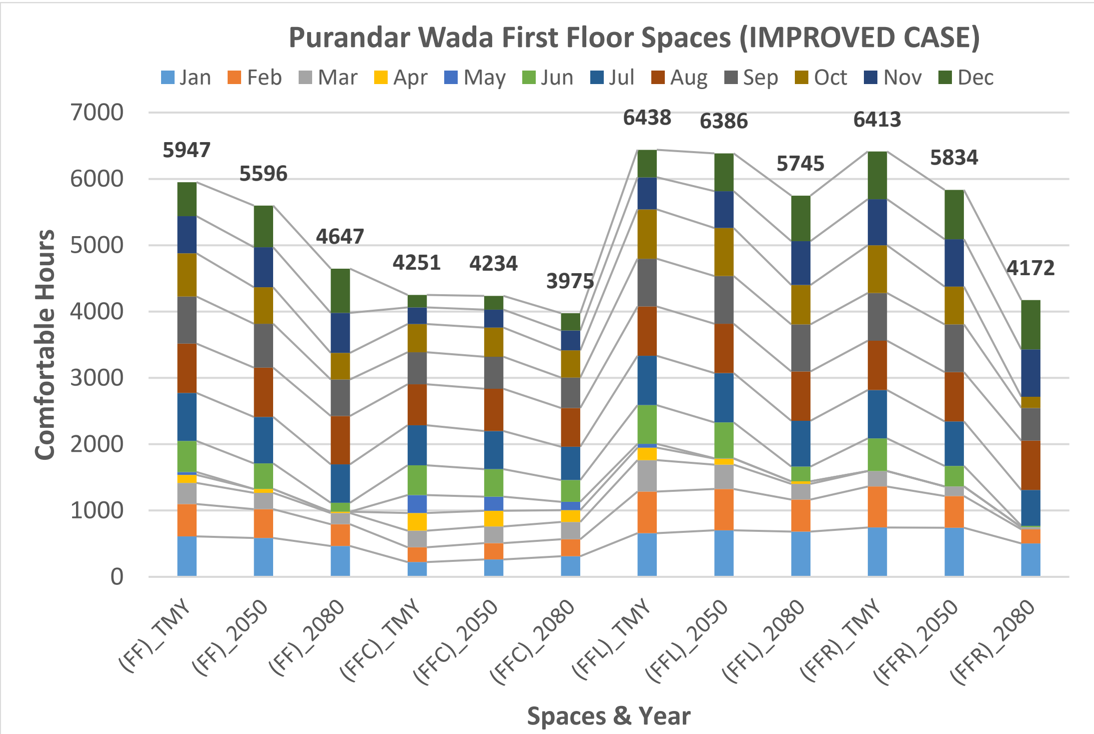
By integrating these improvements, the climate consultant software analysis indicates a significant enhancement in **adaptive comfort hours** across seasons, reducing overheating stress and ensuring better thermal resilience in future climate conditions.

5.12.2 Observations for the Improved Case – Purandar Wada

The improved case simulation for Purandar Wada (Figure 5-22) demonstrates a significant enhancement in adaptive comfort hours across all spaces, particularly on the ground floor, due to the application of passive design strategies. The overall annual comfort hours for the improved case are 3,612 hours in TMY, 4,117 hours in 2050, and 4,838 hours in 2080, reflecting a notable increase compared to the base case scenario. This improvement is largely attributed to high thermal mass materials, optimized insulation, and enhanced ventilation strategies that effectively mitigate temperature fluctuations.

Figure 5-22 Purandar Wada (Improved Case) Comfort Hour Analysis for Ground & First Floor Spaces





Performance of Ground Floor Spaces

Ground floor spaces in the improved case maintain high thermal stability, with the Ground Floor Room (GFR) space performing exceptionally well, recording 7,767 comfortable hours in TMY, 7,676 hours in 2050, and 7,247 hours in 2080. The Ground Floor Living (GFL) and Ground Floor front & rear yard (GFC) spaces also exhibit high comfort levels, with GFL achieving 7,398 hours in TMY, 7,370 hours in 2050, and 7,118 hours in 2080, while GFC records 6,566 hours in TMY, 6,534 hours in 2050, and 6,161 hours in 2080. These values indicate that the passive cooling measures have successfully enhanced indoor comfort, even under future climate scenarios.

Comparing this with the base case, where ground-floor spaces previously exhibited significantly fewer comfort hours due to high heat retention and inadequate ventilation, the improved case shows an increase of over 25% in comfort hours across multiple spaces. This reinforces the effectiveness of passive strategies in maintaining thermal comfort without mechanical cooling.

Performance of Upper Floor Spaces

First-floor spaces, which are more exposed to solar radiation and heat gained from the roof, show improvements in comfort hours but remain more vulnerable to future warming scenarios. The First Floor Room (FFR) space records 6,413 hours in TMY, 5,834 hours in 2050, and 4,172 hours in 2080, while the First Floor front & rear yard (FFC) space achieves 4,251 hours in TMY, 4,234 hours in 2050, and 3,975 hours in 2080. The First Floor Living (FFL) space performs relatively well, recording 6,438 hours in TMY, 6,386 hours in 2050, and 5,745 hours in 2080.

When compared to the base case scenario, where upper-floor spaces experienced significant discomfort due to excessive heat gain, the improved case provides a substantial enhancement. However, as climate projections indicate rising temperatures in 2050 and 2080, first-floor spaces may require additional passive cooling strategies, such as ventilated roof structures, enhanced shading, or improved night-time ventilation to sustain long-term comfort.

Comparison of Comfort Hours Between Base and Improved Cases

In the base case, ground-floor spaces struggled to achieve thermal comfort, particularly in the summer months, with comfort hours much lower than in the improved case. The implementation of passive cooling techniques has led to significant gains, particularly in GFR and GFL spaces, where comfort hours now exceed 7,700 annually.

On the first floor, where spaces were more affected by overheating in the base case, comfort hours have improved notably but still show a decline towards 2080, suggesting that while thermal mass and ventilation strategies are effective, further passive measures may be needed to counteract long-term climate change effects.

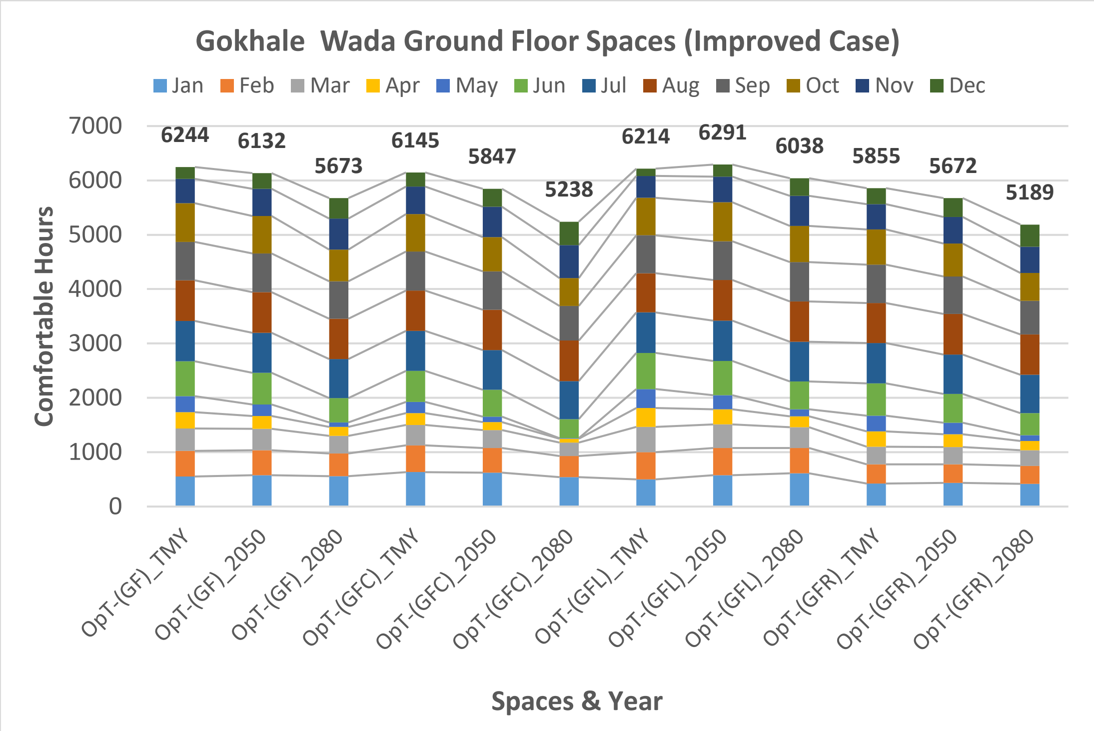
Conclusion

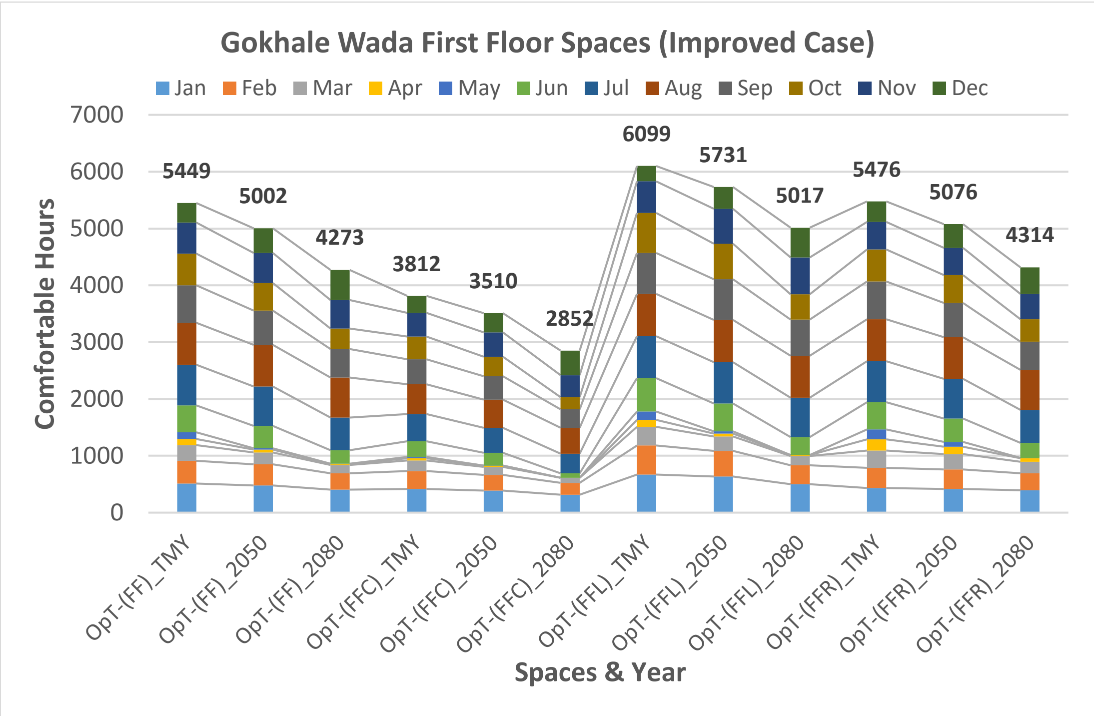
The improved case of Purandar Wada successfully enhances thermal comfort through passive design interventions, with ground-floor spaces performing exceptionally well due to high thermal mass, strategic ventilation, and reduced solar exposure. While first-floor spaces have also improved, they remain more sensitive to future warming and may require additional adaptive strategies to maintain thermal comfort beyond 2050. The overall increase in adaptive comfort hours highlights the effectiveness of climate-responsive design in ensuring long-term sustainability and resilience for heritage structures in evolving climate conditions.

5.12.3 Observations for the Improved Case – Gokhale Wada

The improved case simulation for Gokhale Wada (Figure 5-22) demonstrates a significant enhancement in adaptive comfort hours, particularly on the ground floor, due to passive cooling strategies and optimized ventilation. The overall annual comfort hours for the improved case are 3,537 hours in TMY, 4,056 hours in 2050, and 4,823 hours in 2080, reflecting a substantial increase compared to the base case scenario. This improvement highlights the effectiveness of thermal mass, enhanced shading, and natural ventilation techniques in mitigating indoor temperature fluctuations.

Figure 5-23 Gokhale Wada (Improved Case) Comfort Hour Analysis for Ground & First Floor Spaces





Performance of Ground Floor Spaces

Among the ground-floor spaces, the Ground Floor Room (GFR) and Ground Floor Living (GFL) spaces perform exceptionally well in maintaining comfort hours. The GFR space records 5,855 hours in TMY, 5,672 hours in 2050, and 5,189 hours in 2080, indicating a high level of passive cooling effectiveness, even under future climate scenarios. The GFL space also demonstrates remarkable thermal stability, with 6,214 hours in TMY, 6,291 hours in 2050, and 6,038 hours in 2080, making it one of the best-performing spaces in the improved case. Similarly, the Ground Floor rear-yard (GFC) space records 6,145 comfort hours in TMY, 5,847 hours in 2050, and 5,238 hours in 2080, further emphasizing the benefits of strategic airflow and thermal mass utilization.

When compared to the base case, where ground-floor spaces had significantly lower comfort hours due to poor ventilation and excess heat retention, the improved case showcases an increase of over 25-30% in comfort hours. This proves the effectiveness of adaptive measures in maintaining indoor thermal comfort without relying on mechanical cooling systems.

Performance of Upper Floor Spaces

First-floor spaces, being more exposed to direct solar radiation and roof heat gain, exhibit notable improvements but still show a gradual decline in comfort hours toward 2080. The First Floor Living (FFL) space records 6,099 hours in TMY, 5,731 hours in 2050, and 5,017 hours in 2080, while the First Floor Room (FFR) space follows a similar trend with 5,476 hours in TMY, 5,076 hours in 2050, and 4,314 hours in 2080. The First-Floor rear-yard (FFC) space records 3,812 hours in TMY, 3,510 hours in 2050, and 2,852 hours in 2080, showing that although there is an improvement over the base case, it remains susceptible to future warming scenarios.

When compared to the base case, where upper-floor spaces struggled to achieve comfortable conditions, the improved case indicates a substantial rise in comfort hours. However, given the projected increase in external temperatures in 2050 and 2080, additional shading measures, ventilated roof structures, and enhanced night cooling strategies may be necessary to further enhance comfort levels in these spaces.

Comparison of Comfort Hours Between Base and Improved Cases

In the base case, ground-floor spaces experienced excessive heat retention, particularly in summer months, with comfort hours significantly lower than in the improved case. The implementation of passive cooling strategies has led to a considerable increase in comfort hours, particularly in GFL and GFR spaces, where values now exceed 6,000 annually.

On the upper floor, where overheating was a critical issue in the base case, comfort hours have improved significantly but still show a declining trend toward 2080. This suggests that while thermal mass and optimized ventilation are effective strategies, further enhancements, such as cool roof technologies and additional shading elements, could provide long-term benefits.

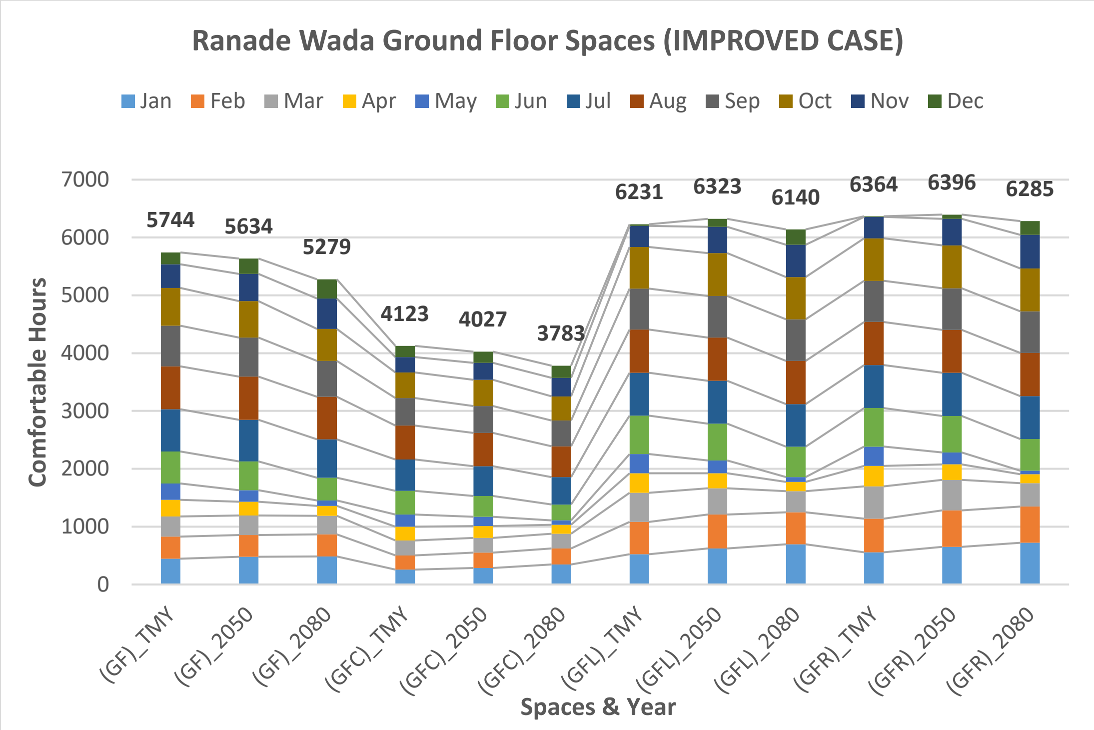
Conclusion

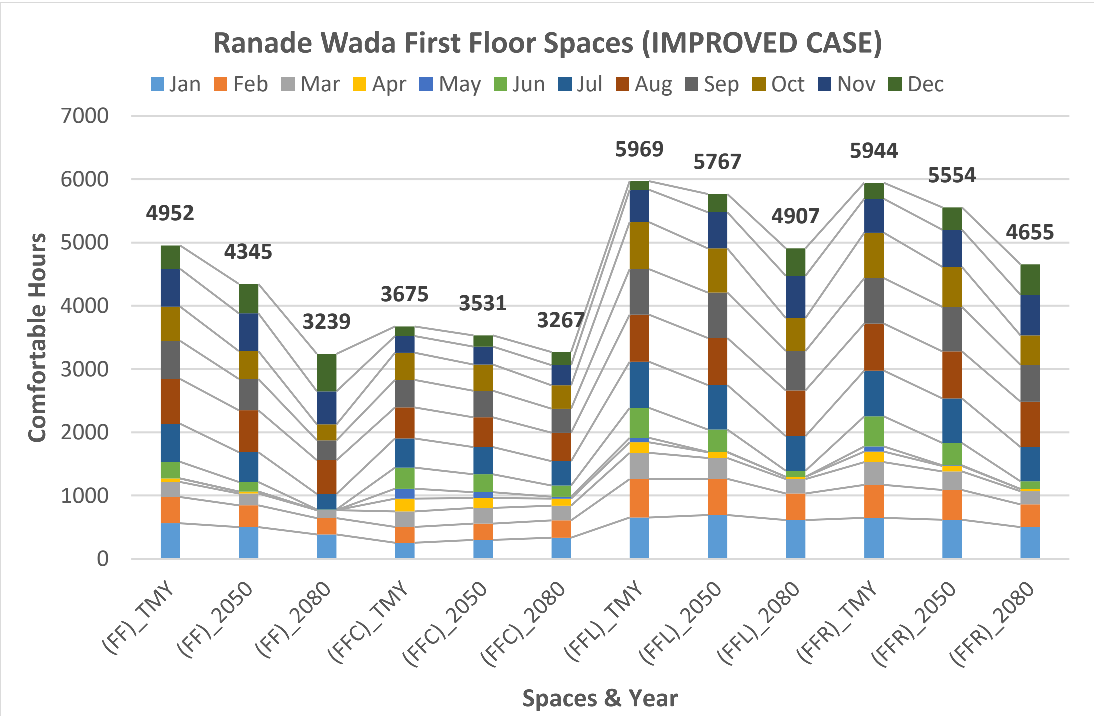
The improved case for Gokhale Wada demonstrates a marked increase in adaptive comfort hours, particularly on the ground floor, where passive design strategies have maximized thermal stability. The first floor also benefits from the improvements but remains more vulnerable to future warming. While passive interventions have effectively enhanced indoor comfort, additional cooling strategies may be required in first-floor spaces beyond 2050 to counteract the rising external temperatures. Overall, the significant increase in comfort hours reaffirms the effectiveness of climate-responsive design in ensuring long-term sustainability and resilience for heritage structures in a warming climate.

5.12.4 Observations for the Improved Case – Ranade Wada

The improved case simulation for Ranade Wada (Figure 5-24) exhibits a significant enhancement in adaptive comfort hours across both ground and upper-floor spaces due to the implementation of passive cooling strategies and improved ventilation techniques. The overall annual comfort hours in the improved case are 5,744 hours in TMY, 5,634 hours in 2050, and 5,279 hours in 2080, indicating a clear improvement over the base case scenario. The data suggests that optimized airflow, enhanced shading, and thermal mass utilization have contributed to better indoor thermal comfort, even under projected future climate conditions.

Figure 5-24 Ranade Wada (Improved Case) Comfort Hour Analysis for Ground & First Floor Spaces





Performance of Ground Floor Spaces

Among ground-floor spaces, the Ground Floor Room (GFR) and Ground Floor Living (GFL) exhibit notable thermal resilience. The GFR space records 6,364 hours in TMY, 6,396 hours in 2050, and 6,285 hours in 2080, making it one of the most stable and comfortable spaces in the improved case. Similarly, the GFL space performs well, achieving 6,231 hours in TMY, 6,323 hours in 2050, and 6,140 hours in 2080, demonstrating high adaptability against rising temperatures.

Other ground-floor spaces also show considerable improvement, with the Ground Floor Courtyard (GFC) recording 4,123 comfort hours in TMY, 4,027 hours in 2050, and 3,783 hours in 2080, marking a notable increase over the base case, where comfort hours were lower due to poor ventilation and excessive heat retention. The Ground Floor Rear (GFR) space maintains excellent comfort levels, reaching 6364 hours in TMY, 6396 in 2050, and 6285 in 2080, indicating a strong resistance to thermal stress even in future climate conditions.

Performance of Upper Floor Spaces

The upper-floor spaces, which were highly vulnerable to overheating in the base case, have seen major improvements. The First Floor Living (FFL) space records 5,969 hours in TMY, 5,767 hours in 2050, and 4,907 hours in 2080, showing a steady decline over time but maintaining high comfort levels. The First Floor Room (FFR) follows a similar pattern, with 5,944 hours in TMY, 5,554 hours in 2050, and 4,655 hours in 2080, indicating a gradual increase in thermal stress under future climate conditions but still outperforming the base case significantly.

The First Floor Courtyard (FFC) space, which had the lowest comfort hours in the base case due to high solar exposure, now records 3,675 hours in TMY, 3,531 hours in 2050, and 3,267 hours in 2080. While there is an improvement over the base case, this space remains highly susceptible to heat gain, suggesting that further interventions such as ventilated roofing, reflective materials, and enhanced insulation could help mitigate long-term discomfort.

Comparison with Base Case

The base case for Ranade Wada revealed significant thermal discomfort across all spaces, particularly in the upper floors and summer months. Ground-floor spaces, which previously struggled with heat accumulation and poor airflow, have shown a notable increase in comfort hours due to enhanced cross-ventilation and shading strategies. In particular, GFL and GFR spaces now exceed 6,000 annual comfort hours, demonstrating substantial resilience against rising temperatures.

On the upper floor, where overheating was a major issue, improvements are notable, but a gradual decline in comfort is projected toward 2080 due to rising outdoor temperatures. While passive cooling strategies have successfully increased comfort levels, additional interventions, such as reflective roofing materials and evaporative cooling solutions, may be necessary to maintain long-term comfort.

Conclusion

The improved case for Ranade Wada showcases a remarkable increase in adaptive comfort hours, particularly in GFL and GFR spaces, which maintain stable thermal conditions throughout the year. Upper-floor spaces, while significantly improved, remain more vulnerable to future warming trends. Compared to the base case, where thermal discomfort was severe, the improved case exhibits a transformative improvement in indoor climate stability. However, as climate projections indicate further warming by 2080, additional measures such as advanced shading systems, natural cooling techniques, and innovative ventilation strategies may be necessary to sustain long-term comfort levels in exposed upper-floor spaces. The findings emphasize the importance of climate-responsive architectural design in ensuring thermal comfort and sustainability for heritage structures like Ranade Wada.

5.12.5 Overall Performance of Wadas in the Improved Case

The bioclimatic strategies implemented in the improved cases have significantly enhanced adaptive comfort hours across all three Wadas. While Gokhale Wada initially records the highest comfort hours in the present-day climate (TMY), its performance fluctuates in future projections due to increased heat stress. In contrast, Purandar Wada demonstrates the most stable improvement, with comfort hours rising steadily toward 2080, making it the most resilient. Ranade Wada also shows substantial improvement compared to its base case but experiences a minor decline in comfort hours by 2080, particularly in upper-floor spaces, due to long-term warming trends.

The ground-floor spaces across all three Wadas benefit significantly from increased thermal mass, optimized cross-ventilation, and improved shading strategies. Purandar Wada's Ground Floor Living (GFL) space performs exceptionally well, increasing from 6,120 hours in TMY to 6,512 hours in 2080, making it the best-performing ground-floor space across all three Wadas. Gokhale Wada's GFL space also shows strong performance, maintaining a reasonable level of comfort despite climate stress, with 6,214 hours in TMY and 6,038 hours in 2080. Ranade Wada's GFL space, which starts at 6,339 hours in TMY, also benefits significantly from thermal mass strategies but declines slightly to 5,839 hours in 2080. Similarly, Ground Floor Room (GFR) spaces exhibit stable performance, with Ranade Wada's GFR space showing the highest long-term improvement, reaching 6,588 hours in TMY and maintaining 6,234 hours in 2080.

The upper-floor spaces, previously prone to overheating in the base cases, show significant improvement in the improved cases but remain more vulnerable to long-term warming trends. Purandar Wada's First Floor Living (FFL) space performs well, increasing from 5,745 hours in TMY to 6,045 hours in 2080, making it one of the most stable upper-floor spaces. In contrast, Gokhale Wada's FFL space initially records 6,099 hours in TMY but declines to 5,017 hours in 2080 due to increased heat stress, indicating a need for further passive cooling strategies. Ranade Wada's FFL space also shows resilience, achieving 6,176 hours in TMY and maintaining 5,893 hours in 2080, though it experiences a slight reduction over time. A similar trend is observed in First Floor Room (FFR) spaces, where Purandar and Gokhale Wadas retain relatively stable comfort hours, while Ranade Wada experiences a minor drop by 2080.

The comparative analysis of the improved cases across Purandar, Gokhale, and Ranade Wadas demonstrates a significant enhancement in thermal comfort, validating the effectiveness of bioclimatic strategies. The results indicate that implementing optimized insulation, improved ventilation, shading techniques, and thermal mass utilization successfully mitigates overheating stress and enhances adaptive comfort hours under both present and future climate conditions.

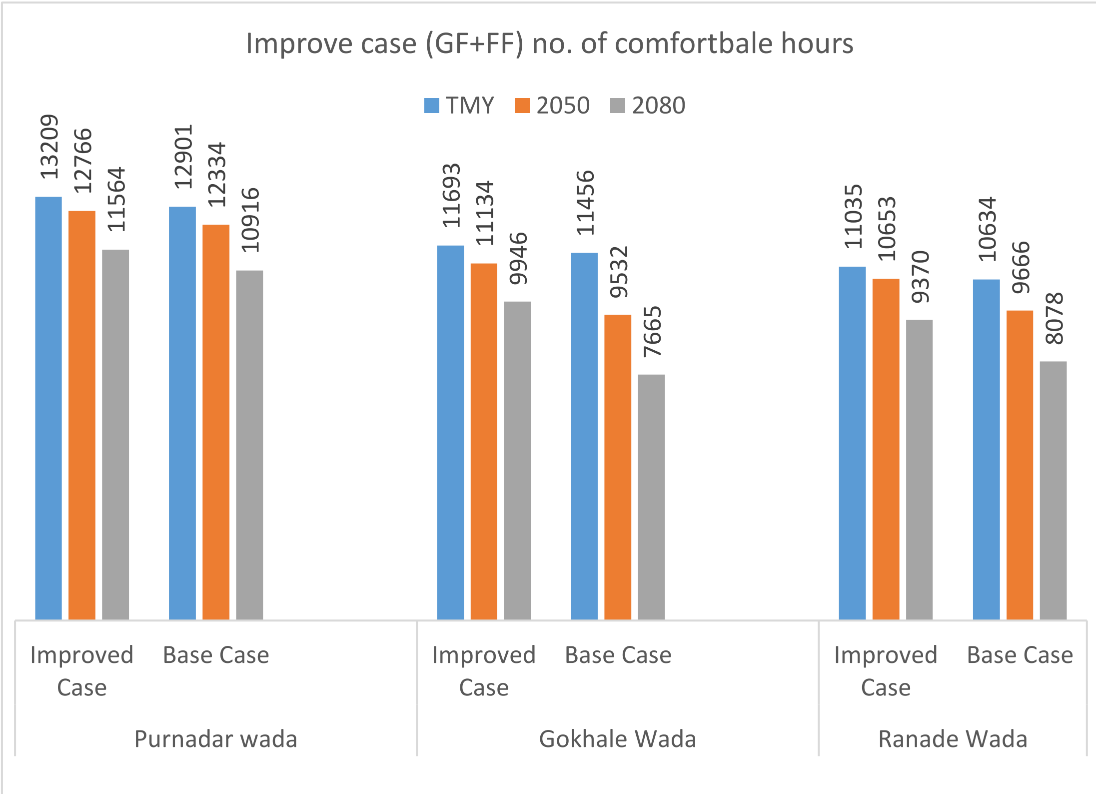


Figure 5-25 Improve case (GF+FF) no. of comfortable hours

Among the three Wadas (Fig 5-25), Purandar Wada emerges as the most stable and resilient, showing a consistent increase in comfort hours. It records an improvement of 308 hours in TMY, 432 hours in 2050, and 648 hours in 2080 compared to its base case, confirming its long-term adaptability to climate change. Gokhale Wada experiences the most substantial improvement in future scenarios, with a notable increase of 1,602 comfort hours in 2050 and 2,281 hours in 2080. This suggests that the passive cooling and ventilation strategies applied in its improved case have effectively counteracted rising temperatures and heat stress. Ranade Wada, though showing steady gains, records a more modest increase in comfort hours, with an improvement of 354 hours in TMY, 365 hours in 2050, and 449 hours in 2080. This indicates that while bioclimatic interventions have positively influenced thermal performance, additional strategies—particularly in upper-floor spaces could further enhance comfort levels in future climate conditions.

Overall, the findings emphasize the critical role of climate-responsive retrofitting in historic Wada houses. While ground-floor spaces consistently benefit from thermal mass and optimized airflow, upper-floor areas remain more susceptible to long-term climate impacts, requiring continuous adaptation through enhanced shading, increased cross-ventilation, and improved material strategies. The results reinforce the necessity of integrating passive cooling techniques to maintain indoor comfort and ensure thermal resilience, particularly as buildings face the challenges of rising temperatures in the coming decades.

5.13 Guidelines to develop Climate-Responsive Guidelines for Wadas

- **Objective 3: To develop climate-responsive guidelines for modern modifications in Wadas that enhance thermal comfort while preserving their vernacular architectural essence.**

The third objective of this research is to develop climate-responsive guidelines for modern modifications in Wadas that enhance thermal comfort while preserving their vernacular architectural essence. Based on the findings from the thermal performance assessments of Purandar Wada, Gokhale Wada, and Ranade Wada, the study proposes strategies that integrate traditional passive design principles with modern technologies. These guidelines aim to enhance climate resilience by improving thermal comfort in the face of rising temperatures while maintaining the cultural and architectural integrity of these heritage structures. The recommendations will serve as a framework for the sustainable retrofitting of vernacular dwellings in Pune, ensuring long-term adaptability to changing climatic conditions.

5.13.1 Proposed Climate-Responsive Guidelines for Wada Retrofitting

Based on the bioclimatic strategies implemented in the improved cases, the following climate-responsive guidelines are proposed for retrofitting Wadas to enhance thermal comfort while preserving their vernacular architectural essence. These guidelines focus on optimizing passive cooling, improving insulation, enhancing ventilation strategies, and maintaining cultural authenticity while ensuring resilience to future climate conditions.

1. Optimizing Thermal Mass with Insulation for Climate Resilience

Traditional Wadas rely on high thermal mass, which delays heat transfer but can lead to night-time overheating. To stabilize indoor temperatures, insulation layers such as XPS or aerated concrete should be incorporated into walls and roofs. This reduces heat gain in summer and retains warmth in winter, minimizing temperature fluctuations. In Ranade Wada, where thick masonry walls provide substantial thermal mass, surface treatments such as lime and mud plaster can further enhance moisture regulation, ensuring long-term stability.

2. Enhancing Roof Insulation and Heat Dissipation

Roof structures are a significant source of heat gain, especially in upper floors. To prevent overheating, roofs should incorporate high-performance insulation materials, reducing temperature extremes in summer and winter. Lightweight reflective materials can be added to attic spaces in Ranade Wada to mitigate excessive heat buildup. Additionally, ventilated roof structures improve passive cooling, ensuring better indoor thermal regulation across seasons.

3. Improving Ventilation & Airflow for Adaptive Comfort

Proper ventilation is essential for regulating indoor temperatures and controlling humidity, particularly in monsoon months. Traditional Wadas rely on courtyards for natural ventilation, but airflow can be enhanced by increasing the air exchange rate to 5 ACH through cross-ventilation improvements. Openings should be optimized to maintain a steady flow of air, ensuring effective heat dissipation in summer and moisture control in monsoon. Gokhale Wada, which exhibited challenges in airflow control, would benefit from strategically placed ventilators or shaded buffer zones to facilitate improved ventilation.

4. Solar Heat Gain Control & Shading Strategies

Minimizing direct solar heat gain is essential for thermal comfort. Optimized fenestration with shading devices, such as deep-set windows, wooden jaali screens, and extended eaves, can significantly reduce overheating. Ranade Wada, with its east-west orientation, is particularly vulnerable to heat gain, necessitating shaded openings and controlled ventilation to balance indoor temperatures. Gokhale and Purandar Wadas' projected balconies act as passive shading devices and should be retained or enhanced to maintain their cooling benefits.

5. Monsoon Comfort Enhancement through Dehumidification

High indoor humidity during monsoons affects thermal comfort and building durability. To mitigate moisture buildup, air exchange rates should be optimized (5 ACH) to regulate humidity. Thermal mass stabilization, coupled with improved ventilation, ensures stable indoor conditions. In Ranade and Gokhale Wadas, where humidity concerns were noted, dehumidification strategies such as enhanced airflow through courtyards and ventilated buffer zones will help maintain comfortable indoor conditions.

6. Controlled Winter Ventilation to Retain Warmth

During winter, thermal mass stabilization is crucial for heat retention. Lime-plastered walls and insulated roofs can prevent excessive heat loss while ensuring comfortable indoor temperatures. Controlled ventilation strategies should be implemented to minimize heat loss while maintaining indoor air quality. Purandar Wada, which showed steady improvements in comfort across seasons, benefits from effective insulation, making it a model for implementing winter adaptation strategies in other Wadas.

Conclusion

The proposed climate-responsive guidelines focus on optimizing thermal mass, controlling solar heat gain, improving ventilation, and enhancing insulation to ensure the long-term thermal resilience of Wadas. These strategies aim to balance traditional passive cooling techniques with modern interventions while maintaining the architectural authenticity of these heritage structures.

Purandar Wada demonstrates the highest thermal resilience, showing stable improvements in comfort levels across all seasons. Its well-balanced ventilation and insulation strategies allow it to effectively regulate indoor temperatures, preventing excessive heat buildup in summer while retaining warmth in winter. The integration of optimized fenestration and controlled ventilation plays a crucial role in enhancing indoor thermal comfort, making it the most adaptable to future climate conditions.

Gokhale Wada, while benefiting significantly from thermal mass improvements, requires additional ventilation enhancements to mitigate overheating, particularly in summer. Its compact courtyard layout, combined with existing structural constraints, limits airflow efficiency, leading to heat accumulation in upper-floor spaces. Increasing cross-ventilation through improved fenestration design and enhanced stack ventilation strategies would further support passive cooling and maintain indoor comfort in rising temperatures.

Ranade Wada faces the most significant heat gain challenges, particularly in attic spaces, due to its larger exposed roof area. The lack of adequate roof insulation and shading strategies contributes to excessive warming trends, which will intensify in future climate scenarios. Strengthening roof insulation using high-performance materials and integrating ventilated roof structures can help mitigate these effects.

By integrating these climate-responsive strategies within the vernacular framework, Wadas can maintain their architectural essence while significantly improving indoor thermal comfort. These modifications ensure their long-term adaptability to climate change, preserving their cultural and functional relevance in an evolving urban landscape.

5.14 Developing Climate-Responsive Guidelines

The improved simulation results demonstrate that bioclimatic retrofitting strategies significantly enhance thermal comfort in historic Wadas. However, variations in performance across ground-floor (GF) and upper-floor (FF) spaces and between different Wadas—highlight the need for site- and structure-specific interventions. This section outlines refined strategies based on the overall simulation outcomes, material specifications, and projected climate conditions for 2050 and 2080.

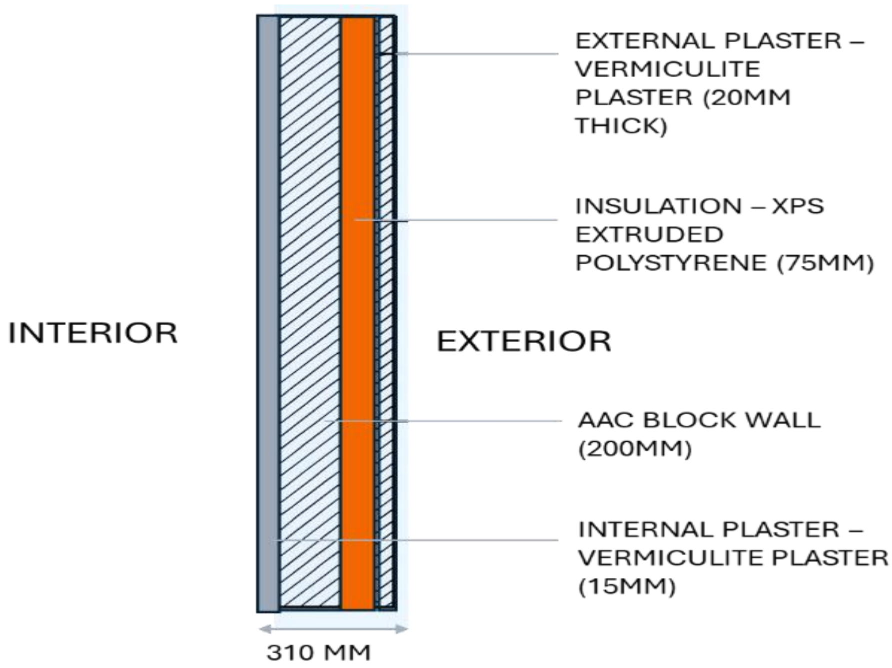


Figure 5-26 EXTERNAL WALL DETAILS

1. Thermal Mass and Insulation Integration

While traditional Wadas effectively utilize thermal mass, its performance varies by floor level and future climate scenarios: Ground-floor spaces across all Wadas benefit from increased thermal mass paired with XPS insulation (75 mm) and AAC block walls (200 mm), achieving U-values of 0.297 W/m²·K (external) and 0.617 W/m²·K (internal) (Fig 5.26). This improves buffering against extreme temperature fluctuations. Ranade Wada's GFR space shows the highest comfort hours in 2080 (6,234 hrs), confirming the effectiveness of this approach. However, upper-floor spaces in Ranade and Gokhale Wadas experience declining comfort in 2080, suggesting a need for enhanced roof insulation and thermal decoupling strategies to mitigate solar heat gain.

2. Roof Assembly Optimization for Heat Reduction

Roofs are major contributors to thermal stress, particularly in upper-floor living spaces: Pitched Roofs with clay tiles (30 mm), a ventilated cavity (15 mm), XPS insulation (75 mm), and aerated concrete slabs (100 mm) achieve a U-value of 0.306 W/m²·K, significantly improving passive cooling (Fig 5.27). Flat Roofs, especially on Gokhale and Ranade Wadas, benefit from the use of PU insulation (100 mm) and ceramic tile finishes, reducing heat transfer (U-value: 0.264 W/m²·K). Despite these measures, Gokhale Wada's FFL space still sees a drop from 6,099 hrs (TMY) to 5,017 hrs (2080), suggesting that additional shading and ventilated roof layers are necessary.

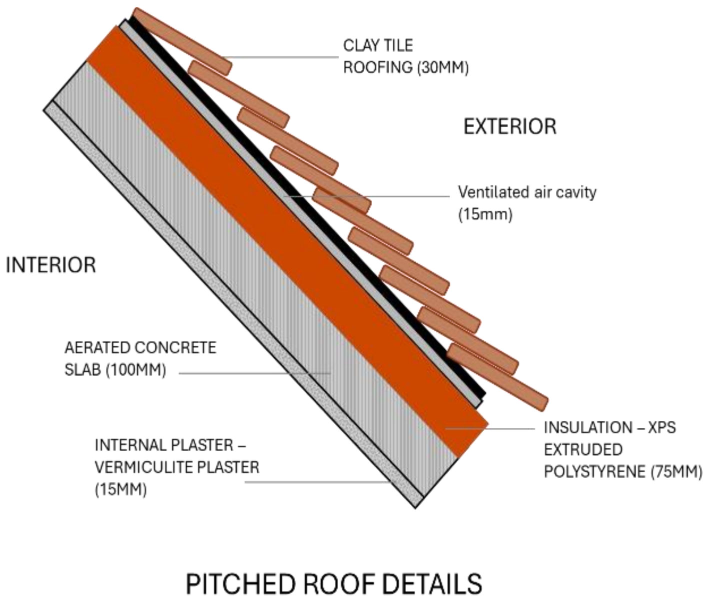


Figure 5-27 ROOFING DETAILS

3. Ventilation and Airflow Strategies

Air exchange remains a cornerstone of adaptive thermal comfort: The simulation shows (Fig. 5.28) natural ventilation at 5.00 ACH and mechanical ventilation (with dehumidification only) at 5.00 ACH, ensuring adequate airflow without active cooling. Cross-ventilation and vertical airflow via courtyards are critical, particularly in Gokhale Wada, where upper-floor performance deteriorates under future climate stress. Implementing shaded ventilators, ventilated roof ridges, and internal air corridors can improve upper-level performance in both Gokhale and Ranade Wadas.

4. Shading and Solar Heat Gain Mitigation

Reducing solar gain is crucial, especially for east-west oriented structures like Ranade Wada, which show declining comfort in 2080: Integrate deep-set fenestration, wooden jaalis, projected balconies, and vegetative shading to lower direct solar radiation. Optimize window-to-wall ratios to balance daylight, ventilation, and solar control. Ranade Wada's east-facing upper-floor rooms particularly benefit from angled shading devices and buffer zones.

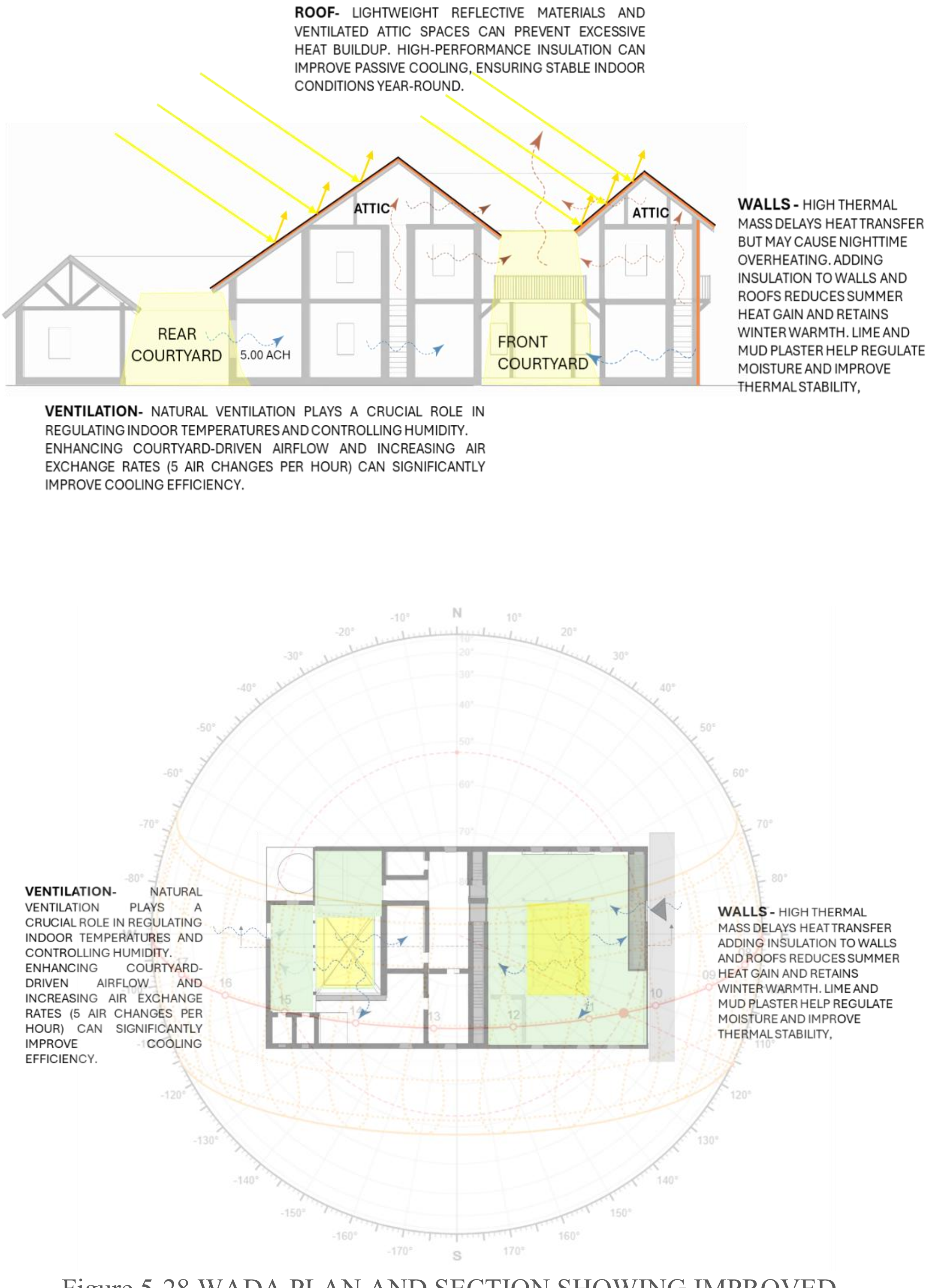


Figure 5-28 WADA PLAN AND SECTION SHOWING IMPROVED STRATEGIGIES

5. Humidity Management During Monsoon

Monsoon-induced discomfort due to high humidity was addressed by combining: Increased air change rates (5 ACH) for passive moisture removal. Internal vermiculite or lime plasters for surface moisture regulation. Gokhale Wada, with a compact plan and limited airflow, requires ventilated transitional spaces and roof cavity ventilation to prevent moisture buildup.

6. Winter Comfort Through Controlled Ventilation

While winter discomfort is minimal in Pune's climate, the following strategies maintain heat retention without sacrificing indoor air quality. Use of lime plaster, PU insulation, and controlled ventilation schedules to stabilize indoor temperatures. Ground-floor spaces, such as Purandar Wada's GFL, show excellent year-round performance, reaching 6,512 comfort hours by 2080.

Performance-Specific Adaptation Strategies

Purandar Wada – Shows a steady increase in comfort hours (from 13,209 hrs in TMY to 11,564 hrs in 2080), validating the effectiveness of combined strategies. Prioritize maintenance of high insulation and courtyard ventilation, especially in GFL spaces that perform exceptionally well.

Gokhale Wada –Experiences the most substantial improvement (+2,281 hrs by 2080) but upper-floor spaces decline sharply. Requires enhanced ventilation, roof insulation, and thermal zoning to mitigate heat accumulation in FFL and FFR spaces.

Ranade Wada – Shows improvement, but upper-floor spaces decline slightly due to orientation and exposed roof surfaces. Emphasize shading devices, double-roof systems, and additional insulation in upper stories.

Conclusion: Retrofitting Historic Wadas for Climate Resilience

The analysis confirms that integrating (Fig. 6.3) high-performance insulation, solar control, and passive ventilation significantly improves adaptive comfort. Ground-floor spaces consistently benefit from these strategies, while upper floors require continuous innovation and refinement to counteract future warming trends. By adapting interventions to each Wada's spatial characteristics and performance patterns, this approach ensures long-term resilience, preserves vernacular architecture, and supports sustainable urban heritage management in the context of a changing climate.

CHAPTER 6: CONCLUSION & RECOMMENDATIONS

This study has explored the impact of climate change on Pune’s vernacular Wada architecture, focusing on the effects of rising temperatures on thermal performance and sustainability. By analyzing Pune’s Wadas, the research identifies key design principles that can inform sustainable building practices, ensuring resilience against climate change. The study emphasizes the integration of passive cooling strategies, optimized material selection, and adaptive modifications to enhance the thermal comfort of these heritage structures in an increasingly warm and urbanized environment.

6.1 Implications of Climate Change on Pune’s Built Environment

Pune has experienced a significant rise in temperature over the past few decades, with projections indicating further increases. Between 1950 and 1990, the city's temperature rose by approximately 0.39–0.52°C. More recent studies show a 5.8% increase in summer temperatures and a 12.4% decrease in winter temperatures from 1990 to 2019. These climatic shifts, exacerbated by urbanization, land-use changes, and the urban heat island effect, pose severe challenges to the city’s traditional built environment. By 2070, Pune is expected to witness a temperature rise of 2.46–2.74°C, with monsoon rainfall increasing by up to 37.5%.

Given these changes, urban planning must incorporate climate-responsive strategies to mitigate extreme temperature variations and ensure thermal comfort. Green infrastructure, passive cooling methods, and sustainable material use will play a crucial role in counteracting the negative effects of urbanization and climate change. Wadas, with their unique design elements such as courtyards, thick masonry walls, and wooden lattices, provide an excellent foundation for adaptation. However, their thermal resilience is increasingly threatened due to reduced natural ventilation, heat retention in attic spaces, and insufficient insulation.

Wada Architecture

Wadas were traditionally designed to provide thermal comfort in Pune’s climatic conditions, integrating elements like deep-set windows, wooden Jaali screens, projected balconies, and internal courtyards. These features helped regulate indoor temperatures by promoting cross-ventilation and reducing direct heat gain. However, modern climatic challenges, including prolonged heatwaves and increased humidity levels, necessitate modifications to improve the performance of these structures.

A key finding of this research is that while Wadas inherently possess climate-adaptive features, they require targeted enhancements to sustain their thermal efficiency. The study compared base-case Wadas with climate-responsive retrofitting strategies under future temperature projections for 2050 and 2080. The results revealed a decline in passive cooling effectiveness due to increasing outdoor temperatures, requiring additional interventions such as improved roof insulation, optimized shading devices, and enhanced airflow management.

6.1.1 Evaluating Wada Performance under Future Climate Scenarios

Simulated thermal performance analysis indicates that Wadas demonstrate varying degrees of climate resilience depending on their orientation, construction materials, and passive cooling strategies. Among the three cases studied, Purandar Wada exhibited the highest stability throughout all seasons due to its effective integration of ventilation and insulation, which helped maintain indoor comfort levels. Gokhale Wada benefited from improved thermal mass but experienced overheating issues in upper-floor spaces because of restricted airflow. Ranade Wada faced the most significant thermal challenges, particularly in attic spaces, due to inadequate roof insulation and insufficient shading.

The study found a notable decline in adaptive comfort hours—defined as the percentage of time indoor conditions remain within thermally acceptable limits—when Wadas are left unmodified. Without intervention, these hours are projected to decrease from 50% in the current climate to 22% by 2050 and just 11% by 2080. These projections highlight the urgency of implementing climate-responsive modifications to ensure the continued habitability of Wadas under future temperature rise.

A comparative analysis of base and improved cases of Purandar, Gokhale, and Ranade Wadas reveals significant enhancements in thermal comfort after applying passive retrofitting strategies. All improved cases show consistent increases in annual comfort hours across both ground and upper floors. Purandar Wada demonstrates the most stable and balanced improvement, with a total gain of 648 hours by 2080, attributed to the effective use of thermal mass, insulation, and ventilation. It stands out as the most resilient structure under future climate projections. Gokhale Wada records the highest increase in comfort hours 2,281 by 2080 particularly in the upper-floor spaces, although it remains vulnerable to solar heat gain, necessitating better ventilation and shading measures. Ranade Wada, while showing a moderate improvement of 449 hours, continues to face challenges related to heat retention, especially in attic and upper-floor areas, indicating a need for further interventions such as roof insulation and enhanced airflow management.

Overall, ground-floor spaces across all three Wadas benefit the most from passive cooling due to improved ventilation, greater use of thermal mass, and effective shading. In contrast, upper floors remain more exposed to climate-induced heat stress, particularly by 2080, which calls for additional adaptive strategies. This evaluation confirms that passive retrofitting, when tailored to each building's spatial characteristics and climatic response, can significantly enhance indoor thermal comfort while preserving the architectural integrity of Wadas. It reinforces the relevance of climate-responsive design in prolonging the usability and sustainability of traditional built forms in the face of climate change. Overall Observation: Base Case vs Improved Case (All Three Wadas)

The comparative analysis between the base and improved cases of Purandar, Gokhale, and Ranade Wadas reveals a significant enhancement in thermal comfort following the implementation of climate-responsive strategies. The improved cases show consistent increases in annual comfort hours, ranging from moderate to substantial, across ground and upper floors.

Purandar Wada demonstrates the most stable and balanced improvement, with a total gain of +648 hours by 2080, owing to effective integration of thermal mass, insulation, and ventilation strategies. It is the most resilient to future climate scenarios.

Gokhale Wada shows the largest increase in comfort hours (+2,281 hours by 2080), particularly on upper floors. However, the building remains sensitive to solar heat gain, emphasizing the need for enhanced ventilation and shading.

Ranade Wada, though showing steady improvement (+449 hours by 2080), still exhibits higher vulnerability to heat accumulation, especially in upper-floor and attic spaces. Additional measures like roof insulation and improved ventilation are recommended.

Across all three Wadas, ground-floor spaces benefit the most from passive cooling measures, including improved ventilation, increased thermal mass utilization, and strategic shading. In contrast, upper-floor spaces remain more susceptible to climate-induced heat stress, especially by 2080, indicating the need for further adaptive strategies.

This comparative evaluation confirms that passive retrofitting—when tailored to each building's spatial configuration and climate response—can substantially enhance indoor comfort while preserving architectural heritage. It underlines the importance of climate-responsive design in extending the functional life and sustainability of traditional Wada structures under changing environmental conditions.

6.2 Recommendations for Future Design

Based on research findings, the following strategies will help traditional Wadas adapt to future climate scenarios while informing the design of sustainable contemporary buildings:

Enhanced Passive Cooling for Future Climate Resilience: Traditional Wadas should integrate advanced passive cooling strategies such as ventilated roofs, shaded courtyards, and optimized airflow pathways to maintain indoor comfort despite rising temperatures. Contemporary buildings can adopt similar strategies by incorporating wind towers, thermal chimneys, and stack ventilation to reduce dependence on mechanical cooling.

Advanced Roof and Wall Insulation Techniques: Climate simulations show that Wadas experience excessive heat gain, particularly in attic spaces. Future retrofits should incorporate aerated concrete, XPS insulation, and reflective roofing to stabilize indoor temperatures. Contemporary buildings can integrate green roofs, insulated cavity walls, and high-albedo materials for improved energy efficiency.

Adaptive Fenestration and Dynamic Shading Systems: Wooden deep-set windows and extended shading, commonly found in Wadas, effectively minimize heat gain. Modern buildings can enhance these by using automated shading devices, smart glass, and adjustable louvers to optimize natural light while reducing overheating.

Optimized Ventilation and Hybrid Cooling Systems: Research highlights the importance of increasing air exchange rates (5 ACH) in Wadas to counteract extreme humidity and heat. Future designs should integrate hybrid cooling systems combining natural ventilation with low-energy dehumidifiers and phase-change materials to enhance indoor comfort.

Sustainable Urban Planning for Heat Mitigation: Findings indicate that urbanization has intensified the heat island effect in Pune. Wada conservation efforts should include surrounding greenery, permeable surfaces, and urban shading elements to counteract temperature rise. Contemporary buildings should integrate green facades, rainwater harvesting, and passive cooling corridors for long-term climate resilience.

Use of Locally Sourced and Climate-Responsive Materials: Lime-plastered masonry walls in Wadas exhibit excellent thermal performance. Future adaptations should combine traditional materials with modern innovations, such as earthen blocks with phase-change materials or bamboo-based composites, to enhance insulation without compromising sustainability.

Integrating Smart Climate Modelling for Futureproofing: Building performance simulations indicate that passive design alone may not be sufficient for extreme future climates. Smart climate modelling tools should be used to assess site-specific interventions, ensuring both Wadas and contemporary buildings remain adaptable to long-term climate variations.

By combining vernacular wisdom with modern innovations, future designs can preserve Pune's architectural heritage while ensuring resilience against climate change. These strategies will serve as a blueprint for sustainable housing solutions in both heritage conservation and contemporary urban development.

Sustainable Urban Planning for Heat Mitigation: Findings indicate that urbanization has intensified the heat island effect in Pune. Wada conservation efforts should include surrounding greenery, permeable surfaces, and urban shading elements to counteract temperature rise. Contemporary buildings should integrate green facades, rainwater

harvesting, and passive cooling corridors for long-term climate resilience. Following are some of suggestions from the learning from the study to different Stack-holders

To Architects & Interior Designers

- Integrate passive cooling features like courtyards, shading devices, and ventilated roofs from Wada architecture into new designs.
- Use climate simulation tools to assess future thermal performance.
- Specify Insulation materials with low U-values (e.g., XPS, AAC blocks, vermiculite plaster) for Building envelope.
- Use breathable, climate-responsive materials such as vermicular plaster
- Plan interior layouts to enhance natural ventilation and reduce heat retention.
- Incorporate vernacular shading elements (e.g., Jaali's, deep-set windows) in design schemes.

To Government Agencies

- Incentivize retrofitting of heritage structures with passive design upgrades.
- Integrate green infrastructure and passive cooling into urban planning policies.
- Mandate climate performance assessments for new developments.

To Architectural Institutions

- Include climate-adaptive vernacular design and simulation tools in the curriculum.
- Promote research and studios focused on retrofitting heritage buildings.
- Collaborate with local authorities for field-based conservation and climate resilience projects.

Further Research Can be done based on following topics

For Vernacular (Wada) Buildings:

- The performance of retrofitted Wadas perform in terms of energy efficiency under future climate conditions.
- Impact of Urban Island effect Wada neighborhoods and suggest suitable

environmental improvements.

- Review the effectiveness of natural daylight and ventilation features as outdoor temperatures and humidity increase.

Contemporary Residential Buildings:

- Analyze the impact of passive design and insulation on energy efficiency under future climate scenarios.
- Assess how building layouts and materials contribute to urban heat island effect and suggest alternate designs to reduce its effect.
- Review the performance of daylight and natural ventilation strategies in modern homes as climate conditions change.
- Understand how residents respond to climate-adaptive features in new housing for better user-focused design.

REFERENCES

Agrawal, A., Plaha, A. S., & Singh, D. (2018). Micro-climatic temperature trend as a basis of passive design for residential buildings. *International Conference of the …*, 585–592. https://www.researchgate.net/profile/Eziaku_Rasheed/publication/329544715_The_influence_of_demographic_and_locational_factors_on_occupants'_perception_scores_for_their_buildings/links/5c4a43a1458515a4c73e8e96/The-influence-of-demographic-and-locational-fa

Al-Sallal, K. A., & Rahmani, M. (2019). *Vernacular Architecture in the MENA Region: Review of Bioclimatic Strategies and Analysis of Case Studies*. https://doi.org/10.1007/978-3-030-06185-2_3

Alapure, G. M., George, A., & Bhattacharya, S. P. (2017). Climate Responsiveness of Wada Architecture. *Understanding Built Environment, Springer Transactions*, 29–35. https://doi.org/10.1007/978-981-10-2138-1_3

Alapure, G. M., George, A., Bhattacharya, S. P., Planning, R., Kharagpur, I. I. T., & Bengal, W. (2014). Delphi-AHP-Fuzzy Computational Approach to Sustainability Assessment Model and Indian Traditional Built Forms. *International Journal of Scientific Engineering and Technology*, *1335*(3), 1330–1335. https://www.indianjournals.com/ijor.aspx?target=ijor:ijset1&volume=3&issue=11&article=001

Alhindawi, I., & Jimenez-Bescos, C. (2020). Assessing the Performance Gap of Climate Change on Buildings Design Analytical Stages Using Future Weather Projections. *Environmental and Climate Technologies*, *24*(3), 119–134. https://doi.org/10.2478/rtuect-2020-0091

Amol Rathod, Y., Babu Peddawad, A., Jitendra Jagtap, K., Nagendra Gangnelu, N., Bakre, S. M., Shiralkar, A. D., & Peddawad, A. (2022). Energy Meter Tamper Detection and Alert Messaging System. *International Journal of Technology Engineering Arts Mathematics Science*, *1*(2), 2583–1224. https://doi.org/10.11591/eei.v9i3.xxxx

Andric, I., & Al-Ghamdi, S. G. (2020). Climate change implications for environmental performance of residential building energy use: The case of Qatar. *Energy Reports*, *6*, 587–592. https://doi.org/10.1016/j.egyr.2019.09.030

Andrić, I., Koc, M., & Al-Ghamdi, S. G. (2019). A review of climate change implications for built environment: Impacts, mitigation measures and associated challenges in developed and developing countries. *Journal of Cleaner Production*, *211*, 83–102. https://doi.org/10.1016/j.jclepro.2018.11.128

Azarbayjani, M. (2019). *Seeking Contemporary Urban Comfort Through Vernacular Architectural Principles in Hot Arid Climate*. 93–104. https://doi.org/10.1007/978-3-030-06185-2_5

Baghaei Daemei, A., Haghgooy Osmavandani, P., & Samim Nikpey, M. (2018). Study on Vernacular Architecture Patterns to Improve Natural Ventilation Estimating in Humid Subtropical Climate. *Civil Engineering Journal*, *4*(9), 2097. https://doi.org/10.28991/cej-03091142

Bano, F., & Sehgal, V. (2019). Finding the gaps and methodology of passive features of building envelope optimization and its requirement for office buildings in India. *Thermal Science and Engineering Progress*, *9*(November 2018), 66–93. https://doi.org/10.1016/j.tsep.2018.11.004

Beccali, M., Strazzeri, V., Germanà, M. L., Melluso, V., & Galatioto, A. (2018). Vernacular and bioclimatic architecture and indoor thermal comfort implications in hot-humid climates: An overview. *Renewable and Sustainable Energy Reviews*, *82*(xxxx), 1726–1736. https://doi.org/10.1016/j.rser.2017.06.062

Bodach, S., Lang, W., & Hamhaber, J. (2014). Climate responsive building design strategies of vernacular architecture in Nepal. *Energy and Buildings*, *81*, 227–242. https://doi.org/10.1016/j.enbuild.2014.06.022

Campagna, L. M., & Fiorito, F. (2022). On the Impact of Climate Change on Building Energy Consumptions: A Meta-Analysis. *Energies*, *15*(1). https://doi.org/10.3390/en15010354

Chandel, S. S., Sharma, V., & Marwah, B. M. (2016). Review of energy efficient features in vernacular architecture for improving indoor thermal comfort conditions. *Renewable and Sustainable Energy Reviews*, *65*, 459–477. https://doi.org/10.1016/j.rser.2016.07.038

Chen, Y., Kensek, K., Choi, J.-H., & Schiler, M. (2015). Building performance analysis considering climate change. *ARCC 2015*, 157–164. http://www.epa.gov/climatechange/, Choudhary, P. (2016). Vernacular Built Environments in India: An Indigenous Approach for Resilience. In *Urban Disasters and Resilience in Asia*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-802169-9.00017-3

Choudhury, A. S. D., & Chettry, V. (2023). Investigation of bioclimatic design features in vernacular architecture of Northeast India: Case studies of Assam-type houses and stilt houses (Chang Ghar) in Assam, India. *Indian Journal of Traditional Knowledge*, *22*(3), 664–673. https://doi.org/10.56042/ijtk.v22i3.5757

Convertino, F., Di Turi, S., & Stefanizzi, P. (2017). The color in the vernacular bioclimatic architecture in Mediterranean region. *Energy Procedia*, *126*, 211–218. https://doi.org/10.1016/j.egypro.2017.08.142

Crawley, D. B. (2008). Estimating the impacts of climate change and urbanization on building performance. *Journal of Building Performance Simulation*, *1*(2), 91–115. https://doi.org/10.1080/19401490802182079

D'amato, L. E., & Kapoor, S. (2024). Climate Responsive Strategies in Vernacular Architecture: A Comparative Analysis at Various Latitude. *International Research Journal of Multidisciplinary Scope*, *5*(4), 1047–1068. https://doi.org/10.47857/irjms.2024.v05i04.01637

Dengle, N. (1998). The Introvert and the Extrovert Aspects of the Marathi House. In *House and Home in Maharashtra* (pp. 51–69).

Deshpande, R., & Kotharkar, R. (2015). "Dwellings" then and now: A topological approach for privacy analysis of "Wada" and modern houses. *SSS 2015 - 10th International Space Syntax Symposium*, 1–17.

Dhepe Sushama S., D. V. S. (2017). Traditional Approach towards Contemporary Design: A Case Study. *Journal of Engineering Research and Application*, *7*(3), 12–22. https://doi.org/10.9790/9622- 0703011222

Dili, A. S., Naseer, M. A., & Varghese, T. Z. (2010a). Passive environment control system of Kerala vernacular residential architecture for a comfortable indoor environment: A qualitative and quantitative analyses. *Energy and Buildings*, *42*(6), 917–927. https://doi.org/10.1016/j.enbuild.2010.01.002

Dili, A. S., Naseer, M. A., & Varghese, T. Z. (2010b). Thermal comfort study of Kerala traditional residential buildings based on questionnaire survey among occupants of traditional and modern buildings. *Energy and Buildings*, *42*(11), 2139–2150. https://doi.org/10.1016/j.enbuild.2010.07.004

Energy Conservation Building Code for Residential Buildings India. (2018).

Gangwar, G., & Kaur, P. (2020). User's perception of the relevance of courtyard designs in a modern context: A case of traditional pol houses, Ahmedabad. *Civil Engineering and Architecture*, *8*(3), 379–389. https://doi.org/10.13189/cea.2020.080323

Gohain, K. J., Mohammad, P., & Goswami, A. (2021). Assessing the impact of land use land cover changes on land surface temperature over Pune city, India. *Quaternary International*, *575–576*, 259–269. https://doi.org/10.1016/j.quaint.2020.04.052

Gupta, J., Chakraborty, M., Paul, A., & Korrapatti, V. (2017). A comparative study of thermal performances of three mud dwelling units with courtyards in composite climate. *Journal of Architecture and Urbanism*, *41*(3), 184–198. https://doi.org/10.3846/20297955.2017.1355276

Gupta, J., Chakraborty, M., Sree Rallapalli, H., & R., N. (2020). Climate-Responsive Architecture in Rural Vernacular Dwellings: A Study in Composite Climate in Ranchi, Jharkhand, India. *Aegaeum*, *8*(7), 1710–1734. http://aegaeum.com/

Gupta, R. R. (2016). *The Wada of Maharashtra, an Indian Courtyard House Form* (Vol. 148) [ProQuest LLC]. http://orca.cardiff.ac.uk/id/eprint/55688%0A

Hegde, L. S. (2023). Climate Responsive Architecture in Warm Humid Climate - A Case of South Kanara Manor houses. *International Journal of Emerging Trends in Engineering Research*, *11*(6), 231–235. https://doi.org/10.30534/ijeter/2023/061162023

Henna, K., Saifudeen, A., & Mani, M. (2021). Resilience of vernacular and modernising dwellings in three climatic zones to climate change. *Scientific Reports*, *11*(1), 1–14. https://doi.org/10.1038/s41598-021-87772-0

Huang, K. T., & Hwang, R. L. (2016). Future trends of residential building cooling energy and passive adaptation measures to counteract climate change: The case of Taiwan. *Applied Energy*, *184*, 1230–1240. https://doi.org/10.1016/j.apenergy.2015.11.008

Indraganti, M. (2018). India : Bio-climatism in Vernacular Architecture. *Sustainable*

Houses and Living in the Hot-Humid Climate, 47–58. https://doi.org/https://doi.org/10.1007/978-981-10-8465-2_5

Keskin, K., & Erbay, M. (2016). A Study on the Sustainable Architectural Characteristics of Traditional Anatolian Houses and Current Building Design Precepts. *Procedia - Social and Behavioral Sciences*, *216*(October 2015), 810–817. https://doi.org/10.1016/j.sbspro.2015.12.078

Khadeeja, H., Saifudeen, A., & Mani, M. (2019). Responsiveness and resilience of existing dwellings in warm-humid climate zone to changing climate. *Comfort At the Extreme 2019*, *April*, 2–17. https://www.researchgate.net/publication/337857816

Kikumoto, H., Ooka, R., Arima, Y., & Yamanaka, T. (2015). Study on the future weather data considering the global and local climate change for building energy simulation. *Sustainable Cities and Society*, *14*(1), 404–413. https://doi.org/10.1016/j.scs.2014.08.007

Kishore, N. (2022). Impact of climate change on future bioclimatic potential and residential building thermal and energy performance in India. *Indoor and Built Environment*, *31*(2), 329–354. https://doi.org/10.1177/1420326X21993919

Kültür, S. (2011). *Spatial Analysis of Toyhane in Traditional Divri ğ i Houses*. *1*, 39–47.

Leo Samuel, D. G., Dharmasastha, K., Shiva Nagendra, S. M., & Maiya, M. P. (2017). Thermal comfort in traditional buildings composed of local and modern construction materials. *International Journal of Sustainable Built Environment*, *6*(2), 463–475. https://doi.org/10.1016/j.ijsbe.2017.08.001

Liu, S., Kwok, Y. T., Lau, K. K. L., Ouyang, W., & Ng, E. (2020). Effectiveness of passive design strategies in responding to future climate change for residential buildings in hot and humid Hong Kong. *Energy and Buildings*, *228*, 110469. https://doi.org/10.1016/j.enbuild.2020.110469

Madan Neha. (2024, May 1). City Experiences Its Cruellest April In More Than A Decade | Pune News - Times of India. *Times of India*, 2. https://timesofindia.indiatimes.com/city/pune/city-experiences-its-cruellest-april-in-more-than-a-decade/articleshow/109740775.cms

Mahadevia, D., Pathak, M., Bhatia, N., & Patel, S. (2020). Climate Change, Heat Waves and Thermal Comfort—Reflections on Housing Policy in India. *Environment and*

Urbanization ASIA, *11*(1), 29–50. https://doi.org/10.1177/0975425320906249

Maligi, R., Abhigna, B., Paul, R., & Changali, S. (2024). *The Role of Vernacular Practices in the Mitigation of Impact of Climate : Insights from the Vernacular Settlement of Guledgudda in India . 11*(12), 76–89.

Manu, S., Brager, G., Rawal, R., Geronazzo, A., & Kumar, D. (2019). Performance evaluation of climate responsive buildings in India - Case studies from cooling dominated climate zones. *Building and Environment*, *148*, 136–156. https://doi.org/10.1016/j.buildenv.2018.10.063

Michael, A., Demosthenous, D., & Philokyprou, M. (2017). Natural ventilation for cooling in mediterranean climate: A case study in vernacular architecture of Cyprus. *Energy and Buildings*, *144*, 333–345. https://doi.org/10.1016/j.enbuild.2017.03.040

Moazami, A., Nik, V. M., Carlucci, S., & Geving, S. (2019). Impacts of future weather data typology on building energy performance – Investigating long-term patterns of climate change and extreme weather conditions. *Applied Energy*, *238*(September 2018), 696–720. https://doi.org/10.1016/j.apenergy.2019.01.085

Nagapurkar, A. S., & Narkhede, P. (2019). *PATTERN OF URBAN HOUSING CHANGES : CASE STUDY OF*. 1314–1326.

Nagapurkar, S., Narkhede, P., & Sheriff, V. A. (2020). Energizing the Future with Memories of the Past: The Wadas of Pune City. *E3S Web of Conferences*, *170*. https://doi.org/10.1051/e3sconf/202017005006

Naik, A., & Oswal, S. (2020). Investigating the Relevance of Vernacular Parameters in Developing a Passive-Right Approach for Design-In the Context of Housing in Bangalore. *International Journal of Architecture (IJA)*, *6*(1), 43–55.

Nguyen, A. T., Truong, N. S. H., Rockwood, D., & Tran Le, A. D. (2019). Studies on sustainable features of vernacular architecture in different regions across the world: A comprehensive synthesis and evaluation. *Frontiers of Architectural Research*, *8*(4), 535–548. https://doi.org/10.1016/j.foar.2019.07.006

Nie, Q., Zhao, S., Zhang, Q., Liu, P., & Yu, Z. (2019). An investigation on the climate-responsive design strategies of vernacular dwellings in Khams. *Building and Environment*, *161*(June), 106248. https://doi.org/10.1016/j.buildenv.2019.106248

Palme, M., Isalgué, A., & Coch, H. (2013). Avoiding the possible impact of climate change on the built environment: The importance of the building's energy robustness. *Buildings*, *3*(1), 191–204. https://doi.org/10.3390/buildings3010191

Pandya, Y. (2016). *Courtyard houses of India*. Mapin Publishing Pvt. Limited. https://books.google.co.in/books/about/Courtyard_Houses_of_India.html?id=P0AVMQAACAAJ&redir_esc=y

Parishwad, O., & Shinkar, V. (2017). Critical review of the Climate Change Impact on urban areas by assessment of Heat Island effect. Case of Pune, India. *Geospatial World Forum 2017*, *8*(1), 553–559.

Patidat, S., & Raghuwanshi, B. (2014). Changes in culture and architecture from vernacular to modern: M.P., India. *30th International PLEA Conference: Sustainable Habitat for Developing Societies: Choosing the Way Forward - Proceedings*, *3*(December), 125–132.

Philokyprou, M., & Michael, A. (2020). Environmental Sustainability in the Conservation of Vernacular Architecture. The Case of Rural and Urban Traditional Settlements in Cyprus. *International Journal of Architectural Heritage*, *00*(00), 1–23. https://doi.org/10.1080/15583058.2020.1719235

Philokyprou, M., Michael, A., & Thravalou, S. (2013). Assessment of the Bioclimatic Elements of Vernacular Architecture. The Historic Centre of Nicosia, Cyprus. *Heritage, Architecture, Landesign: Focus on Conservation, Regeneration, Innovation*, *3*(39), 666–675.

R Deshpande & R Kotharkar. (2015). 'Dwellings' then and now: A topological approach for privacy analysis of 'Wada' and modern houses. *Proceedings of the 10th International Space Syntax Symposium*, *July 2015*. https://www.researchgate.net/publication/319980412_'Dwellings'_then_and_now_A_topological_approach_for_privacy_analysis_of_'Wada'_and_modern_houses

Radhakrishnan, S., Priya, R. S., Nagan, S., & Sundarraja, M. C. (2011). Climate responsive traditional architecture of Chettinadu housing in Tamilnadu, India - A qualitative and quantitative analysis during summer. *International Journal of Ventilation, Taylor & Francis*, *10*(1), 89–97. https://doi.org/10.1080/14733315.2011.11683937

Rajapaksha, M., & Kariyawasam, M. (2024). Enhancing Thermal and Daylight Performance of Historic Buildings with Passive Modifications; A Tropical Case Study. *KDU Journal of Multidisciplinary Studies*, *6*(1), 134–144. https://doi.org/10.4038/kjms.v6i1.117

Rawal, R., Shukla, Y., Vardhan, V., Asrani, S., Schweiker, M., de Dear, R., Garg, V., Mathur, J., Prakash, S., Diddi, S., Ranjan, S. V., Siddiqui, A. N., & Somani, G. (2022). Adaptive thermal comfort model based on field studies in five climate zones across India. *Building and Environment*, *219*. https://doi.org/10.1016/j.buildenv.2022.109187

Ray, B., & Shaw, R. (2018). Changing built form and implications on urban resilience: Loss of climate responsive and socially interactive spaces. *Procedia Engineering*, *212*, 117–124. https://doi.org/10.1016/j.proeng.2018.01.016

Remali, A. M., Salama, A. M., Wiedmann, F., & Ibrahim, H. G. (2016). A chronological exploration of the evolution of housing typologies in Gulf cities. *City, Territory and Architecture*, *3*(1), 1–15. https://doi.org/10.1186/s40410-016-0043-z

Robert, A., & Kummert, M. (2012). Designing net-zero energy buildings for the future climate, not for the past. *Building and Environment*, *55*, 150–158. https://doi.org/10.1016/j.buildenv.2011.12.014

Rubio-Bellido, C., Pulido-Arcas, J. A., & Cabeza-Lainez, J. M. (2015). Adaptation strategies and resilience to climate change of historic dwellings. *Sustainability (Switzerland)*, *7*(4), 3695–3713. https://doi.org/10.3390/su7043695

Saifudeen, A., & Mani, M. (2024). Adaptation of buildings to climate change: an overview. *Frontiers in Built Environment*, *10*(February), 1–17. https://doi.org/10.3389/fbuil.2024.1327747

Santy, Matsumoto, H., Tsuzuki, K., & Susanti, L. (2017). Bioclimatic analysis in pre-design stage of passive house in Indonesia. *Buildings*, *7*(1). https://doi.org/10.3390/buildings7010024

Shabahang, S., Vale, B., & Gjerde, M. (2019). The problem of the modern built environment and enhanced urban warming in Iran. In *Smart Innovation, Systems and Technologies* (Vol. 131). Springer International Publishing. https://doi.org/10.1007/978-3-030-04293-6_33

Shaeri, J., Yaghoubi, M., Aflaki, A., & Habibi, A. (2018). Evaluation of thermal comfort in traditional houses in a tropical climate. *Buildings*, *8*(9). https://doi.org/10.3390/buildings8090126

Shanthi Priya, R., Sundarraja, M. C., Radhakrishnan, S., & Vijayalakshmi, L. (2012). Solar passive techniques in the vernacular buildings of coastal regions in Nagapattinam, TamilNadu-India - A qualitative and quantitative analysis. *Energy and Buildings*, *49*, 50–61. https://doi.org/10.1016/j.enbuild.2011.09.033

Shastry, V., Mani, M., & Tenorio, R. (2014). Impacts of modern transitions on thermal comfort in vernacular dwellings in warm-humid climate of Sugganahalli (India). *Indoor and Built Environment*, *23*(4), 543–564. https://doi.org/10.1177/1420326X12461801

Sheng, W., Wen, B., & Zhang, L. (2021). Envelope performance of residential building in cool, warm and hot climatic zones: Results from self-designed in-situ monitoring campaigns. *Energy and Buildings*, *232*, 110655. https://doi.org/10.1016/j.enbuild.2020.110655

Singh, C., Madhavan, M., Arvind, J., & Bazaz, A. (2021). Climate change adaptation in Indian cities: A review of existing actions and spaces for triple wins. *Urban Climate*, *Volume 36,*(100783). https://doi.org/https://doi.org/10.1016/j.uclim.2021.100783

Singh, M. K., Mahapatra, S., & Atreya, S. K. (2010). Thermal performance study and evaluation of comfort temperatures in vernacular buildings of North-East India. *Building and Environment*, *45*(2), 320–329. https://doi.org/10.1016/j.buildenv.2009.06.009

Stagrum, A. E., Andenæs, E., Kvande, T., & Lohne, J. (2020). Climate change adaptation measures for buildings-A scoping review. *Sustainability (Switzerland)*, *12*(5). https://doi.org/10.3390/su12051721

Subramanian, C. V, Ramachandran, N., & Kumar, S. S. (2016). *Performance Evaluation of the Designed Solar Passive Architecture Incorporated Residence in Warm Humid Climate*. *7*(6), 523–535.

Summa, S., Tarabelli, L., Ulpiani, G., & Di Perna, C. (2020). Impact of climate change on the energy and comfort performance of nzeb: A case study in Italy. *Climate*, *8*(11), 1–16. https://doi.org/10.3390/cli8110125

Takebayashi, H. (2019). Thermal environment design of outdoor spaces by examining redevelopment buildings opposite central osaka station. *Climate*, *7*(12). https://doi.org/10.3390/cli7120143

Tambe, N. C. (2016). *The Vanishing Wadas of Pune, India* (Issue May) [UNIVERSITY OF SOUTHERN CALIFORNIA]. https://digitallibrary.usc.edu/archive/The-vanishing-Wadas-Of-Pune--India-2A3BF16BK29R.html

Tandon, M., & Sehgal, V. (2017). Traditional Indian religious streets: A spatial study of the streets of Mathura. *Frontiers of Architectural Research*, *6*(4), 469–479. https://doi.org/10.1016/j.foar.2017.10.001

TERI. (2014). *Prepared for Department of Environment, Government of Maharashtra Assessing Climate Change Vulnerability and Adaptation Strategies for Maharashtra: Maharashtra State Adaptation Action Plan on Climate Change (MSAAPC)*. https://moef.gov.in/uploads/2017/09/Maharashtra-Climate-Change-Final-Report.pdf

Thapa, S., Rijal, H. B., Pasut, W., Singh, R., Indraganti, M., Bansal, A. K., & Panda, G. K. (2023). Simulation of thermal comfort and energy demand in buildings of sub-Himalayan eastern India - Impact of climate change at mid (2050) and distant (2080) future. *Journal of Building Engineering*, *68*(February), 106068. https://doi.org/10.1016/j.jobe.2023.106068

Thapa, S., Singh, R., Bundele, M., Thapa, S., Thadathil, G., & Kr. Jakhar, Y. (2021). Study of thermal comfort in the residents of different climatic regions of India—Effect of the COVID-19 lockdown. *Indoor Air*, *31*(3), 899–917. https://doi.org/10.1111/ina.12778

Tungnung, K. (2020). Parametric strategy on passive design affordances in cool-humid climate zones of North-East India. *Solar Energy*, *207*(June), 1–9. https://doi.org/10.1016/j.solener.2020.06.024

Vakharia, M. (2017, September). Thermal Performance of courtyard in Pol House of Ahmedabad. *Insite*, *10*(07), 55–57.

Vishnu, A., Prakash, P., Singh, P., & Sudhakaran, P. (2023). Kerala Traditional Architecture and Climatic Responsiveness-A Review. *European Chemical Bulletin*, *12*(Special issue 8), 8830–8852.

Wang, X., Lei, B., Bi, H., & Yu, T. (2019). Study on the thermal performance of a hybrid heat collecting facade used for passive solar buildings in cold region. *Energies*, *12*(6).

https://doi.org/10.3390/en12061038

Wang, Y., Li, X., & Gan, Y. (2016). Study on the Green Design Strategies of "neo-Vernacular Architecture." *Procedia Engineering*, *169*, 367–374. https://doi.org/10.1016/j.proeng.2016.10.045

Wright, A., & Venskunas, E. (2022). Effects of Future Climate Change and Adaptation Measures on Summer Comfort of Modern Homes across the Regions of the UK. *Energies*, *15*(2), 1–26. https://doi.org/10.3390/en15020512

Zhai, Z. (John), & Previtali, J. M. (2010). Ancient vernacular architecture: characteristics categorization and energy performance evaluation. *Energy and Buildings*, *42*(3), 357–365. https://doi.org/10.1016/j.enbuild.2009.10.002

Zięba, Z., Dąbrowska, J., Marschalko, M., Pinto, J., Mrówczyńska, M., Leśniak, A., Petrovski, A., & Kazak, J. K. (2020). Built environment challenges due to climate change. *IOP Conference Series: Earth and Environmental Science*, *609*(1). https://doi.org/10.1088/1755-1315/609/1/012061

Zune, M., Rodrigues, L., & Gillott, M. (2020). Vernacular passive design in Myanmar housing for thermal comfort. *Sustainable Cities and Society*, *54*(December 2019), 101992. https://doi.org/10.1016/j.scs.2019.101992

ANNEXURES

List of publications

1. Vakharia, M. N., & Joshi, M. (2022). Thermal Characteristics of Vernacular Architecture in Warm Humid Region. Ecology, Environment and Conservation, 28(2), 874–878. https://doi.org/10.53550/eec.2022.v28i02.044
2. Vakharia, M. N., & Joshi, M. (2023). Impact of Climate Change on Future Thermal Performance of Residential Architecture of Pune. India Eur. Chem. Bull, 12(S3), 1678–1686. https://doi.org/10.31838/ecb/2023.12.s3.187
3. Vakharia, M. N., & Joshi, M. (2023). Climate-responsive vernacular Wada housing of Pune, India. AIP Conf. Proc. 2800, 020190 (2023), 020190. https://doi.org/10.1063/5.0162691
4. Vakharia, M. N. & R. K. (2024). CLIMATE CHANGE ADAPTATION AND VERNACULAR ARCHITECTURE OF PUNE, INDIA. International Journal of Cultural Studies and Social Sciences, 15(1), 37–48.
5. Vakharia, M. N., & Joshi, M. (2024). Climate-responsive wada architecture: a bioclimatic design for climate change resilience. Journal of Asian Architecture and Building Engineering, 00(00), 1–14. https://doi.org/10.1080/13467581.2024.2396609

Conference Presentation & Participation

1. Vakharia, M. N., & Joshi, M. presented a paper "*Influence of Climate Change on Prospective Thermal Efficiency in Residential Architecture of Pune*, *India"* under the theme of Sustainability and Green Architecture in the International Conference on Future of Skills in Architecture, Design, Planning and Allied Fields held on 29-20 Aug 2023 organized by School of Architecture, Urban Development and Planning, Symbiosis Skills and Professional University Pune India.
2. Vakharia, M. N., & Joshi, M. presented a paper "*Climate-Responsive Vernacular Wada housing of Pune, India"* in the International Conference on Materials for Emerging Technologies (ICMET-21) held on February 18-19, 2022, organized by department of research Impact and Outcome, division of research and development, Lovely Professional University, Punjab India.
3. Participated in the International Conference on Built Environment Science and Technology at the School of Architecture and Interior Design SRM Institute of Science and Technology on 20-21 February 2021

Annexures-1

LIST OF ABBREVIATION:

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEE	Bureau of Energy Efficiency
BEPS	Building Energy Performance Simulation
BIM	Building Information Modeling
CBE	Center for the Built Environment
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
CSEB	Compressed Stabilized Earth Block
CVRSME	Coefficient of Variation of the Root Mean Square Error
DBT	Dry Bulb Temperature
DC	Discomfort Index
DE	Design Envelope
ECBC	Energy Conservation Building Code (2017)
ECBC for Residential	Energy Conservation Building Code for Residential Buildings (2018)
EIA	Environmental Impact Assessment
EPW	EnergyPlus Weather File

ETTV	Envelope Thermal Transfer Value
IAQ	Indoor Air Quality
IGBC	Indian Green Building Council
IMAC-R	Indian Model for Adaptive Comfort – Residential (Develop by Rawal et al., (2022))
IOT	Internet of Things
MBE	Mean Bias Error
MoEFCC	Ministry of Environment, Forest, and Climate Change
NBC	National Building Code (2016)
NZEB	Net Zero Energy Building
OTTV	Overall Thermal Transfer Value
PCA	Principal Component Analysis
PCMC	Pimpri-Chinchwad Municipal Corporation
PDEC	Passive Downdraught Evaporative Cooling
PMV	Predicted Mean Vote
PV	Photovoltaic
RETV	Residential Envelope Transmittance Value
RH	Relative Humidity
RMC	Ready Mix Concrete
RSME	Root Mean Square Error

SDG	Sustainable Development Goals
SHGC	Solar Heat Gain Coefficient
TERI	The Energy and Resources Institute
TMY	Typical Meteorological Year
UHI	Urban Heat Island
WWR	Window-to-Wall Ratio