Thermal Comfort in Vernacular Shavadans vs. Contemporary Above-Ground Rooms: A Two-Season Field Study in Dezful, Iran

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ORIGINAL RESEARCH ARTICLE

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Abstract

Background and Objectives: Shavadans—traditional underground spaces in Dezful, Iran—have long served as passive thermal spaces in a hot semi-humid climate. Despite their historical significance and recognised potential for moderating extreme temperatures, comprehensive two-season field studies comparing their thermal comfort performance with co-located above-ground mixed-mode rooms remain scarce.

This study aims to provide empirical evidence on how Shavadans perform in both summer and winter, determine seasonal neutral temperatures, and assess their potential contribution to contemporary climate-responsive design.

Method: A two-season field campaign was conducted in ten Shavadans during winter (December 2022) and summer (July 2023). Air temperature, relative humidity, and air velocity were measured every three hours from 06:00 to 18:00 at multiple depths. Simultaneously, Level-3 adaptive comfort questionnaires were administered to residents, yielding in 422 valid responses (102 winter and 109 summer datasets for both underground and above-ground spaces). Linear regression of TSV–temperature relationships and the Bin Method were used to

Keywords:
Shavadan,
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Adaptive comfort,
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Research Questions:

1. How do thermal comfort conditions in traditional Shavadans of Dezful compare with those in above-ground buildings?
2. What differences exist in neutral temperature and thermal comfort conditions between underground and above-ground spaces?
3. How can findings from Shavadans contribute to enhancing energy efficiency in the design of contemporary buildings?

derive neutral temperatures and acceptable comfort ranges for each season and space type.

Findings and Conclusion: Summer results showed that Shavadans maintained significantly cooler indoor conditionsthan above-ground rooms. The neutral temperature decreased from 26.6 °C (above-ground) to 24.5 °C (Shavadan), and only depths greater than 5 m remained fully within the comfort range. The deepest zones (>7 m) were up to 16.1 °C cooler than the courtyard at peak heat, demonstrating the strong thermal buffering capacity of underground construction. In winter, both environments exhibited neutral or near-neutral conditions; however, the Shavadan maintained more stable temperatures and slightly warmer sensations due to its high thermal mass, with a neutral temperature of 23.1 °C compared with 22.5 °C above-ground.

Overall, Shavadans mitigate heat stress effectively in summer and provide stable thermal conditions in winter, while above-ground rooms offer slightly better comfort during the cold season. These findings deliver the first dual-season empirical benchmark in Iran and highlight the potential of hybrid underground–surface strategies for low-energy, climate-responsive architectural design.

Introduction

Shavadans are traditional underground spaces found in many residential buildings of Dezful and the northern Khuzestan region, designed to provide thermal comfort in the area's hot semi-humid climate. Typically constructed 5 to 12 metres below ground level and accessed via a flight of stairs, they rely on the high thermal capacity of the earth and natural ventilation to moderate indoor temperatures.[1] Archaeological evidence suggests their existence in Dezful since the Sassanid era.[2]

With the spread of mechanical cooling systems and the reduced use of steep staircases in modern houses, the functional role of Shavadans has declined, raising concerns for sustainable architecture. Architecturally, Shavadans consist of several key elements,[3] (Figure 1): an entrance from the

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[1] Mohsen Bina, 'Climatic Analysis of Shavadans in the Traditional Houses of Dezful,' *Honar-ha-ye Ziba* 33, no. 33 (2008).

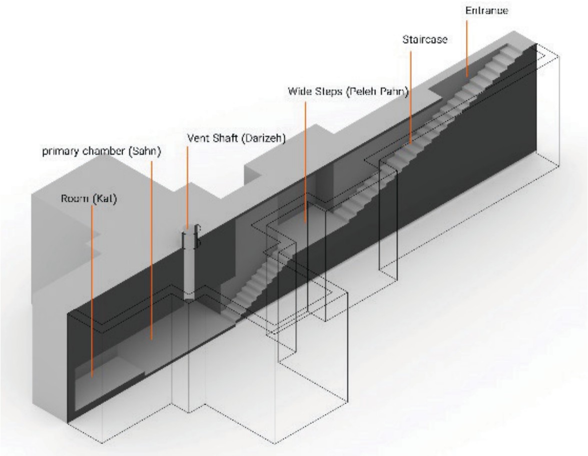
[2] Mohammadali Emam (Ahvazi), *Historical Geography of Dezful* (Dezful: Dar al-Mo'menin 2003).

courtyard, a staircase with intermittent wide steps (Peleh-Pahn) serving as landings, a central courtyard (*Sahn*), adjoining chambers (*Kat*), connecting tunnels (*Tal*), and vertical ventilation shafts (*Darizeh*). Together, these elements illustrate an integrated vernacular system of underground design (Figure 2).

On the other hand, thermal comfort— recognised as a subjective and multidimensional indicator of indoor air quality—is shaped by environmental, psychological, cultural, and behavioural factors. However, international standards such as ASHRAE-55[4] and ISO 7730[5] do not fully account for the specific differences between underground and above-ground spaces or for the role of individual adaptability.

This study builds on the authors' earlier research, which focused exclusively on summer conditions in Shavadans in Dezful.[6] In the present work, the scope is extended to include a comparative assessment of thermal comfort in underground Shavadans and above-ground mixed-mode buildings during both hot and cold seasons. The central aim is to provide empirical evidence that can inform the development of optimised passive design strategies for contemporary architecture.

Figure 1 (Left). The elements of Shavadan.



Research Questions and Objectives

Significance of the Study

Since the 1960s, vernacular architecture has been recognised as a valuable source of strategies to address the shortcomings of modern design. Research in this field not only examines its distinctive features but also seeks to identify rational and applicable principles that can inform contemporary architectural practice.[7]

Amos Rapoport distinguishes two main approaches to vernacular architecture. The first is the direct imitation of forms and details, often with a nostalgic outlook. The second is a model-based approach that derives architectural principles by analyzing environmental behaviour.[8]

The use of underground dwellings has a long history worldwide, ranging from cave houses in China and Kandovan (Iran) to the underground villages of Meymand (Iran) and Mesa (United States).[9]

Figure 2 (Right). An image of the wide steps (Peleh-Pahn) in the Tizno House Shavadan.

[3] Mostafa Mohebian, Mahnaz Ashrafi, and Amin Kivanloo, 'Investigating the Typology of Troglodytic Shavadans in Dezful,' *Richt-Journals* 43, no. 1 (2022).

[4] ASHRAE-55, '55, Thermal environmental conditions for human occupancy,' (Atlanta, 2020).

[5] IOF Standardsation, 'Ergonomics of the thermal environment: analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria,' *International Organsation for Standardsation* (2005).

[6] Faezeh Babaee and Shahin Heidari, 'Thermal comfort and structural optimisation of Shavadans: a multi-criteria approach: Case study–Hot and semi-humid climate, city of Dezful-Iran,' *Tunnelling and Underground Space Technology* 162 (2025).

In contemporary times, challenges such as population growth, land scarcity, depletion of energy resources, and environmental pollution have intensified interest in the thermal capacity of the earth and the potential of underground buildings.

These spaces can contribute significantly to sustainable design by reducing energy consumption, enhancing thermal comfort, and improving acoustic quality[10]. However, they also present challenges, including limited natural lighting, high humidity, construction costs, and psychological concerns for occupants[11].

In Iran, Shavadans represent a prominent example of traditional underground architecture, historically used for summer habitation in the hot and semi-humid climate of northern Khuzestan.

Despite their cultural and architectural importance, only a limited number of studies have examined the thermal comfort of Shavadans, and most have focused solely on temperature measurements or numerical simulations. This research addresses that gap by combining field data collection with statistical analysis to quantify the thermal comfort range in both Shavadans and above-ground spaces, while also examining user thermal behaviour. In doing so, it validates traditional knowledge and offers strategies for integrating underground architectural principles into sustainable contemporary design.

The aim of this study is to conduct a comparative investigation of thermal comfort conditions in traditional Shavadans of Dezful and above-ground buildings with mixed-mode ventilation during both summer and winter. By collecting data on air temperature, relative humidity, and air velocity, this study identifies the differences in thermal comfort between the two types of spaces and offers design strategies for applying Shavadan principles in contemporary architecture.

Literature Review

In recent years, the high thermal capacity of the earth has increasingly been recognised as a passive system for reducing energy consumption and improving building performance. Underground buildings, in particular, have the potential to meet many of the criteria set by LEED guidelines and net-zero energy building standards.[12]

These advantages have drawn significant research attention to underground spaces and the utilisation of the ground's thermal capacity. Consequently, the number of studies focusing on energy performance in underground environments has shown an upward trend, peaking in 2016 (Figure 3). This trend reflects the growing appeal of the field over the past decade, largely driven by rapid urbanisation and the implementation of incentive policies in many countries.[13]

At the practical and case-study level, numerous field and numerical investigations have demonstrated that semi-underground and fully underground spaces effectively reduce daily and seasonal temperature fluctuations. These spaces provide enhanced cooling performance during summer and ensure more stable thermal conditions in winter compared with above-ground environments.[14]

Despite their long-standing historical role as passive architectural strategies, only a limited number of studies have examined the thermal comfort of Shavadans, with most research pri-

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7. Lawrence Wodehouse, *Indigenous Architecture Worldwide: A Guide to Information Sources* (Gale Research, 1980).

8. Amos Rapoport, 'Vernacular design as a model system,' *L. Asquith and M. Vellinga (ed. s), Vernacular Architecture in the Twenty-First Century (Theory, Education, and Practice), Taylor and Francis, London, UK* (2006).

9. Morteza Hazbei et al., 'Reduction of energy consumption using passive architecture in hot and humid climates,' *Tunnelling and Underground Space Technology* 47 (2015). A Benardos, I Athanasiadis, and N Katsoulakos, 'Modern earth sheltered constructions: A paradigm of green engineering,' *Tunnelling and Underground Space Technology* 41 (2014).

10. Akubue Jideofor Anselm, 'Passive annual heat storage principles in earth sheltered housing, a supplementary energy saving system in residential housing,' *Energy and Buildings* 40, no. 7 (2008).

marily focusing on their energy performance. Field measurements consistently demonstrate that Shavadans maintain moderate indoor temperatures while minimising seasonal fluctuations, highlighting their potential as resilient and energy-efficient architectural solutions.[15]

Numerical studies have proposed a range of strategies to enhance performance: Hazbei et al. (2015)[16] recommended shallower Shavadans, mechanical fans, and smart control systems to improve penetration of daylight and reduce humidity; Mohammadshahi et al. (2016, 2019)[17] analysed components such as kat, wide stairs, and shabestan, identifying forms that optimise ventilation; Samsam-Khayani et al. (2018)[18] demonstrated that adding tals improves air flow distribution; and Sadoughi et al. (2019)[19] confirmed effective thermal performance. Collectively, these studies underscore the efficiency of Shavadans in maintaining thermal comfort across seasons.

While these studies demonstrate thermal efficiency, understanding how these conditions affect human sensation requires predictive comfort models. The Fanger PMV–PPD model, developed based on experiments in climate-controlled chambers, is grounded in heat balance equations between the human body and its environment. Over the past fifty years, it has been widely applied and examined[20].

Several studies[21] explicitly or implicitly validated the model, while others(Enescu, 2017; Ikeda et al., 2021; Li et al., 2020) pointed to its limited predictive power.

Cheung et al. (2019)[22] reported that its accuracy in predicting actual thermal sensation was only 34%. Although reliable under uniform, controlled conditions, the model often fails in dynamic and heterogeneous real-world environments.[23] Its tolerance range for individuals in the same environment can exceed one unit[24], and it is valid primarily for healthy adults, often excluding children, the elderly, or people with disabilities.

In contrast, adaptive thermal comfort approaches link occupants' sensations to outdoor air temperature through linear regression and rely primarily on field data[25] . These approaches assume that humans actively interact with their thermal environment, incorporating physiological, behavioural, and psychological adaptation at a general level[26]. Because adaptive models are applied across diverse locations and conditions, they allow a wider acceptable range of indoor temperatures and have been integrated into international and national standards, playing a key role in energy-efficient building design and operation[27].

Despite the substantial body of evidence, a systematic gap remains in the Iranian literature and even in some international studies: the absence of comparative field research that simultaneously and survey-wise evaluates thermal comfort conditions—including temperature, humidity, air velocity, and human/subjective responses—in traditional underground spac-

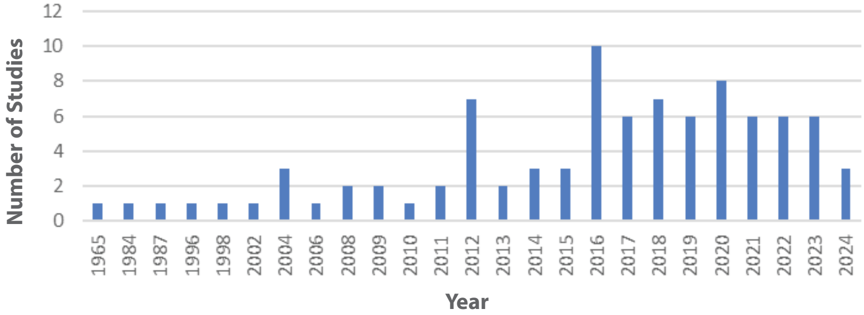

Figure 3. The number of studies on energy performance in underground buildings up to 2024.

11. Rajnish K Goel, Bhawani Singh, and Jian Zhao, *Underground infrastructures: planning, design, and construction* (Butterworth-Heinemann, 2012).

12. H Feng and K Hewage, 'Energy saving performance of green vegetation on LEED certified buildings,' *Energy and buildings* 75 (2014). AJ Marszal et al., 'Zero Energy Building–A review of definitions and calculation methodologies.: 971–9. 2011,' (2011).

es and modern above-ground buildings (with mixed or active ventilation systems) across both summer and winter seasons. Recent reviews have also emphassed the need to integrate field data, conduct statistical analyses (e.g., determining neutral temperature), and incorporate users' behavioural and psychological components into assessment models. This study addresses precisely this gap by collecting data from 10 Shavadans in Dezful and comparing them with above-ground buildings, providing new empirical evidence as well as practical design recommendations and decision-making criteria. Consequently, the scientific relevance and distinctive contribution of this research within the existing literature are clear and well-founded.

Research Methodology

Location and Climate

Dezful is located in the northern part of the Khuzestan Province in southern Iran. The city is built on a type of conglomerate that rises above the Dez River. According to the Köppen climate classification, Dezful has a hot semi-arid climate (BSh), with extremely hot summers and mild winters. Based on the effective temperature throughout the year, Dezful experiences cold conditions for 7.6% of the time, comfortable conditions in shaded areas for 29.1% of the time, and warm conditions for 63.7% of the time.[28]

Meteorological data over a 20-year period indicate that the city's maximum and minimum daily average temperatures are 41.4°C and 2.9°C, respectively. The maximum average relative humidity is 99%, and the minimum is 7.7%. Moreover, the city receives an average of 8.12 hours of sunshine per day (data from Safiabad Meteorological Office). Table 1 shows the 20-year climatic statistics of Dezful from 2002 to 2022 (1381–1401 in the Iranian calendar).

Table 1. Twenty-Year Climatic Data of City of Dezful.

Month (Gregorian)	Avg Daily Temp (°C)	Max Daily Temp (°C)	Min Daily Temp (°C)	Avg Monthly Precipitation (mm)	Avg Daily RH (%)	Max Daily RH (%)	Min Daily RH (%)	Avg Daily Sunshine Hours
March–April	21.3	29.8	12.3	39	56.4	95.3	24.7	7.3
April–May	27.9	36.4	16.4	20.2	40.9	90	16	8
May–June	33.6	40.7	26.5	0.3	26.5	51.3	7.7	10.4
June–July	36	40.6	30.2	0	25.9	49	8.7	10.8
July–August	36.6	41.4	32.3	0	29.8	59	11	10.7
August–September	33.6	39.5	25.9	1	37.1	69.7	10.3	10.2
September–October	28.3	35	18.4	1.6	44.8	76.5	14.3	9
October–November	21.4	29.5	12.8	41.9	60.1	95	28.5	6.8
November–December	15	22.2	5.2	65	72.2	99	31.5	5.9
December–January	12.5	18.7	4	44.2	73.4	99	36.5	5.8
January–February	13.4	21.4	2.9	44.2	69.4	96.5	33.5	5.8
February–March	17	25	8.1	32.3	62.9	97	33.5	6.7

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using variational autoencoder,' *Building and Environment* 207 (2022).

15. M. Bina, 'Climatic Analysis of Shavadans in the Traditional Houses of Dezful', *Honar-ha-ye Ziba* 33, no. 33 (2008),https://jhz.ut.ac.ir/article_19039_bdd8626d54f4f9bcae7ca0d993d60902.pdf; H. Moradi and H. Eskandari, 'An experimental and numerical investigation of Shovadan heating and cooling operation', *Renewable Energy* 48 (2012): 364–368.

Measurements

This study was conducted in two stages to estimate the comfort range and examine climatic variables in the Shavadans of Dezful. Ten Shavadans in the old part of Dezful were selected based on their depth and accessibility. Their names and general layout are presented in Figure 4, and the basic information of each is provided in Table 2.

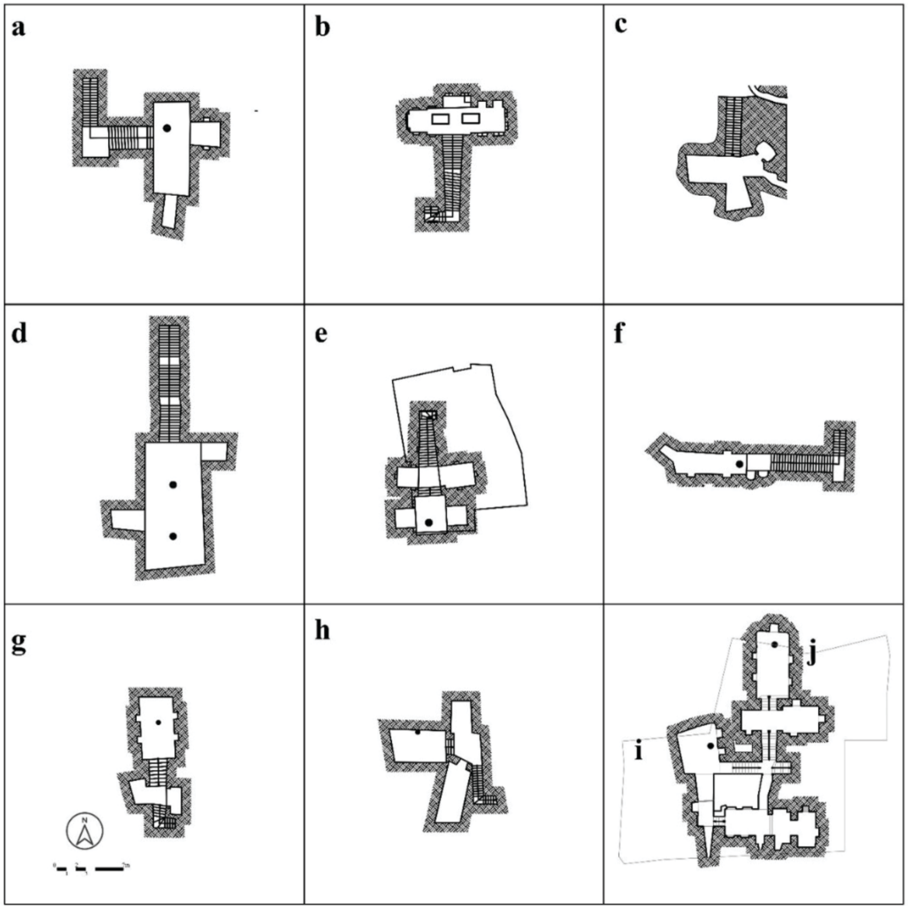
According to the results obtained by Heidari and Sharples, there was a very good agreement between short-term and long-term studies regarding thermal comfort in the city of Ilam. Based on this, the present research was conducted as a short-term study in the winter season from December 24 to December 31, 2022, and from July 1 to July 6, 2023.

Thermal comfort assessments and questionnaire collection were conducted in the main spaces of the Shavadans listed in Table 2, at the deepest section of each Shavadan, as well as in one room within the same buildings that was ventilated naturally and mechanically. However, the western Shavadan of the Saniee House was excluded due to a depth of less than 7 metres, and the Shavadans of Sheikh Rukn al-Din School and the Karnasion Mosque were excluded due to potential collapse and the presence of animals. After completing the measurements, the findings were compared with the climatic data recorded in the Shavadans and generalsed.

The main reason for not using globe temperature was the temperature stability in the basement and the absence of lighting equipment that could affect globe temperature. As noted in the study by Masoudinejad et al., there was no significant difference between globe temperature and air temperature at the depths of Shavadans. In the above-ground rooms, measurements were also conducted away from windows and artificial lighting.

During questionnaire completion, air temperature and relative humidity were measured simultaneously. Participants were required to refrain from eating and drinking for one hour prior to the measurements and to remain seated for at least 30 minutes. Measurements were taken at a height of 120 cm above the ground and in close proximity to the participants. Due to cultural considerations and privacy concerns,

Figure 4. The layout of selected Shavadans.



photographing participants during the survey was not permitted. Figure 5 illustrates the placement of measurement devices relative to the participants in a schematic form.

Air temperature, relative humidity, and airflow were measured at different depths, at points where entrances, landings or main spaces existed, for the ten selected Shavadans according to Figure 6. These measurements were conducted at three-hour intervals from 6:00 a.m. to 6:00 p.m. during both the summer and winter seasons.

Considering the limitations of private ownership of most Shavadans and the lack of calibrated equipment, the measurement schedule was designed to assess three Shavadans consecutively each day, based on the prioritsation in Table 3. This approach allowed for the optimisation of the measurement process and reduced potential errors caused by environmental varia-

16. 'Reduction of energy consumption using passive architecture in hot and humid climates'.

Shavadan Name	Shovadan Label	maximum depth (m)	Number of Darizehs	Number of windows at ground level	Location of Darizehs	Entrance Shape	Area of Main Sections (m^2)
Tizno's house	a	10.2	1		yard	on the floor	52
Ali Malik Shrine	b	8.8	0	1	-	on the wall	37
Sheikh Ruknuddin Dormitory School	c	6.6	0		-	on the floor	33
Dezful Grand Mosque	d	8	2		yard	on the floor	96
Seyed Shams-al-din's house	e	8	1		Roof	on the wall	41
Kornasian Mosque	f	9.8	1		yard (was closed)	on the floor	25
Razavizadeh house	g	9.2	1		The room (was closed)	on the floor	37
Morid house	h	8.35	1		Street on the shade	on the wall	48
Sanaee's house West Shavadan	i	3.6	1		Room	on the floor	21
Saniee's house North Shavadan	j	6.8	1		Room	on the floor	44

Table 2. Properties of Shavadans.

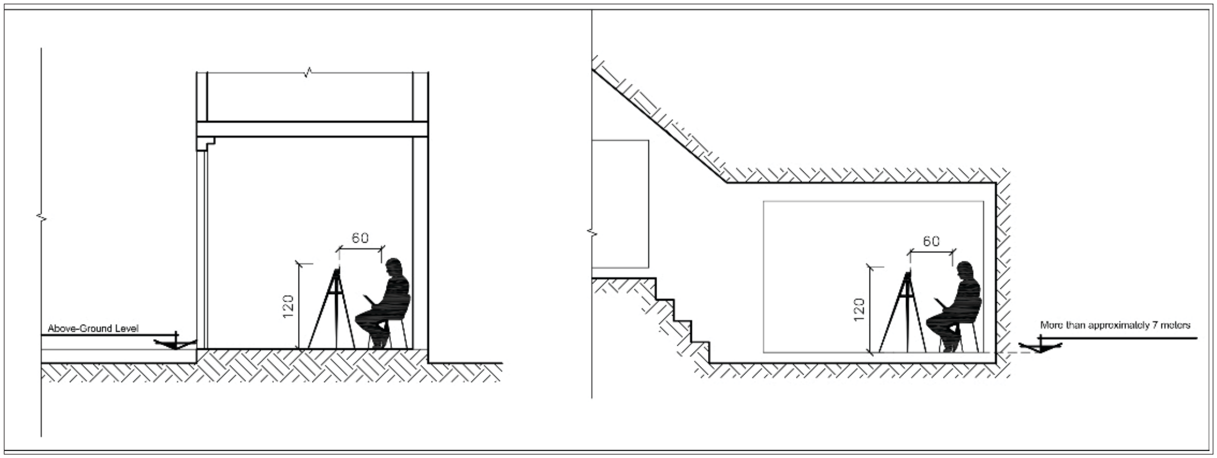


Figure 5. Schematic representation of measuring equipment placement to participants, with sensors positioned at 1.2 metres to align with the breathing zone of seated individuals.

tions. Due to these constraints, the measurements and questionnaire collection were conducted on separate days, with some overlap. Details of the instruments used for both sets of measurements are provided in Table 3.

Study Participants

In this field study, 225 volunteers (116 women and 109 men) residing in residential buildings throughout Dezful participated. Efforts were made to ensure a balanced distribution in terms of age and gender, and residents of the selected houses were also included in the study. In total, 422 valid questionnaire datasets were collected. Specifically, during the winter season, 102 datasets were obtained for above-ground rooms and 102 for Shavadans, while in the summer season, 109 datasets were collected for above-ground rooms and 109 for Shavadans. Table 4 summarses the physical characteristics of the participants. All participants had lived in Dezful for at least 15 years, and their experiences reflect the climatic adaptation of the local residents.

questionnaires

The questionnaires were of the Level 3 type, as described in the study by Nicol et al., meaning that, in addition to environmental measurements, clothing insulation, activity, movement from one point to another, and other factors were also assessed. The questionnaires were completed between 8:00 a.m. and 6:00 p.m. in the deepest section of the Shavadans (over 7 metres) and in above-ground buildings. All questions and subjective scales were explained

Table 3. Detailed information on related instruments.

Parameters	Instrument	Range	Accuracy
Air temperature	CEM-DT-172/172TK	-40 to 70℃	±0.5 ◦C
Relative humidity		0 to 100%	±3.5%
Air velocity	Benetech-GT8911	0 to 30 m/s	±3%

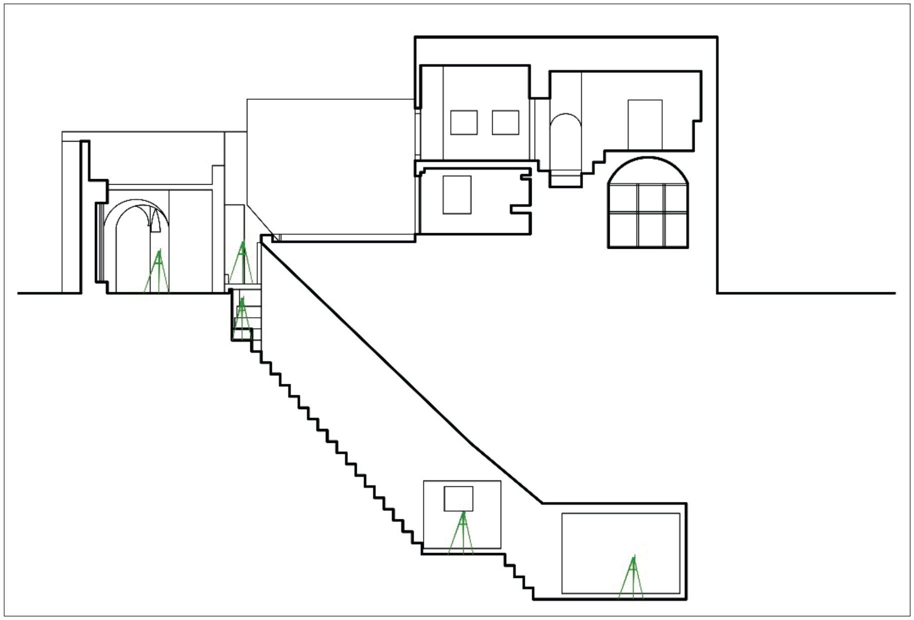


Figure 6. Schematic Position of Measurement Equipment at Various Depths of Shavadans.

Gender	N	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m²)	Clothing Insulation (clo)
Female	116	39.34 ± 15.60*	160 ± 5.69	63.42 ± 12.71	24.57 ± 4.72	0.48 ± 0.17
Male	109	45.48 ± 13.8	170.23 ± 12.59	79.43 ± 9.57	28.00 ± 12.02	0.55 ± 0.25
Total	225	42.52 ± 15.14	165.85 ± 11.03	71.24 ± 13.83	26.50 ± 9.21	0.52 ± 0.22

*. Standard Deviation

Table 4. Physical Information of Participants.

to participants before the start of the survey.

The questionnaire consisted of three sections: the first section included personal information such as gender, age, height, weight, and type of clothing, which was completed by the participant under the supervision of the researcher. The second section focused on evaluating the participants' thermal sensation, using the seven-point ASHRAE scale. In addition, thermal preferences were assessed simultaneously with the measurement and recording of air temperature and relative humidity (Tables 5 and 6).

All scales are presented in the corresponding charts in the Results section. Clothing insulation was determined by summing the insulation values of individual clothing items based on ASHRAE standards and the 2020 guidelines.

The third section of the questionnaire focused on evaluating participants' behavioural priorities under cold and hot weather conditions. For the cold season, the options included: 'drawing curtains to allow sunlight in', 'turning on heating devices', 'moving to a warmer place', 'wearing additional clothing', 'consuming warm food and beverages', 'taking a warm shower,' and 'other actions', For the summer season, the options included: 'opening doors and windows', 'turning on cooling devices', 'moving to a cooler environment', 'wearing lighter clothing,' 'consuming cold food and beverages', 'taking a cold shower', and 'other actions'.

Questionnaire Reliability and Validity

To assess the reliability of the questionnaire, two methods were applied: Cronbach's alpha and split-half reliability. Initially, Cronbach's alpha was calculated for the variables of air temperature and thermal sensation in both summer and winter seasons, yielding values of 0.63 in summer and 0.62 in winter. These values indicate moderate reliability, which is slightly below the reference standard of 0.7 commonly considered acceptable for good reliability. However, in thermal comfort studies, multiple factors such as humidity, airflow, and individual conditions influence the results, so a lower Cronbach's alpha does not necessarily indicate a weak questionnaire.

For a more precise evaluation of reliability, the split-half method was employed, in which the data were randomly divided into two halves and the correlation between them was assessed. The results showed a reliability of 1.0 in both seasons, indicating perfect correlation between the randomly split halves and very high reliability. These findings demonstrate that the questionnaire is sufficiently reliable and provides consistent results across both seasons. They confirm that the relationship between air temperature and thermal sensation in the collected data is stable, making the use

Table 6. Thermal Preference Scale (ASHRAE).

Thermal Preference	Warmer	No Change	Cooler
ASHRAE Scale	+1	0	–1

Table 5. Thermal Sensation Scale (ASHRAE 7-point).

Thermal Sensation	Very Hot	Hot	Slightly Warm	Neutral	Slightly Cool	Cool	Very Cold
ASHRAE Scale	+3	+2	+1	0	–1	–2	–3

17. Shabnam Mohammadshahi, Mahdi Nili-Ahmadabadi, and Omid Nematollahi, 'Improvement of ventilation and heat transfer in Shavadoon via numerical simulation: A traditional HVAC system', Renewable Energy 96 (2016); Shabnam Mohammadshahi et al., 'Investigation of naturally ventilated shavadoons component: Architectural underground pattern on ventilation' *Tunnelling and Underground Space Technology* 91 (2019).

18. Hadi Samsam-Khayani et al., 'Numerical study of effects of Shavadoon connections (a vernacular architectural pattern) on improvement of natural ventilation' *Tunnelling and Underground Space Technology* 82 (2018).

19. Arezou Sadoughi et al., 'Thermal performance analysis of a traditional passive cooling system in Dezful, Iran', *Tunnelling and Underground Space Technology* 83 (2019).

of these indicators for thermal comfort analysis both reasonable and valid. Therefore, although Cronbach's alpha indicated moderate reliability, the split-half results confirm the reliability and suggest that the collected data are trustworthy. Consequently, this questionnaire is considered a valid and reliable tool for analyzing thermal sensation under different climatic conditions.

To ensure the validity of the questionnaire, content validity was applied. The questionnaire was developed based on previous successful studies and reviewed by experts in the field of thermal comfort, with necessary modifications made according to their recommendations. This review confirmed that the designed questions effectively measure the intended variables, indicating that the questionnaire has appropriate content validity.

Results

Environmental Thermal Conditions

Figure 7 illustrates the temporal variations of the outdoor environmental parameters. During the study period, the average daily outdoor temperature was 12.8°C in winter and 36.2°C in summer. The average daily relative humidity was 85% in winter and 25% in summer. These values are in good agreement with the long-term data for the months of Dey (December, January) and Tir (June and July) presented in Table 2, indicating stable climatic conditions during the measurement period. For example, the average daily temperature in Dey and Tir in Table 2 was 12.5°C and 36.0°C, respectively, which corresponds well with the measurements obtained in this study.

Participant Evaluation

Thermal Sensation and Preference

The distribution of thermal sensation votes (TSV) across summer and winter revealed distinct seasonal patterns between the above-ground rooms and the Shavadan. In summer, most responses were concentrated in the neutral (TSV = 0) and slightly warm (TSV = +1) categories. A higher proportion of respondents in the above-ground rooms reported feeling slightly warm, whereas in the Shavadan, a larger share of votes fell into the neutral category. Additionally, a small fraction of votes at votes of TSV = +2 were observed in both spaces, and TSV = +3 appeared only in the above-ground rooms. This pattern indicates that the Shavadan provided more balanced and neutral conditions, while above-ground rooms tended to shift toward warmer sensations (Figure 8).

In winter, the the majority of responses in both spaces were concentrated in the neutral category (TSV = 0), with 77.5% in the above-ground rooms and 72.5% in the Shavadan. A

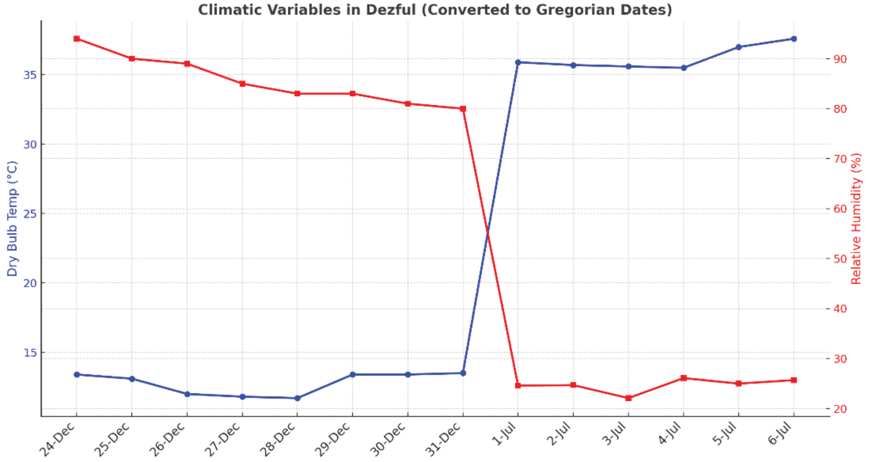


Figure 7. Daily mean outdoor temperature and relative humidity during the study period.

considerable share of respondents reported slightly cool sensations (TSV = -1). However, the proportion of slightly warm responses (TSV = +1) was notably higher in the Shavadan (11.8%) compared with the above-ground rooms (2.9%). This suggests that in winter, the Shavadan exhibited a greater tendency towards warmer sensations, likely due to its higher thermal mass and heat retention properties (Figure 9).

Overall, the comparison across the two seasons shows that the Shavadan acted as a thermally moderating space: reducing the tendency toward heat stress in summer while providing slightly warmer conditions in winter, thereby ensuring a more stable and comfortable indoor environment throughout the year.

As shown in Figure 10, in summer, the majority of responses were concentrated in the cooler (-1) category. More than 70% of respondents in both the above-ground rooms (71.6%) and the Shavadan (72.5%) expressed a preference for lower temperatures. Approximately 28% selected no change (0), while virtually none of the respondents opted for the warmer (+1) category. This pattern suggests that even within the Shavadan, the prevailing tendency in summer was a desire for cooler conditions, reflecting the intensity of outdoor heat stress.

In winter (Figure 11), the distribution shifted, with the majority of responses falling into the no change (0) category (61.8% in above-ground rooms and 58.8% in the Shavadan). At the same time, a significant proportion of respondents expressed a preference for warmer conditions (+1), accounting for 35.3% in above-ground rooms and 25.5% in the Shavadan. A smaller fraction selected the cooler (-1) option, with slightly higher values reported in the Shavadan (15.7%) compared with the above-ground rooms (2.9%).

Overall, the seasonal comparison highlights that in summer, occupants predominantly preferred cooler conditions, whereas in winter, most considered the existing conditions acceptable, with a notable share showing a tendency towards warmer indoor environments (Table 7).

Figure 8. Distribution of participants' thermal sensation votes in summer (Above-ground vs. Shavadan).

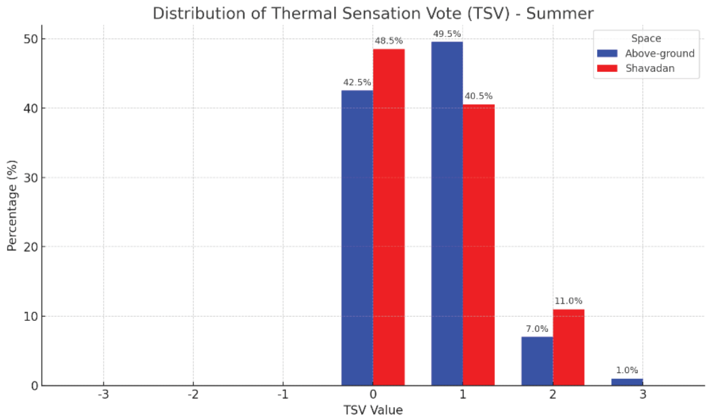
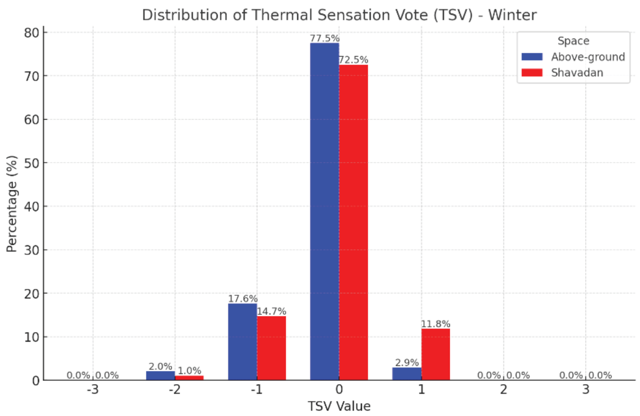


Figure 9. Distribution of participants' thermal sensation votes in winter (Above-ground vs. Shavadan).



In summer, both above-ground rooms and the Shavadan showed a dominant preference for cooler conditions (-1). In above-ground rooms, a considerable share of respondents at TSV = +1 (slightly warm) expressed a desire for cooler environments. By contrast, in the Shavadan, the distribution was more balanced, with a larger proportion of votes concentrated around the neutral category (TSV = 0). This indicates that the Shavadan provided more stable and neutral thermal conditions compared with above-ground spaces (Figure 11).

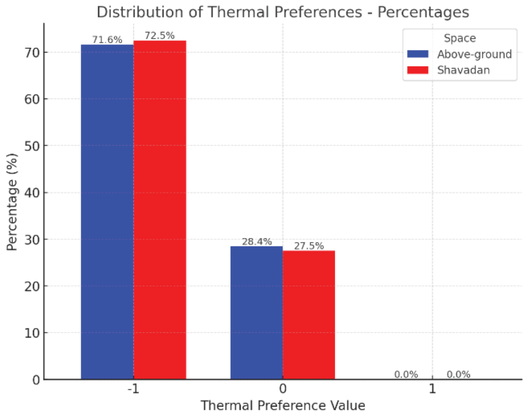
In winter, neutral sensations (TSV = 0) dominated in both environments. However, thermal preferences revealed differences: in above-ground rooms, the majority selected no change (0), while in the Shavadan a higher share of participants expressed a preference for warmer conditions (+1). This reflects the Shavadan's ability, due to its higher thermal mass and heat retention, to provide slightly warmer and more stable conditions than the above-ground rooms (Figure 12).

Neutral Temperature and Comfort Range

The regression analysis revealed a clear relationship between air temperature and thermal sensation, enabling the estimation of neutral temperatures and acceptable comfort ranges for both above-ground rooms and Shavadans. As shown in Table 8, in summer the neutral temperature in above-ground rooms was higher, while the Shavadan shifted this point to a cooler level, thereby reducing the sensation of heat stress and providing more favorable indoor conditions. In winter, the neutral temperatures of both spaces were close to each other, but the Shavadan displayed more stable and consistent thermal responses, as indicated by its higher coefficient of determination. The acceptable comfort ranges confirmed this pattern: in above-ground rooms, ranges tended to be slightly wider and more influenced by fluctuations in ambient conditions, while in Shavadans they were narrower and more stable, reflecting the buffering effect of underground construction.

When comparing the two analytical approaches, simple regression (Table 8) suggested

Figure 10. Thermal preference distribution in summer (Above-ground vs. Shavadan).



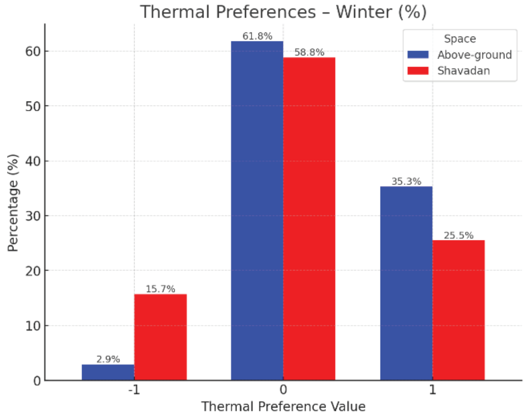


Figure 11. Thermal preference distribution in winter (Above-ground vs. Shavadan).

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20. anisius Karyono et al., 'The adaptive thermal comfort review from the 1920s, the present, and the future', *Developments in the Built Environment* 4 (2020). Mohammad Tahsildoost and Zahra S Zomorodian, 'Indoor environment quality assessment in classrooms: An integrated approach', *Journal of Building Physics* 42, no. 3 (2018); Qiantao Zhao, Zhiwei Lian, and Dayi Lai, 'Thermal comfort models and their developments: A review', *Energy and Built Environment* 2, no. 1 (2021).

Season / Index	Space	Dominant TSV Pattern	Dominant Thermal Preference	Key Interpretation
Summer	Above-ground	TSV mostly at 0 and +1, some at +2 and +3	Majority Cooler (-1) (71.6%)	More tendency towards warmer TSV than Shavadan, but still strong desire for cooling
	Shavadan	TSV mostly at 0, then +1, minor at +2	Majority Cooler (-1) (72.5%)	More stable and closer to neutrality compared with above-ground
Winter	Above-ground	TSV mainly 0 (77.5%), then -1, small share at +1	Majority No change (0) (61.8%), followed by Warmer (+1) (35.3%)	Mostly neutral, but noticeable demand for warmer conditions
	Shavadan	TSV mainly 0 (72.5%), then -1, higher share at +1 (11.8%)	Majority No change (0) (58.8%), followed by Warmer (+1) (25.5%)	Slightly greater tendency towards warmer sensations than above-ground, overall stable

Table 7. Seasonal comparison of thermal sensation (TSV) and thermal preference in Above-ground rooms and Shavadan.

meaningful differences in neutral temperatures and comfort boundaries, but the Bin Method (Table 9) provided stronger correlations, with coefficients of determination reaching up to 0.93, reinforcing the robustness of the findings. The distribution of TSV responses, illustrated in Figures 14 and 15, also highlighted distinct seasonal patterns: in summer, responses clustered around neutral (TSV=0) and slightly warm categories, with the Shavadan showing a higher share of neutral votes, while in winter the majority of responses were neutral or slightly cool, again with the Shavadan offering more stable thermal conditions closer to neutrality.

Overall, the combined evidence from regression models, bin-method analysis, and the distribution charts (Figures 14-15, Tables 8-9) highlight that Shavadans are able to lower neutral temperature in hot conditions and maintain a stable, near-neutral indoor climate in cooler seasons.

Correlation between Clothing Thermal Insulation, Humidity, Airflow, and Thermal Sensation

Given that the clothing insulation rate of most participants fell within a narrow range, no con-

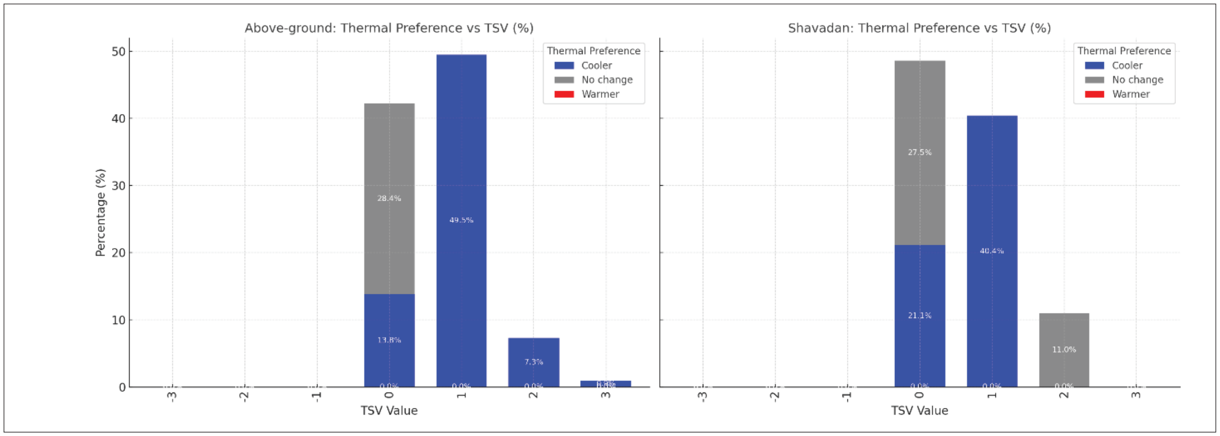


Figure 12. Thermal sensation and preference in summer (Above-ground vs. Shavadan).

21. PO Fanger, 'Fundamentals of thermal comfort', in *Advances In Solar Energy Technology* (Elsevier, 1988). Abed Al-Waheed Hawila et al., 'An analysis of the impact of PMV-based thermal comfort control during heating period: A case study of highly glazed room', *Journal of Building Engineering* 20 (2018). P. Ole Fanger and Jørn Toftum, 'Extension of the PMV model to non-airconditioned buildings in warm climates',

siderable variation in clo values was observed. Moreover, the regression analysis indicated that the relationship between clothing insulation, relative humidity, and air velocity with thermal sensation vote (TSV) was weak and statistically insignificant, as the coefficient of determination (R^2) for all cases was found to be below 0.1. This suggests that these factors did not play a decisive role in explaining the variations in TSV.

Behavioural Adaptation

In the summer season, 70% of the respondents reported prioritising the use of cooling devices such as evaporative and air conditioners. Around 30% preferred wearing light and bright clothing, while only 10% referred to changes in dietary habits, such as consuming cold drinks. These findings highlight the greater emphasis of residents on direct strategies for reducing heat stress (Figure 16).

In the winter season, 60% of the respondents indicated that wearing warmer clothing was the most important strategy for coping with cold conditions. Meanwhile, 40% reported using heating appliances such as heaters and fireplaces. Only 15% mentioned reducing the time spent in outdoor spaces, suggesting that the mild winters of Dezful have a limited impact on daily activities (Figure 17).

Environmental Variables in Shavadans and Thermal Comfort Range

Air temperature, relative humidity, and air velocity were monitored at different depths of ten Shavadans during winter and summer, with measurements taken every three hours from 6 a.m.

Season / Space	Regression Equation for TSV	R^2	Slope	Lower Comfort Limit (°C)	Upper Comfort Limit (°C)	Neutral Temperature (°C)
Summer – Above-ground	TSV = 0.28 Air Temperature – 7.57	0.56	0.28	24.9	28.4	26.6
Summer – Shavadan	TSV = 0.24 Air Temperature – 5.97	0.28	0.24	22.4	26.5	24.5
Winter – Above-ground	TSV = 0.20 Air Temperature – 4.53	0.34	0.20	20.0	25.0	22.5
Winter – Shavadan	TSV = 0.24 Air Temperature – 5.44	0.36	0.24	21.0	25.2	23.1

Table 8. Regression models of TSV and comfort temperatures for Above-ground rooms and Shavadan (summer and winter).

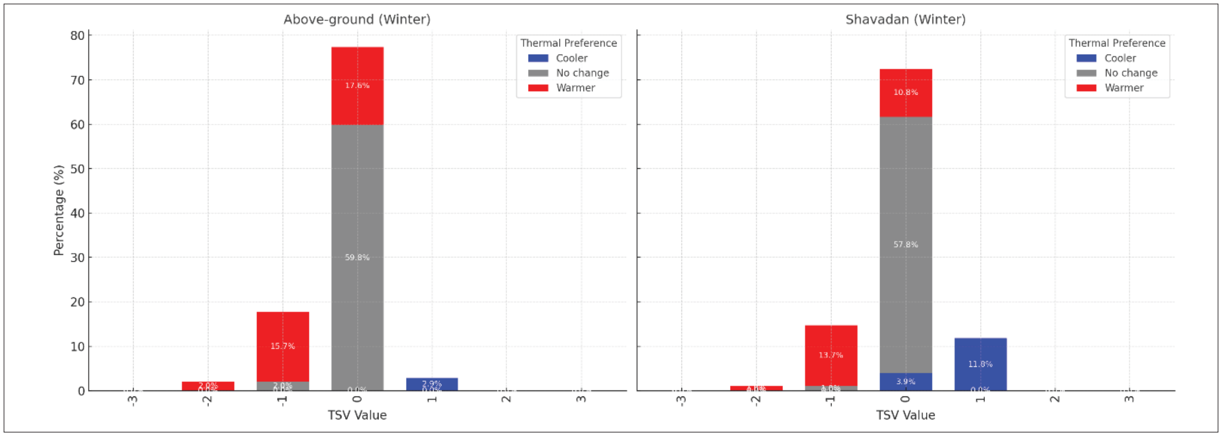


Figure 13. Thermal sensation and preference in winter (Above-ground vs. Shavadan)
Neutral Temperature and Comfort Range.

Energy and Buildings 34, no. 6 (2002); Naji Sirhan and Saar Golan, 'Efficient PMV computation for public environments with transient,' *Energy and Buildings* 231 (2021). Jorn Toftum, Anette S. Jorgensen, and P. O. Fanger', *Energy and Buildings* 28, no. 1 (1998). Jing Wu et al., 'A PMV-based HVAC control strategy for office rooms subjected to solar radiation,' *Building and Environment* 177 (2020).

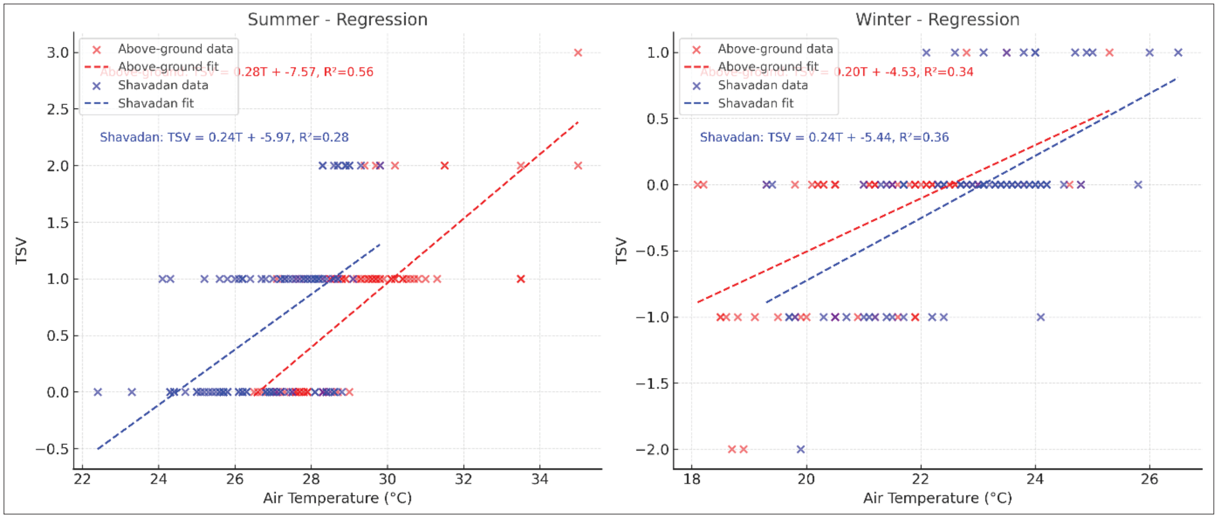


Figure 14. Regression of TSV and air temperature in above-ground rooms (red) and Shavadan (blue) during summer (left) and winter (right).

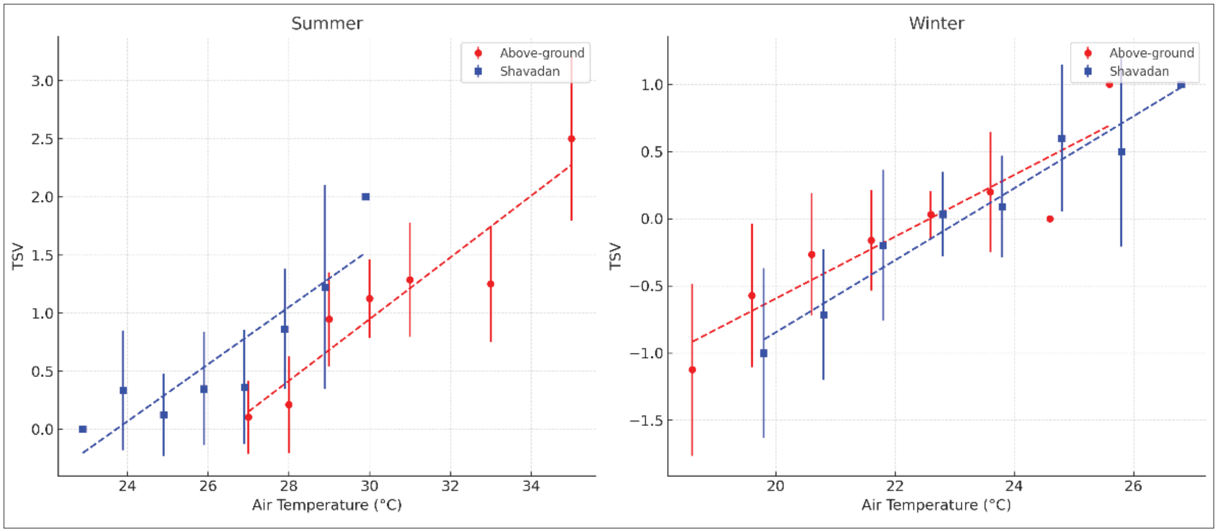


Figure 15. Bin Method analysis of TSV and air temperature in above-ground rooms (red) and Shavadan (blue) during summer (left) and winter (right).

Table 9. Regression models on bin means of TSV and comfort temperatures for Above-ground rooms and Shavadan (summer and winter).

Season/Space	Regression (on bin means)	R²	Slope	Neutral Temp (°C)	Lower (Neutral−2)	Upper (Neutral+2)
Summer – Above-ground	TSV = 0.21· Air Temperature – 5.54	0.80	0.21	25.9	23.9	27.9
Summer – Shavadan	TSV = 0.22· Air Temperature – 5.23	0.80	0.22	23.6	21.6	25.6
Winter – Above-ground	TSV = 0.23· Air Temperature – 5.10	0.86	0.23	22.6	20.6	24.6
Winter – Shavadan	TSV = 0.26· Air Temperature – 6.08	0.93	0.26	23.2	21.2	25.2

to 6 p.m. In winter, all parts of the Shavadans remained within the thermal comfort range.

Air Temperature

The depth of 5–7 metres showed the closest temperature to the neutral point (22.7 °C). While the courtyard reached a maximum of 19.5 °C, the above-ground room and Shavadans at depths of 1–3 m, 3–5 m, 5–7 m, and >7 m recorded maximum values of 22.4, 21.4, 21.8, 21.9, and 24.2 °C, respectively. Minimum temperatures varied from 16.8 °C in the courtyard to 24.0 °C at depths greater than 7 m, confirming the stabilsing effect of underground spaces (Figure 18).

Detailed results of the summer monitoring campaign were reported in our previous study. In summary, only the average air temperatures below depths greater than 5 m remained within the comfort range, with the deepest zone (>7 m) being up to 16.1 °C cooler than the courtyard during peak heat hours. The present analysis therefore focuses on winter results as a complement to those earlier findings.

Relative humidity

In winter, relative humidity increased with depth and reached its lowest values around noon due to rising air temperature. The courtyard showed maximum and minimum values of 45.1% and 36.7%, while at depths greater than 7 m, values ranged from 49.6% to 44.7%. The above-ground room and Shavadans at 1–3 m, 3–5 m, and 5–7 m recorded maximum values of 45.0%, 43.4%, and 48.3%, respectively. Table 21 summarses these results, alongside the comfort range (Figure 19).

As previously documented, summer results also showed an increase in humidity with depth, with the highest values observed below 7 m (up to 42.8%), while the courtyard and above-ground room had considerably lower values.

Air velocity

Air velocity inside the Shavadans was minimal in both seasons. In winter, the courtyard reached a maximum of 0.45 m/s, while the underground sec-

Figure 16. Behavioural adaptations in summer.

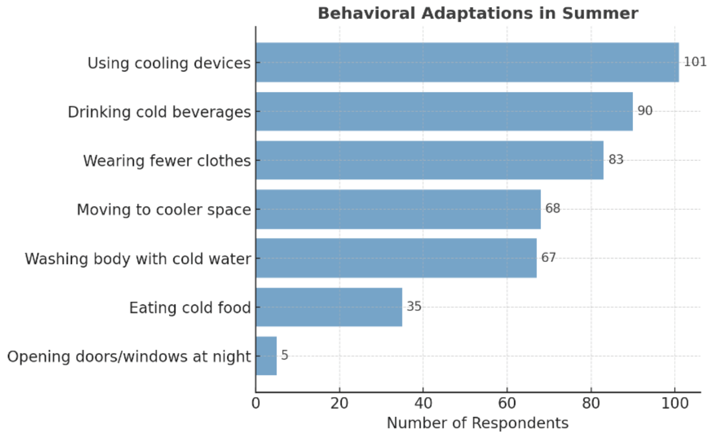
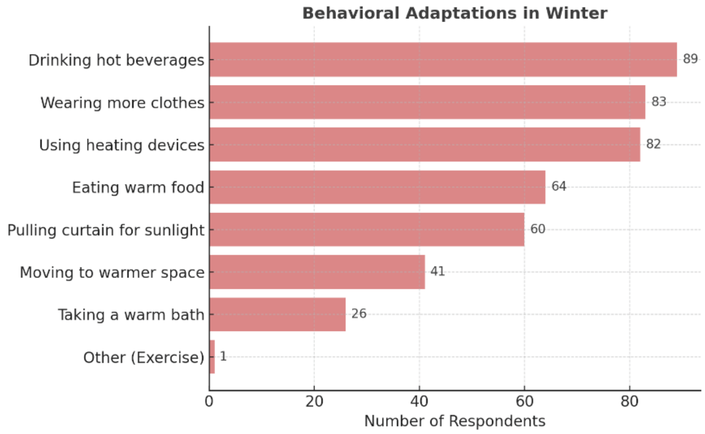


Figure 17. Behavioural adaptations in winter.



22. Toby Cheung et al., 'Analysis of the accuracy on PMV–PPD model using the ASHRAE Global Thermal Comfort Database II,' *Building and Environment* 153 (2019).

23. Qian Chai et al., 'Using machine learning algorithms to predict occupants' thermal comfort in naturally ventilated residential buildings,' *Energy and Buildings* 217 (2020).

tions fell below 0.1 m/s. At depths of 1–3 m, 3–5 m, 5–7 m, and >7 m, maximum values were 0.05, 0.04, 0.02, and 0.02 m/s, respectively (Figure 20).

For summer, velocities were slightly higher in the courtyard (up to 0.47 m/s), but remained very low inside the underground sections, consistent with the stabilising nature of the spaces. Detailed values have been reported previously.

Discussion

The findings of this study reveal that Shavadans maintain significantly cooler and more stable

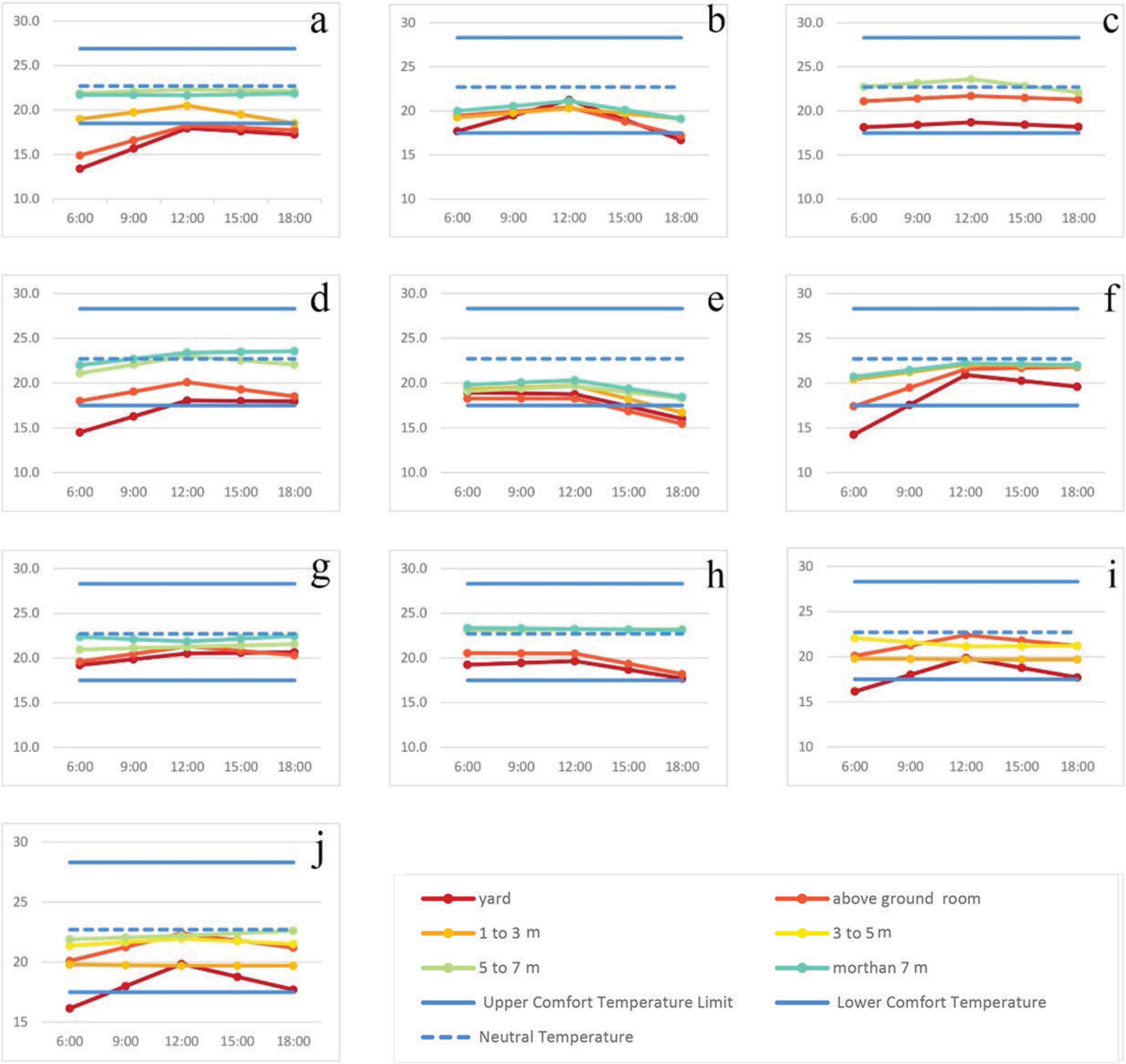


Figure 18. Comparison of air temperature at different depths with the comfort range in winter.

24. Sunil Kumar Sansaniwal, Mathur Jyotirmay, and Sanjay and Mathur, 'Review of practices for human thermal comfort in buildings: present and future perspectives,' *International Journal of Ambient Energy* 43, no. 1 (2022).

25. R. de Dear et al., 'A review of adaptive thermal comfort research since 1998,' *Energy and Buildings* 214 (2020).

26. Jeetika Malik, Ronita Bardhan, and Pradipta Banerji, 'Rethinking indoor thermal comfort in the era of rebound and pre-bound effect for the developing world: A systematic review,' *Indoor air* 30, no. 3 (2020).

27. Runa T. Hellwig et al., 'A framework for adopting adaptive thermal comfort principles in design and operation of buildings,' *Energy and Buildings* 205 (2019).

indoor environments in summer compared with above-ground rooms, with temperature differences of up to 16.1 °C relative to outdoor courtyards being recorded. This outcome confirms that Shavadans, through their depth, thick walls, and earthen materials, function similarly to earth-sheltered buildings, as emphassed in previous reviews highlighting the role of ground thermal mass in stabilsing indoor environments[29]. In winter, relatively stable conditions were also observed, although above-ground rooms occasionally provided higher comfort.

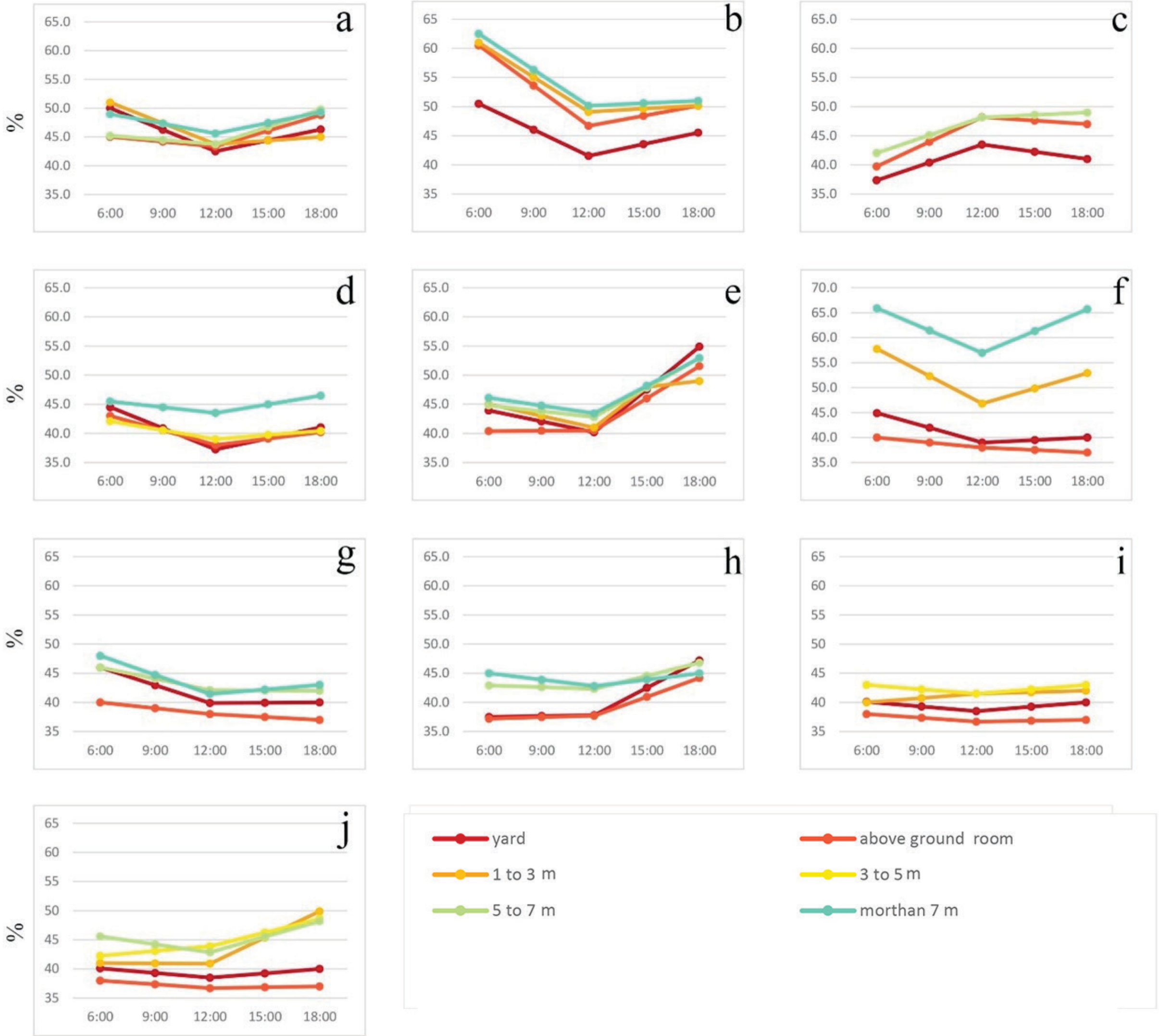


Figure 19. Comparison of relative humidity at different depths in winter.

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28. Zahra Hejazizadeh, Seyed Morovat Eftekhari, and Hiva Solki, 'Optimising the orientation of open spaces in Dezful based on climatic conditions,' *Geography* 10, no. 32 (2012).

29. Giouli Mihalakakou et al., 'Earth-sheltered buildings: A review of modeling, energy conservation, daylighting, and noise aspects,' *Journal of Cleaner Production* 472 (2024); Yu, Kang, and Zhai, 'Advances in research for underground buildings: Energy, thermal comfort and indoor air quality.'

A key finding of this study was the important role of seasonal expectations in shaping thermal comfort. In Dezful's hot climate, where high temperatures dominate much of the year, many participants reported that during January and February they expected cooler weather, describing this period as 'a little colder.' This observation is consistent with Luo et al.[30], who argued that seasonal expectations may dominate other comfort factors. Similarly, Cao et al.[31] confirmed that local climate significantly influences thermal comfort and adaptive capacity.

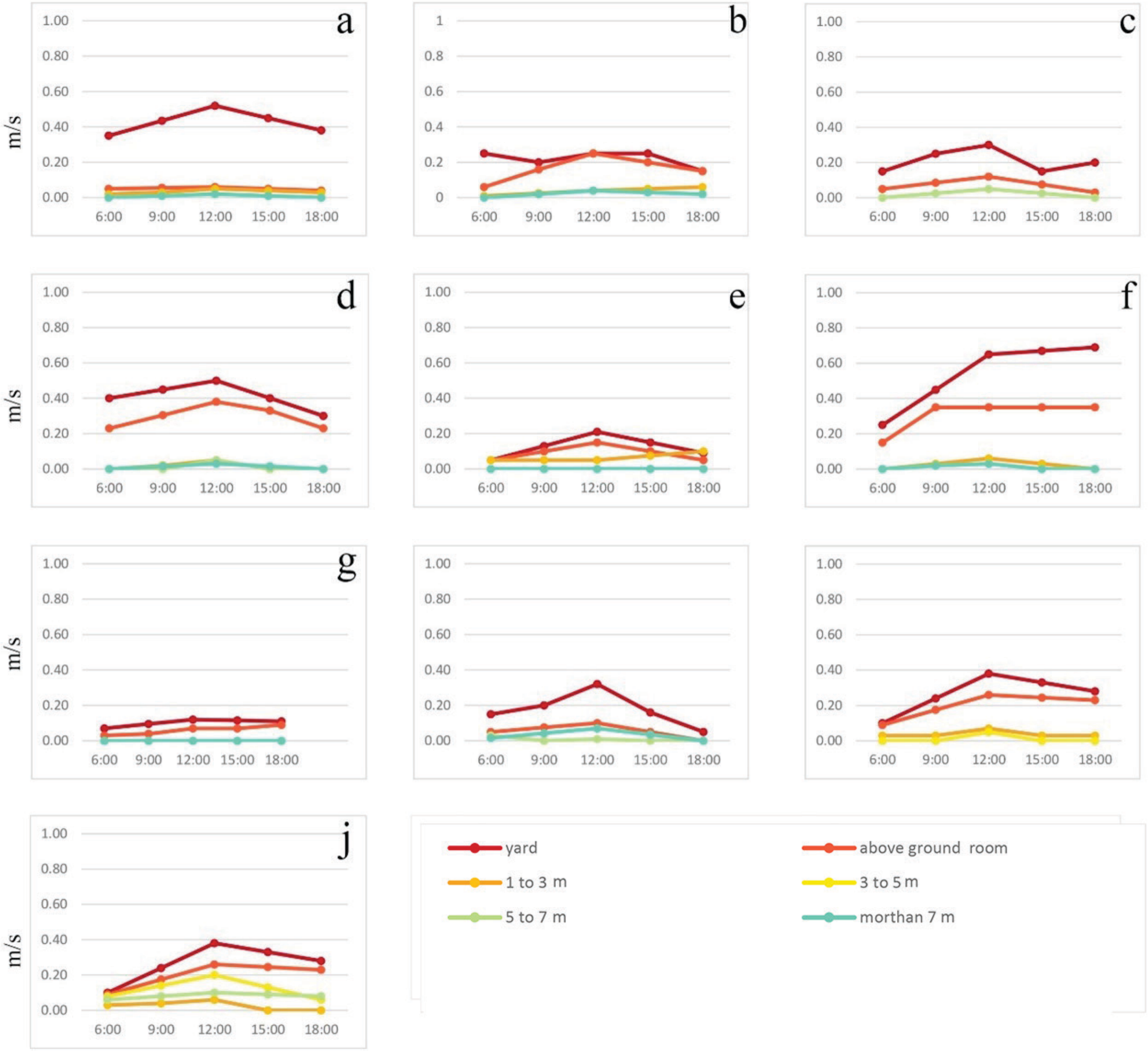

Figure 20. Comparison of air flow velocity at different depths in Shavadans during winter.

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30. Maohui Luo et al., 'The underlying linkage between personal control and thermal comfort: psychological or physical effects?,' *Energy and Buildings* 111 (2016).

31. Bin Cao et al., 'Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing,' *Energy and Buildings* 43, no. 5 (2011).

In Dezful's mild winters, indoor temperatures in residential spaces often remained within the comfort zone, and thus adaptive behaviours were limited to personal strategies such as wearing warmer clothing or drinking hot beverages. This is consistent with Rissetto et al.[32], who demonstrated that occupant expectations positively affect comfort and adaptive actions. Cognitive mechanisms, including attitudes, perceived control, self-efficacy, personal norms, and thermal history, were also found to play a role in shaping indoor expectations.

Regarding physical factors, Bahdad and Fadzil[33] showed that wall thickness and soil thermal conductivity are among the most influential parameters for thermal comfort and energy performance in underground spaces. The results of the present study indicated that Shavadans naturally apply these principles without mechanical energy input. Furthermore, Li et al.,[34] in a large-scale field investigation across 95 Chinese cities, found significant discrepancies between PMV and actual mean thermal sensation (AMTS), confirming that adaptive models provide a more accurate representation in underground environments. Field evidence from the current study aligned with these findings.

Humidity was also found to be a critical factor. Liu et al.[35] demonstrated that dry-bulb temperature alone is insufficient to evaluate comfort in underground hydropower tunnels, and humidity must be considered. Similarly, in Shavadans, high winter humidity at depths greater than 7 m resulted in warmer thermal sensations than air temperature alone suggested. The mean air temperature difference between summer and winter at this depth was approximately 2 °C, which corresponds well with the findings of Sadoughi et al.[36], who reported a difference of 1.22 °C. These consistencies add validity to the results and highlight the natural thermal stability of Shavadans.

Ventilation measurements showed that airflow inside Shavadans was minimal, and thermal stability was primarily achieved through massive walls rather than ventilation. This finding is consistent with Wen et al.[37], who emphassed that effective natural ventilation in underground spaces cannot rely on multiple openings alone but requires integrated above- and below-ground design.

From a behavioural perspective, it was observed that occupants adapted by using cooling devices and lighter clothing in summer and warmer clothes or heating appliances in winter. These adaptive actions are consistent with the adaptive comfort model[38] and confirm that thermal comfort emerges from the interaction between human behaviour and building characteristics. At the same time, psychosocial research[39] suggested that underground spaces may cause feelings of isolation or insecurity; However, Shavadans, rooted in the cultural and historical context of Dezful, can also contribute to strengthening social identity.

In summary, several innovations were achieved in this study:

- Two-season field data collection under real-life conditions.
- Direct comparison between Shavadans and above-ground mixed-mode rooms.
- Simultaneous analysis of thermal, humidity, and adaptive behaviour.
- Consideration of seasonal expectations and psychosocial dimensions of comfort.
- Emphasis on the cultural and social values of

[32] Romina Rissetto, Riklef Rambow, and Marcel Schweiker, 'Assessing comfort in the workplace: A unified theory of Behavioural and thermal expectations,' *Building and Environment* 216 (2022).

[33] Ali Ahmed Salem Bahdad and Sharifah Fairuz Syed Fadzil, 'An Investigation-Based Optimisation Framework of Thermal Comfort Analysis in Underground Enclosed Spaces Affected by Multiple Parameters for Energy Performance in Tropics,' *Journal of Daylighting* 9, no. 1 (2022).

[34] Yong Li et al., 'Study of thermal comfort in underground construction based on field measurements and questionnaires in China,' *Building and Environment* 116 (2017).

[35] Fuquan Liu et al., 'Thermal comfort in typical seasons of summer and winter in personnel intensive areas of underground public buildings of Xi'an in China,' *Thermal Science*, no. 00 (2025).

[36] Sadoughi et al., 'Thermal performance analysis of a traditional passive cooling system in Dezful, Iran.' (2019)

vernacular underground architecture.

Unlike many simulation-based studies (e.g., EnergyPlus, CFD), which are often limited by the absence of real user data, this study provided a more realistic depiction of thermal comfort in underground environments. As Yu et al.,[40] emphassed, field investigations are essential to complement simulation research. Ultimately, Shavadans were shown to achieve thermal comfort without mechanical energy, effectively resolving the trade-off between energy consumption and comfort, and offering a sustainable and inspiring model for the design of underground spaces in hot-arid climates.

Limitations

This study faced several limitations. One of the main constraints was the private ownership of most Shavadans, which made long-term occupancy impossible. As a result, the investigation was conducted as a short-term study. Nevertheless, comparison of the findings with other studies indicates that no significant differences exist between these results and those of long-term investigations, as discussed in the 'Discussion' section.

In addition, air temperature was used in this study to assess thermal comfort conditions as well as the thermal performance of Shavadans. Although globe temperature was not measured, due to the stability of temperatures at greater depths and the uniformity of thermal conditions, it can be reasonably assumed that the results would have been consistent if globe temperature had also been considered.

Furthermore, the abandoned state of some Shavadans, the risk of structural collapse, and the presence of certain animals prevented the completion of thermal comfort questionnaires directly inside them.

Future Research Directions

The present study highlighted the potential of Shavadans in providing thermal comfort in hot-arid climates. However, further interdisciplinary research is needed to address aspects not fully covered here. Future investigations are recommended in the following areas:

1. Psychological aspects of users – Exploring perceptions, attitudes, and satisfaction to better understand mental comfort and social acceptance of underground spaces.

2. Lighting conditions – Assessing the role of natural and artificial lighting in visual and psychological comfort.

3. Comparative studies – Examining similarities and differences between Shavadans and other underground spaces in Iran and abroad (e.g., qanats, sardabs).

4. Cultural and social factors – Investigating local beliefs and values to identify barriers and opportunities for the reuse of Shavadans.

5. Economic feasibility – Evaluating cost–benefit aspects and energy-saving potential to support sustainable development decisions.

6. Regulatory frameworks – Reviewing building codes and legal requirements to integrate Shavadans into modern urban planning.

Conclusion

The results of this study demonstrate that Shavadans, by harnessing the thermal mass of the ground—particularly at depths greater than 5 m—are able to buffer extreme summer heat while maintaining stable, near-neutral indoor conditions during winter. Nonetheless, above-

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37. Wen et al. (2024),

38. (Cheung & de Dear)

39. (De Dear, Burke, & King, 2017)

40. Yu, Kang, and Zhai, 'Advances in research for underground buildings: Energy, thermal comfort and indoor air quality.' (2020)

ground rooms offer certain advantages. This indicates that a hybrid underground–surface strategy can provide an effective, low-energy, and climate-responsive solution for hot and semi-humid regions.

The significance of this study lies in providing novel field-based evidence from Iran comparing the thermal comfort of Shavadans and above-ground spaces, establishing a link between vernacular knowledge and contemporary sustainable design.

References

Anselm, Akubue Jideofor. 'Passive Annual Heat Storage Principles in Earth Sheltered Housing, a Supplementary Energy Saving System in Residential Housing.' *Energy and Buildings* 40, no. 7 (2008): 1214–1219. https://doi.org/10.1016/j.enbuild.2007.11.002.

ASHRAE. *Standard 55: Thermal Environmental Conditions for Human Occupancy.* Atlanta, (2020).

Babaee, Faezeh, and Shahin Heidari. 'Thermal Comfort and Structural Optimisation of Shavadans: A Multi-Criteria Approach: Case Study – Hot and Semi-Humid Climate, City of Dezful-Iran.' *Tunnelling and Underground Space Technology* 162 (2025): 106620.

Bahdad, Ali Ahmed Salem, and Sharifah Fairuz Syed Fadzil. 'An Investigation-Based Optimisation Framework of Thermal Comfort Analysis in Underground Enclosed Spaces Affected by Multiple Parameters for Energy Performance in Tropics.' *Journal of Daylighting* 9, no. 1 (2022): 48–63.

Benardos, A., I. Athanasiadis, and N. Katsoulakos. 'Modern Earth Sheltered Constructions: A Paradigm of Green Engineering.' *Tunnelling and Underground Space Technology* 41 (2014): 46–52.

Bina, Mohsen. 'Climatic Analysis of Shavadans in the Traditional Houses of Dezful.' *Honar-ha-ye Ziba* 33, no. 33 (2008). https://jhz.ut.ac.ir/article_19039_bdd8626d54f4f9bcae7ca0d993d60902.pdf.

Cao, Bin, Yingxin Zhu, Qin Ouyang, Xiang Zhou, and Li Huang. 'Field Study of Human Thermal Comfort and Thermal Adaptability during the Summer and Winter in Beijing.' *Energy and Buildings* 43, no. 5 (2011): 1051–1056. https://doi.org/10.1016/j.enbuild.2010.09.025.

Chai, Qian, Huiqin Wang, Yongchao Zhai, and Liu Yang. 'Using Machine Learning Algorithms to Predict Occupants' Thermal Comfort in Naturally Ventilated Residential Buildings.' *Energy and Buildings* 217 (2020): 109937. https://doi.org/10.1016/j.enbuild.2020.109937.

Cheung, Toby, Stefano Schiavon, Thomas Parkinson, Peixian Li, and Gail Brager. 'Analysis of the Accuracy on PMV–PPD Model Using the ASHRAE Global Thermal Comfort Database II.' *Building and Environment* 153 (2019): 205–217.

de Dear, R., J. Xiong, J. Kim, and B. Cao. 'A Review of Adaptive Thermal Comfort Research since 1998.' *Energy and Buildings* 214 (2020): 109893. https://doi.org/10.1016/j.enbuild.2020.109893.

Emam (Ahvazi), Mohammadali. *Historical Geography of Dezful*. Dezful: Dar al-Mo'menin, (2003).

Fanger, P. O. 'Fundamentals of Thermal Comfort.' In *Advances in Solar Energy Technology*, 3056–3061. Elsevier, 1988.

Feng, H., and K. Hewage. 'Energy Saving Performance of Green Vegetation on LEED Certified Buildings.' *Energy and Buildings* 75 (2014): 281–289.

Goel, Rajnish K., Bhawani Singh, and Jian Zhao. *Underground Infrastructures: Planning, Design, and Construction.* Butterworth-Heinemann, (2012).

Hawila, Abed Al-Waheed et al. 'An Analysis of the Impact of PMV-Based Thermal Comfort Control during Heating Period: A Case Study of Highly Glazed Room.' *Journal of Building Engineering* 20 (2018): 353–366. https://doi.org/10.1016/j.jobe.2018.08.010.

Hazbei, Morteza et al. 'Reduction of Energy Consumption Using Passive Architecture in Hot and Humid Climates.' *Tunnelling and Underground Space Technology* 47 (2015): 16–27.

Hejazizadeh, Zahra, Seyed Morovat Eftekhari, and Hiva Solki. 'Optimising the Orientation of Open Spaces in Dezful Based on Climatic Conditions.' *Geography* 10, no. 32 (2012): 7–28. https://mag.iga.ir/Article_705178_5a3e2c5a82119e64d02c15638e5ecd3f.pdf.

Hellwig, Runa T. et al. 'A Framework for Adopting Adaptive Thermal Comfort Principles in Design and Operation of Buildings.' *Energy and Buildings* 205 (2019): 109476. https://doi.org/10.1016/j.enbuild.2019.109476.

Karyono, Kanisius et al. 'The Adaptive Thermal Comfort Review from the 1920s, the Present, and the Future.' *Developments in the Built Environment* 4 (2020): 100032. https://doi.org/10.1016/j.dibe.2020.100032.

Li, Yong et al. 'Study of Thermal Comfort in Underground Construction Based on Field Measurements and Questionnaires in China.' *Building and Environment* 116 (2017): 45–54.

Liu, Fuquan et al. 'Thermal Comfort in Typical Seasons of Summer and Winter in Personnel Intensive Areas of Underground Public Buildings of Xi'an in China.' *Thermal Science* (2025): 140–140.

Luo, Maohui et al. 'The Underlying Linkage between Personal Control and Thermal Comfort: Psychological or Physical Effects?' *Energy and Buildings* 111 (2016): 56–63.

Malik, Jeetika, Ronita Bardhan, and Pradipta Banerji. 'Rethinking Indoor Thermal Comfort… Developing World: A Systematic Review.' *Indoor Air* 30, no. 3 (2020): 377–395.

Marszal, A. J. et al. 'Zero Energy Building – A Review of Definitions and Calculation Methodologies.' 2011.

Mas'oudi-nejad, Mostafa et al. 'The Study of the Thermal Performance of Shavadoons…' *Journal of Iranian Architecture Studies* 7, no. 13 (2022): 49–70. https://doi.org/10.22052/1.13.49.

Mihalakakou, Giouli et al. 'Earth-Sheltered Buildings: A Review…' *Journal of Cleaner Production* 472 (2024): 143482.

Mohammadshahi, Shabnam et al. 'Improvement of Ventilation and Heat Transfer in Shavadoon via Numerical Simulation.' *Renewable Energy* 96 (2016): 295–304.

Mohammadshahi, Shabnam et al. 'Investigation of Naturally Ventilated Shavadoons Component…' *Tunnelling and Underground Space Technology* 91 (2019): 102990.

Mohebian, Mostafa, Mahnaz Ashrafi, and Amin Kivanloo. 'Investigating the Typology of Troglodytic Shavadans in Dezful.' *Richt-Journals* 43, no. 1 (2022): 18.

Moradi, H., and H. Eskandari. 'An Experimental and Numerical Investigation of Shovadan Heating and Cooling Operation.' *Renewable Energy* 48 (2012): 364–368. https://doi.org/10.1016/j.renene.2012.05.016.

Fanger, P. Ole, and Jørn Toftum. 'Extension of the PMV Model to Non-Air-Conditioned Buildings in Warm Climates.' *Energy and Buildings* 34, no. 6 (2002): 533–536. https://doi.org/10.1016/S0378-7788(02)00003-8.

Qiao, Renlu et al. 'Improvement of Thermal Comfort for Underground Space: Data Enhancement Using Variational Autoencoder.' *Building and Environment* 207 (2022): 108457.

Rapoport, Amos. 'Vernacular Design as a Model System.' In *Vernacular Architecture in the Twenty-First Century*, edited by L. Asquith and M. Vellinga, 179–198. London: Taylor and Francis, (2006).

Rissetto, Romina, Riklef Rambow, and Marcel Schweiker. 'Assessing Comfort in the Workplace: A Unified Theory of Behavioural and Thermal Expectations.' *Building and Environment* 216 (2022): 109–115.

Sadoughi, Arezou et al. 'Thermal Performance Analysis of a Traditional Passive Cooling System in Dezful, Iran.' *Tunnelling and Underground Space Technology* 83 (2019): 291–302.

Samsam-Khayani, Hadi et al. 'Numerical Study of Effects of Shavadoon Connections…' *Tunnelling and Underground Space Technology* 82 (2018): 170–181.

Sansaniwal, Sunil Kumar et al. 'Review of Practices for Human Thermal Comfort in Buildings…' *International Journal of Ambient Energy* 43, no. 1 (2022): 2097–2123. https://doi.org/10.1080/01430750.2020.1725629.

Sirhan, Naji, and Saar Golan. 'Efficient PMV Computation for Public Environments with Transient Populations.' *Energy and Buildings* 231 (2021): 110523.

International Organsation for Standardsation. *Ergonomics of the Thermal Environment… PMV and PPD Indices.* ISO, 2005.

Tahsildoost, Mohammad, and Zahra S. Zomorodian. 'Indoor Environment Quality Assessment in Classrooms: An Integrated Approach.' *Journal of Building Physics* 42, no. 3 (2018): 336–362. https://doi.org/10.1177/1744259118759687.

Toftum, Jørn, Anette S. Jørgensen, and P. O. Fanger. 'Upper Limits of Air Humidity for Preventing Warm Respiratory Discomfort.' *Energy and Buildings* 28, no. 1 (1998): 15–23.

Wodehouse, Lawrence. *Indigenous Architecture Worldwide: A Guide to Information Sources.* Gale Research, 1980.

Wu, Jing, Xiangdong Li, Yang Lin, Yihuan Yan, and Jiyuan Tu. 'A Pmv-Based Hvac Control Strategy for Office Rooms Subjected to Solar Radiation.' *Building and Environment* 177 (2020/06/15/ 2020): 106863. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.106863

Wu, Jing et al. 'A PMV-Based HVAC Control Strategy for Office Rooms Subjected to Solar Radiation.' *Building and Environment* 177 (2020): 106863.

Yu, Jia, Yanming Kang, and Zhiqiang John Zhai. 'Advances in Research for Underground Buildings: Energy, Thermal Comfort and Indoor Air Quality.' *Energy and Buildings* 215 (2020): 109916.