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Impact of wind in urban planning: A comparative study of cooling and natural ventilation systems in traditional Iranian architecture across three climatic zones

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Abstract: This study explores the role of wind in shaping traditional Iranian architecture across three distinct climatic zones: cold mountainous (Hajij), hot desert (Yazd), and humid coastal (Rasht) with a focus on passive cooling and natural ventilation techniques. By examining the effects of wind on urban layouts, building orientation, and material selection, the research highlights architectural features such as windcatchers, courtyards, and insulation techniques that enhance thermal comfort across diverse environments. The study employs a comparative approach, analysing architectural adaptations like compact layouts and windbreaks in mountainous regions, and windcatchers and open courtyards in desert areas, illustrating how vernacular architecture aligns with each climate's challenges. Using a combination of EnergyPlus simulations, field observations, and quantitative climate data, this research validates the efficiency of these traditional methods in moderating indoor temperatures, reducing energy demands, and providing sustainable comfort solutions. Comparative tables demonstrate the architectural adaptations across Rasht, Yazd, and Hajij, with metrics on urban density, building orientation, and material thermal properties. The findings underscore the enduring relevance of these ancient strategies in modern sustainable design, offering valuable insights for energy efficient, climate-responsive urban planning that minimises reliance on mechanical systems. By re-evaluating these indigenous cooling strategies, the study advocates for an integrated approach that merges local knowledge with modern sustainability practices, fostering resilience in architectural design for varied climatic contexts.

Keywords: wind energy, passive cooling, vernacular architecture, thermal comfort, natural ventilation

INTRODUCTION

This study examines how traditional Iranian architecture in three distinct climatic zones—cold and mountainous, hot and dry desert, and moderate and humid northern regions—utilises wind for passive cooling. The focus is on how wind influences the design and layout of cities, the form and materials of houses, and the traditional technologies used to harness wind power. By comparing the effectiveness of these passive cooling systems, the research analyses architectural elements, building materials, and wind-related components, exploring their impact on indoor air temperatures and overall comfort in different environmental conditions.

Traditional Iranian architecture is renowned for its innovative use of passive cooling techniques, particularly in harnessing natural wind power to regulate indoor temperatures. These methods, which are deeply rooted in sustainable practices, provide valuable insights into eco-friendly building designs that are tailored to their environmental context. By examining how these systems function across three distinct climatic zones in Iran—cold and mountainous, hot and dry desert, and moderate and humid northern regions—this research aims to uncover how traditional technologies, and architectural forms effectively utilise wind power. In contrast, contemporary building design often prioritises aesthetics and modern materials over sustainability, relying heavily on technology for heating, lighting, and cooling. This approach frequently neglects the geographical and climatic characteristics of a region, leading to energy inefficiency and contributing to environmental degradation. Traditional Iranian architecture, with its thoughtful adaptation to local climates and efficient use of natural resources such as wind and sunlight, offers a compelling model for sustainable design. By studying these traditional systems, this research seeks to inform the development of modern cooling solutions that align with the principles of clean energy and environmental sustainability.

LITERATURE REVIEW

The development of cities across different geographical regions is deeply influenced by various factors such as topography, soil type, and the availability and utilisation of natural resources. These factors play a crucial role in shaping urban planning and architectural practices. In his book Iran's Climate and Architecture, Reza Shatrian explores how different climatic conditions across various regions of Iran have influenced the architectural styles and urban development of these areas (Shaterian, 2009). Similarly, Morteza Kasmai, in Climate and Architecture, delves into the impact of climatic elements like wind and sunlight on the architecture and urban planning of different climatic zones in Iran. He discusses how varying wind intensities in different climates have shaped the design and orientation of buildings (Kasmaei, 2005). Numerous studies have been conducted on related topics (Roshan et al., 2020), including the design and function of windcatchers, which have been extensively analysed to understand their mechanisms and types (Mahmoudi, 2009; Bahadori et al., 2014). This body of work contributes significantly to the broader discourse on the interplay between climate and architecture, emphasising the adaptive strategies employed in response to specific environmental conditions (Suleiman and Himmo, 2012).

Researchers have undertaken numerous studies and experiments to achieve thermal comfort in buildings, exploring various components and approaches. Their efforts focus on maximising the use of natural energy resources while minimising energy loss, with the aim of creating energy-efficient structures that suit their regional climates. The following section outlines a selection of research articles from 2024, each addressing thermal comfort through diverse design and optimisation techniques. These studies collectively aim to improve thermal comfort and energy efficiency. Utilising advanced tools such as Design Builder, ENVI-met, EnergyPlus, and CFD, researchers have explored methods ranging from optimising building orientation and envelope design to integrating renewable energy systems and urban wind strategies. By addressing specific climate conditions and urban environments, these studies underscore the importance of comprehensive design strategies that incorporate local climate, urban dynamics, and sustainable technologies. Their findings offer valuable insights for architects and urban planners to develop buildings and cities that are more resilient and energy-efficient, enhancing human comfort while minimising environmental impact.

In the article published in Case Studies in Thermal Engineering, the study used Design Builder software to assess the impact of building proportions and orientation on energy consumption in Rasht City. It found that east-west-oriented buildings with a 1:4 ratio reduced energy use by 16% compared to a 1:1 ratio, providing practical insights for optimising energy performance (Zafari et al., 2024). Similarly, in the article titled "Comparing universal thermal climate index (UTCI) with selected thermal indices to evaluate outdoor thermal comfort in traditional courtyards with BWh climate," published in Urban Climate, ENVI-met software was used to evaluate outdoor thermal comfort in traditional Bushehr houses. The analysis of 12 courtyard designs revealed that forms #7, #2, and #6 exhibited the best thermal performance, offering valuable guidance for modern outdoor design (Mahdavinejad et al., 2024). Furthermore, in Sustainable Cities and Society, the article "Numerical and experimental investigation of a novel vertical solar chimney power plant for renewable energy production in urban areas" employed CFD and EnergyPlus software to propose a novel design for solar chimney power plants (SCPPs) for urban buildings, showing enhanced power output with a lower chimney height compared to traditional systems (Bagheri and Ghodsi Hassanabad, 2023).

Another study titled "Multi-objective optimization of energy and daylight performance for school envelopes in desert, semi-arid, and Mediterranean climates of Iran," published in Building and Environment, utilised LBT software and found that fixed exterior shading systems (FESSs) in Yazd reduced energy use by 25.22%, highlighting varying effects across different climates (Talaei and Sangin, 2024). Additionally, Sim Build published "Evaluating the Effects of Physical Parameters of Shanashir on Thermal Comfort based on UTCI Index, a Case Study," where Design Builder and Ladybug software were used to conclude that a 1.2-meter deep Shanashir with a 45-degree angled roof optimises thermal comfort in Bushehr's semi-outdoor spaces (Fani et al., 2024). In Daylighting, the article "A Multi-objective Optimisation of Window and Light Shelf Design in Office Buildings to Improve Occupants' Thermal and Visual Comfort" explored design optimisations using Grasshopper, Honeybee, and Octopus plugins, achieving up to 70.1% reduction in discomfort glare in an office in Tehran (Rezaei et al., 2024). The review article titled "Urban wind energy with resilience approach for sustainable cities in tropical regions" in Renewable and Sustainable Energy Reviews explored urban wind energy via small turbines and emphasised the need for resilience analysis in future research (Vallejo Díaz and Herrera Moya, 2024).

In Frontiers of Architectural Research, the article "Multiscale urban design based on the optimisation of the wind and thermal environments: A case study of the core area of Suzhou Science and Technology City" proposed a multi-scale framework for integrating urban climate analysis with design, focusing on three levels of urban interaction (Liu et al., 2024). Another contribution from Sustainable Cities and Society titled "A novel framework for multi-city building energy simulation: Coupling urban microclimate and energy dynamics at high spatiotemporal resolutions" utilised urban weather generator (UWG) software to analyse 15 German cities, revealing that dense, tall, low-vegetation areas consume more energy (Li et al., 2024). In Energy Conversion and Management, "Multi-objective optimisation of energy consumption pattern in order to provide thermal comfort and reduce costs in a residential building" employed MATLAB, EnergyPlus, and NSGA-II algorithm to assess HVAC efficiency, highlighting the profitability impact of energy pricing in Iran (Alimohamadi and Jahangir, 2024).

In another article from Energy Conversion and Management, titled "A multi-objective optimisation framework for performance-based building design considering the interplay between buildings and urban environments," the authors utilised Open Studio SketchUp and EnergyPlus to improve design decisions for a high-rise office in China, reducing heat emissions and energy use while improving indoor comfort (Qiu et al., 2024). Finally, Energy & Buildings published "Significance of external wind conditions on the convective heat transfer coefficients (CHTC) and energy performance in multi-zone high-rise buildings," where BCVTB and MATLAB were used to reveal that traditional models underestimate wind impact, stressing the need for dynamic modelling (Ding et al., 2024). According to the focus of this research, the literature review highlights the growing significance of wind energy and passive cooling systems in sustainable architecture, with emphasis on energy efficiency, thermal comfort, and minimising environmental impact.

In the article titled "Optimizing Windcatcher Designs for Effective Passive Cooling Strategies in Vienna's Urban Environment," published in Buildings, the researchers used Design Builder and ASHRAE software to evaluate traditional Iranian windcatchers as sustainable cooling solutions, identifying optimal designs and demonstrating that integrating windcatchers with an earth tube system enhances cooling efficiency in hot conditions (Shayegani et al., 2024). Similarly, in the article titled "Investigating Inlet Height Effect on Natural Ventilation Efficiency in Vernacular House Solar Chimneys," published in the Journal of Urban Management and Energy Sustainability, the researchers employed Ansys Fluent software to simulate the impact of inlet height on solar chimney efficiency, finding that while floor-level inlets offer stable airflow, ceiling-level inlets—commonly used in traditional Iranian architecture—achieve higher airspeed and enhance solar chimney efficiency. Moreover, in the article titled "Evaluating Windcatchers in UAE Heritage Architecture: A Pathway to Zero-Energy Cooling Solutions," published in the Ain Shams Engineering Journal, the researchers utilised Design Builder software to assess the sustainability of traditional windcatchers in modern UAE buildings, discovering that windcatchers outperform conventional cooling systems by maintaining cooler indoor temperatures without energy consumption, thereby reducing carbon emissions and operational costs (Chohan et al., 2024).

Furthermore, in the article titled "Can Windcatcher's Natural Ventilation Beat the Chill? A View from Heat Loss and Thermal Discomfort," published in Building and Environment, the researchers used Ansys Fluent software to evaluate windcatchers' performance in temperate climates. The study, conducted in Nottingham, UK, revealed that while windcatchers are effective for passive cooling, they can cause over-ventilation and significant heat loss in winter, highlighting the need for control strategies and heat recovery systems (Liu et al., 2024). Additionally, in the article titled "Enhancing Thermal Comfort and Natural Ventilation in Residential Buildings: A Design and Assessment of an Integrated System with Horizontal Windcatcher and Evaporative Cooling Channels," published in Energy, the researchers employed Ansys Fluent and MATLAB software to evaluate a hybrid cooling system, finding that the system reduced energy consumption by up to 50% compared to vertical windcatchers while improving thermal comfort and lowering electricity usage during hot seasons in Tehran, Iran (Heidari et al., 2024).

In the article titled "Parametric Enhancement of a Window-Windcatcher for Enhanced Thermal Comfort and Natural Ventilation," published in Atmosphere, the researchers used Energy Plus software to optimise a window-windcatcher design, discovering that the optimal configuration improved the actual ventilation rate by 13.2% and the actual-to-required ventilation rate by 8.6% compared to the baseline design, aligning with ASHRAE standards (Obeidat et al., 2023). Furthermore, in the article titled "Quantifying Energy Reduction and Thermal Comfort for a Residential Building Ventilated with a Window-Windcatcher: A Case Study," published in Buildings, the researchers utilised Design Builder software to evaluate the impact of window-windcatchers on energy performance and thermal comfort, finding that the system reduced annual energy consumption by 23.3% and decreased thermal discomfort hours by 290 annually (Obeidat et al., 2023). Lastly, in the article titled "Assessment of Natural Ventilation Techniques by Means of Measurements and Retrospective CFD Simulation on a Test Building," published in the Journal of Architectural Engineering, the researchers employed Energy Plus software to analyse natural ventilation techniques in a UAE building aimed at passive cooling, revealing that the ventilation strategies effectively reduced indoor temperatures by an average of 0.7°C, which supports sustainable building design; however, real-world airflow behaviours can occasionally challenge the effectiveness of these strategies (Belpoliti et al., 2024).

The research on wind energy and passive cooling systems emphasises their vital role in sustainable architecture. As climate change intensifies, passive cooling techniques like windcatchers, solar chimneys, and natural ventilation are crucial for minimising energy consumption and enhancing thermal comfort. Utilising tools like Design Builder, Ansys Fluent, and Energy Plus, these studies optimise designs to meet modern standards such as ASHRAE while boosting energy efficiency. The importance of this research lies in its alignment with global sustainability goals by reducing carbon emissions and energy costs. It also highlights the potential of traditional architectural elements to achieve zero-energy buildings, blending passive cooling methods with modern technology to combat climate change and advance clean energy systems in urban areas.

RESEARCH FOCUS

This research will investigate three different climatic zones in Iran: 1. moderate and humid northern regions, 2. cold and mountainous, 3. hot and dry desert. This research centres on the urban form of cities and buildings across three distinct climatic regions in Iran mentioned in Fig. 1, emphasising the crucial role of wind energy and sunlight in shaping the unique characteristics of each area. While water and vegetation are acknowledged as important factors, their impact will be explored to a lesser degree in this study. The research will investigate the traditional architecture and urban layouts of these regions, focusing on how wind is utilised to influence design and enhance thermal comfort. By examining the interaction between wind and sunlight in these environments, the study aims to reveal how traditional Iranian architecture has effectively adapted to its climate, offering valuable insights for sustainable urban planning and building design.

Traditional building characteristics:

- Temperate regions: Air movement is significant.
- Cold mountainous regions: Windbreakers are installed, and buildings are designed to prevent cold wind penetration.
- Desert Region: Wind is absorbed by windcatchers and the layout of houses with central courtyards.

Key architectural features include materials with different heat transfer coefficients, height, and openings, as well as the absorption or rejection of sunlight. Tab. 1 provides quantitative climate data, including temperature, humidity, wind patterns, and average wind speeds for Rasht, Yazd, and Hajij, showcasing the distinct environmental conditions that influence each city's architectural design.

Tab. 1. Comparative climate metrics of Rasht, Yazd, and Hajij. (Authors, 2024)

Category	Rasht	Hajij	Yazd
Climate Type	Humid Subtropical	Semi-arid / High-altitude	Hot Desert
Average Annual Temperature (°C)	16.5°C	14°C	22.5°C
Average Humidity (%)	85%	50%	30%
Predominant Wind Direction	Northeast, with frequent rain-bearing winds	Northwest, strong seasonal winds	Varies, but often from desert regions
Average Wind Speed (km/h)	15–25 km/h	20–30 km/h (higher in mountainous areas)	5–15 km/h

Fig. 1. Map of Iran highlighting the cities selected as case studies. (Photo: Authors, 2024)

MATERIALS, DATA AND METHODS

This study examines how architecture in three Iranian cities Rasht, Hajij in Kermanshah, and Yazd adapts to different climatic conditions, focusing on the role of wind direction and intensity. The methodology incorporates qualitative and quantitative approaches to establish a robust, comparative analysis across varying climatic zones. The methods used are:

- Case Study Selection: Three cities representing distinct climate zones humid subtropical (Rasht), cold high-altitude (Hajij in Kermanshah), and hot desert (Yazd), were selected to reflect a range of environmental adaptations in Iranian architecture.

- Climate Analysis and Data Collection: A comprehensive climate analysis for each city was conducted, focusing on regional wind patterns, temperature ranges, and humidity levels. Data were collected from meteorological sources to provide objective measurements for comparing how climatic factors impact architectural strategies in each location.

- Urban and Architectural Analysis: The urban layout, building materials, roof heights, and the size and placement of openings were examined for each city. This analysis focused on how these architectural elements are adapted to local wind conditions and contribute to passive cooling and ventilation. Comparative data tables were generated to illustrate these differences across cities objectively.

- Literature Review: A review of existing research on climate-responsive architecture, particularly regarding wind and ventilation strategies in traditional Iranian buildings, was conducted. This informed the theoretical framework and supported the development of comparative metrics across case studies.

- Simulation with Energy Plus Software: Energy simulations were carried out for each city using Energy Plus software to analyse thermal performance under various wind conditions. These simulations provided quantitative data on how architectural adaptations influence indoor temperatures and energy efficiency in each climate.

- Site Visits and Field Observations: On site visits were conducted in each city to gather qualitative insights and validate the simulation data. Observations included first-hand examination of building orientation, material wear, and ventilation effectiveness in real settings.

- Modelling and Visualisation: Three-dimensional models and visualisations were created for each case study using specialised software. These models illustrated the architectural features adapted to each climate, including airflow simulations to visually represent the impact of wind on the buildings' thermal performance.

This mixed methods approach allows for a comparative assessment of climate adaptive architecture across distinct climatic zones in Iran. By combining objective data analysis with qualitative insights, the study provides a comprehensive view of how traditional architectural elements have been optimised for wind utilisation, revealing design strategies that could inform sustainable urban planning in similar climates worldwide.

NUMERICAL ANALYSIS AND MODELLING

To demonstrate the internal and external heat dynamics, as well as the factors influencing the absorption and dissipation of thermal energy, the following diagrams present the results of EnergyPlus software modelling. This modelling is conducted across three distinct climates: temperate and humid, cold and mountainous, and hot and dry desert. For this purpose, we utilised a standard building size with a floor plan of 6×8 meters. Initial variables such as ceiling height, materials, number, size, and orientation of openings were input into the model for each of the three climates. The results derived from the data for these different climates were obtained using the EnergyPlus software version: 24.1.0, as illustrated in the following diagrams.

These diagrams and models represent basic and simplified versions, excluding urban planning elements and ancient techniques specific to the architecture of each region. These three factors are the primary considerations that have influenced the construction of houses and architecture since the beginning, without complex or specialised elaborated processes. The availability of local materials in each region naturally shaped the way buildings were constructed. Moreover, these materials play a significant role in regulating the internal temperature of the buildings, contributing effectively to the thermal comfort of the structures. The models and information indicate that, without incorporating the ancient wisdom inherent in local architecture, buildings in hot regions would experience higher internal temperatures, and in cold regions would experience lower internal temperatures reduced airflow and wind circulation and diminished thermal comfort for occupants.

However, by incorporating a few simple elements and techniques tailored to each climate, we observe more efficient utilisation of wind and solar energy, as well as an improved alignment of indoor temperatures with standard thermal comfort levels. Throughout history, architectural and urban planning innovations have emerged, not only shaping the appearance of buildings but also deeply rooted in cultural, social, and defensive considerations. Discoveries through trial and error have contributed significantly to adjusting internal temperatures closer to optimal levels. The interaction of cities and buildings with wind varies by climate. In hot-dry or temperate-humid climates, wind aids in air circulation and thermal comfort, while in cold mountainous regions, wind can excessively cool buildings, necessitating measures to minimise its infiltration (Fathy, 1969).

Indoor Air Temperature Profile is a heatmap that depicts the indoor air temperature (measured in degrees Celsius) throughout the year. The x-axis represents the months of the year, while the y-axis shows the time of day, from midnight to midnight (24 hours). The colour scale, ranging from blue to red, indicates temperature values, with cooler temperatures in blue and warmer temperatures in red. This heatmap provides a visual representation of how indoor air temperature fluctuates over time. Key insights from the heatmap include:

- Daily Temperature Patterns: It shows how temperatures change throughout the day, reflecting the influence of external weather conditions, occupancy patterns, and the operation of heating, ventilation, and air conditioning (HVAC) systems.

- Seasonal Variations: The chart highlights seasonal shifts in indoor temperatures, indicating periods of increased heating or cooling demand.

- Comfort Levels: The distribution of temperature values helps assess whether the indoor environment remains within desired comfort levels year-round.

Overall, this heatmap is a powerful tool for understanding the thermal behaviour of the building. It highlights periods when indoor temperatures may deviate from comfort ranges, offering insights into opportunities for optimising heating, cooling, or ventilation systems. These charts, when analysed together, provide a holistic understanding of the building's energy performance and thermal comfort throughout the year.

The following graphs (1 and 2 for Rasht, 4 and 5 for Kermanshah, and 7 and 8 for Yazd) illustrate the indoor and outdoor temperatures of buildings simulated using Energy Plus software over a one-year period. The accompanying Tab. 2, 3, and 4 respectively for Rasht, Kermanshah, and Yazd presents the average monthly internal and external temperatures at two specific hours—12 noon and 6 p.m.—for each climate zone. During the first week of July 2024, temperatures were validated through field experiments across all three climates illustrated in diagram 3 for Rasht, 6 for Kermanshah and 9 for Yazd, confirming that the external temperatures closely matched the software predictions (Moghtader et al., 2022). However, significant discrepancies were observed in the internal temperatures, attributed to additional factors not accounted for in the software modelling, such as urban layout, construction techniques, and technological interventions. These factors, detailed below, have a measurable impact on indoor temperatures and align with findings from previous field-tested research. Achieving thermal comfort within buildings necessitates energy absorption and retention during winter, as well as promoting air circulation and cooling during summer (Nejat et al., 2021).

Tab. 2. Monthly average indoor and outdoor temperatures of Rasht at 12:00 p.m. and 6:00 p.m. (Authors, 2024, created using EnergyPlus software 24.1.0)

	T outdoor		T indoor	
Month	Hour 12	Hour 6	Hour 12	Hour 6
1	2.90	5.66	20.26	20.53
2	6.23	7.15	20.86	21.45
3	9.78	12.68	22.13	23.12
4	16.00	17.09	25.05	26.20
5	23.29	24.23	27.92	29.03
6	29.53	32.11	30.69	32.41
7	33.75	36.25	32.03	34.02
8	31.80	35.34	33.04	34.80
9	28.45	29.79	33.15	34.46
10	21.90	22.03	29.04	30.01
11	10.88	12.66	22.70	23.27
12	6.24	6.65	20.21	20.41

Rasht

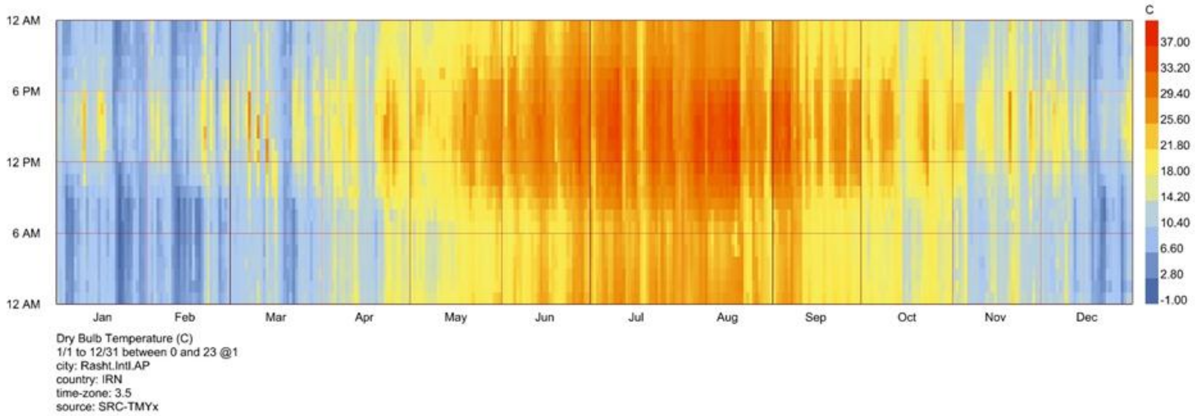

Fig. 2. Annual outdoor temperature profile of Rasht. (Source: Authors, 2024, created using EnergyPlus software 24.1.0)

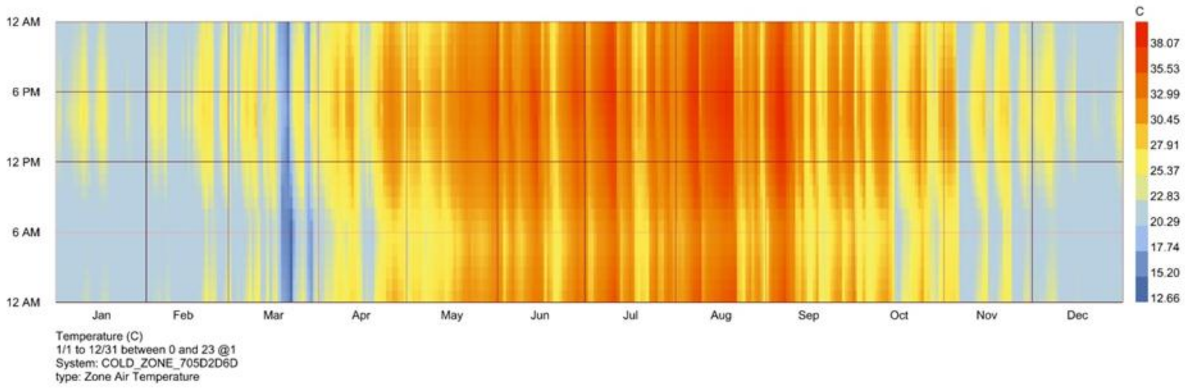

Fig. 3. Annual indoor temperature profile of Rasht. (Source: Authors, 2024, created using EnergyPlus software 24.1.0)

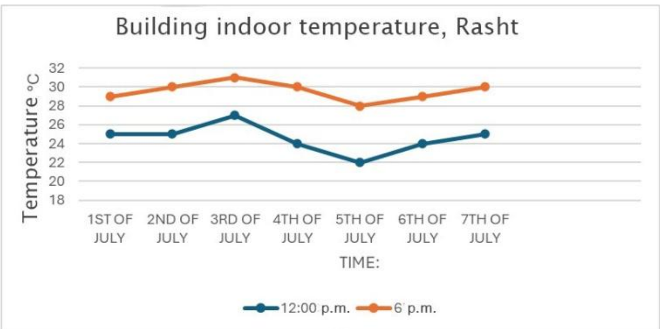

Fig. 4. Experimentally measured indoor temperature in Rasht during the first week of July at 12:00 p.m. and 6:00 p.m. (Source: Authors, 2024)

The average indoor temperature of the building modelled in EnergyPlus software for the month of July in Rasht was estimated to be 32°C at 12 p.m. and 34°C at 6 p.m. In contrast, field experiments conducted in a traditional building in Rasht during the first week of July measured the average indoor temperature at 24.5°C at 12 p.m. and 29.5°C at 6 p.m.

Kermanshah

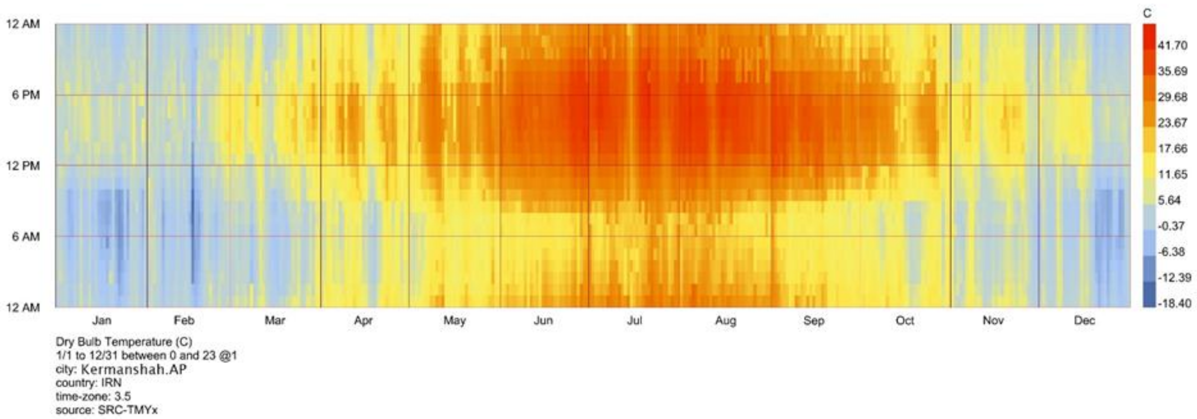

Fig. 5. Annual outdoor temperature profile of Kermanshah. (Source: Authors, 2024, created using EnergyPlus software 24.1.0)

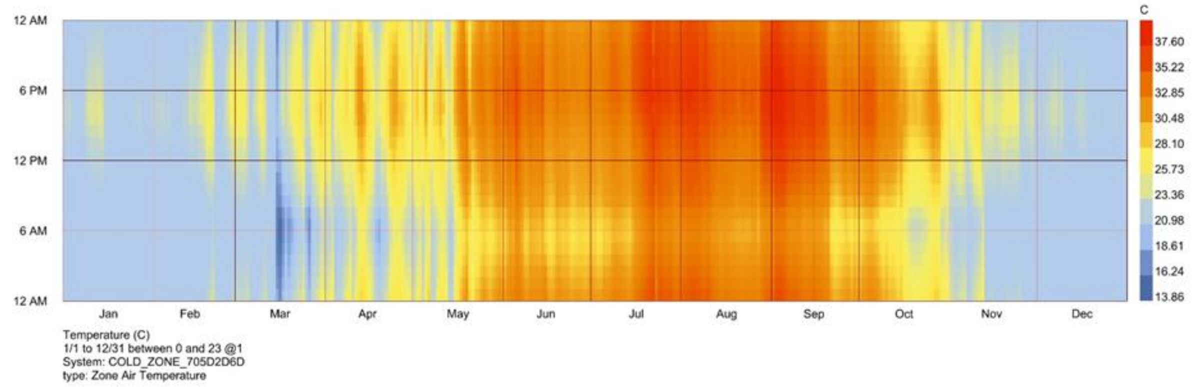

Fig. 6. Annual indoor temperature profile of Kermanshah. (Source: Authors, 2024, created using EnergyPlus software 24.1.0)

Tab. 3. Monthly average indoor and outdoor temperatures of Kermanshah at 12:00 p.m. and 6:00 p.m. (Source: Authors, 2024, created using EnergyPlus software 24.1.0)

	T outdoor		T indoor	
Month	Hour 12	Hour 6	Hour 12	Hour 6
1	2.11	2.64	20.00	20.00
2	1.59	2.67	20.00	20.00
3	7.17	10.07	15.42	17.37
4	14.88	15.12	16.38	19.74
5	20.38	22.45	21.22	24.85
6	30.26	32.13	26.86	30.78
7	30.32	34.40	27.89	31.55
8	31.37	34.79	28.15	32.14
9	28.60	29.05	25.30	29.53
10	18.51	20.23	17.78	21.14
11	8.06	10.34	19.75	19.82
12	3.65	4.01	20.00	20.00

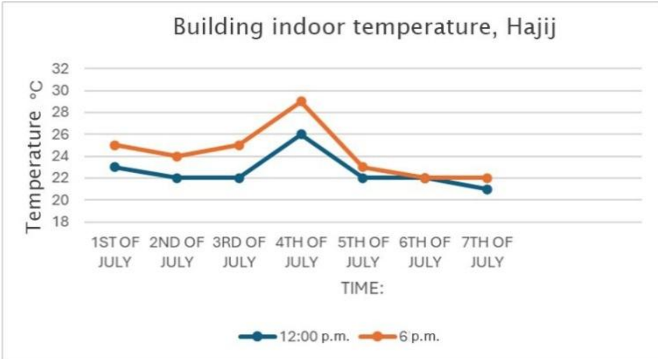

Fig. 7. Experimentally measured indoor temperature in Kermanshah during the first week of July at 12:00 p.m. and 6:00 p.m. (Source: Authors, 2024)

The average indoor temperature of the building modelled in EnergyPlus software for the month of July in Kermanshah was projected to be 27.8°C at 12 p.m. and 31.5°C at 6 p.m. Meanwhile, field experiments conducted in a traditional building in Kermanshah during the first week of July recorded an average indoor temperature of 22.5°C at 12 p.m. and 24°C at 6 p.m.

Yazd

The average indoor temperature of the building simulated in EnergyPlus software for the month of July in Yazd was estimated to be 32.7°C at 12 p.m. and 36.7°C at 6 p.m. In comparison, field experiments conducted in a traditional building in Yazd during the first week of July registered an average indoor temperature of 21.5°C at 12 p.m. and 22°C at 6 p.m.

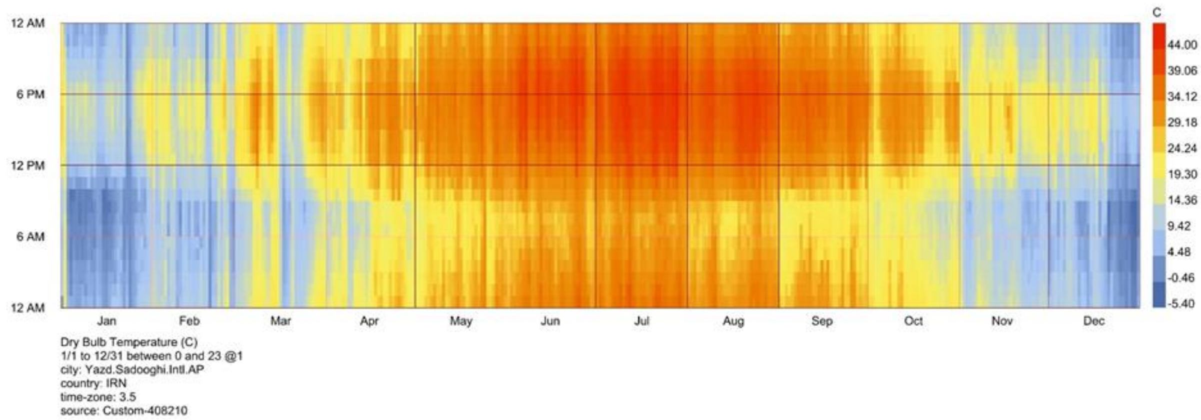

Fig. 8. Annual outdoor temperature profile of Yazd. (Source: Authors, 2024, created using EnergyPlus software 24.1.0)

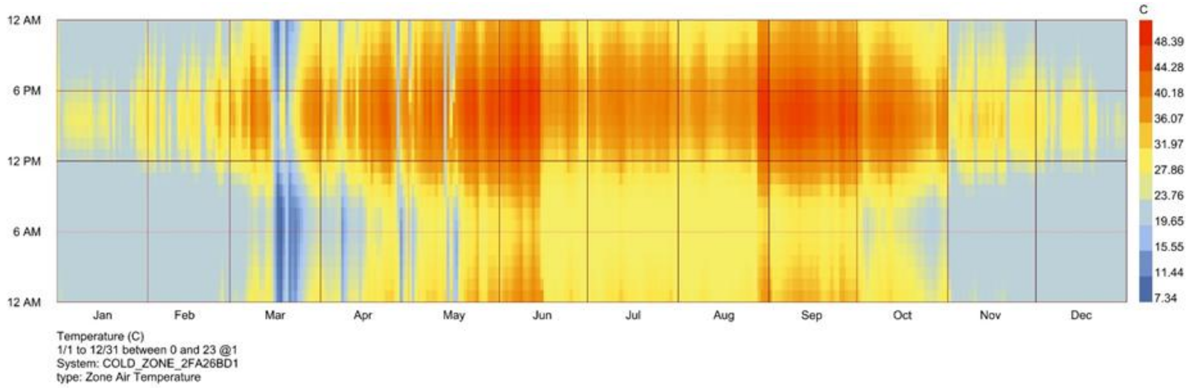

Fig. 9. Annual indoor temperature profile of Yazd. (Source: Authors, 2024, created using EnergyPlus software 24.1.0)

Tab. 4. Monthly average indoor and outdoor temperatures of Yazd at 12:00 p.m. and 6:00 p.m. (Source: Authors, 2024, created using EnergyPlus software 24.1.0)

	T outdoor		T indoor	
Month	Hour 12	Hour 6	Hour 12	Hour 6
1	7.86	11.90	21.34	21.79
2	13.21	14.25	27.24	29.07
3	18.35	21.06	15.42	17.37
4	24.57	2610	31.65	33.30
5	29.45	32.29	36.08	37.13
6	33.32	38.17	35.68	39.68
7	36.10	39.76	32.74	36.72
8	34.06	37.77	32.77	36.16
9	29.77	34.10	38.84	41.12
10	23.58	27.39	33.97	34.89
11	15.67	18.60	25.65	25.86
12	9.91	10.42	22.07	21.93

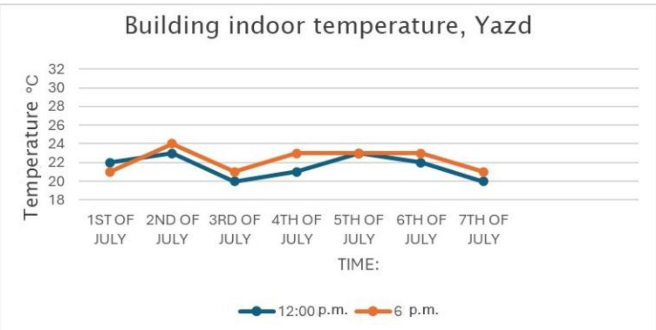

Fig. 10. Experimentally measured indoor temperature in Yazd during the first week of July at 12:00 p.m. and 6:00 p.m. (Source: Authors, 2024)

ARCHITECTURAL AND URBAN PLANNING FACTORS INFLUENCING INDOOR TEMPERATURE IN DIFFERENT CLIMATES OF IRAN

Humid and mild climate

As it is shown in Fig. 11, in the vernacular houses of this region, the yard and porch are two connected spaces that are highly dynamic due to daily activities such as animal husbandry, agriculture, and cooking. These areas also serve as spaces for social interactions, fostering connections with the environment and neighbours. Given the relationship between the physical structure of the houses and their surrounding environment, builders paid close attention to ensuring harmony between the colour, materials, and forms used in the context of the region's climate. The sloped roof design of these buildings was specifically chosen to address climate challenges, providing protection against winter cold, heavy rainfall, and summer heat. The architecture of cities and villages in the humid and mild climate of northern Iran, particularly in the Gilan region (e.g., Rasht and surrounding villages), is deeply influenced by the area's environmental conditions but mostly single houses with distance from each other. The region's high humidity, frequent rainfall, and moderate temperatures shape the design of buildings and the use of materials. The local architecture is aimed at ensuring comfort by facilitating ventilation, protecting against moisture, and maximising the use of natural light (Daemei, et al., 2016).

Fig. 11. Shape and material of traditional building of temperate region, Gilan Rural Heritage Museum. (Photo: Authors, 2024)

1. Topography and Layout

- Scattered Layout: Villages in Gilan feature a more scattered layout. Houses are typically spaced apart to allow air to circulate freely around them, which is crucial in a humid climate to prevent the build-up of moisture and mould (Zafari et al., 2024).

- Proximity to Nature: The lush greenery and fertile land of northern Iran encourage integration with the natural environment. Homes are often surrounded by gardens, rice paddies, and orchards. This connection to nature is a key characteristic of the region's architecture.

2. Architectural Features

- Elevated Structures: Houses in Gilan are often built on stilts or elevated platforms, known locally as "Pileh Khaneh." This elevation helps prevent flood damage during heavy rains, protects the structure from ground moisture, and promotes airflow underneath the house, which helps reduce humidity inside.

- Gable Roofs with Wide Eaves: The roofs in this region are steeply pitched (gable roofs) to efficiently shed rainwater. The wide eaves extend well beyond the walls of the house, providing additional protection from the heavy rainfall typical in the area. These overhangs also create shaded outdoor spaces, where residents can enjoy the fresh air without being exposed to direct sunlight or rain (van Woensel et al., 2018).

- Balconies and Verandas: Houses often have wraparound balconies or verandas, known locally as "Ivan." These open, covered spaces are used for social activities, relaxation, and even food preparation. They allow for ventilation while providing shelter from both sun and rain. Verandas also function as transitional spaces between the indoors and outdoors.

3. Use of Wind and Sunlight

- Ventilation and Wind Management: Ventilation is a key concern in the humid climate of northern Iran. Houses are designed with multiple openings, including large windows, doors, and louvered vents that allow air to flow through the interior spaces. The orientation of houses often considers the prevailing winds, ensuring that breezes can cool the interior and reduce humidity levels (Naghibi et al., 2021).

- Maximising Natural Light: Sunlight is essential in a region with frequent rainfall, so houses are designed to make the most of available light. Large windows, often with wooden shutters or lattices, allow sunlight to penetrate deep into the living spaces, helping to reduce dampness and mould. The placement of these windows is carefully considered to balance the need for light with the desire to avoid overheating the interior.

4. Building Materials

- Wood: Wood is the primary construction material in the Gilan region, thanks to the abundance of forests in northern Iran. Wooden beams, planks, and shingles are used for everything from the structural frame to the walls and roofing. Wood is lightweight, which is suitable for the elevated structures, and it also provides flexibility in construction (Al-Mudhaffer et al., 2022).

- Clay and Mud Bricks: In addition to wood, clay and mud bricks are used in the construction of walls. These materials are sometimes combined with wood in a technique known as "Khesht" or wattle and daub, which involves weaving wood branches together and covering them with a mixture of mud and straw. This method provides insulation and is relatively resistant to moisture when properly maintained.

- Thatch Roofing: In more traditional homes, thatch made from rice straw or reeds is used for roofing. This natural material is abundant and provides excellent insulation while being lightweight and effective at shedding rain. However, it requires regular maintenance and replacement.

5. Climate Adaptation

- Protection from Rain: The steeply pitched roofs and wide eaves are essential in managing the region's frequent rainfall. By efficiently draining water away from the building and providing covered outdoor spaces, these features help prevent water damage and ensure that homes remain dry inside.

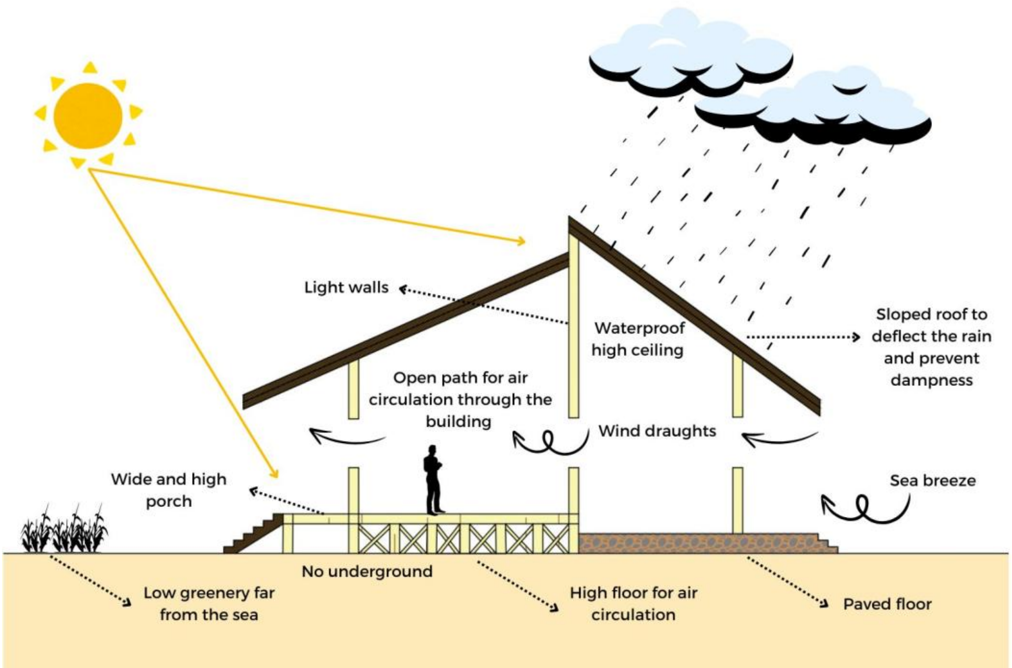

Fig. 12. Traditional house form in Rasht. (Source: Authors, 2024)

- Dealing with Humidity: The emphasis on ventilation and airflow is critical in preventing the build-up of moisture inside the home, which can lead to mould and structural problems. Elevated structures and the use of wood also help to mitigate the effects of ground moisture and ensure that air can circulate freely (Soleymanpour et al., 2015).

6. Cultural and Social Aspects

- Outdoor Living Spaces: The verandas and balconies that are characteristic of Gilan architecture are not only functional but also reflect the social and cultural lifestyle of the region. These spaces serve as gathering places for families and neighbours, where people can enjoy the natural beauty of their surroundings while staying sheltered from the elements.

- Traditional Aesthetics: The use of local materials and traditional construction techniques gives Gilan's architecture a distinctive aesthetic that harmonises with the lush, green landscape. The combination of wood, clay, and natural fibres creates a warm, organic look that is both practical and beautiful.

In summary, as it is illustrated in Fig. 12, the architecture of humid and mild climate cities and villages in northern Iran, like those in the Gilan region near Rasht, is shaped by the region's environmental conditions. Elevated wooden structures with gable roofs, wide eaves, and verandas reflect the need for ventilation, protection from rain, and integration with the natural landscape. The use of natural materials like wood, clay, and thatch ensures that these homes are well-suited to the humid climate, while their design emphasises both comfort and cultural values (Daemei, Eghbali and Khotbehsara, 2019). In the traditional houses of Gilan province, located in the humid and mild climate of northern Iran, architectural features such as high ceilings, specific building materials, and numerous openings are designed to naturally cool the indoor environment during the hot and humid summer months. These elements help reduce indoor temperatures by 3–7°C (5.4–12.6°F) compared to the outside, depending on factors such as house orientation, wind patterns, and the surrounding environment (Bahadori, 2011).

Cold and mountainous climate

The architecture of cold and mountainous cities in western Iran, such as the village of Hajij in Kermanshah, reflects the region's adaptation to a harsh climate, steep terrain, and the availability of natural resources. These architectural styles are deeply rooted in the cultural and environmental context, designed to provide warmth, protection, and energy efficiency (Hashemi and Ghaffary, 2017).

1. Topography and Layout

- Steep Terrain and Terraced Layout: In mountainous regions like western Iran, cities and villages are often built on steep hillsides. The layout typically follows the natural contours of the terrain, resulting in terraced structures. In villages like Hajij, houses are built in such a way that the roof of one house serves as the courtyard for the house above it. This interconnected and compact design minimises land use and helps create windbreaks (Akbari and Rafiei, 2024).

- Compact Urban Fabric: The densely packed structures reduce heat loss in winter and maximise protection from the cold mountain winds. This compactness also helps in reducing construction costs in terms of material and labour (Ansarimanesh et al., 2019).

2. Architectural Features

- Thick Stone and Mud Walls: The primary construction materials are stone and mud, which are locally available. Stone is excellent for insulation, helping keep houses warm in the winter and cool in the summer. Mud plaster is often used as a binding material and as insulation, preventing heat escape during cold months.

- Flat Roofs: Many houses have flat roofs, which can be used for various purposes, including drying crops and accessing sunlight. The roofs are made of wood beams covered with mud and straw, which provide insulation against the cold.

- Small Windows: Due to the harsh winters, windows are generally small to minimise heat loss (Heiranipour et al., 2021). They are strategically placed to allow maximum sunlight during the day while preventing cold draughts from entering.

3. Use of Wind and Sunlight

- Solar Orientation: Houses are typically oriented to maximise sunlight, especially during the cold winter months. South-facing windows are common, allowing homes to capture the warmth of the sun throughout the day. This passive solar heating is crucial for maintaining comfortable indoor temperatures.

- Wind Management: The architecture in these regions often incorporates natural wind patterns into the design. In mountainous areas, cold winds can be intense, so houses are built with their backs to the prevailing winds. The terraced and compact nature of the settlements also helps in creating windbreaks, reducing the impact of strong winds.

- Courtyards and Verandas: Some homes have internal courtyards that serve as wind-protected spaces where residents can enjoy the sunlight. These courtyards are also used to provide natural ventilation in the summer, allowing cool air to circulate through the home while curbing the cold mountain winds in winter (Aram and Alibaba, 2018).

4. Building Materials

Fig. 13. Shape and material of traditional building of cold mountainous regions, Hajij Village. (Photo: Authors, 2024)

- Stone: As it is shown in Fig. 13, stone is the dominant building material in this region due to its abundance in mountainous terrains. Stone walls are thick, providing excellent insulation against the cold.

- Wood: Wood is used primarily for roofing and structural elements. Beams and supports are crafted from local trees, and wooden frames are used in windows and doors.

- Mud and Straw: Mud mixed with straw is used as plaster on walls and roofs. This combination acts as an additional layer of insulation, trapping heat within the home.

- Clay and Adobe: In some cases, adobe bricks made from a mixture of clay, straw, and water are used for building. These bricks provide thermal mass, helping regulate indoor temperatures.

6. Climate Adaptation

- Winter Protection: The architecture is designed to deal with heavy snowfall and freezing temperatures. Sloped roofs are rare in this region, as flat roofs can manage snow loads if properly constructed. Thick walls and small windows are key features that reduce heat loss.

- Summer Cooling: Despite the cold winters, summers in these regions can be hot. Thick stone walls help in keeping interiors cool during the hot days. Additionally, homes often have shaded verandas or semi-open spaces that allow residents to enjoy the outdoors without being exposed to direct sunlight.

7. Cultural and Social Aspects

- Community-Centric Design: The compact layout of villages like Hajij in Kermanshah promotes a strong sense of community. The terraces and interconnected roofs mean that neighbours live in close proximity, fostering social interaction.

- Traditional Aesthetics: The use of local materials and construction techniques gives the architecture a distinctive and traditional aesthetic that blends seamlessly with the natural environment. The stone and mud structures often harmonise with the surrounding landscape, creating a visually cohesive village.

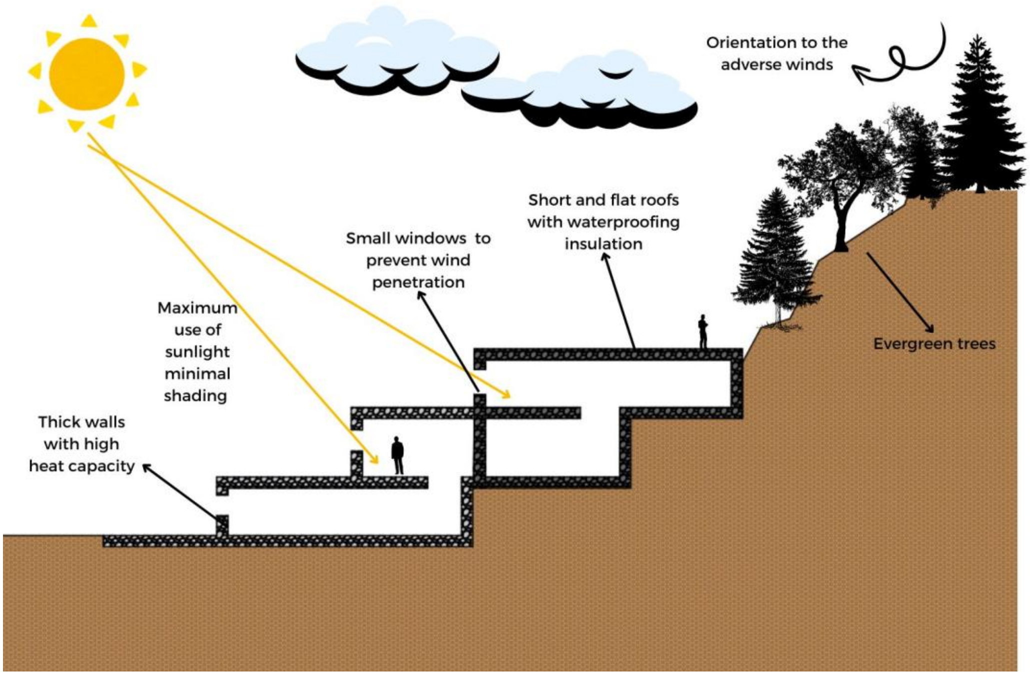

Fig. 14: Traditional house form in Kermanshah. (Source: Authors, 2024)

In summary, as it is illustrated in Fig. 14, the architecture in cold and mountainous cities in western Iran, such as Hajij, reflects the region's adaptation to its climate, topography, and cultural heritage. The use of thick stone walls, small windows, flat roofs, and strategic orientation towards sunlight are all critical features that help residents manage the harsh environmental conditions. The materials are locally sourced, sustainable, and provide the necessary insulation for both winter and summer conditions. In the terraced village of Hajij in the Kermanshah province, the traditional architectural features, such as thick stone walls, small openings, and low ceilings, play a crucial role in insulating homes during the cold winter months. These design elements are specifically adapted to the cold mountainous climate, and they significantly increase the indoor temperature compared to the harsh conditions outside. The combination of these features can raise the indoor temperature by 5-10°C (9-18°F) or more, depending on factors like wall thickness, materials used, and heat sources inside the house (Eghtedari and Mahravan, 2021).

Dry desert climate

The architecture of dry desert cities in the centre of Iran, such as Yazd, is a remarkable example of how people have adapted to extreme environmental conditions. The city of Yazd, located in a desert region with hot summers and cold winters, has developed unique architectural solutions to combat the harsh climate. These architectural features focus on maximising ventilation, as it is shown in Fig. 15, minimising heat absorption, and making the most efficient use of water and natural resources (Viana et al., 2018).

1. Topography and Layout

- Compact Urban Fabric: The layout of cities like Yazd is characterised by narrow, winding streets that create shade and reduce the impact of hot desert winds. Buildings are densely packed to minimise surface exposure to the sun, which helps reduce heat gain and conserve energy (Shahri et al., 2023).

- Courtyard Houses: Traditional houses in Yazd often have central courtyards, known as "Hozkhaneh," around which the rooms are arranged. These courtyards serve as microclimates, providing shade, reducing heat, and creating a cool, tranquil environment. The courtyard is often planted with trees or has a small water feature that helps cool the air through evaporative cooling.

2. Architectural Features

- Thick Mud-Brick Walls: The walls of traditional houses in Yazd are made of thick mud bricks, which provide excellent insulation against the desert heat. Mud bricks (known as adobe) have a high thermal mass, meaning they can absorb heat during the day and release it slowly at night, keeping the interiors cool during the day and warm at night.

- Domed and Vaulted Roofs: Many buildings in Yazd feature domed or vaulted roofs, which help to disperse heat more effectively. The curved surfaces minimise direct sun exposure and allow heat to rise and dissipate, keeping the interior spaces cooler. Domes and vaults also allow for the use of natural light without overheating the interiors.

- Windcatchers (Badgirs): One of the most iconic architectural features in Yazd is the windcatcher, or "Badgir." These tall, tower-like structures capture wind at the top and direct it down into the building, providing natural ventilation and cooling. Windcatchers are oriented to catch the prevailing winds and can cool the interior spaces significantly, even in the scorching desert heat (Sangdeh and Nasrollahi, 2022).

3. Use of Wind and Sunlight

- Wind Management (Badgirs): As mentioned, windcatchers are essential in the architecture of Yazd. They work by catching the wind and funnelling it down into the house, where it can be circulated through the rooms. The windcatchers often direct the cool air over a pool of water (in the courtyard or a dedicated room), enhancing the cooling effect through evaporation. This passive cooling system is incredibly efficient in the hot, dry desert climate where mechanical cooling options were traditionally limited (Jomehzadeh et al., 2020).

- Sunlight Management: Sunlight is carefully managed to minimise heat gain. Thick walls and small windows help keep the interiors cool by reducing the amount of direct sunlight entering the buildings. Openings are often placed on the north side of buildings to avoid the intense sun from the south. Additionally, screens and latticework (called "Mashrabiya") are used to diffuse sunlight while still allowing light into the interiors without excessive heat (Roshan et al., 2020).

- Shade and Reflection: The narrow alleys and shaded courtyards are designed to provide as much shade as possible. Buildings are often painted in light colours, which reflect sunlight and reduce heat absorption.

4. Building Materials

- Mud Bricks (Adobe): The primary material used in Yazd's architecture is mud brick, made from a mixture of clay, straw, and water. This material is ideal for the desert climate because it provides thermal insulation and is easily sourced from the surrounding environment. Adobe construction is also cost-effective and durable in dry climates, although it requires regular maintenance to protect against erosion.

- Plaster and Lime: Adobe walls are often coated with a layer of plaster or lime to protect them from the elements and to further enhance their thermal insulation properties. Limewash, which has reflective properties, is sometimes used to coat exterior surfaces, helping to reduce heat absorption.

- Wood: Wood is used sparingly in Yazd due to its scarcity in desert environments. When it is used, it is typically for doors, window frames, and the structural support of domes and windcatcher.

Fig. 15: Shape and material of traditional building of desert region, Lariha House, Yazd. (Photo: Authors, 2024)

5. Climate Adaptation

- Heat Management: Yazd's architecture is designed to deal with the intense heat of the desert. The use of thick walls, domed roofs, and windcatchers creates a comfortable indoor environment despite the extreme temperatures outside. The focus on natural ventilation and passive cooling techniques helps reduce reliance on energy-intensive cooling systems (Shahri et al., 2023).

- Water Conservation: Water is a precious resource in desert environments, and the architecture of Yazd reflects this. Courtyards often feature small water pools that cool the air through evaporation. Additionally, the city is famous for its Qanats—underground aqueducts that bring water from distant mountains to the city. This ancient system allows for efficient use of water in an environment where surface water is scarce (Beigli and Lenci, 2016).

6. Cultural and Social Aspects

- Private and Communal Spaces: The design of houses in Yazd balances private and communal spaces. The central courtyard serves as a family gathering space, while the interiors of the houses offer privacy from the outside world. The design also reflects Islamic principles, with an emphasis on modesty and protection from the harsh elements.

- Sustainable and Environmentally Integrated: The architecture of Yazd is a great example of sustainable design. The materials are locally sourced and environmentally friendly, and the design strategies are low-tech yet highly effective in creating comfortable living conditions. These traditional methods of construction are in harmony with the natural environment, ensuring that resources are used efficiently (Jafari Sharami, 2023).

In summary, the architecture of desert cities like Yazd in central Iran is a sophisticated response to the harsh desert climate. As it is illustrated in Fig. 16, features like windcatchers, thick adobe walls, domed roofs, and shaded courtyards work together to create comfortable living conditions despite extreme temperatures

(Aliabadi et al., 2015). The use of natural ventilation, careful management of sunlight, and conservation of water are all critical elements of this architecture, which reflects both the ingenuity of its designers and the cultural values of the region. In the desert city of Yazd, architectural elements like windcatchers (Badgirs), central courtyards (Hozkhaneh), dome roofs, adobe materials, and water pools work together to create a cooling effect that significantly reduces indoor temperatures compared to the scorching heat outside. The effectiveness of these features can vary depending on their design, orientation, and the specific environmental conditions, but they can reduce indoor temperatures by 10–15°C (18–27°F) or more, making living spaces much more comfortable in the desert climate (Izadpanahi et al., 2021).

Tab. 5. Architectural Adaptations to Climate in Rasht, Hajij, and Yazd. (Authors, 2024)

Architectural Adaptations	Rasht	Hajij	Yazd
Urban Density	Low	Compact	Medium
Building Orientation	Typically, oriented to maximise airflow and cooling	Oriented to shield from high winds	Oriented to minimise direct sunlight exposure
Material Thermal Properties	Wood and brick; highly responsive to humidity	Stone and mortar; insulation for colder temperatures	Adobe and mud brick; high thermal mass
Roof Design	Sloped roofs with overhangs to handle rain and humidity	Pitched roofs to handle snow and rain	Flat roofs to minimise sun exposure and maximise cooling at night
Wall Thickness	Moderate to thick, with plaster to resist moisture	Moderate, with additional insulation	Very thick to reduce heat gain
Openings and Ventilation	Large windows and verandas to enhance airflow	Limited windows to reduce heat loss and minimise wind impact	Small openings and badgirs (windcatchers) to capture and cool air
Courtyard Design	Rare, due to high humidity	Courtyards used to harness sun and block wind	Central courtyards for cooling effect
Wind Efficiency Measures	Open layouts and elevated floors for cross-ventilation	Limited wind exposure in building design, stone as a thermal barrier	Badgirs, thick walls, and small courtyards for cooling

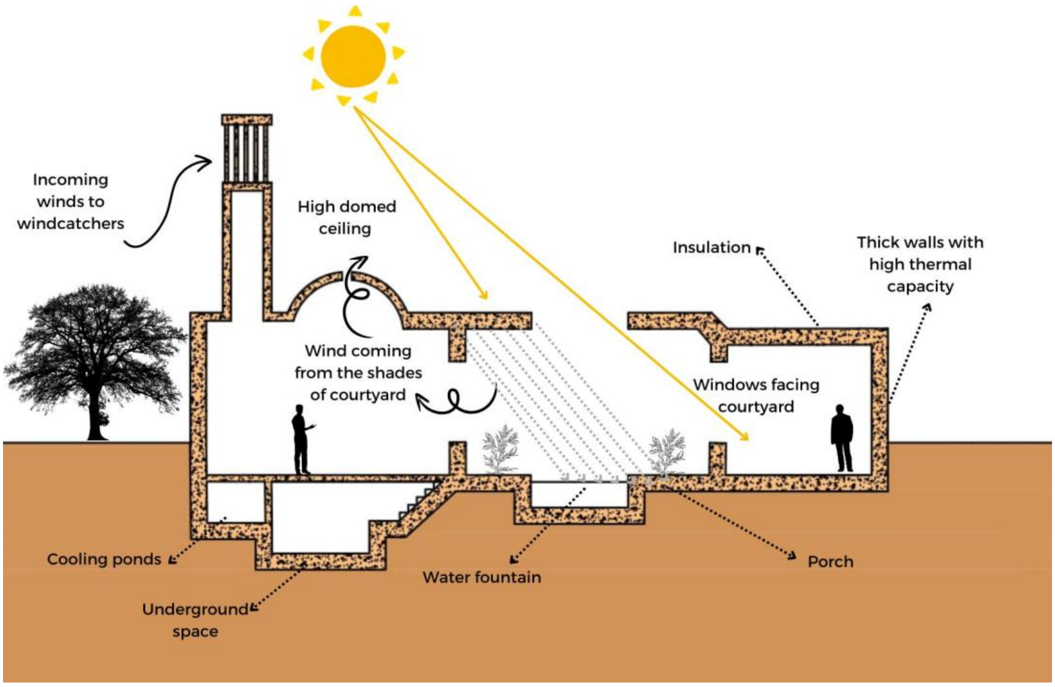

Fig. 16. Traditional house form in Yazd. (Source: Authors, 2024)

Tab. 5 compares key architectural features such as urban density, building orientation, thermal properties of materials, and wind efficiency measures, highlighting how traditional designs in each city are tailored to local climate challenges.

DISCUSSION AND CONCLUSION

This study examined bioclimatic architecture across three Iranian cities with distinct climatic conditions Rasht, Hajij and Yazd to understand how architectural elements respond to environmental challenges in each location. Each case reflects how traditional design strategies have been tailored to optimise comfort and minimise energy usage through natural means. In Rasht, characterised by a humid, subtropical climate, the architecture utilises features like large openings, overhanging eaves, and cross-ventilation strategies to counteract the high humidity and frequent rainfall. These elements promote airflow while reducing direct sunlight exposure, providing a cooling effect indoors without extensive energy input. Yazd, with its hot desert climate, presents a different adaptation approach. Here, passive cooling techniques such as badgirs (windcatchers), thick mudbrick walls, and semi-underground spaces are employed to manage the intense heat. The orientation of buildings and use of courtyards promote airflow and shade, effectively lowering indoor temperatures and enhancing thermal comfort.

Hajij in Kermanshah, located at a higher altitude, experiences colder winters and cooler summers. The architecture in this region incorporates compact building forms and thermal insulation through materials such as stone and adobe to retain heat during winter and provide a cool environment in summer. This adaptation to the mountainous climate exemplifies how high-altitude architecture can sustain comfort through thermal mass and strategic orientation. Overall, these case studies highlight how vernacular design in Iranian architecture integrates climatic considerations uniquely in each region. The traditional elements openings, insulation techniques, and orientation are strategically chosen to align with the prevailing environmental conditions of each city, reflecting a deep-rooted, sustainable approach that modern practices can learn from.

This study reinforces the value of regionally adapted architecture as a sustainable response to diverse climatic challenges. By comparing bioclimatic strategies across Rasht, Hajij, and Yazd we observe how traditional architectural elements contribute to environmental comfort, energy efficiency, and a lower carbon footprint. In Rasht, large openings and cross ventilation address humidity; in Yazd, thick walls, windcatchers, and courtyards mitigate desert heat; and in Hajij, the use of thermal mass and compact forms respond to cooler, high-altitude conditions. The findings suggest that local climate responsive designs are both effective and essential for sustainable development. For future urban planning and architectural design, a return to these traditional strategies optimised with modern materials and technologies could bridge the gap between comfort and environmental responsibility. This comparative analysis of bioclimatic strategies in varying Iranian climates thus provides valuable insights for architects and urban planners worldwide seeking to design resilient, climate sensitive buildings.

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