

Original Article

Vernacular Knowledge for Modern Sustainability: Integrating Traditional Construction Practices for Thermal Comfort in Rajasthan

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Abstract - Achieving thermal comfort in built environments is essential for sustainable development, especially in arid areas like Rajasthan, where extreme summer heat poses challenges for conventional construction practices. This paper explores the incorporation of vernacular construction techniques, such as lime plaster on red burnt brick walls and the use of locally sourced Dulmera sandstone, in modern sustainable architecture. Traditionally used indoors, lime plaster facilitates natural breathability, humidity control, and thermal regulation, which supports green building principles. Dulmera sandstone, utilized on exterior façades, boasts high thermal mass and natural insulation properties, which help minimize internal heat gain without relying on mechanical solutions. These materials not only lower energy consumption but also assist in achieving green certification standards like GRIHA and LEED, particularly regarding passive design and material requirements. The paper proposes a hybrid model that combines these traditional practices with contemporary technologies, such as insulation layering, structural retrofitting, and smart ventilation systems. This method promotes energy efficiency, occupant comfort, and cultural continuity while adhering to environmental policies focused on carbon reduction and climate adaptation. Through case studies and performance evaluations, this paper underscores the promise of region-specific, climate-responsive strategies in developing future-ready sustainable buildings, particularly within institutional and organizational contexts throughout the Western part of Rajasthan in India. This approach not only enhances the resilience of structures against extreme weather conditions but also fosters a sense of community and identity by integrating local architectural styles. By prioritizing sustainable practices, stakeholders can ensure that future developments are both environmentally responsible and culturally relevant, paving the way for a more sustainable future in the region. This commitment to sustainability addresses the immediate challenges posed by climate change and empowers local communities by creating job opportunities and promoting the use of indigenous materials. To understand the hybrid model, two diverse urban patches of Bikaner, the vernacular area and the modern colonial settlement, respectively, were analyzed. A hybrid model, focused on in this paper, emphasizes integrating traditional materials and passive strategies in the development of contemporary urban forms. As a result, these developments can serve as models for other regions, demonstrating the potential for harmonizing modern needs with traditional values. Values, fostering a sense of pride and ownership among residents. By integrating traditional practices with innovative technologies, these projects can help preserve cultural heritage while addressing contemporary issues, ultimately leading to resilient and vibrant communities.

Keywords - Vernacular architecture, Thermal comfort, Sustainable construction, Lime plaster, Dulmera sandstone, Passive design, Green building certifications.

1. Introduction

The Thermal comfort assessment in built environments is essential in arid and semi-arid regions, especially in Western Rajasthan, where summer temperatures often exceed 45°C. The severe climate, coupled with low humidity and intense solar radiation, necessitates building solutions that are both climate-responsive and energy-efficient. Although modern construction typically relies on mechanical systems like air conditioning and ventilation to ensure comfort, this dependence significantly raises energy consumption,

operational costs, and carbon emissions. In contrast, traditional Rajasthani architecture embodies a wealth of local knowledge, or the vernacular architecture that employs passive cooling techniques, making it inherently sustainable and well-suited to its environment [1]. Among the most effective traditional methods are the use of lime plaster and locally sourced Dulmera sandstone, which are materials that feature prominently in heritage buildings across the Bikaner district. The Rampuria Havelis, a notable cluster of 19th-century mansions in Bikaner, epitomize this approach. These



structures feature thick walls made from red burnt bricks covered in lime plaster on the interior and finely dressed Dulmera sandstone on the exterior. The hygroscopic properties of lime plaster help regulate humidity and buffer indoor temperatures, while the sandstone's high thermal mass reduces heat transfer, keeping interiors cool even during peak heat [2].

These enduring techniques not only offer thermal comfort but also contribute to long-term durability and low maintenance. However, modern construction has largely neglected these practices in favour of concrete and synthetic materials. This paper argues that incorporating the discussed vernacular techniques with contemporary building systems can lead to thermally comfortable, energy-efficient, and environmentally sustainable constructions, as evaluated with the help of a comparative analysis of two distinct patches of the same city showing change in development [3].

Moreover, the proposed methods can assist in facilitating compliance with green building rating systems like GRIHA and LEED, which increasingly acknowledge the value of regional materials and passive design strategies. By revisiting and adapting these traditional practices, the modern sustainability targets can be met without sacrificing climatic suitability or cultural heritage. This paper clearly examines the integration of traditional construction methods, such as lime plaster on red burnt brick walls and locally sourced Dulmera sandstone, into modern sustainable architecture. Traditionally used indoors, lime plaster enhances breathability, humidity control, and thermal regulation, supporting eco-friendly building principles. Dulmera sandstone, applied on exterior façades, offers high thermal mass and natural insulation, reducing internal heat gain without mechanical systems. These materials lower energy use and help meet green certification standards related to passive design and material quality. The study in the paper suggests a hybrid approach that combines traditional practices with modern technologies, including insulation layers, structural retrofitting, and smart ventilation, to boost energy efficiency, comfort, and cultural heritage. This approach aligns with carbon reduction and climate adaptation policies, ensuring future developments are environmentally responsible and culturally meaningful. To cover the research gap, the proposed initiatives can serve as models for other regions under similar climatic conditions, which would blend modern needs with traditional values or heritage practices with innovative solutions. The suggestions in this paper can preserve cultural identity while addressing current challenges, leading to resilient and sustainable communities.

2. Literature Review

The architectural heritage of Rajasthan exemplifies an adaptive response to extreme climatic conditions through the application of passive design techniques and locally sourced materials. Numerous scholars have investigated the ways in

which traditional practices in arid regions, particularly in Western Rajasthan, have successfully achieved thermal comfort without reliance on mechanical systems. According to Mehta (2014), vernacular residences in locales such as Bikaner were purposefully designed with thick masonry walls, internal courtyards, and shaded façades to optimize ventilation and mitigate heat ingress. These features, in conjunction with indigenous materials, significantly contribute to indoor thermal regulation [4].

The chosen region of study demonstrates how vernacular construction practices evolved in response to the hot, arid climate. In the old city, dense urban layout with application of locally sourced materials on buildings like Dulmera sandstone, lime plaster, mud mortar, and red burnt bricks provides excellent thermal insulation, passive cooling, and long-term sustainability. These materials and techniques were climate-responsive, culturally rooted, and environmentally friendly. In contrast, the modern extensions of Bikaner city have largely adopted RCC, synthetic paints, and glass façades, which are unsuitable materials for the region and often lead to higher energy consumption. Reintegrating traditional materials and knowledge systems into modern construction, through hybrid techniques like lime-treated brick walls, novel stone cladding techniques, and passive ventilation systems, could improve thermal comfort, support cultural continuity, and promote sustainability. This approach is imperative for developing a climate-resilient urban fabric that balances heritage conservation with contemporary growth in Bikaner.

Lime plaster, extensively utilized as both an internal and external wall finish, possesses remarkable hygroscopic properties that buffer indoor humidity and stabilize interior temperatures. The material's chemical composition and physical properties enable it to absorb and release moisture, thereby enhancing occupant comfort while also providing resistance to heat and microbial growth. In contrast to cement plaster, lime-based finishes exhibit breathability and possess lower embodied energy [5]. Equally noteworthy is the utilization of Dulmera sandstone in the façades of traditional Havelis in Bikaner. This locally sourced sandstone, characterized by its high thermal mass and low thermal conductivity, effectively delays heat transfer from the exterior to the interior during peak daytime temperatures. When employed in combination with lime plaster and traditional construction techniques, such as recessed windows, high ceilings, and ventilated courtyards, these materials create a synergistic effect that enhances thermal performance.

This paper focuses on the novelty of bridging vernacular knowledge with contemporary needs by comparing old and new city areas, as demonstrated in the comparative study section of this paper, which contributes scalable strategies for thermal comfort. It addresses a critical gap by proposing region-specific, material-conscious solutions adaptable to modern sustainability frameworks [6]. The following is the

generated data for the climate summary through the CBE Clima tool, considering Bikaner's EPW file.

Location: Bikaner, India,
Longitude: 73.2772,
Latitude: 28.0207,
Elevation above sea level: 224.0 m,

This file is based on data collected between 2009 and 2023.

Köppen–Geiger climate zone: BWh. Subtropical desert.

Average yearly temperature: 27.3 °C (Figure 1)

Hottest yearly temperature (99%): 43.4 °C (Figure 2 and

Figure 3)

Coldest yearly temperature (1%): 7.3 °C (Figure 3)

Annual cumulative horizontal solar radiation: 2037.92 kWh/m²,

Age of diffuse horizontal solar radiation: 26.7% (Figure 4).

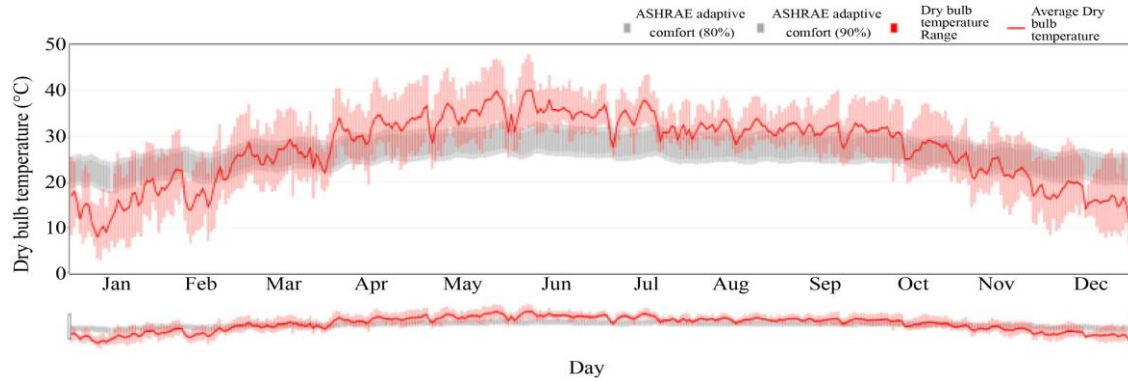


Fig. 1 Average dry bulb temperature range of bikaner

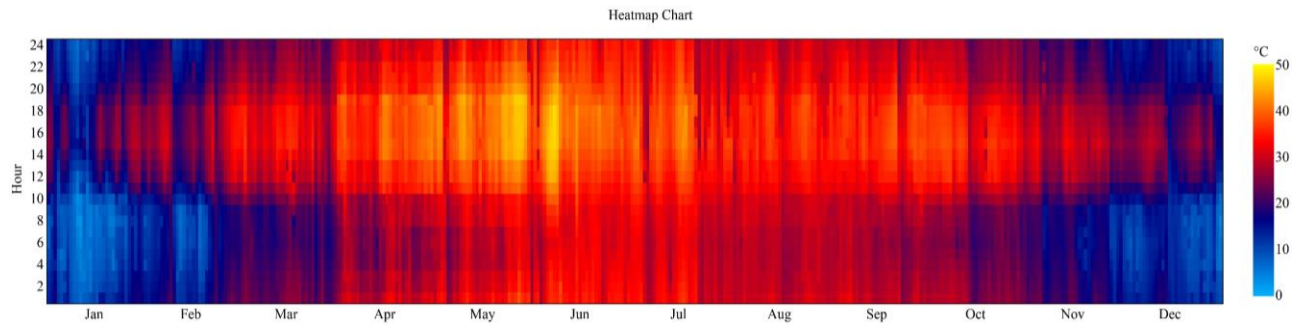


Fig. 2 Heat map of bikaner

Month	Mean(°C)	std (°C)	min(°C)	1% (°C)	25% (°C)	50% (°C)	75% (°C)	99% (°C)	max (°C)
Jan	14.68	5.86	2.9	4.7	10	14.35	18.6	27.5	28.8
Feb	19.75	6.01	6.4	7.21	15.4	19.6	24	33.66	34.8
Mar	25.92	4.82	16.4	17.8	22	25.3	29.9	35.96	37
Apr	31.91	5.07	19.4	22.44	27.9	31.7	35.92	41.78	42.6
May	35.15	5.43	22.9	24.53	31	34.55	39.52	46.2	46.9
Jun	35.74	4.1	26.4	27.24	32.68	35.3	38.52	46.46	47.8
Jul	33.27	3.87	25.3	26.33	30.08	33.1	36.02	42.06	43.6
Aug	31.57	3.01	25.9	26.34	29.3	30.8	33.8	38.4	38.9
Sep	31.44	3.83	23.4	24.2	28.3	30.8	34.8	39	39.9
Oct	28.75	4.81	19.6	20.2	25	27.9	32.6	38	38.8
Nov	22.3	4.89	10.6	11.36	18.5	22	26.3	32.56	34
Dec	16.58	5.31	4.5	6.74	12.5	15.6	20.6	27.76	29.6
Year	27.28	8.49	2.9	7.3	21.7	28.6	33.5	43.44	47.8

Fig. 3 Descriptive temperature statistics of Bikaner

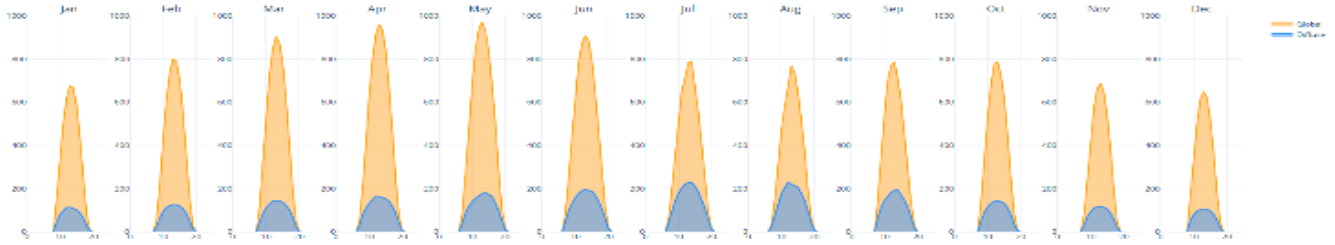


Fig. 4 Global and diffuse horizontal solar radiation (Wh/m²)

Contemporary research underscores the potential of these materials in modern sustainable construction. Assessment tools such as LEED and GRIHA currently advocate for the use of regional and low-impact materials [7]. However, their widespread implementation in contemporary architecture remains restricted. Scholars such as Sharma (2022) contend

that the integration of vernacular wisdom with modern technologies, such as thermal simulation and energy modeling, has the potential to bridge this gap and follow the regionally adaptive, sustainable construction practices, which are suitable for the region [8].

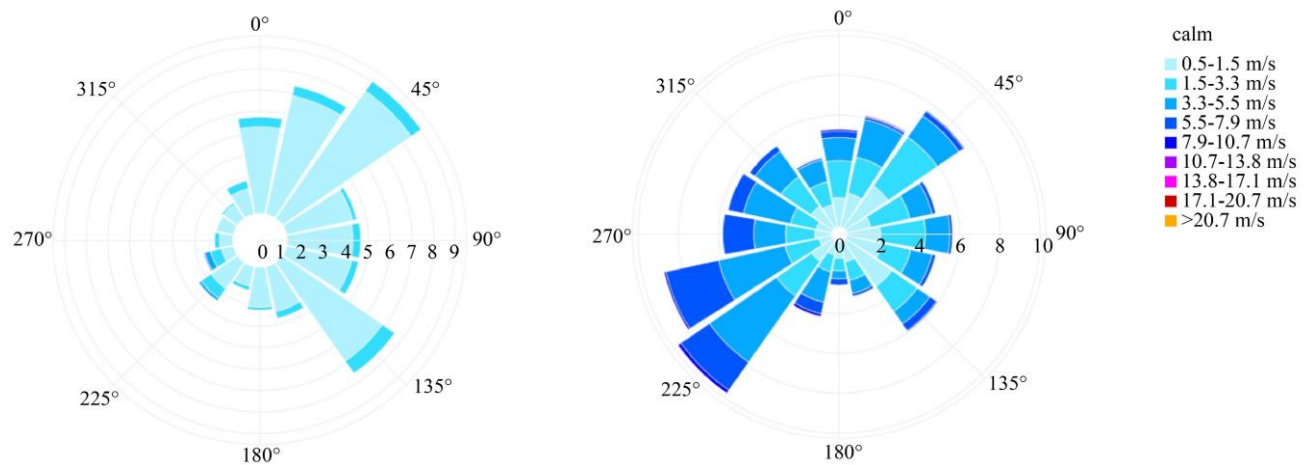


Fig. 5 Seasonal wind rose

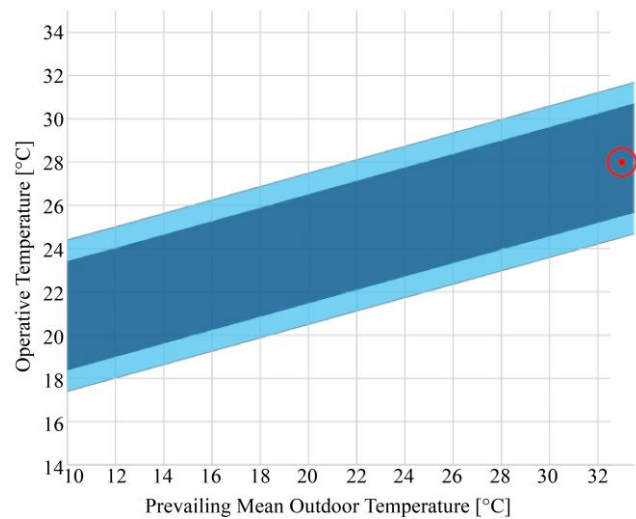
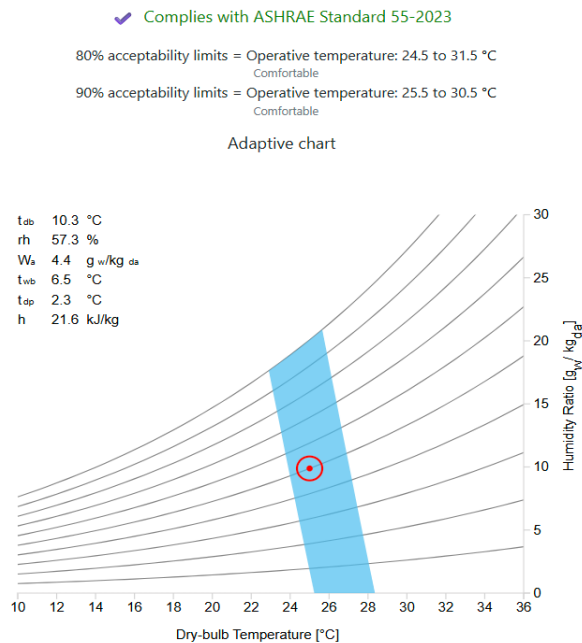


Fig. 6 Psychrometric charts as per ASHRAE Standard 55-2023 (adaptive model)

The part of Figure 5 shows Observations between the months of December and February between 01:00 hours and 24:00 hours. Selected observations 2160 of 8760, or 24 %. 436 observations have calm winds. Observations between the months of Mar and May between 01:00 hours and 24:00 hours. Selected observations 2208 of 8760, or 25 %. 137 observations have calm wind.

The psychrometric graphs in Figure 6 show that the tested condition (marked by the red circle) is beyond the designated comfort zone, supporting the statement that occupants may feel both heated and dissatisfied. The similarity between the CBE tool (Center for the Built Environment) and field survey outputs adds credibility to the simulation results for thermal comfort evaluation in this indoor setting.

2.1. Theoretical Framework

The study's foundation is passive design, which highlights the importance of hygrothermal regulation and thermal mass in building performance. Green building guidelines and sustainability objectives are supported by the incorporation of historic elements into modern frameworks. This approach not only enhances energy efficiency but also preserves cultural heritage, creating a harmonious blend of old and new. By prioritizing these principles, architects and builders can contribute to a more sustainable future while respecting the past [9].

2.2. Vernacular Architecture and Thermal Performance

Research indicates that lime plaster's moisture buffering capabilities contribute to indoor thermal regulation, while Dulmeria sandstone's high thermal mass reduces heat ingress [10]. These materials have been effectively used in traditional Rajasthani architecture to combat extreme temperatures [11].

The above map shows planned roads and colonies of the outer part of the old city of Bikaner, where houses are planned with compact planning. There are no observed courtyards, and as a result, there is more dependency on mechanical ventilation.

2.2.1. Green Building Certifications and Regional Adaptation

Green building rating systems like GRIHA and LEED recognize the importance of local materials and passive design strategies. Incorporating vernacular practices can aid in achieving certification by meeting energy efficiency and occupant comfort criteria.

2.2.2. Case Study Selection for Hybrid Model Development and Performance Evaluation

To develop a hybrid model by integrating vernacular and modern construction practices, two extremes, contrasting urban patches within the city of Bikaner were selected using ArcGIS Earth imagery as shown in Figure 7 and 8: one from the old city with dense, compact vernacular fabric, and another from a modern residential colony characterized by rough grid-

planned roads, modern planning and open surroundings. The selection criteria included variation in street layout, building typology, construction materials, and microclimatic response. The hybrid model proposes retrofitting and new constructions using vernacular materials such as Dulmeria stone cladding, lime plaster, and passive cooling elements within modern layouts to achieve a climate-responsive design model. Performance evaluation includes thermal simulation, material analysis, and comparative on-site measurements of indoor temperatures, wind flow patterns, and surface radiation during peak summer months. This dual site selection strategy allows for assessing the adaptability and efficacy of vernacular techniques when reintroduced in contemporary urban forms.



Fig. 7 The old unplanned and walled city of Bikaner

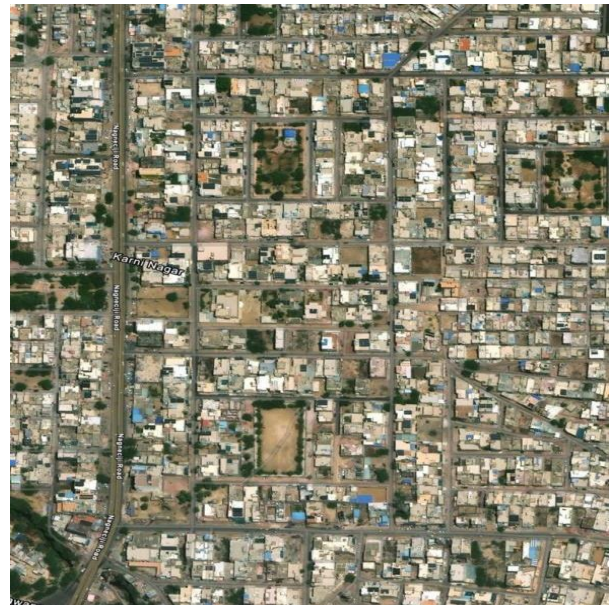


Fig. 8 New and planned city of Bikaner showing compact plans without a courtyard

Considering information on contemporary and traditional case studies as displayed in Figures 7 and 8, the following is a

comparison between modern planned development and the historic unplanned old city fabric (Havelis cluster).

Table 1. Unplanned old city -Havelis cluster area [Author]

Haveli No.	Height (Ground + Floors)	Site Area (approx.)	Closed Space Area (approx.)	BCR (%)
1	G+2 (Stone masonry/Haveli)	150–300 m ²	120–250 m ²	70–85%
2	G+2 (Stone masonry/Haveli)	100–250 m ²	90–210 m ²	75–85%
3	G+2 (Stone masonry/Haveli)	120–220 m ²	100–200 m ²	80–90%
4	G+2 (Stone masonry/Haveli)	180–280 m ²	140–260 m ²	70–85%

Table 2. Planned development- modern area [Author]

House No.	Height (Ground + Floors)	Site Area (approx.)	Closed Space Area (approx.)	BCR (%)
1	G+2 (Modern RCC)	250–450 m ²	130–260 m ²	50–60%
2	G+2 (Modern RCC)	300–500 m ²	150–280 m ²	50–55%
3	G+2 (Modern RCC)	350–600 m ²	160–320 m ²	45–55%
4	G+2 (Modern RCC)	400–650 m ²	180–350 m ²	45–50%

Note: BCR = Built-up Coverage Ratio (closed area ÷ site area * 100), Key Observations: Material differences, layout irregularities, space planning, and street networking significantly influence microclimate, pedestrian movement, and urban living conditions across both areas. Thermal comfort parameters are equally distinct.

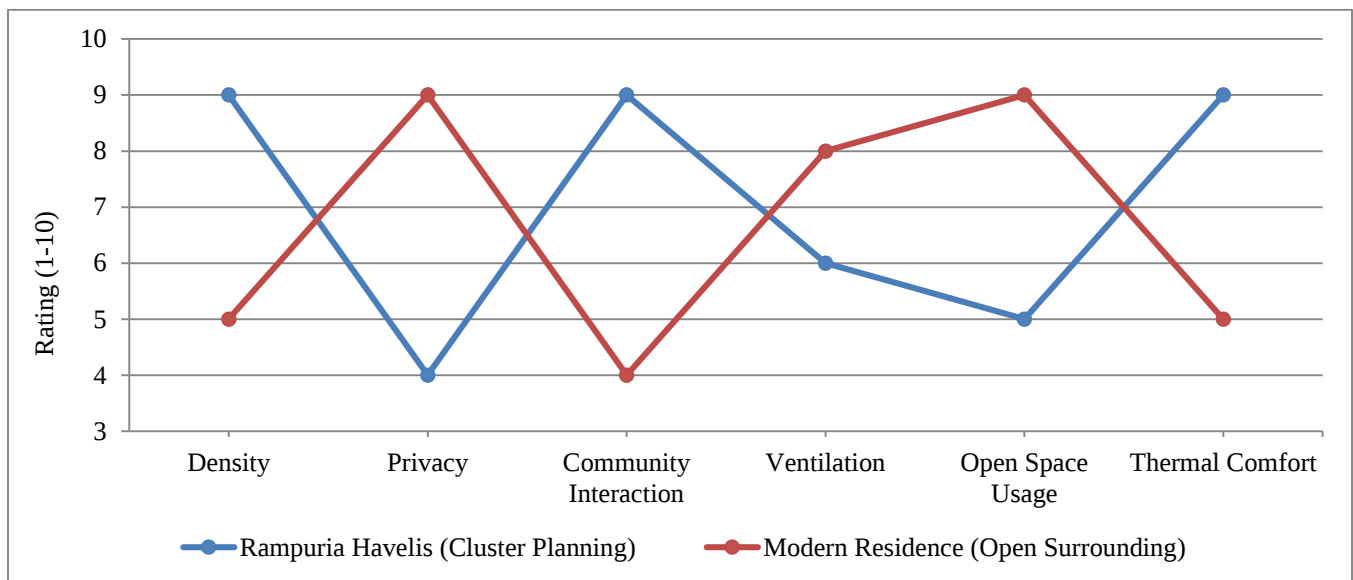


Fig. 9 Spatial planning and comfort analysis: comparison between cluster planning and open planning areas of Bikaner

Figure 9 shows a comparison between a modern home in an open environment and the spatial design of a Haveli in the old city of Bikaner, evaluating the key factors like density, privacy, social interaction, ventilation, open space usage and thermal comfort.

3. Methodology

3.1. Materials and Methods

The study involves a comparative analysis of buildings utilizing traditional materials versus those employing modern construction techniques. Materials for data collection include thermal measurements and occupant comfort surveys.

3.2. Conceptual Boundaries

The study focuses on structures in Western Rajasthan, a location known for its harsh desert climate, in which high temperatures and low humidity substantially impact the built environment. In this context, the study investigates how locally available materials, such as lime plaster and Dulmera sandstone, are employed in traditional construction processes to solve climate change challenges.

The availability of these materials has a significant impact on building sustainability and thermal performance. It considers the cultural significance of these materials, which are strongly ingrained in the local vernacular architecture and

reflect the region's historical and architectural identity. Its goal is to emphasize the possibilities for incorporating these materials and traditional construction processes into current practices by studying how they have been adapted to local ecological conditions.

This novel approach not only promotes environmental stewardship but also fosters a sense of the region's pride and sustainability of architectural values. By merging modern techniques with vernacular methods, structures that respect the past can be created while addressing the pressing needs of the present and future with supportive comparative analysis [12].

3.3. Inclusion Criteria

The inclusion criteria for this study have been established on site with permission from the residents of the vicinity to conduct field surveys and with the help of digital parameters. To ensure applicability to the environmental, material, and performance contexts of Western Rajasthan. First, the study looks at structures that use lime plaster and/or Dulmera sandstone, as these materials are crucial to the study's focus on vernacular construction and thermal performance.

Lime plaster is noted for its breathability and moisture-regulating capabilities, while Dulmera sandstone has a high thermal mass, both of which help to improve indoor comfort in hot, dry settings. Second, only structures in Rajasthan's desert zones are included, particularly those subjected to harsh summer temperatures and low humidity, to ensure that the climatic backdrop is consistent with the study's objectives. Finally, buildings must have readily available thermal performance data, either from on-site measurements, past studies, or published simulations [13].

This criterion is essential for objectively evaluating how traditional materials influence thermal behavior and for comparing performance with modern construction approaches. Together, these criteria help identify cases that are representative of region-specific construction practices and suitable for assessing their relevance in contemporary sustainable architecture.

By establishing a clear framework for evaluating these buildings, researchers can better understand the impact of traditional materials on energy efficiency and overall sustainability. This knowledge informs future architectural designs and encourages a more thoughtful integration of historical practices into modern construction methodologies [14, 15].

3.4. Exclusion Criteria

The exclusion criteria are set to ensure the study's findings are authentic and reliable. Buildings that have undergone considerable renovations, such as replacing original lime plaster or Dulmera sandstone with modern

materials like cement or concrete, are not eligible. Such changes can affect the assessment of conventional thermal performance, making it impossible to separate the effects of vernacular materials and procedures. Furthermore, structures with insufficient documentation or data on their thermal performance are not evaluated. It is difficult to assess and compare their effectiveness in delivering thermal comfort without trustworthy data, whether from field measurements, historical records, or modeling studies. These exclusions ensure that the selected case studies appropriately reflect traditional construction processes while also providing relevant insights into their role in sustainable architecture.

3.5. Validating the Search Result

Validating search results is an important step in ensuring the reliability and quality of the data utilized in this study. This technique entails comparing field measurements, such as indoor temperature, humidity levels, and thermal response over time, with modeling results from software tools such as EnergyPlus or DesignBuilder. Differences between actual and simulated performance can be recognized and rectified, increasing the trustworthiness of findings reached.

Additionally, the data is compared to conclusions from current scholarly literature to ensure consistency and contextual relevance. Experts in architectural restoration and climate-responsive design are often consulted to help validate conclusions. The multi-layered validation approach confirms the authenticity of the chosen cases and demonstrates the broader applicability of incorporating vernacular practices into modern sustainable building frameworks [16].

4. Results

Preliminary findings show that buildings built with lime plaster and Dulmera sandstone outperform modern structures in terms of thermal control. These traditional buildings reliably keep internal temperatures below acceptable ranges, decreasing or eliminating the need for artificial cooling even during peak summer months.

Case studies from Bikaner show that older buildings within the walled city, with narrow streets, internal courtyards, and dense urban fabric, improve passive cooling through reciprocal shadowing and controlled airflow. Modern city expansions outside the historic core, with broader highways and exposed building envelopes, are more prone to heat gain and discomfort.

The findings highlight the efficacy of combining material performance with contextual urban design, emphasizing the importance of vernacular planning strategies in sustainable development. Below is the heat loss calculation as per the applied vernacular material in the ancient homes of Rajasthan to maintain indoor thermal comfort, especially in peak summers, shown in Figure 10.

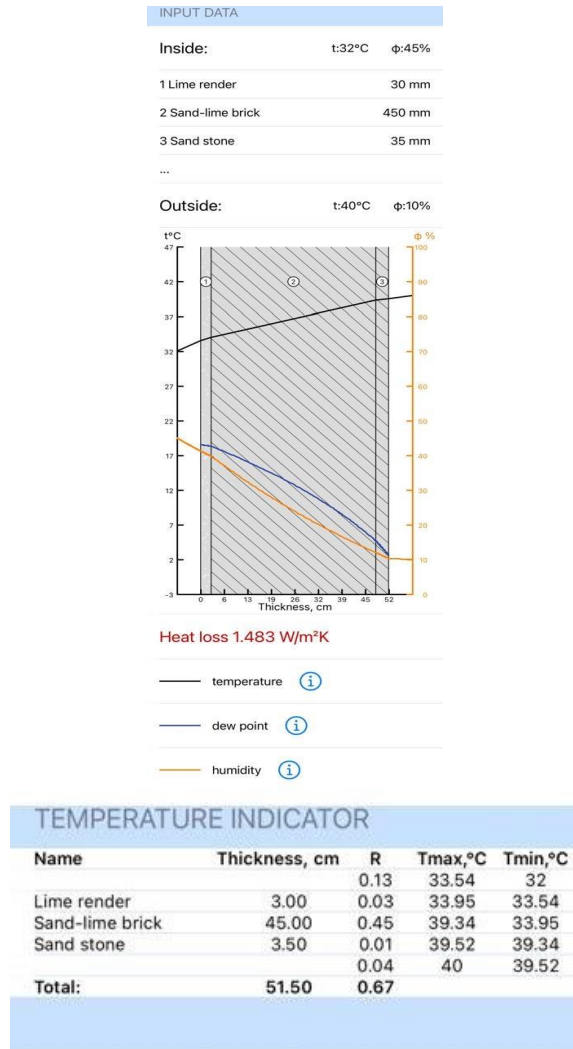


Fig. 10 Heat loss calculation chart of the vernacular home of Rajasthan

5. Discussion

The incorporation of traditional materials such as lime plaster and Dulmera sandstone into modern architecture offers a viable approach to achieving thermal comfort and sustainability in dry locations like Western Rajasthan. Because of their low embodied energy and local availability, these materials lessen reliance on mechanical cooling systems while also supporting environmentally friendly activities. However, there are still obstacles in integrating these vernacular practices with modern building standards, structural safety requirements, and large-scale construction procedures. Additionally, competent labor for traditional craftsmanship is increasingly scarce, providing barriers to widespread use. Despite these limitations, the study shows that combining traditional materials with current technologies, such as insulation systems and thermal models, can produce climate-responsive designs. Such hybrid techniques can satisfy both performance and cultural sustainability goals in the urban development of the city [17, 18].

6. Conclusion

An efficient strategy to improve thermal comfort in Rajasthan's severe climate is to revive traditional building techniques like the use of lime plaster and Dulmera sandstone. Because of their low embodied energy and Inherent insulating qualities, these materials—which have their roots in local knowledge systems—are climate-resilient and environmentally sustainable. According to this study, conventional structures made of these materials continuously keep their interior temperatures lower without requiring a lot of mechanical assistance. These results highlight the materials' potential to support sustainable development, particularly in dry areas [19].

Furthermore, by incorporating indigenous techniques into modern building design, regional architectural identity is preserved, and future construction is guaranteed to be both environmentally responsible and culturally appropriate. This study emphasizes even more how crucial it is to use contemporary analytical methods to assist vernacular construction processes [20].

To verify climate data and evaluate indoor comfort levels in conventional structures, the CBE Thermal Comfort Tool was utilized. The close alignment of modeling and field observation results showed how reliable these materials are at controlling internal temperatures. Furthermore, it was discovered that passive cooling was improved by urban planning features like the shaded streets, interior courtyards, and dense layouts seen in Bikaner's old districts.

On the other hand, heat gain is often made worse by contemporary planning that features exposed structures and dispersed layouts. This disparity bolsters the claim that local materials combined with urban morphology are essential for fostering thermal comfort and energy efficiency. Although there are many advantages to incorporating traditional building methods into contemporary construction, several obstacles need to be removed to allow for wider adoption. These include the requirement for further training in legacy craftsmanship, revised construction rules that allow for traditional materials, and demonstration projects that highlight performance and scalability.

Opportunities for alignment are presented by the growing recognition of local materials and passive design techniques by frameworks such as GRIHA and LEED [21, 22]. To achieve environmental performance and cultural preservation goals, this study promotes a hybrid approach that combines conventional techniques with contemporary technologies and analytical tools. These long-standing methods can contribute to the creation of tomorrow's robust, sustainable buildings with the correct policies [23, 24].

Future research should focus on conducting long-term performance monitoring of structures employing traditional

materials like lime plaster and Dulmera sandstone over several seasons to build on the insights gained from this study. This would give us a more thorough grasp of how they behave in a variety of climates outside of the hottest summer months. To satisfy these materials' current safety and performance criteria, it is also necessary to investigate creative building methods that combine conventional materials with modern systems like thermal insulation, energy modeling, and structural reinforcements.

Standardized rules for incorporating such materials into green building certification systems like GRIHA and LEED could also be the focus of future research. Furthermore, to assess how these materials function under various design models, extensive simulation studies spanning diverse urban typologies could be carried out utilizing programs like EnergyPlus or the CBE Thermal Comfort Tool. It would also be beneficial to compare Rajasthan's traditional and modern advancements, particularly in the fast-growing metropolitan areas of Bikaner and Jodhpur. In the interest of improving thermal comfort and sustainability in hot, dry regions, this

paper encourages the possibilities of using passive methods and vernacular materials in newly developed urban areas. Future studies can evaluate long-term performance analysis through a bigger window of time, real-time monitoring, and extend this hybrid strategy across a variety of urban typologies covered under similar climatic conditions.

Nevertheless, there are various obstacles, including the lack of technically skilled craftsmen for stone masonry installation in a novel way and lime work implementation for thermal comfort, monitoring gaps in building regulations that acknowledge traditional materials, and inventor resistance because of perceived costs or unfamiliarity. Scaling such climate-responsive design solutions requires addressing these issues through governmental backing, education, and updated skill training programs. To ensure that the sustainability benefits of vernacular practices are fully realized in future urban development, interdisciplinary research involving architects, conservationists, policymakers, and local artisans is crucial to preserving indigenous knowledge of the region while adapting it to the modern demands of time and region.

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