



Original Article



Evaluation of the Environmental Performance of Seasonal Spaces in the Vernacular Architecture of the Regions With Cold Climate: A Case Study in Ardabil

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Abstract

Background: Attention to climatic elements has played a crucial role in fostering harmony between the built environment and nature. Incorporating these elements into the design of modern buildings not only enhances the health and well-being of occupants but also helps mitigate anthropogenic environmental pollution. In this context, the present study aims to examine the environmental performance of various spaces in the vernacular architecture of Ardabil across cold and hot seasons. The objective is to identify climate-responsive strategies that contribute to reducing energy consumption and minimizing environmental pollution.

Methods: To this end, two traditional houses in Ardabil were studied using a data logger. Data collection was carried out through field observations and logical reasoning, followed by numerical analyses to evaluate the environmental performance of the structures.

Results: The results indicated that the temperature of the indoor spaces in these houses was at least 10.45 °C higher than that of the outdoor spaces during the cold months of the year.

Conclusion: The application of climate-responsive strategies, particularly passive solar designs during winter, in the construction of traditional houses was estimated to reduce CO₂ emissions by 218.47 kg and natural gas consumption by 82.07 kg per month for every 100 m² of space during the cold seasons. In contrast, during the hot seasons, while indoor temperatures in most spaces exceeded outdoor temperatures, they remained within the acceptable range of human thermal comfort.

Keywords: Environmental performance, Seasonal spaces, CO₂ emission, Cold climate, Vernacular architecture, Ardabil

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Introduction

In recent years, rapid technological advancements have significantly increased the consumption of various resources.¹ This has led to a rise in environmental issues, particularly human-induced pollution.² Among these concerns, the growing emission of greenhouse gases has raised alarms, resulting in a strong demand for reducing the reliance on non-renewable energy sources and fossil fuels.³ A considerable portion of the environmental impact stems from the energy consumption of buildings.⁴ According to the World Health Organization (WHO), occupants of buildings are increasingly affected by sick building syndrome, which highlights the health risks posed by poor indoor environmental quality.⁵ To promote environmental sustainability, it is crucial to develop building designs that are compatible with

natural ecosystems and minimize energy waste.⁶ Research suggests that traditional housing structures tend to be more energy-efficient and environmentally harmonious compared to modern constructions.⁷ Over time, traditional architecture has evolved through trial and error, achieving a stable and efficient combination of structural elements.⁸ These traditional designs were inherently more aligned with natural conditions and climate, resulting in reduced energy consumption and enhanced synergy with the surrounding environment. As such, vernacular architecture offers valuable insights into the implementation of climate-responsive strategies in the design of contemporary buildings.⁹ By assessing the environmental performance of structural spaces—such as their thermal and humidity characteristics—it is possible to identify effective design strategies that can be applied by



modern architects and urban planners.¹⁰

The vernacular architecture of Ardabil represents an under-researched area within the context of climate-responsive design. Given the region's cold and semi-arid climate, the architectural characteristics of local buildings have not been extensively examined in relation to their physical environment. Despite the climatic challenges, numerous innovations and practical strategies have been employed in the construction of traditional houses in Ardabil, enhancing their compatibility with environmental conditions. Most previous studies have focused on the principles, criteria, and climatic strategies underpinning traditional housing in the region. However, the environmental performance of the various spaces within these buildings has not been systematically explored using experimental data. Therefore, a detailed investigation of these traditional houses from this perspective may unveil subtle aspects of vernacular architecture that could be adapted for use in contemporary buildings. To address this specific research gap, the present study aims to identify practical climate-responsive strategies employed in the vernacular architecture of Ardabil that could reduce energy consumption and pollutant emissions during both cold and hot seasons. This study will experimentally examine traditional houses and their indoor environments, utilizing data on thermal performance, energy consumption, and pollutant emissions.

To achieve this objective, the factors contributing to environmental performance, along with the characteristics of the region's vernacular architecture, were first identified through a comprehensive literature review. Subsequently, environmental data spanning the last 14 years, obtained from the Ardabil Meteorological Administration, were collected and analyzed using specialized computer software. The results were then compared with the features of vernacular architecture in the region. In addition, thermal performance data from traditional houses were gathered using data loggers during both the cold and hot seasons of the year. These measurements were then compared with environmental variables. The mean temperatures of different indoor and outdoor spaces, along with their dimensions, were utilized to estimate energy consumption and pollutant emissions. Based on these findings, effective climate-responsive strategies inherent in the vernacular architecture were identified through an analysis of the buildings' environmental performance.

Materials and Methods

Environmental Performance

Environmental performance in any region is primarily influenced by the local climate. This aspect has gained increasing importance in recent years due to the ongoing energy crisis.¹¹ In addition to providing comfort for occupants, optimizing a building's environmental performance can significantly reduce

energy consumption.¹² Environmental performance is a critical factor that affects occupants' reliance on natural or mechanical heating and cooling systems.¹³ Essentially, occupants adjust these systems based on the thermal comfort they experience, which is determined by both physical and mental conditions. Thermal comfort is achieved through a balanced combination of fundamental factors, including climate, psychological traits, and environmental conditions.⁵ Beyond personal factors, the structural characteristics of a building and climatic elements—such as temperature, humidity, sunlight, and wind—are essential for evaluating its environmental performance.¹⁴ Therefore, local architectural strategies that are employed in building construction, along with the thermal performance of interior spaces, are influenced by a combination of structural and environmental factors. A strong interaction between these elements can enhance the environmental performance of buildings, leading to more sustainable and comfortable living conditions.

The region under investigation and its climatic variables

Ardabil is a city located in the northwest of Iran, positioned at a latitude of 38° 5' to 38° 28' north and a longitude of 48° 10' to 48° 41' east (Figure 1). It lies within a fertile plain surrounded by mountains, covering an area of approximately 40 km by 25 km, with a mean altitude of 1350 m above sea level.¹⁵ The city's historical core, occupying an area of about 117 hectares, is situated in its central part, as depicted in Figure 1. This area represents the original nucleus of Ardabil. Over various periods of expansion, the city has developed in a circular pattern.¹⁶ Due to factors such as structural instability and earthquakes, the oldest remaining houses within Ardabil's historical texture date back to the mid-19th and early 20th centuries, and consist mainly of one- or two-story buildings.¹⁷

Situated in the outskirts of Mount Sabalan and the maritime area of Astara, Ardabil is recognized as one of the cold and semi-arid regions in Iran.¹⁸ In order to explore the climatic features of the region in greater details, the climatic data of the last 14 years were taken from Ardabil Meteorological Administration in the form of EPW file and analyzed by Climate Consultant 6.0 Software.¹⁹ For the primary objective of the study, it was crucial to identify the climatic features of the region and the architectural strategies employed to address them. Figure 2 presents the average high, average low, and mean dry-bulb temperatures, as well as the comfort zones for each month in Ardabil. As shown, the highest mean temperatures occur during the hot months of Jun, July, August, and September, exceeding the upper limit of the indoor comfort zone. Conversely, the lowest mean temperatures are observed during the cold months of December, January, February and March, falling significantly below the minimum comfort zone threshold, necessitating continuous use of heating systems both day and night.

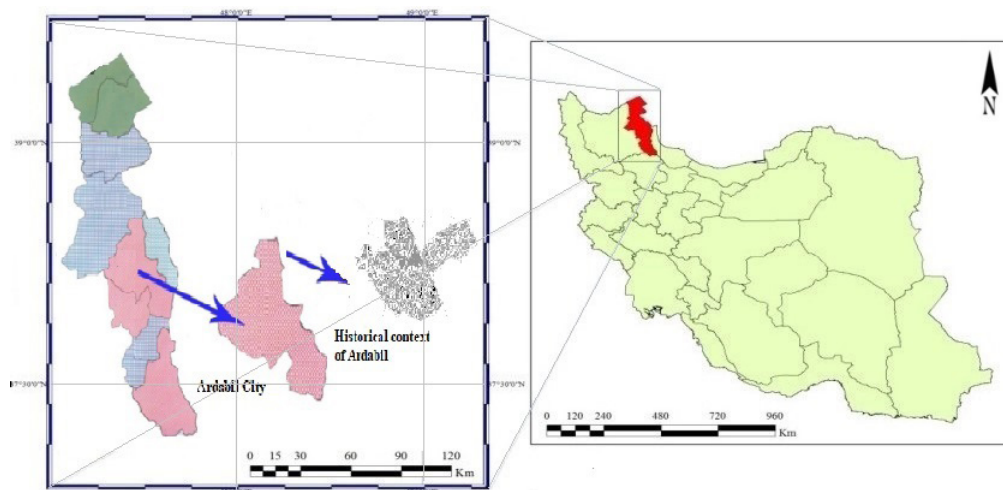


Figure 1. Location and Approximate Coordinates and the Primary Texture of Ardabil City

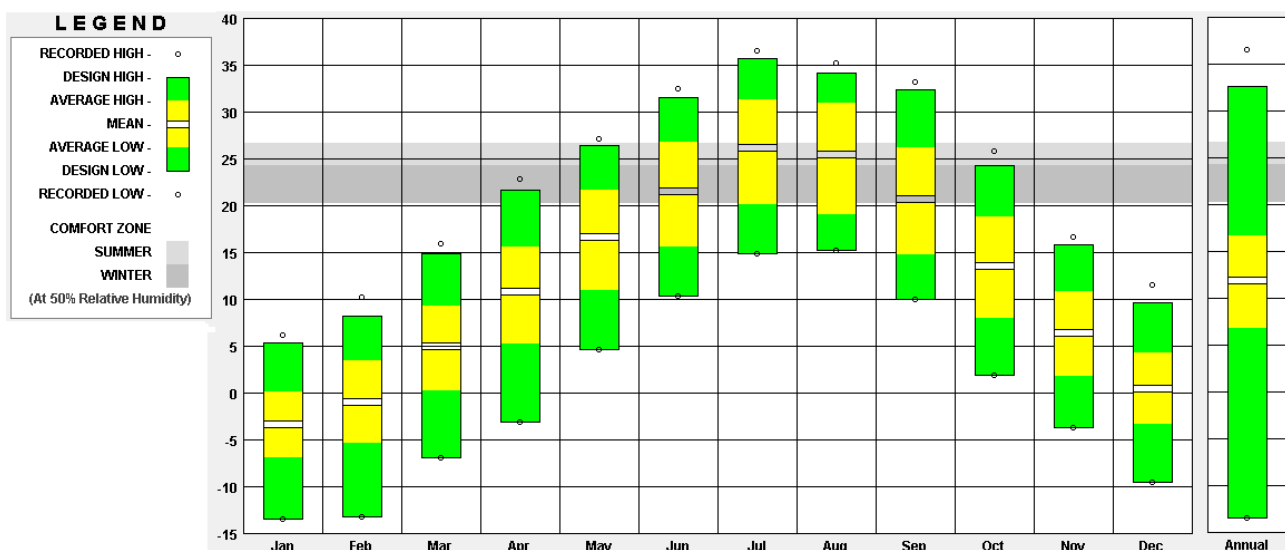


Figure 2. Mean maximum temperature, mean minimum temperature, mean temperature, and comfort zone in different months of the year in Ardabil, (Climate Consultant 6.0 Software)

Considering that the lower and upper limits of the comfort zone in Ardabil are 21 °C and 25 °C, respectively,²⁰ Figure 2 also indicates that, for the remaining months of the year, indoor spaces only fall within the comfort zone on a limited number of days or during specific times of the day. At other times, such as nighttime or cooler periods, temperatures drop below the comfort zone, requiring additional heating.

Figure S1 illustrates the seasonal variation in humidity levels, which range from 35% to 70%. During the winter months, relative humidity is higher due to the dominance of cold weather, while in the hot seasons, humidity levels decrease.

Figures S2 and S3 illustrate the shading and sunshine conditions in Ardabil during the cold and hot seasons of the year. These figures, along with Table 1, indicate that the demand for sunshine is significantly greater than for shading. Sunshine can be effectively utilized to enhance the thermal conditions of indoor spaces during the cold seasons, reducing the need for mechanical heating.

Conversely, during the hot seasons, there is less demand for shading structures or canopies, as natural ventilation and passive cooling strategies can be more effective in maintaining comfortable indoor temperatures.

The predominant wind directions in Ardabil are from the east and southwest, accounting for 23.68 and 10.04% of the total winds, respectively.²⁰ The average wind speed in this region is 13.8 m/s. The southwestern wind, which is weaker during the summer months, is considered unfavorable due to its role in increasing evaporation and soil desiccation. In contrast, the eastern wind is stronger in summer and is seen as beneficial because it brings moisture from the Caspian Sea.²¹

As shown in Figure S4, despite the prevalence of extreme cold during the colder seasons, the region receives a significant amount of sunlight. Throughout the year, especially in the cold seasons, the area experiences a combination of scattered, horizontal, and direct sunlight, with average insolation levels of 200, 340, and 300 Wh/m², respectively. The highest solar radiation during winter is

Table 1. Climatic Strategies of Shading and Sunshine in Different Seasons in Ardabil Based on Temperature

Seasons	Shading		Sunshine
	Temperature of higher than 27 °C	Temperature of higher than 20 °C	Temperature of lower than 20 °C
Winter and spring	103 hours (4 days of early Tir)	42 hours (18 days of Tir and Khordad)	1938 hours (two and half months of winter)
Summer and fall	735 hours (one month of summer)	738 hours (one month of summer)	1125 hours (one and half months of Azar and Aban)

received from the southwest and west, while the lowest solar radiation during summer comes from the north and south. Since building performance is evaluated on an annual basis, a southern orientation is considered the most suitable for maximizing solar gain in this region.²² This orientation allows buildings to receive the highest amount of sunlight during the cold seasons and the least during the hot seasons. Additionally, a southwest orientation provides the maximum solar exposure during winter. For those seeking more exposure to the desirable eastern winds, a southeast orientation is recommended.²³

Thus, it is essential to use passive solar systems for heating purposes during the cold seasons of the year (Table 2). Optimal conditions can also be achieved during the relatively short period of hot seasons via the proper use of natural ventilation and eastern wind.

Given that cold weather is the predominant and most critical climatic condition in the region throughout the year, distinguishing between the seasonal aspects of houses is not a primary concern. However, in some buildings, spaces have been compartmentalized based on seasonal characteristics to enhance occupant comfort.⁹

Potentials for Controlling Unfavorable Climatic Conditions by Climate-Responsive Strategies in the Local Houses of Ardabil

Regarding the environmental variables in Ardabil’s climate, although the city’s radial layout does not allow for a uniform building orientation, the indoor spaces are designed to optimize the use of sunlight and wind. In most traditional houses in Ardabil, the halls and rooms are oriented towards the south or southeast to offer spatial diversity and comfort during both cold and hot seasons. The vernacular architecture of the region incorporates several strategies to address the challenges of cold winters and hot summers:

- *Central Courtyard:* A key feature in these buildings, the courtyard is designed with small dimensions to protect it from direct sunlight during the hot seasons. The presence of vegetation, trees, and a water pool creates a pleasant environment during summer. However, during winter, the courtyard falls outside the comfort zone. Although positioned lower than the passageway to benefit from ground heat, its primary function in cold seasons is to allow sunlight and solar heat to penetrate deep into the indoor spaces due to its optimal sunbeam angle²⁴ (Figure S5). The courtyard also serves different functions depending on the season. The northern façade, which is the most frequently used area, receives the highest amount

Table 2. The Percentage of Climatic Strategies Use During Cold and Hot Seasons in Ardabil (Climate Consultant 6.0 Software)

Seasons	Climatic Strategies (%)		
	Passive Solar System	The Thermal Mass of the Materials	Heating System
Cold seasons	15%	23%	44%
Hot seasons	Canopy 9%		Cooling system 8.2%

of southern sunlight and is predominantly utilized during winter. In contrast, the southern and western façades, receiving minimal northern and eastern sunlight, are mainly used during summer.²⁵

- *Sardab:* In the houses of this region, sardabs are located in the basement beneath the main hall. Constructing buildings below ground level helps minimize temperature fluctuations. Sardabs experience lower temperature variability due to their surrounding soil, arched low ceilings, and small entrance doors.¹⁹ These spaces are primarily used as summer rooms or for food storage, as they maintain a desirable temperature and are directly connected to the kitchen.
- *Rooms:* These spaces are deep, with low ceilings, and are situated on the northern side of the structure near the main hall. Their design keeps indoor spaces warm during winter as they are directly connected to the kitchen, allow sunlight to penetrate deeply, have thick walls, and are compact. These features make them ideal living spaces during winter. In summer, since they receive less southern sunlight, the rooms maintain a mild, desirable temperature, allowing them to function as summer rooms as well.²⁶
- *Greenhouse effect:* This passive solar heating mechanism is commonly found in traditional houses, particularly in the halls and *shahneshin* rooms, due to the presence of large *Orsi* windows. These windows, typically composed of two or three layers, allow sunlight to penetrate deep into indoor spaces. The solar heat is trapped inside, warming the interiors.²⁰ During summer, the *Orsi* windows can be rolled up, enabling natural ventilation, which creates a pleasant atmosphere indoors.
- *Materials and construction techniques:* The choice of materials and construction methods plays a crucial role in ensuring the occupants’ physical comfort. To minimize heat exchange and temperature fluctuations, natural materials with high thermal capacity and thermal mass have been used in the region’s buildings.²⁰ Travertine, black basalt, and

granite are commonly used in the construction of courtyards, plinths, and foundations. Dual-clad roofs with an air gap, supported by wooden beams, and insulated with gunny sacks coated with plaster and adobe, are characteristic of traditional houses. Additionally, lime and soil mortar bricks with plaster coatings are used for internal walls, while bricks made with plaster and lime are utilized for external walls. The buildings also adopt a bearing wall system, where the thickness of the walls, coupled with the high thermal capacity of the materials, reduces temperature fluctuations, thus enhancing thermal comfort.

- *Hallways, atriums, and passageways:* These architectural elements are located at the entrances of houses and serve to prevent the direct influx of cold air and undesirable winds into indoor spaces. Acting as buffers, they regulate the indoor temperature during the cold seasons by controlling the airflow into the house.

Methods

This study used a mixed-method approach, combining both qualitative and quantitative methods. First, the environmental performance and climate-responsive strategies commonly used in the traditional houses of Ardabil were identified through a comprehensive review of library resources and related literature. Next, the region's climatic characteristics were analyzed using data recorded by the Ardabil Meteorological Administration over the past 14 years, with the aid of Climate Consultant Software. These results were then compared with the prevalent climatic strategies employed in the vernacular architecture of Ardabil. Data on the thermal performance of seasonal spaces were collected through field investigations, using data loggers to record temperatures. The quantitative data obtained were analyzed in conjunction with environmental variables. Using a purposive sampling method, two traditional houses in Ardabil were selected for detailed investigation. The selection criteria included the feasibility of conducting field observations and ensuring that the structures remained unaltered by residents or authorities. The primary objective of this study was to assess energy consumption and pollutant emissions during the hot and cold seasons, based on regional climatic data. Additionally, the study aimed to analyze average indoor and outdoor temperatures to identify climate-responsive architectural elements that could be incorporated into contemporary building design (Figure 3).

Experimental Tests

The analysis of climatic data, such as temperature and humidity, is crucial for assessing the thermal performance of buildings.²⁷ To investigate these factors in the traditional houses of Ardabil, a BENETECH GM1365 data logger was employed. This data logger measures temperature and

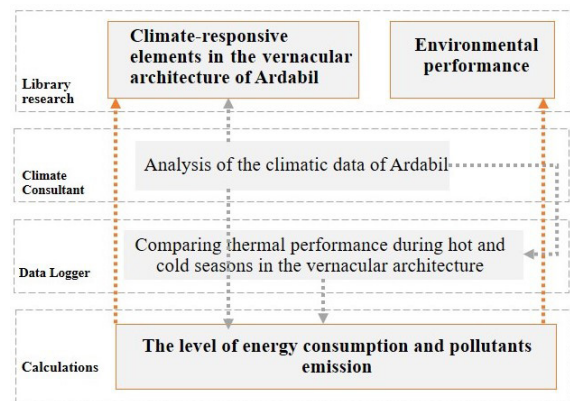


Figure 3. Research Process

humidity using sensors with an accuracy of 0.1 °C. The device begins recording environmental variables when placed at the center of the space under investigation, at a height of 80 cm above the floor. The selected spaces in the sample houses were evaluated accordingly, as shown in Table 3. The objective was to compare the indoor data, obtained from spaces featuring various passive climate solutions, with the temperature and humidity of outdoor spaces. To achieve this, different indoor spaces of the selected houses were assessed for temperature and humidity every three hours, during both the cold and hot seasons (Figure 2).

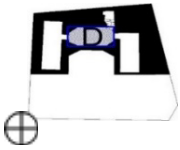
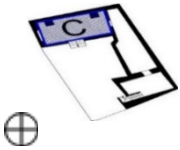
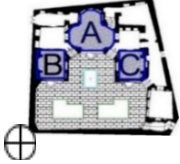
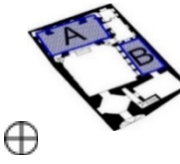
Investigation of the Selected Cases

In this study, the thermal performance of the Ebrahimi and Ershadi Traditional Houses was investigated. Both houses are located in the historical district of Ardabil (Figure 4). Their relatively smaller sizes make them comparable to contemporary buildings, and their accessibility allows for the collection of field data. Additionally, these houses feature rooms with various orientations designed to address the region's cold climate. All rooms in the Ebrahimi House are oriented towards the south, while in the Ershadi House, the hall and *shahneshin* room face the south-east, and the five-door room is oriented towards the south-west.

The Ebrahimi House, with a total area of 398 m², is south-facing and constructed over two levels (underground and ground floor). The structure is positioned in the northern and eastern sections of the central courtyard (Table 3). Bearing walls, ranging from 60 cm to 1 m in thickness, were employed in its construction. Other architectural strategies include dual-clad roofs with air gaps for insulation and dehumidification channels to manage moisture and prevent damage to the building's foundation (Figure S6).

The Ershadi House, with an area of 277 m², also consists of two floors (underground and ground floor) and features a compact layout. The central courtyard is oriented towards the south-east. The materials used in its construction are similar to those of the Ebrahimi House (Figure S7). Climate-responsive strategies employed in the Ershadi House include thick walls, a thick ceiling,

Table 3. Plans of Ebrahimi and Ershadi Houses and the Rooms Under Investigation

Plan	Ebrahimi Traditional House	Ershadi Traditional House
Sardab		
Ground Floor		

and a dome with a large surface area and low height (3.20 m and 1.40 m, respectively) positioned above the shahneshin room. These domes are particularly suited to the region’s cold climate, as they maximize sunlight and heat absorption while minimizing shading.²⁸ Additional strategies include fireplace channels for ventilation, high Orsi windows to allow sunlight to penetrate deep into indoor spaces, and hallways that prevent the direct inflow of cold air into the interior. These design elements, found in both the Ebrahimi and Ershadi Houses, effectively mitigate the challenges posed by the region’s harsh climate (Table 3).

Results and Discussion

The objective of this study was to assess the environmental performance of seasonal spaces in the traditional houses of Ardabil. Specifically, the thermal performance, temperature, and humidity levels of the houses were measured and analyzed. Figures 5A and 5B display the temperature variations across different indoor and outdoor spaces of the Ebrahimi and Ershadi houses on the coldest and hottest days of the year. As shown, the temperatures in all indoor spaces exceed those of the outdoor spaces during the colder months. Conversely, during the hottest days in summer, the indoor spaces frequently remain within the comfort zone.

Table 4 presents the average temperatures of indoor spaces, notably the *shahneshin* room and the *3-dari* room located in the western part of the Ebrahimi House, and the *sardab* and *shahneshin* room in the Ershadi House. These indoor spaces exhibit higher temperatures than the outdoor spaces during the cold season. The temperature difference between indoor and outdoor spaces is especially pronounced in the south-facing *shahneshin* room of the Ebrahimi House, attributed to the greenhouse effect, and in the *sardab* of the Ershadi House, due to the thermal capacity of the surrounding soil. Additionally, nighttime temperatures tend to be slightly higher than daytime temperatures. The winter temperature in the Ebrahimi House is 0.60 °C higher than that in the Ershadi House, likely due to the south-facing orientation, the presence of air-filtering features (e.g., hallways), the use of double-clad roofing, and the incorporation of materials with

high thermal capacity. Furthermore, the Ershadi House features a central courtyard at the same level as the passageway, which is smaller than the courtyard of the Ebrahimi House. As a result, it experiences more shading during the colder months of the year.

Furthermore, as illustrated in Figures 5A and 6A and summarized in Table 4, only the *sardab* in the Ershadi House demonstrates lower temperature fluctuations and reduced thermal load during the hot seasons, due to its underground location. The *sardab* maintains a cool environment in summer and a warm one in winter. The roof of the *sardab* is constructed with bricks in the form of barrel vaults, and the thick walls are composed of carcass stone, lime mortar, and *Sarooj*, which effectively regulate the moisture content in the surrounding soil. During summer, the temperature in the Ershadi House is 3.5 °C lower than that of the Ebrahimi House. This temperature difference can be attributed to the extended periods of shading experienced by the Ershadi House, caused by the dome-shaped roof of the *shahneshin* room, the side walls of the central courtyard, and the presence of trees. Additionally, the deep construction of the *sardab* underground and the southeastern orientation of the entire building contribute to the relatively cooler indoor climate in the Ershadi House during the summer months.

Figures 5B and 6B illustrate the relative humidity levels in the indoor and outdoor spaces of both the Ebrahimi and Ershadi Houses on the hottest and coldest days of the year. In both houses, the relative humidity indoors is consistently lower than outdoors during both extreme hot and cold days, which enhances occupant comfort. During cold days, the outdoor relative humidity levels for Ebrahimi and Ershadi Houses are 85.93 and 63.08%, respectively, while on hot days, these levels are 77.93 and 52.16%. In contrast, the relative humidity in the indoor spaces of Ebrahimi and Ershadi Houses is 52.56 and 48.56% during hot days and 41.37 and 38.02% during cold days, respectively. As depicted in Figures 5B and 6B, the relative humidity in the rooms of Ershadi House is lower than that in the Ebrahimi House. This difference can be attributed to the southeastern orientation of the Ershadi House, which benefits from eastern winds year-round. Additionally, the rooms in both houses have lower relative humidity compared to the *sardab*, as they are above ground and exposed to more airflow, whereas the *sardab* is surrounded by soil. Furthermore, the fluctuations in relative humidity within the indoor spaces during both winter and summer are minimal, contributing to a more stable and comfortable indoor environment. As shown in Table 4, the indoor temperatures of both Ebrahimi and Ershadi Houses during the cold season are higher than the outdoor temperatures, without the use of any heating energy. This energy conservation can be estimated by calculating the differences between the average indoor and outdoor temperatures. Consequently, the amount of natural gas saved and the reduction in carbon dioxide emissions can also be determined based on these



Figure 4. Location of Ebrahimi and Ershadi Houses in the Historical Texture of Ardabil

temperature differentials.

In the study conducted by Hashemi and Heydari, the amount of energy required for heating residential buildings in Ardabil was the minimum temperature of 15 °C during cold seasons.²⁹ Utilizing their findings, along with the dimensions and average indoor and outdoor temperatures of the houses analyzed in the current study, the approximate amounts of energy saved and the reduction in carbon dioxide emissions during the cold season can be estimated. This estimation highlights the potential environmental benefits of the architectural features of these traditional houses. Since detailed explanations regarding the calculations, obtained values, and required conditions for estimating the thermal loads of various spaces in residential buildings in Ardabil have already been provided in the study by Hashemi and Heydari, we consider it unnecessary to repeat the entire process here. Instead, we have utilized their findings for the purposes of this study. Using the thermal loads obtained, alongside the heating value of natural gas (50 MJ/kg),³⁰ its average chemical formula ($C_{1.04}H_{3.97}$),³¹ and its complete combustion (each kilogram of natural gas produces 2.663 kg of carbon dioxide),³² it is possible to estimate the energy savings and the amount of CO₂ emissions avoided (Table 5). The analysis of the climatic variables reveals that, during the four coldest months of the year, the conditions in this region are far from the comfort zone, necessitating the use of heating systems in residential buildings in Ardabil. Therefore, only these four months have been considered in the calculation of the thermal load. During the hot months, however, the temperature remains within the comfort zone, even on the hottest days of the year. As a result, natural ventilation is sufficient to maintain optimal indoor temperatures, eliminating the need for any cooling systems during the hot season.

Thus, as seen in Table 5, the amount of energy saved in Ebrahimi and Ershadi Houses during the cold seasons are 342 kg and 186 kg, respectively. Also, the emission of CO₂

is reduced by 911 kg and 497 kg, respectively.

Conclusion

The analysis of environmental performance of the Ebrahimi and Ershadi Traditional Houses demonstrates the effectiveness of various climate-responsive elements. These elements include passive solar strategies such as the greenhouse effect, the thermal capacity of soil (utilized through underground floors), a south-facing orientation, the use of high thermal mass materials, thick walls, double-clad roofs, air-filtering spaces, and shading reduction techniques. These features collectively contributed to indoor temperatures being higher than outdoor temperatures during the cold seasons. Specifically, the temperature difference between indoor and outdoor spaces in the Ebrahimi House was 12.74 °C, while in the Ershadi House, it was 8.16 °C. On average, the indoor temperature of both houses was 10.45 °C higher than the outdoor environment. These findings suggest that incorporating climate-responsive elements can significantly enhance energy efficiency. In particular, such designs can prevent the release of approximately 218.47 kg of CO₂ into the atmosphere and reduce natural gas consumption by 82.07 kg per month during the cold seasons, for a space of 100 m² with a ceiling height of 3 meters.

During the hot seasons, the indoor average temperature of Ebrahimi House was 6.85 °C higher than the outdoor temperature, while the difference in the Ershadi House was 3.35 °C. Meanwhile, the relatively moderate summer climate of the region ensures that indoor temperatures rarely exceed the comfort zone. Moreover, the short duration of the hot days has limited the need for extensive cooling strategies. Instead, emphasis has been placed on utilizing the thermal capacity of the soil, orienting the houses to the southeast (to capture prevailing eastern winds), and incorporating shade-providing structures. These strategies, although fewer in number compared to the colder seasons, are effective in

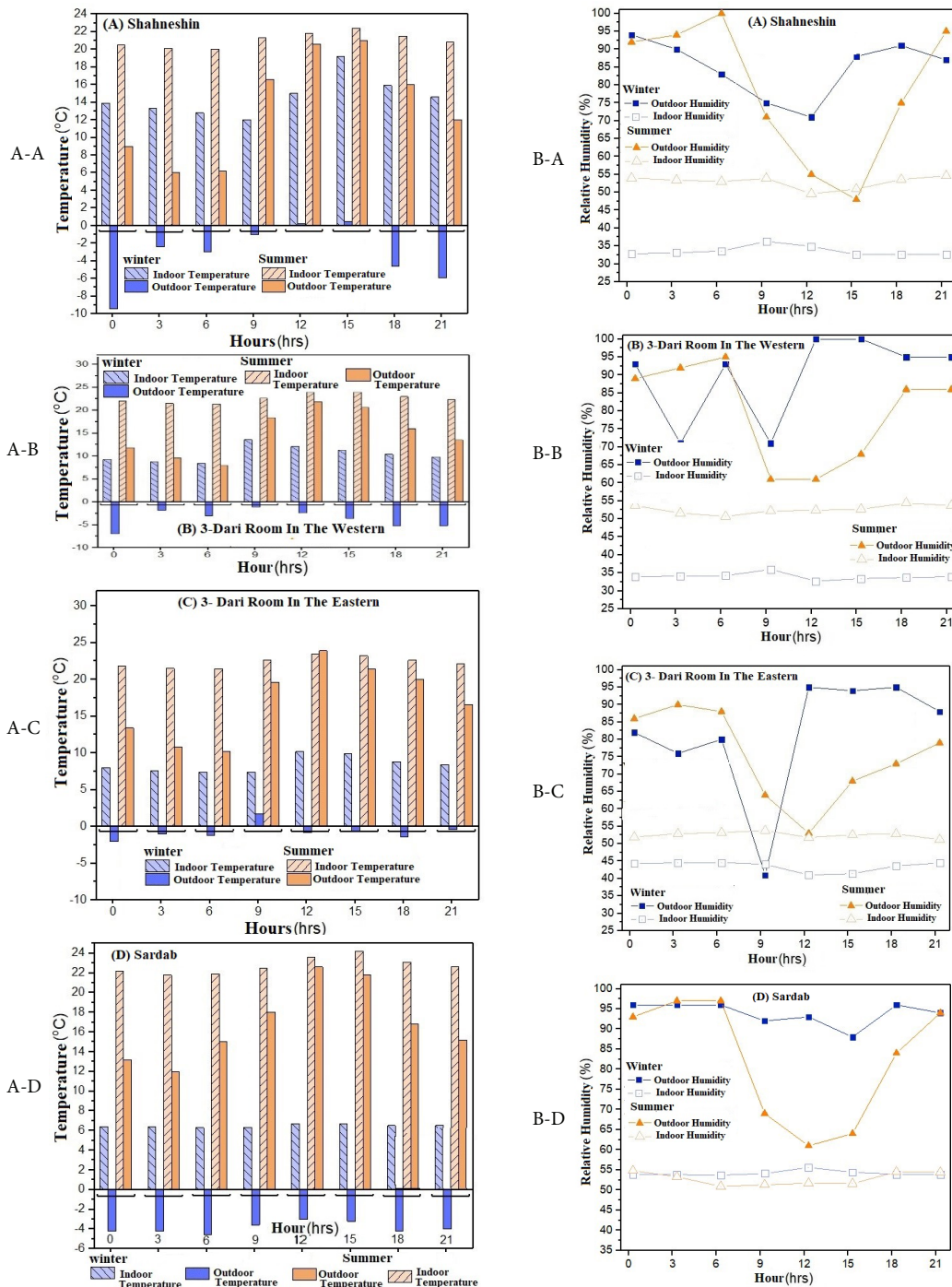


Figure 5. Filed data obtained from Ebrahimi House using a data logger. Column A: Temperature during the cold and hot seasons of the year. Column B: Temperature during the cold and hot seasons of the year

Table 4. Dimensions of Spaces and Differences of Mean Outdoor and Indoor Temperatures in Ebrahimi and Ershadi Houses

Ebrahimi Traditional House	Space Dimensions		Cold Seasons		Hot Seasons		Ershadi Traditional House	Space Dimensions		Cold Seasons		Hot Seasons	
	Area	Height	Average Indoor Temperature	Average Outside Temperature	Temperature Difference	Temperature Difference		Area	Height	Average indoor temperature	Average Outside Temperature	Temperature Difference	Temperature Difference
shahneshin	29.60	4	+14.75	-3.25	+18	+7.62	shahneshin	27	6.60	+9.37	+2.87	+6.50	+7.30
sardab	20.45	2.50	+6.25	-4.25	+10.50	+6.25	sardab	37.30	2.30	+9.12	-6.12	+15.24	-2.75
3-dari room western	16	2.60	+9.87	-4	+13.87	+7.37	5-dari room	20.80	3.30	+9.87	+7.12	+2.75	+5.51
3-dari room Eastern	15.70	2.60	+7.62	-1	+8.62	+5.88							

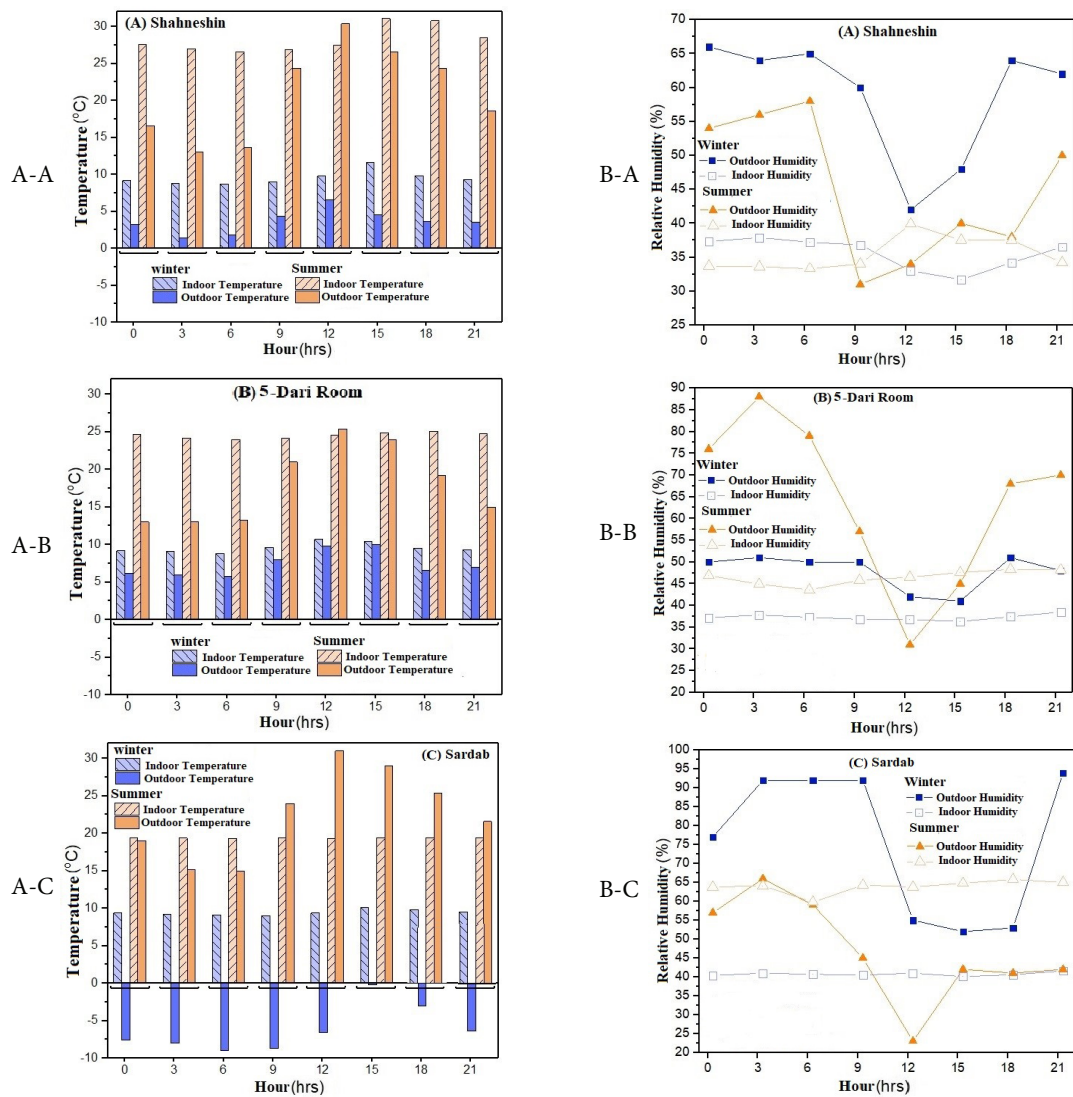


Figure 6. Filed data obtained from Ershadi House using a data logger. Column A: Temperature during the cold and hot seasons of the year. Column B: Humidity during the cold and hot seasons of the year

Table 5. The Amount of the Energy Saved and CO₂ not Released to the Environment in the Different Spaces of the Traditional Houses in Ardabil During the Cold Seasons of the Year

Name of the Houses and Their Different Spaces	The Energy Saved (kg) (the Amount of Natural Gas)	The CO ₂ not Released to the Environment (kg)
shahneshin	202.90	540.34
Ebrahimi Traditional House	sardab	48.45
	3-dari room in the western	52.76
	3-dari room in the Eastern	38.21
Total	342.34	911.65
Ershadi Traditional House	shahneshin	110.24
	sardab	51.18
	5-dari room	25.22
Total	186.64	497.03

mitigating uncomfortable indoor temperatures during the summer. Consequently, the climate-responsive design strategies used in the traditional houses of Ardabil can serve as valuable principles for contemporary building construction. By integrating these strategies, it is possible to enhance the environmental performance of modern structures throughout both cold and hot seasons, thereby reducing energy consumption and CO₂ emissions on a larger scale.

Authors' Contribution

Conceptualization: Mahsa Javadi Nodeh.

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Competing Interests

The authors declare they have no conflict of interest.

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Supplementary Files

Supplementary file 1 contains Figures S1-S7.

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