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Original Research Article

The Influence of Enclosed and Semi-Open Transitional Spaces in Residential Houses on Human Thermal Comfort in the Hot and Arid Climate of Iran (Kerman)*

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Abstract

Problem statement: In hot and arid regions such as Kerman, vernacular architectural design plays a crucial role in ensuring optimal thermal conditions and long-term comfort for residents amid increasing temperature fluctuations. Given this significance, assessing the impact of enclosed and semi-open spaces in Kerman's traditional buildings from the perspectives of thermal environment and adaptive thermal behavior is of high importance.

Research objective: This study aims to comprehensively examine the influence of enclosed and semi-open spaces in Kerman's vernacular buildings on thermal environment, thermal adaptation behaviors, and residents' thermal responses in a hot and arid climate.

Research method: Utilizing advanced statistical methods, this research gathered and analyzed data from a year-long field study. The assessments included environmental measurements in both enclosed and semi-open spaces and the determination of thermal comfort indices based on existing standards.

Conclusion: Findings indicate a significant difference in the thermal environments of enclosed and semi-open spaces, leading to varied thermal comfort conditions at different times of the day. Furthermore, residents' thermal adaptation behaviors are closely linked to the spatial configuration of buildings. Notable findings include differences in neutral temperature, acceptable temperature (80% satisfaction), and preferred temperature, measured at 1.1°C and 0.9°C (neutral temperature), 2.2°C and 2.7°C (acceptable temperature), and 1.6°C (preferred temperature) during transitional seasons and summer, respectively. The results confirm that the thermal diversity present in Kerman's vernacular buildings significantly impacts adaptive thermal behaviors and residents' comfort levels. The smart design of enclosed and semi-open spaces, by offering distinct thermal conditions, enhances thermal adaptation and improves overall comfort, emphasizing the critical role of vernacular architecture in adapting to hot and arid climates.

Keywords: *Semi-open spaces, transitional spaces, residential house, thermal comfort, hot and arid climate.*

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Introduction

In recent years, global crises such as energy shortages, environmental pollution, and climate change have emerged as fundamental challenges for contemporary societies. These crises have deeply affected human life and the environment, raising concerns about the sustainability of economic and social development. Particularly in hot and arid regions like Kerman, the need for buildings that can withstand extreme climatic conditions and provide optimal thermal comfort has become increasingly evident.

According to Köppen's climate classification, Kerman is characterized as a hot desert climate (BWh), exhibiting extreme summer temperatures, significant temperature fluctuations, and low humidity. These conditions pose substantial challenges for architectural design.

In this context, vernacular architecture has been recognized as an effective solution. Traditional buildings leverage passive design strategies and locally sourced materials to reduce energy consumption and enhance residents' thermal comfort (Shao et al., 2018, 32; Fernandes et al., 2019, 45). This type of architecture integrates smart spatial configurations such as verandas, which facilitate natural ventilation and air circulation, thereby reducing indoor temperatures and contributing to environmental sustainability (Farnad et al., 2022, 67; Kamran Kasmaei et al., 2017, 53). However, previous studies have not sufficiently examined the direct impact of these architectural spaces on thermal comfort and adaptive thermal behaviors in rural areas (Chen et al., 2020, 98; Zhang et al., 2018, 112). Therefore, comprehensive research is needed to further investigate the role of vernacular architecture in improving thermal comfort and reducing energy consumption.

This study aims to explore the comprehensive impact of enclosed and semi-open spaces in Kerman's vernacular buildings on the thermal environment, adaptive thermal behaviors, and residents' thermal responses. The main research questions include:

- How do enclosed and semi-open spaces in Kerman's vernacular buildings influence the thermal environment and residents' thermal comfort levels?
- What are the differences in neutral temperature, acceptable temperature, and preferred temperature between enclosed and semi-open spaces, and what are the implications for architectural design?

Research Objectives

The research objectives are categorized into two main areas:

- Measuring and comparing thermal parameters such as air temperature, relative humidity, radiation temperature, and wind speed to gain a precise understanding of thermal differences between enclosed and semi-open spaces.
- Analysis of Adaptive Thermal Behaviors and Residents' Thermal Responses: Identifying and examining the differences in neutral temperature, acceptable temperature, and preferred temperature in enclosed and semi-open spaces to assess the role of thermal adaptation in enhancing residents' comfort.

These objectives contribute to the development of sustainable design strategies and energy efficiency improvements in vernacular buildings, highlighting the essential role of traditional architecture in adapting to hot and arid climates.

Literature Review

This study, focusing on the hot and arid climate of Kerman and the comprehensive analysis of enclosed and semi-open spaces in vernacular buildings, establishes a robust scientific foundation for the design of thermally efficient and sustainable buildings (Rijal, 2021, 13; Farnad et al., 2022, 89). Furthermore, the analysis of adaptive thermal behaviors and residents' thermal responses highlights the key role of vernacular architecture in facilitating human adaptation to climatic variations (Chen et al., 2020, 105; Shao et al., 2018, 76). The novelty of this research lies in its comprehensive and integrated assessment of the influence of enclosed and semi-open spaces on thermal comfort and adaptive thermal behaviors of residents in Kerman's arid climate - an area that has not been extensively explored (Zakaria et al., 2015, 97; Zhang et al., 2018, 123). Given the significance of architectural adaptation to local climates and the crucial role of enclosed and semi-open spaces in enhancing thermal comfort, this research serves as a valuable reference for architects and researchers in the field of sustainable and thermally optimized building design for hot and arid climates (Shao et al., 2018, 81; Soleymanpour et al., 2015, 65). To better understand the role of vernacular buildings in enhancing thermal comfort and climatic adaptation, a comprehensive literature review is conducted. This review examines previous studies on the adaptation of vernacular buildings to climatic conditions and the analysis of residents' thermal behaviors. Table 1 provides a summary of relevant research, highlighting the diversity of architectural strategies and the findings obtained in various climatic regions.

Previous studies confirm that vernacular buildings utilize passive strategies such as thick walls, courtyards, and cross ventilation to create thermally comfortable environments (Li et al., 2018, 45; Fernandes et al., 2019, 52; Toe & Kubota, 2015, 37). Furthermore, multiple studies emphasize that adaptive thermal behaviors play a key role in enhancing thermal comfort (Zhang et al., 2018, 88; Chen et al., 2020, 67; Shao et al., 2018, 73). However, limited research has been conducted on the direct impact of enclosed and semi-open spaces on residents' thermal behaviors - a crucial knowledge gap that this study aims to address. By comprehensively analyzing the enclosed and semi-open spaces in Kerman's vernacular buildings, this research seeks to offer a detailed understanding of their impact on the thermal environment and adaptive thermal behaviors. Beyond contributing to sustainable design strategies, this study serves as a key reference for architects and researchers in the domain of thermally efficient and sustainable buildings for hot and arid climates. By aligning with prior studies, this research underscores the critical role of vernacular architecture in facilitating human adaptation to climatic variations - an aspect that has not been extensively explored (Zakaria et al., 2015, 90; Zhang et al., 2018, 123).

Theoretical Foundation

The theoretical framework of this study forms the backbone for analyzing and interpreting the research findings. This framework is based on concepts and theories related to thermal comfort, human thermal adaptation, and passive design strategies in vernacular architecture in hot and arid climates. The objective of this framework is to establish a foundation for explaining the direct relationship between the design of enclosed and semi-open spaces in Kerman's vernacular houses and residents' thermal comfort levels, as well as to illustrate how thermal adaptation can be enhanced in response to climatic variations.

- **Concept of thermal comfort**

Thermal comfort refers to a state in which an individual feels thermally satisfied without requiring additional adjustments (such as modifying clothing or using heating/cooling devices) (ASHRAE, 2017, 29; Li et al., 2018, 4). This concept is derived from the balance between body heat production and heat exchange with the environment and encompasses both physical and psychological aspects. The physical aspect includes parameters such as air temperature, relative humidity, air velocity, and radiant temperature. The psychological aspect is linked to personal expectations and experiences regarding the thermal environment (Dili et al., 2010, 55; Indraganti, 2010, 6). Several theories have been proposed to explain thermal comfort, including physical models (such as Fanger's PMV model) and adaptive models (Chen et al., 2020, 68; Yu et al., 2017, 70).

- **Adaptive thermal comfort model**

The adaptive thermal comfort model, introduced in ASHRAE Standard 55 (2017), is based on the principle that human thermal comfort is influenced by

Table 1. Summary of studies on vernacular architecture, human comfort, and climate. Source: Authors.

Research Topic	Region	Author(s)	Findings
Influence of passive design strategies in earthen buildings	Portugal	Fernandes et al. (2019)	Earthen buildings are closely linked to local conditions and effectively reduce high summer temperatures using passive strategies.
Role of courtyards in building cooling	Saudi Arabia	Al-Hemiddi & Al-Saud (2001)	Courtyards with water features, shading, and mist cooling significantly lower surrounding space temperatures.
Impact of thick walls on indoor temperature stability in Yaodong houses	China	Liu et al. (2011)	Thick walls in Yaodong houses effectively reduce external temperature fluctuations and maintain stable indoor temperatures.
Effect of shading devices and cross ventilation in cooling environments	Malaysia	Toe et al. (2015)	Traditional Malay houses with shading and cross ventilation maintain cool outdoor spaces and improve microclimates.
Reduction of indoor temperature through Chinese shop-house courtyards	Malaysia	Zakaria et al. (2015)	Courtyards in Malacca's Chinese shop-houses can reduce indoor temperatures by 0.3–1.7°C.
Enhancing thermal comfort through vernacular design strategies	Iran	Soleymanpour et al. (2015)	The use of climate-responsive architectural strategies in Iranian vernacular buildings significantly improves thermal comfort.
Thermal comfort comparison in traditional vs. modern houses	Kerala, India	Dili et al. (2010)	Traditional houses provide higher indoor comfort and greater occupant satisfaction than modern houses.
Rural residents' adaptation to hot and arid climates	Nepal	Rijal et al. (2010)	Residents of Nepalese traditional houses demonstrate high thermal adaptability, with an average comfort temperature of 10.7°C.
Determining thermal comfort adaptation coefficient in Tibetan regions	China	Yu et al. (2017)	In Tibet, the adaptive coefficient (k) for thermal comfort is 0.34, defining an acceptable comfort range for indoor environments.
Thermal tolerance of rural residents in cold conditions	China	Xiong et al. (2019)	Rural residents in China exhibit greater tolerance for winter cold in modern buildings.
Neutral thermal temperature in Chinese rural homes	China	Zhang et al. (2018)	Neutral temperature: 26.8°C, acceptable range: 22.9–30.7°C, with 90% satisfaction.
Analysis of neutral and acceptable thermal temperature in warm climates	China	Han et al. (2017)	Neutral thermal temperature: 28.61°C, acceptable range: 22.0–25.91°C in hot-humid conditions.
Climate-responsive vernacular architecture in Yazd heritage	Iran	Keshtkaran (2011)	Case study in Yazd demonstrates that vernacular designs harmonized with climate enhance thermal comfort.
Adaptation of vernacular architecture in the humid temperate plains of Gilan	Gilan, Iran	Kamran Kasmaei et al. (2017)	Traditional designs in western Gilan, using local materials, effectively improve thermal comfort.
Spatial configuration and thermal comfort in Kerman's traditional houses	Kerman, Iran	Kamlipour et al. (2012)	Semi-open spaces play a crucial role in improving thermal comfort in Kerman's vernacular houses.
Effect of thick walls and semi-open spaces in Yazd	Yazd, Iran	Keshtkaran (2011)	Vernacular designs with thick walls and semi-open spaces improve thermal comfort in hot summers.
Influence of semi-open spaces on thermal comfort in Guangzhou	Guangzhou, China	Zhang et al. (2018)	A year-long field study indicates higher thermal neutrality and acceptable temperature ranges in semi-open spaces than in enclosed spaces.
Role of daily activities in thermal acceptance	Chongqing, China	Du et al. (2014)	Outdoor and semi-open space activities enhance thermal acceptance in summer.

current environmental conditions, past experiences, and the individual's level of adaptation to the environment. According to this model, individuals can adjust their neutral thermal temperature in response to climatic changes - a concept particularly relevant in regions such as Kerman, which is classified as a hot desert climate (BWh) according to the Köppen climate classification (Li et al., 2018, 47; Xiong et al., 2019, 52). In other words, thermal comfort is closely linked to an individual's ability to adapt to environmental changes, and increased positive thermal experiences can expand their thermal comfort range (Yu et al., 2017, 59). This model is particularly applicable in regions with extreme climatic variations, demonstrating how thermal adaptation can mitigate heat stress and improve quality of life (Rijal, 2021, 64).

- **Human thermal adaptation to the environment**

Thermal adaptation refers to the set of behaviors and responses individuals adopt to maintain thermal comfort in the face of temperature fluctuations and environmental changes (Chen et al., 2020, 72; Yu et al., 2017, 61).
This adaptation includes:
- Physical adjustments (e.g., using fans, opening/closing doors and windows)

- Behavioral changes (e.g., modifying clothing and daily activities) (Shao et al., 2018, 66; Zhang et al., 2018, 80).

In hot and arid climates, thermal adaptation behaviors are a crucial factor in reducing heat stress and improving residents' comfort levels (Chen et al., 2020, 74).

Research has shown that rural residents respond to high temperatures by:

- Using fans
- Moving activities to semi-open spaces
- Wearing lighter clothing (Zhang et al., 2018, 84; Shao et al., 2018, 69).

• Vernacular architecture and passive design strategies

Vernacular architecture refers to building designs that utilize local materials and passive strategies to achieve optimal thermal performance in alignment with climatic conditions (Fernandes et al., 2019, 50; Li et al., 2018, 47). In hot and arid regions, such as Kerman, which is classified as a hot desert climate (BWh) according to Köppen's classification, various passive design strategies are employed, including:

- Thick walls to minimize heat gain
- Internal courtyards for natural ventilation
- Shading devices to reduce solar radiation
- Cross-ventilation for enhanced airflow (Toe & Kubota, 2015, 36; Farnad et al., 2022, 55).

These strategies not only minimize energy consumption but also contribute to sustainable and climate-responsive environments (Zakaria et al., 2015, 92). Numerous studies indicate that using local materials with favorable thermal properties helps stabilize indoor temperatures. Additionally, semi-open spaces such as verandas facilitate natural airflow, reducing indoor temperatures during peak hours (Li et al., 2018, 49; Zhang et al., 2018, 85).

• Influence of enclosed and semi-Open spaces on thermal comfort

The design and technology incorporated into enclosed and semi-open spaces in vernacular architecture play a fundamental role in achieving thermal comfort. Semi-open spaces, such as verandas, enable natural ventilation and air circulation, reducing indoor temperatures and enhancing thermal comfort (Du et al., 2014, 59; Kamran Kasmaei et al., 2017, 62). The use of local materials with high thermal inertia helps maintain stable indoor temperatures (Li et al., 2018, 51; Zhang et al., 2018, 87). These spaces effectively:

- Promote natural airflow, reducing summer heat and increasing morning coolness
- Provide a transition between indoor and outdoor environments, optimizing thermal comfort throughout the day (Farnad et al., 2022, 70).

Additionally, research indicates that well-designed enclosed and semi-open spaces influence residents' thermal adaptation behaviors, ultimately enhancing overall thermal comfort (Zhang et al., 2018, 90; Shao et al., 2018, 68).

This study's theoretical framework is based on the adaptive thermal comfort model and concepts related to human thermal adaptation to the environment. This approach enables the investigation of the impact of indoor and semi-open spaces on occupants' thermal comfort and is directly related to the design strategies of vernacular architecture in hot and dry regions (ASHRAE, 2017, 33; Li et al., 2018, 45; Chen et al., 2020, 62). Furthermore, the theoretical framework in question investigates inhabitants' thermal adaptation behaviors and their impact on thermal comfort levels (Zhang et al., 2018, 79; Shao et al., 2018, 68).

In other words, this framework demonstrates how optimal design of indoor and semi-open spaces can improve thermal comfort while also increasing occupant adaptation to hot and dry climate requirements.

The theoretical framework presented in this study integrates key thermal comfort concepts, adaptive comfort models, and vernacular architectural strategies in hot and arid climates. The findings reinforce that:

- Thermal comfort is dynamic, and influenced by both environmental and behavioral factors.
- Adaptive comfort models are particularly relevant in regions with extreme climatic variations.

- Vernacular architecture employs effective passive design strategies to enhance thermal comfort and reduce energy dependency.
- Enclosed and semi-open spaces significantly impact thermal comfort and adaptation behaviors in Kerman's traditional houses.

By understanding these interrelationships, architects and designers can develop more effective climate-responsive solutions, ensuring sustainable, energy-efficient, and thermally comfortable built environments (Fig. 1).

Research Methodology

This section provides a detailed explanation of the research methods employed to examine the impact of enclosed and semi-open spaces in vernacular buildings of Kerman on residents' thermal comfort. The research methodology comprises the following key components:

Climate analysis of Kerman: To assess the climatic influences on vernacular architecture and thermal comfort.

Examination of vernacular architectural features: A structural and pattern-based analysis of local architecture.

Field study implementation: Conducting surveys and environmental measurements.

Data analysis: Utilizing appropriate statistical software for data interpretation.

Sample size determination and evaluation of thermal comfort indices: Including resident characteristics and environmental parameters.

This scientific approach enables a comprehensive and precise assessment of the impact of enclosed and semi-open spaces on thermal comfort, ensuring reliable and valid results. The use of rigorous methodologies, in-depth climate analysis, consistency in the application of the solar calendar, and detailed explanations through tables and graphs significantly enhance the scientific credibility of this section.

- **Climate analysis of Kerman**

A comprehensive climate analysis of Kerman was conducted to establish a precise foundation for evaluating the climatic impact on vernacular architecture and residents' thermal comfort. Geographically, Kerman is located at 30.29°N latitude and 57.06°E longitude, falling within a hot and arid climate zone. According to the Köppen climate classification, Kerman's climate is categorized as a hot desert climate (BWh). This region is characterized by:

- Extremely high summer temperatures

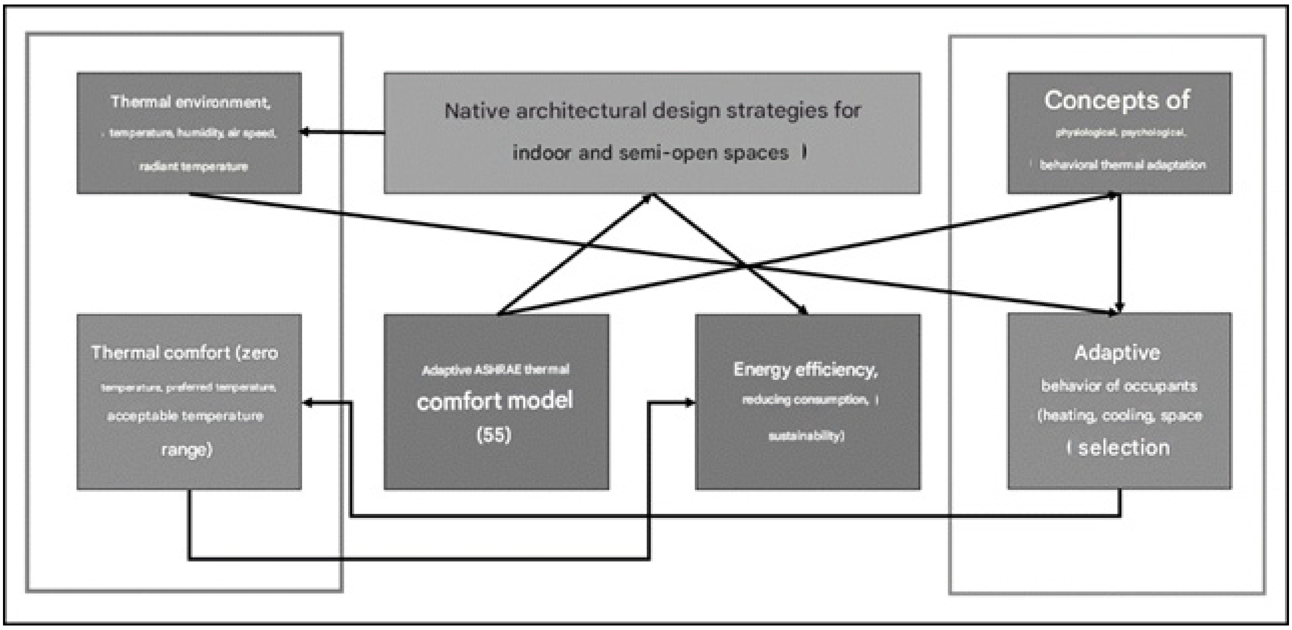


Fig. 1. Theoretical framework of the research. Source: Authors.

- Sharp temperature fluctuations
- Minimal precipitation

The annual precipitation in Kerman is approximately 132.4 mm, indicating semi-desert climatic conditions. Summer temperatures often exceed 22°C, while winter temperatures drop below 10°C. These extreme variations necessitate architectural designs that can effectively adapt to climatic conditions and ensure residents' thermal comfort (Farnad et al., 2022, 74; Kamran Kasmaei et al., 2017, 58). Thus, an in-depth climatic analysis of Kerman was selected as a prerequisite for this study to comprehensively examine the direct impact of climate on vernacular building design and thermal comfort (Table 2).

- **Features of vernacular buildings in Kerman**

Vernacular buildings in Kerman are designed using local materials and passive design strategies to adapt to the hot and arid climate. These buildings are traditionally divided into three main zones:

1. Enclosed Spaces:
- Constructed using thick adobe or mud-brick walls (500–700 mm thickness).
- Act as effective thermal insulators, stabilizing indoor temperatures against external fluctuations (Farnad et al., 2022, 63; Kamlipour et al., 2012, 54).

2. Semi-Open Spaces:
- Verandas and courtyards are designed to promote cross-ventilation and natural airflow, reducing indoor temperatures during early morning hours.
- Function as an integral part of natural ventilation systems, enhancing heat dissipation (Tayari & Nikpour, 2022, 42).

3. Open Spaces:
- Primarily used for gardening and auxiliary activities.
- Play a crucial role in microclimate regulation.

Additionally, flat roofs with soil or reed coverings significantly reduce solar heat absorption and enhance natural cooling (Memarian & Brown, 2003, 47). The use of local materials and traditional techniques fosters a sustainable and climate-responsive environment, ultimately improving residents' quality of life (Keshtkaran, 2011, 55).

Table 2. Climate data of Kerman (Monthly averages for maximum, daily, and minimum temperatures & precipitation). Source: National Meteorological Organization, 1402.

Month	Avg. Max Temp (°C)	Avg. Daily Temp (°C)	Avg. Min Temp (°C)	Precipitation (mm)
April	11.8	4.4	-4.0	29.0
May	14.2	7.1	-1.1	26.7
June	18.6	12.1	3.4	32.0
July	23.8	17.2	7.9	19.5
August	29.8	22.9	12.0	8.6
September	34.8	28.0	15.6	0.5
October	35.5	28.9	17.0	0.7
November	34.0	26.9	14.2	0.6
December	31.0	23.3	9.8	0.3
January	25.7	17.4	4.8	0.7
February	19.2	10.8	-0.7	5.1
March	14.1	6.2	-3.6	18.4

- **Field study methodology**

- Questionnaire and measurement

To collect subjective and objective data, both survey-based and environmental measurement methods were employed:

1. Surveys:
- A questionnaire was distributed among rural residents of Kerman.

2. Environmental Measurements:
- Temperature, humidity, radiation temperature, and wind speed were recorded using digital thermometers and hygrometers.

- Thermal measurements

A U-shaped vernacular building in Kerman was selected for in-depth thermal testing. Interior walls: 400 mm thick adobe bricks/ Exterior walls: 500 mm thick adobe bricks/ Roof structure: 200 mm thick wooden beams covered with soil layers/ Windows: 1.5m × 1.5m openings for optimized airflow. Thermal measurements were conducted across different seasons (summer, spring, and winter) using: TESTO 175H2 for temperature and humidity monitoring/ TESTO 425 anemometer for wind speed assessment.

- **Sample size and respondents**

A total of 1,170 valid questionnaires were collected from rural residents of Kerman: 470 responses related to enclosed spaces & 700 responses related to semi-open spaces. Findings revealed 75% of respondents preferred semi-open spaces in transitional and summer seasons & 95% of respondents preferred enclosed spaces in winter. For statistical analysis, SPSS (Version 22.0) was used, employing: T-tests and linear regression to analyze thermal comfort variations.

- **Thermal comfort assessment indices**

Thermal comfort was evaluated using environmental parameters including: Air temperature/ Radiant temperature/ Relative humidity/ Wind speed ASHRAE Standard 55 (2017, 31). Was referenced for selecting thermal comfort parameters. The operative temperature, reflecting combined thermal effects, was calculated using standard formulas. Additionally, neutral and acceptable temperature ranges were identified through adaptive comfort models (Farnad et al., 2022).

- **Statistical data analysis**

Various statistical methods were applied: T-tests: To compare mean temperature variations between enclosed and semi-open spaces/ Linear and polynomial regression: To analyze the relationship between operative temperature and residents' thermal perception/ Data binning (0.5°C intervals): To observe thermal comfort trends. All analyses were conducted using SPSS software, with significance levels set at 0.05 (Farnad et al., 2022).

Findings

This section presents the findings from the conducted analyses, evaluating the impact of enclosed and semi-open spaces in vernacular buildings of Kerman on residents' thermal comfort. The results are categorized into three key areas: Thermal environment/ Thermal behavior/ Subjective thermal responses. Each chart and table is systematically discussed to facilitate the reader's understanding of the correlation between data and findings.

- **Thermal environment**

The distribution of air temperature in enclosed and semi-open spaces in Kerman is illustrated in Fig. 2-a. During summer months, the mean temperature in enclosed spaces ranged between 31.5°C and 32.0°C, whereas in semi-open spaces, it varied between 32.2°C and 32.5°C. This difference indicates that semi-open spaces experience greater temperature fluctuations than enclosed spaces. Key Observations is from 03:00 to 14:00, the air temperature in semi-open spaces was lower than in enclosed spaces, leading to a higher preference for these areas during the early hours of the day & from 15:00 to 17:00, enclosed spaces exhibited a cooler temperature, making them more favorable for use (Tayari & Nikpour, 2022, 42; Keshtkaran, 2011, 40). The distribution of air velocity is shown in Fig. 1-b; During summer, the mean air velocity was 0.21 m/s in enclosed spaces and 0.40 m/s in semi-open spaces, During transitional seasons, air velocity in semi-open spaces was slightly higher than in

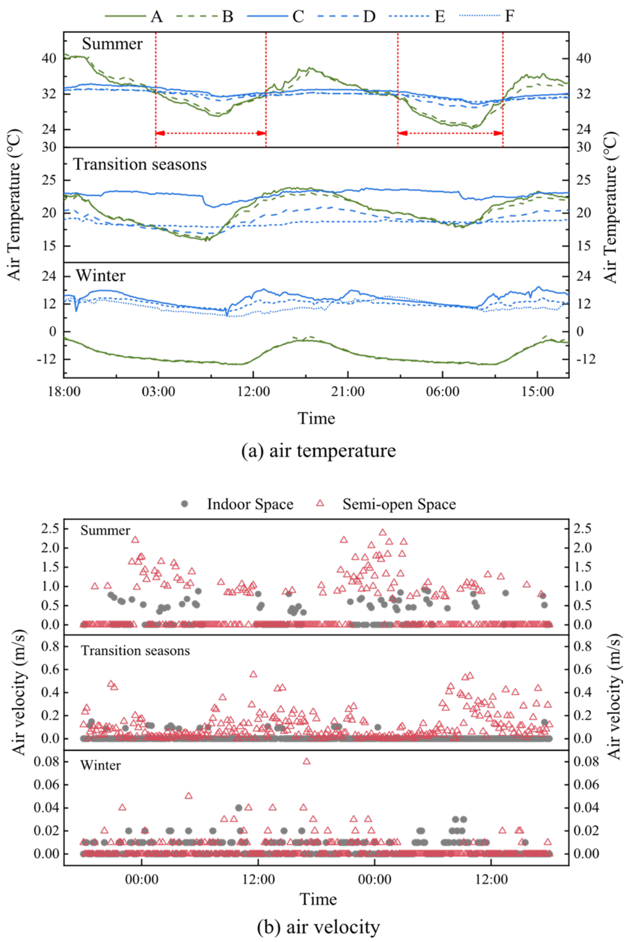


Fig. 2. Distribution of environmental parameters. Source: Authors.

enclosed spaces, ranging from 0 to 0.56 m/s for semi-open spaces and 0 to 0.15 m/s for enclosed spaces, In winter, air velocity remained low in both spaces, showing no significant variation. These results confirm that higher air velocities in semi-open spaces positively contribute to improved thermal comfort.

- **Thermal behavior**

In Kerman, as in other arid regions, behavioral adaptations play a crucial role in maintaining thermal comfort. Table 3 presents the frequency of various thermal adaptation behaviors among residents. Key Findings:

Heating Behavior: In winter, 95% of residents relied on heating systems, highlighting their importance in enhancing indoor thermal conditions/ Fan usage was observed in 68% of cases during transitional seasons and 74% in summer, correlating with increasing outdoor temperatures, demonstrating that residents naturally adapt to temperature variations (ibid.).

Space Selection Behavior: The preference for semi-open spaces varied across seasons/ In winter, only 0.9% of residents used semi-open spaces, whereas in transitional seasons, this figure increased to 2.25%, and in summer, it reached 4.74%/ This highlights space selection as a notable thermal adaptation behavior in Kerman (Kamlipour et al., 2012).

Water Sprinkling Behavior: 5.9% of residents used water sprinkling in semi-open spaces and 18.3% in open spaces during transitional seasons and summer/ this aligns with traditional Persian architectural practices, where water features are used for cooling (Farnad et al., 2022).

Other Behaviors: Additional thermal adaptation behaviors included using electric fans, changing clothing, consuming hot or cold beverages, taking showers, using handheld fans, and adjusting doors/ windows/ These behaviors are consistent with findings from similar studies on thermal comfort in comparable climates (Pourvahidi & Özdeniz, 2013; Rodriguez et al., 2023).

- **Subjective thermal responses**

- Thermal Sensation Votes (TSV)

Residents' thermal sensation votes in Kerman are depicted in Fig. 3. In summer, the most frequent TSV in enclosed spaces was +1 (slightly warm), while in semi-open spaces, it was 0 (neutral). This indicates that residents tend to feel warmer indoors, with a significant proportion experiencing heat discomfort (Kamlipour et al., 2012). In winter and transitional seasons, the majority of TSVs were 0 (neutral), suggesting overall satisfaction with the thermal environment. Over 90% of thermal sensation votes fell within the -1 to +1 range, confirming resident satisfaction with building thermal conditions in these seasons (Keshtkaran, 2011) (Table 3).

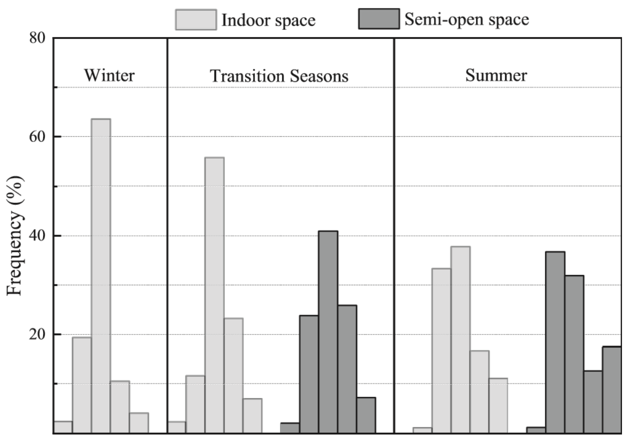


Fig. 3. Thermal sensation vote distribution. Source: Authors.

Table 3. Sample survey data statistics. Source: Authors.

Space Type	Season	Sample Size	Height (cm)	Weight (kg)	Clothing Insulation (Clo)	Metabolic Rate (Met)
Enclosed Spaces	Winter	321	7.0/42.0/92.0	120.0/163.6/187.0	25.0/61.7/86.0	0.8/1.1/2.0
	Transitional Seasons	59	20.0/47.5/74.0	155.0/163.7/175.0	50.0/61.1/75.0	1.0/1.0/1.2
	Summer	90	9.0/35.8/73.0	130.0/163.8/180.0	35.0/59.4/95.0	0.7/1.2/2.0
Semi-open Spaces	Winter	7	22.0/45.2/60.0	160.0/161.0/163.0	60.0/63.3/70.0	0.8/1.3/2.0
	Transitional Seasons	195	15.0/46.5/76.0	155.0/163.4/180.0	50.0/59.6/75.0	0.7/1.0/1.6
	Summer	498	7.0/39.8/85.0	110.0/164.2/185.0	25.0/61.4/95.0	-

- Thermal preference votes

The distribution frequency of thermal preference votes in enclosed and semi-open spaces is illustrated in Fig. 4. During summer, 70% to 80% of the residents in both spaces voted for -1 (cooler). In winter and transitional seasons, the most frequent thermal preference vote was 0 (no change). Approximately 30% of the residents in both spaces voted for +1 (warmer) during transitional seasons. This suggests that although thermal sensation is close to neutral, residents still prefer a slightly warmer environment, possibly due to their adaptation to higher temperatures.

In Kerman, Iran, the concept of neutral thermal temperature, as defined by ASHRAE 55 (2017), is highly significant in understanding residents' thermal comfort. To determine neutral temperature, the operative temperature was divided into 0.5°C intervals, and regression analysis was performed on the mean operative temperature of each interval against the mean thermal sensation votes (MTS). The regression analysis for enclosed and semi-open spaces in Kerman revealed in Table 4.

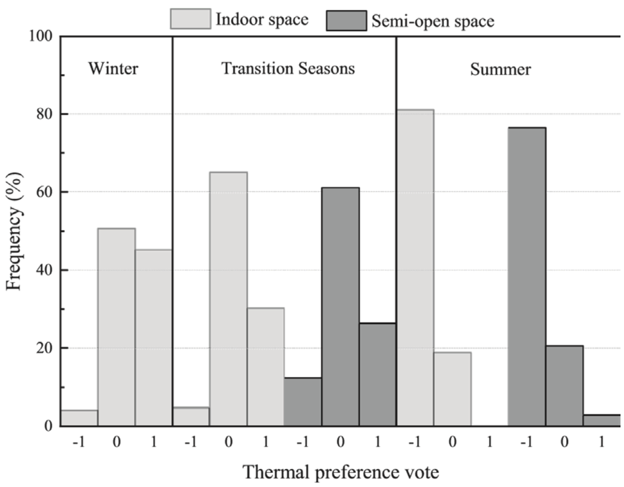


Fig. 4. Frequency distribution of thermal preference votes. Source: Authors.

Seasonal Neutral Temperatures:

- Winter: The neutral temperature in enclosed spaces was 18.3°C.
- Transitional Seasons: Enclosed Spaces: 23.0°C & semi-open Spaces: 21.9°C.
- Summer: Enclosed Spaces: 26.6°C & semi-open Spaces: 27.5°C.

Seasonal Variation:

- The study observed a progressive increase in neutral temperature and regression slope from winter through transitional seasons to summer.
- This suggests that as outdoor temperatures rise, residents adapt to climatic changes, and their neutral temperature increases.
- Simultaneously, there is a reduction in clothing insulation and an increase in residents' sensitivity to temperature variations (Keshtkaran, 2011; Tayari & Nikpour, 2022).

- **Acceptable thermal temperature**

In Kerman, the concept of neutral thermal temperature, as defined by ASHRAE 55, is critical in understanding thermal comfort. The operative temperature was divided into 0.5°C intervals, and regression analysis was performed on the mean operative temperature of each interval against the mean thermal sensation votes (MTS). The regression analysis for enclosed and semi-open spaces showed:

- Winter: The neutral temperature in enclosed spaces was 18.3°C.
- Transitional Seasons: Enclosed Spaces: 23.0°C/ Semi-open Spaces: 21.9°C
- Summer: Enclosed Spaces: 26.6°C/ Semi-open Spaces: 27.5°C

These results indicate that as outdoor temperatures rise, neutral thermal temperature also increases, suggesting residents' adaptation to climatic changes (ibid.) (Table 5).

Table 4. Detailed instrumentation information. Source: Authors.

Brand	Description	Measured Parameter	Range	Accuracy
Testo 175H2	Digital Temperature & Humidity Recorder	Air Temperature, Humidity	-20 to 70°C, 0-100%	±0.5°C, ±3%
Testo 454	Globe Thermometer (150mm Black Sphere)	Mean Radiant Temperature	-60 to 130°C	±0.41K
Testo 425	Hot Wire Anemometer	Air Velocity	0-20 m/s	±0.03 m/s + 5%

- **Preferred temperature**

The acceptable temperature range, in which at least 80% of respondents in Kerman felt comfortable, was determined based on the three central categories of thermal sensation votes (TSV): -1 (cool), 0 (neutral), and +1 (slightly warm). Seasonal Acceptable Temperature Ranges:

- Winter: Enclosed spaces: 14.9°C to 29.4°C
- Transitional Seasons: Enclosed spaces: 21.9°C to 32.22°C/ Semi-open spaces: 19.7°C to 29.27°C
- Summer: Enclosed spaces: Upper acceptable limit: 32°C/ Semi-open spaces: Upper acceptable limit: 34°C

The preferred temperature in Kerman represents the temperature that residents found most desirable. This study counted thermal preference votes in 0.5°C intervals, considering responses of +1 (warmer preference) and -1 (cooler preference). In winter, residents preferred a temperature of 23.4°C in enclosed spaces, which is 5.1°C higher than the neutral temperature. During summer, the preferred temperature was 23.3°C in enclosed spaces and 24.9°C in semi-open spaces, indicating a preference for cooler environments during hot periods (Figs. 5-7).

This tendency aligns with findings from similar studies in other regions.

Discussion

This section aligns the obtained results with the theoretical framework of the research and discusses their significance in the context of vernacular architectural design in Kerman. The analyses indicate that enclosed and semi-open spaces in Kerman's vernacular buildings play a crucial role in regulating the thermal environment and enhancing residents' thermal comfort. These findings align with the adaptive thermal comfort model and the concepts of human thermal adaptation to the environment established in the theoretical framework. For instance, the increase in neutral thermal temperature in semi-open spaces in response to rising outdoor temperatures

Table 5. Thermal response ratings. Source: Authors.

Thermal Sensation		Thermal Acceptance	Thermal Preference
-3	Very Cold	Clearly Unacceptable	-
-2	Cold	Clearly Unacceptable	Cooling Desired
-1	Cool	Just Unacceptable	Cooling Desired
0	Neutral	-	No Change
1	Slightly Warm	Just Acceptable	Warmer Preferred
2	Warm	Clearly Acceptable	-
3	Very Warm	-	-

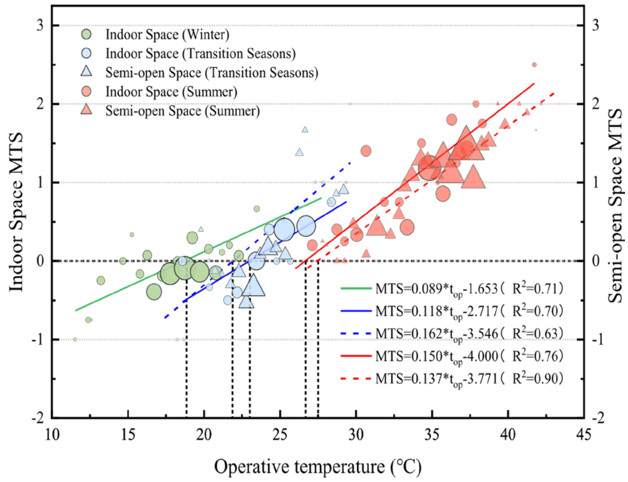


Fig. 5. Relationship between MTS and operative temperature. Source: Authors.

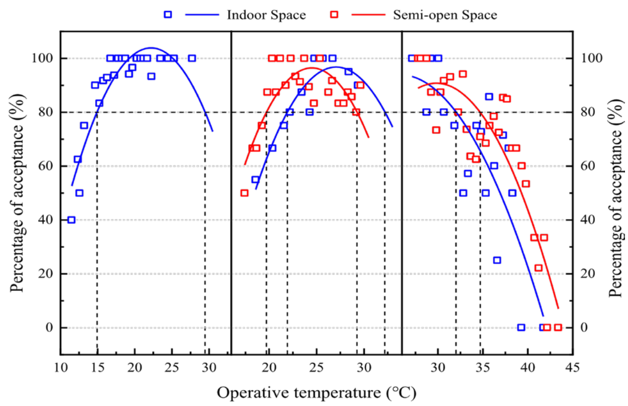


Fig. 6. Thermal acceptability analysis. Source: Authors.

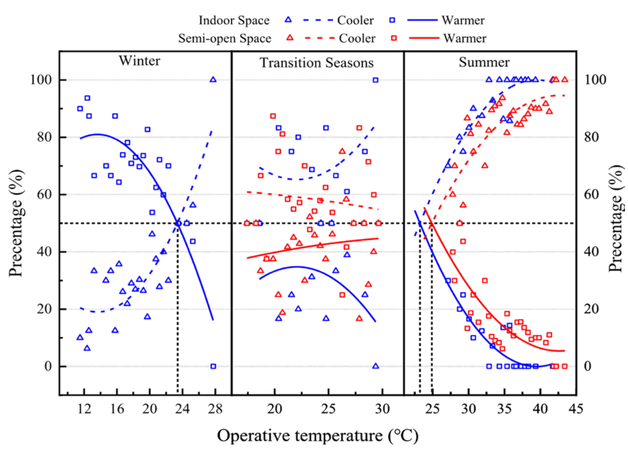


Fig. 7. Preferred temperature. Source: Authors.

demonstrates residents' adaptation to Kerman's hot and arid climate. Additionally, thermal adaptation behaviors, such as the use of fans and spatial selection across different seasons, have significantly contributed to improving thermal comfort. This study underscores that the design of enclosed and semi-open spaces can directly impact residents' thermal comfort, facilitating their adaptation to hot and arid climates. The use of thick walls and semi-open spaces not only reduces energy consumption but also contributes to creating a sustainable and comfortable environment for residents. These findings highlight the importance of passive design strategies in vernacular architecture and emphasize the pivotal role of architecture in facilitating human adaptation to climatic changes.

- **Living spaces and human thermal comfort**

In Kerman's vernacular architecture, enclosed and semi-open spaces play a critical role in creating a thermally comfortable environment for residents. This thermal comfort extends the duration during which residents can comfortably spend time in these buildings, enhancing their overall thermal experience. The thermal differences between enclosed and semi-open spaces enable residents to actively select their preferred space based on thermal conditions. Particularly during summer and transitional seasons, semi-open spaces are preferred, which correlates with the high frequency of spatial selection behaviors during these periods (Memarian & Brown, 2003). Residents experience varying levels of thermal comfort across different spaces. In summer, neutral temperature, the upper limit of 80% acceptable temperature, and preferred temperature in semi-open spaces are approximately 0.9°C, 2.7°C, and 1.6°C higher than in enclosed spaces. Conversely, during transitional seasons, neutral temperature and the lower limit of 80% acceptable temperature in semi-open spaces are approximately 1.1°C and 2.2°C lower than in enclosed spaces (Keshtkaran, 2011). In summary, the diverse spatial composition of Kerman's vernacular architecture creates a complementary thermal environment, prolonging comfortable thermal conditions, influencing and stimulating adaptive thermal behaviors, and ultimately enhancing thermal comfort across different spaces.

- **Living spaces and human thermal adaptation**

According to the international ASHRAE 55 standard (2017), which adopts an adaptive model for thermal comfort in naturally ventilated spaces, residents of Kerman exhibit strong thermal adaptation to their climate (Table 6).

The acceptable temperature range in semi-open spaces often exceeds ASHRAE 55 standards, particularly during transitional seasons and summer, suggesting that semi-open spaces enhance residents' climatic adaptation, especially in warmer months.

Human thermal adaptation encompasses behavioral, physiological, and psychological aspects.

- Analyzing residents' thermal adaptation behaviors (as discussed in Section 3.2) reveals a positive

Table 6. Thermal adaptation behaviors in Kerman. Source: Authors.

Season	Active Behaviors (Heating & Electric Fans)	Specific Behaviors	Common Behaviors
Winter	Heating: 96.4%	Spatial Selection: 0.9%	Clothing adjustment: 10.9%, Opening/closing doors and windows: 12.7%, Activity modification: 0.9%
Transitional	Electric Fans: 68.9%	Spatial Selection: 25.2%, Water Sprinkling: 5.9%	Clothing adjustment: 3.0%, Drinking hot/cold beverages: 0.7%, Showering: 11.1%, Handheld Fans: 4.4%, Opening/closing doors and windows: 11.1%, Activity modification: 2.2%
Summer	Electric Fans: 74.7%	Spatial Selection: 74.4%, Water Sprinkling: 18.3%	Clothing adjustment: 61.9%, Drinking hot/cold beverages: 60.8%, Showering: 56.9%, Handheld Fans: 53.1%, Opening/closing doors and windows: 51.8%, Activity modification: 1.1%

correlation between the frequency of spatial selection behaviors and thermal adaptation, particularly during transitional seasons and summer.
- This indicates that vernacular building typologies can stimulate residents' thermal adaptation behaviors, enhancing their ability to cope with changing climatic conditions (Kamlipour et al., 2012).

Residents in Kerman's semi-open spaces engage in activities such as cooking and socializing, which reduce their thermal demands from the built environment. In contrast, enclosed spaces are predominantly used for sedentary activities, necessitating higher thermal comfort requirements. Semi-open spaces offer greater opportunities for adaptation, such as water sprinkling, to cool the environment. Furthermore, the psychological impact of being in semi-open spaces, which are typically brighter and more open than enclosed spaces, also contributes to enhanced thermal adaptation (Pourvahidi & Özdeniz, 2013).

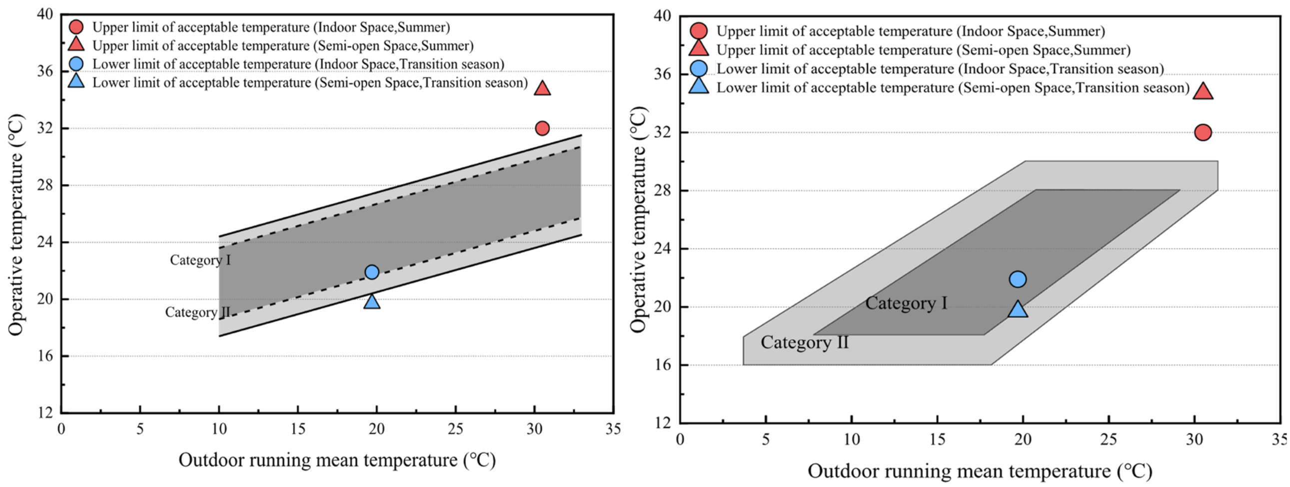
- **Practical implications**

In rural areas such as Kerman, where population density is lower and land costs are lower, vernacular buildings often feature extensive open or semi-open spaces, such as courtyards. The impact of these spaces on thermal conditions, residents' adaptive thermal behaviors, and thermal responses requires further investigation. However, it is evident that architectural design in rural areas should emphasize the comfort and functionality of open and semi-open spaces, as they play a crucial role in the sustainable development of vernacular architecture and the built environment (Fig. 8).

Conclusion

A comprehensive study was conducted focusing on the thermal environment of buildings and residents' thermal comfort in enclosed and semi-open spaces of vernacular buildings in Kerman's hot-arid climate. This study confirmed the holistic impact of vernacular building spaces on thermal conditions, residents' adaptive thermal behaviors, and their thermal responses, offering strategies for enhancing thermal adaptation in these architectural spaces. Key Findings are:

1. Thermal Environment Characteristics:
- Enclosed and semi-open spaces in Kerman exhibit distinct thermal conditions, providing comfort at different times.
- During summer, semi-open spaces with higher temperatures and air velocities are favored by residents.
- Between 15:00 and 17:00, enclosed spaces become preferable due to peak outdoor temperatures.



(a) Comparison with ASHRAE 55

(b) Comparison with GBT50785-2012

Fig. 8. Comparison with existing standards note: given Kerman's climatic conditions, the mean outdoor air temperature during transitional and summer seasons is 19.7°C and 30.5°C, respectively. Source: Authors.

- During transitional seasons, semi-open spaces exhibit slightly higher temperatures than enclosed spaces.
- In winter, enclosed spaces provide significantly warmer environments, making them the preferred areas for comfort.

2. Diversity in Adaptive Thermal Behaviors:

- Residents in Kerman employ various thermal adaptation strategies, including clothing adjustments, fan usage, and spatial selection.
- During transitional seasons, the frequency of spatial selection (25.2%) is comparable to fan usage, whereas in summer, it reaches 74.4%, nearly equal to electric fan usage.

3. Thermal Comfort Variations across Spaces:

- Significant differences in thermal comfort levels exist between spaces, highlighting the need for diverse spatial configurations in vernacular architecture.

4. Impact on Comfort and Adaptation:

- Enclosed and semi-open spaces in Kerman extend the duration of comfortable thermal conditions, stimulate adaptive thermal behaviors, and enhance overall thermal comfort.

These findings emphasize that the diversity of spaces in Kerman's vernacular architecture facilitates distinct thermal environments, stimulates adaptive behaviors, and ultimately enhances residents' thermal comfort and adaptation.

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