Article

Lessons from Sustainable and Vernacular Passive Cooling Strategies Used in Traditional Iranian Houses

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ABSTRACT

Passive cooling strategies have long been used in vernacular and traditional architecture practices. Today, with the surge in energy consumption, excessive carbon emissions and lingering climate change challenges, the shift to passive solutions to heat and cool buildings is crucial. Despite this urgency, we heavily rely on electricity and gas to maintain thermal comfort inside buildings. Since heating and cooling accounts for 40% of household energy use, devising passive strategies in housing design can make a significant difference in energy consumption. This paper explores the characteristics of Iranian traditional housing that contribute to making indoor spaces thermally comfortable. The examination of sustainable strategies used in seven case studies in the hot and dry climate of Iran indicates that such measures have a significant impact on the microclimate of traditional houses and considerably reduce the need for electricity and mechanical power. The study suggests that designing tall, north-facing walls, large and shallow pools in the courtyards, multiple openings in the courtyard-facing wall in the same room, stack-cooling for instigating the convective air movement, night purge ventilation, dome ceilings, earth coupling and using thermally massive materials, as well as seasonal relocation across the courtyard are among the most important strategies for mitigating the heat in Iranian houses. Finally, this work puts forward a set of recommendations to improve the passive design of future buildings in hot and arid climates.

KEYWORDS: passive cooling; sustainability; Iran; housing; hot and dry climate

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INTRODUCTION

Buildings account for a significant proportion of the total energy and carbon emissions worldwide [1]. Over the recent decades, there has been a significant increase in the use of air conditioning for cooling buildings around the globe [2]. Identifying and adopting passive cooling measures used in traditional buildings can therefore assist in developing zero or low energy buildings. Drawing on seven case studies in three cities within the hot and dry region of Iran, this study aims to identify passive cooling measures used in traditional houses and investigate how the design of buildings can contribute to their thermal performance. The findings of this research can then inform the design and construction of contemporary buildings in similar climate conditions.

Iran is located in the northern hemisphere with around 65% of its land under arid and extremely arid climates [3,4]. In such harsh climate conditions, the establishment of proper environmental strategies that offers thermal comfort and decreases energy consumption in buildings has been inevitable. In the hot and dry cities of Iran, several design measures have been incorporated into traditional buildings to provide passive cooling and mitigate the heat load [5], considering climatic factors as well as local construction materials and natural cooling systems [6].

This research begins with a climate study in three cities in Iran: Yazd, Kashan and Isfahan. In the subsequent sections, it explores the sustainable strategies used in traditional houses. The methodology begins with understanding the solar access and radiation to the buildings through calculating the outdoor shadow length and area. The study then investigates how the design of these houses and their elements (e.g., openings, orientations, etc.) could create passive cooling opportunities for residents through earth coupling, natural ventilation, evaporative cooling, dome ceiling, seasonal relocations, as well as the use of local and thermally massive materials. The final section draws on the case studies and their features and brings together the findings from this study.

Findings suggests that the sustainable and passive methods used in traditional houses in Iran have the potential to be applied to the modern and contemporary buildings of 21st century. The methods are backed up with natural systems and therefore, are valid regardless of the time. For example, hot air always rises facilitating the stack cooling effect; or knowing the fact that sun always rises in the east and sets in the west can inform people's relocations to stay cool in the house daily and seasonally.

Although most of the recommendations of this study will work for houses in similar climate conditions, the design decisions still need to be adapted according to each individual project and context.

Contribution of Vernacular Architecture to Urban Sustainability

Vernacular architecture refers to "structures built using locally available materials in a functional style devised to meet the needs of common people in their time and place. Most of the vernacular architecture responds to the regional climate" [7]. It is the result of hundreds of years of optimisation to provide comfortable shelters using local materials and known construction techniques. Numerous studies have established the importance of vernacular architecture and its social, cultural and environmental values [8–10]. Vernacular architecture has been "an inspiration for innovations in environmental and socio-economically sustainable design and planning" [11]. Several studies have explored passive design techniques and energy-efficient design in the vernacular architecture of different regions, including Turkey [11], North India [7], Vietnam [12], Nepal [13] and Cyprus [14]. The vernacular architecture of Iran, with its rich history and different climatic regions, has also been the subject of a few studies exploring traditional insights that can be adopted for the optimisation of modern buildings energy performance [15–17].

Overview of Traditional Iranian Houses and Sustainability

In Iran, a series of strategies for thermal comfort were adopted by traditional builders in various cities, including in hot and arid regions, to meet their specific climatic conditions [18]. A critical investigation of sustainable design and construction strategies in Iran showed how traditional housing responded to local culture and climate restrictions in ways that can be used in contemporary design frameworks [19]. For instance, previous studies have shown that internal courtyards help with thermal comfort [20]. The use of courtyards in buildings was initiated in the hot and dry climatic regions of the world [21]. However, courtyards have since been implemented in other types of climate as well [22].

The inclusion of seasonal rooms (north-facing in summer and south-facing in winter) was another strategy used to cope with the harsh climate conditions [23]. These rooms are usually located on two, three or four sides of the courtyard.

Addition of basements is often acknowledged as one of the main vernacular architectural solutions to help residents cope with the hot and dry climate of Iran [23]. Foruzanmehr's study of thermal comfort in traditional houses in Yazd showed that basements are the only living space providing thermally comfortable temperatures throughout an entire typical hot summer's day [24]. However, they are perceived to be unhealthy , inconvenient, uneconomic and often impractical [25]. Despite this, basements have frequently been used as afternoon living spaces in traditional houses in Iran [25].

Most external walls in the vernacular architecture of Iran in the hot and dry regions are constructed 50–80 cm thick with adobe bricks and rendered with a mud and straw mixture [23]. Being a good thermal mass , with high heat-retaining capacities, adobe bricks are able to capture the heat from outside during the day time and slowly release it during the night. Considerable fluctuations of temperature between day and night are made tolarable by this heat absorption and release through massive walls.

Geometry is another important feature of traditional buildings in Iran. The level of thermal comfort in a building is determined by the effects of microclimatic factors, particularly solar radiation and wind. The house and courtyard's geometry, dimensions, proportions and orientations are some of the most influential design variables for microclimatic conditions and the provision of thermal comfort [26,27]. One of the main passive cooling features in traditional houses is the shaded area of the internal courtyard that mitigates the heat [28].

Iranian traditional houses also benefited from natural ventilation strategies, such as cross ventilation and stack cooling using solar chimneys and wind catchers, which were popular ventilation systems for hot climates [29]. A wind catcher is an energy-efficient system that helps to air condition the house by providing convective cooling or, evaporative cooling (inward, or outward), or by cooling the "structure of buildings down by either coupling the internal air temperatures to those of the night sky or with the earth in basements and underground tunnels and streams, typically in regions too hot for internal convective cooling to be enough during the day" [30].

Stack cooling works by being positioned in a suitable direction according to the wind, building size and the number of air traps necessary to cool the building [31]. In addition, night purge ventilation has been employed in some traditional houses in Iran. This is the result of the circulation of cool night air in interior spaces, reducing the temperature of the inside thermal mass [32]. Bringing the cool night air inside reduces the peak daytime temperature resulting in thermal comfort [33].

Climate and Contextual Studies

To understand how architectural design has contributed to the notion of sustainability in traditional housing in Iran, this study has analysed seven traditional buildings in three cities with similarly hot and dry climatic conditions: Yazd, Esfahan and Kashan.

To understand the behaviour of the houses in hot and dry climate conditions, several assessment criteria have been considered, including building form and orientation, solar access, building materials and openings. All the case studies had internal courtyards, however, the height of the south wall around the courtyard was highest in the Tabatabais, the Laris, the Borojerdis, and the Tosizade houses and lowest in the Samaeeyan, the Zehtab and the Seirafi houses. Also, all houses had large pools in the courtyard and all the liveable rooms around the yard had multiple openings to facilitate natural ventilation. Moreover, all of the houses had summer rooms and winter rooms in the southern, and northern parts of the courtyard respectively. The spaces in most of the houses were similarly arranged and were linearly from south to –north to create minimum exposure to the burning southern sun. However, subtle deviations in this south-to-north orientation were identified in the Tabatabais, and the Zehtab houses.

Table 1 shows the altitude of the sun during the summer solstice for each city.

Table 1. Altitude calculation.

City	Latitude	Longitude	GMT Time Zone	Summer Solstice	Altitude based on Day Time		
					9 am	12 pm	3 pm
Yazd	31.8974° N	54.3569° E	+4.5 h	21 June	38.05°	75.33°	61.02°
Kashan	33.9850° N	51.4100° E	+4.5 h	21 June	35.82°	72°	63°
Esfahan	32.6546° N	51.6680° E	+4.5 h	21 June	35.88°	72.98°	63.11°

The climate studies for this paper were conducted using Climate Consultant, a graphic-based computer program that helps with the analysis and visualisation of the climate data acquired from the closest weather station.

Location: Yazd

The climate analysis indicated that Yazd experiences a significant temperature range between −6 at night in January and +43 during daylight in August (Figure 1). The wind wheel showed that between May and October (during the hot season) in Yazd, the prevailing wind blows from the north-west direction.

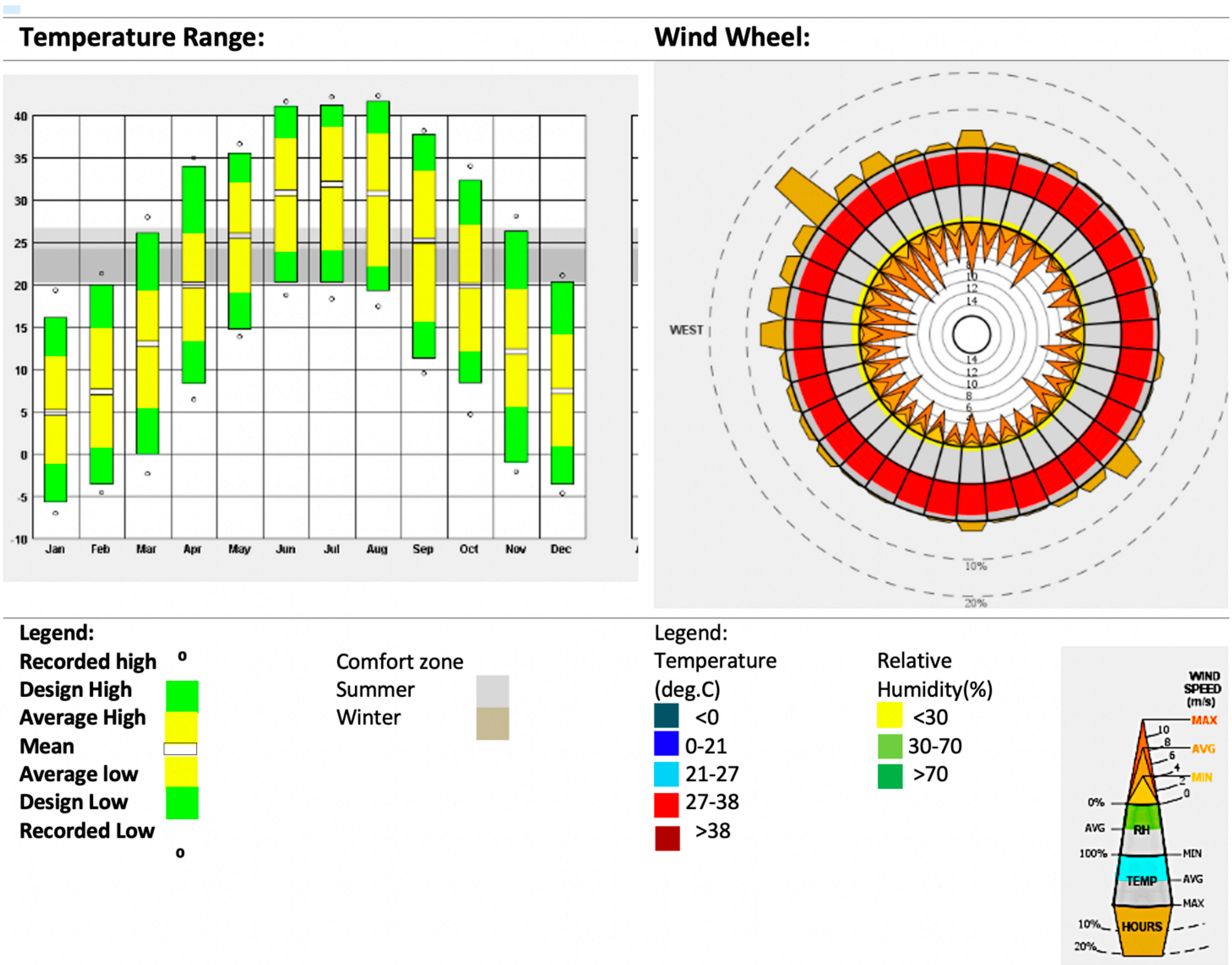
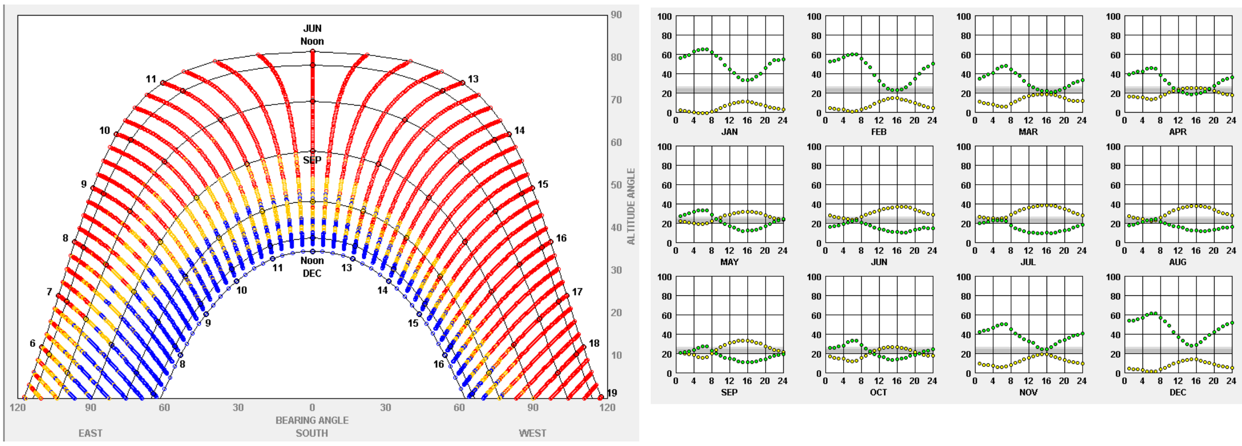


Figure 1. Yazd temperature range and wind wheel [4].

The sun shading and dry bulb charts indicate that between June and September (the hottest and driest months) from 10:00 am until 7:00 pm, Yazd faces overheating conditions, with the dry bulb temperature above the comfort range and the relative humidity usually lower than 30%, below the typical comfort range of 30–70% [4].

Sun Shading Chart:	**Dry Bulb and Relatively Humidity:**



Legend:	**Plot months:**	Legend:	Comfort Zone
o Warm/Hot >27 °°C June 21 to December 21		Dry Bulb ○	Summer
o Comfort >20 °C		Humidity ●	Winter
o Cool/Cold <20 °C			

Figure 2. Sun shading chart, dry bulb temperatures and relative humidity for Yazd [4].

Location: Esfahan and Kashan

Esfahan and Kashan also experience a significant temperature range, from −7 at night in January to +39 during daytime in August. The wind wheel shows that between June and August (the hottest months), the prevailing wind travels from the east and the north-east. Similar to Yazd, Esfahan and Kashan also have dry days with less than 30% relative humidity in summer (Figure 3).

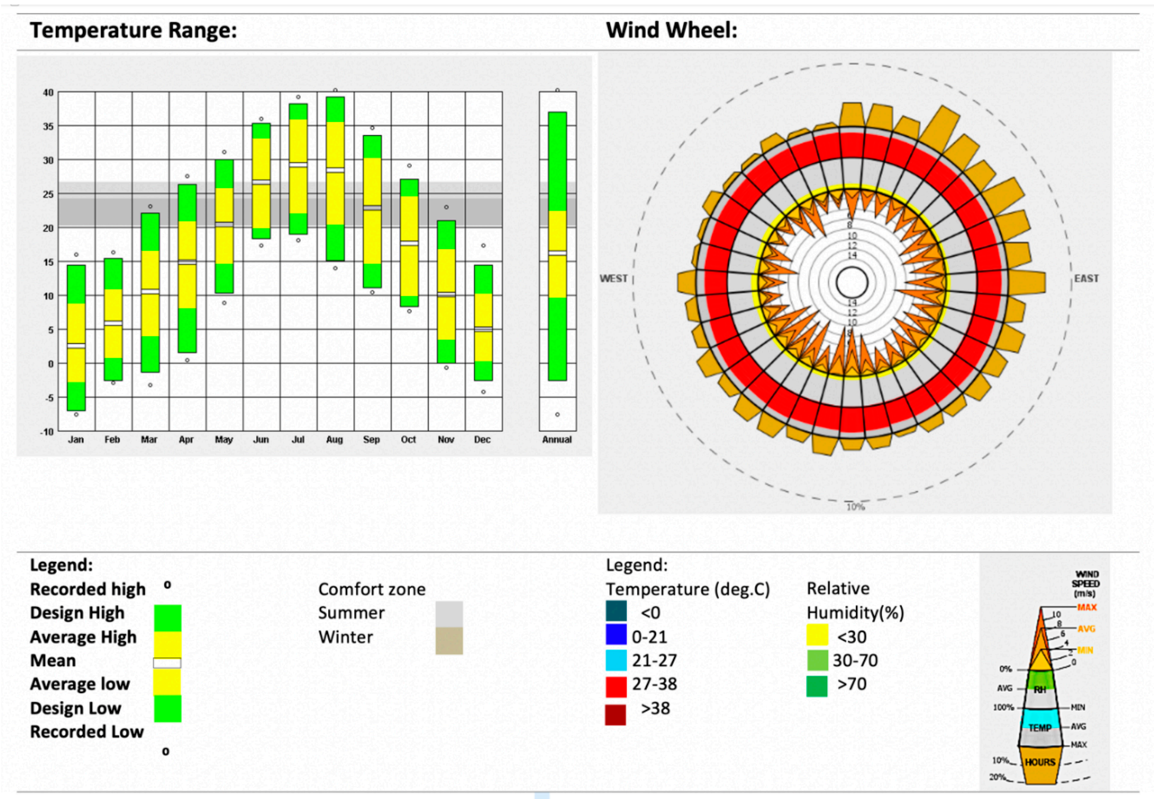


Figure 3. Esfahan and Kashan temperature range and wind wheel [4].

The sun shading chart indicates that between June and September (the hottest and driest months) between 11:00 am and 7:00 pm, Esfahan and Kashan experience overheating conditions, where the dry bulb temperature is above the comfort range and the relative humidity is below the comfort range discussed above (Figure 4).

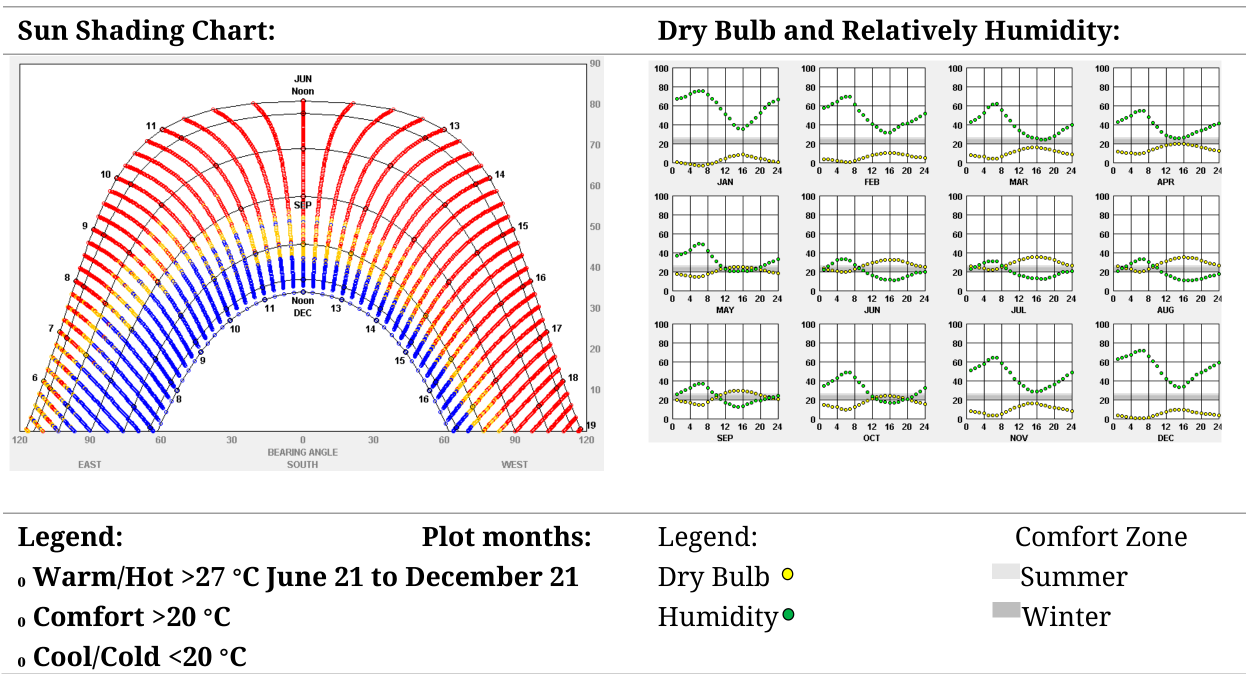


Figure 4. Sun shading chart, dry bulb temperature and relative humidity for Esfahan and Kashan [4].

To identify and evaluate the sustainable design strategies utilised in these cities, the plans and sections of seven traditional houses were analysed. The researchers also examined the percentage of the building in shade during different times of the day and the relationship of this shade with the architectural design. Other strategies, such as natural ventilation and earth coupling, were also explored to understand the performance of the buildings when the temperature rose above the comfort level.

IDENTIFYING PASSIVE COOLING STRATEGIES

Shadowing: Solar Access and Solar Radiation

Szokolay (2004) argues that the thermal behaviour of a building has the greatest effect on energy use and sustainability and that solar radiation has the most notable input into buildings that are considered thermal systems with a series of heat inputs and outputs [34]. In order to understand how traditional design in Iranian houses responded to solar radiation to create thermal comfort through shading in hot and dry areas, the shaded area in each house was calculated by considering the solar radiation and access in courtyards during the summer solstice. The shaded area was calculated by multiplying the shadow length by the courtyard width. The shadow length was calculated based on the south wall's height and the altitude angle of the sun (Figures 5 and 6).

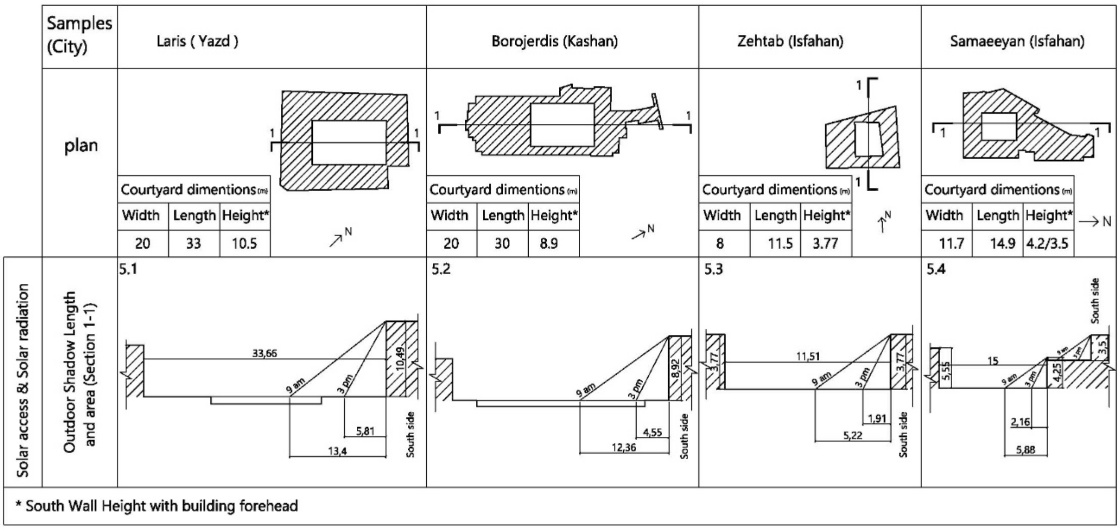


Figure 5. Outdoor shadow length (Source: Authors, based on Climate Consultant program) [4].

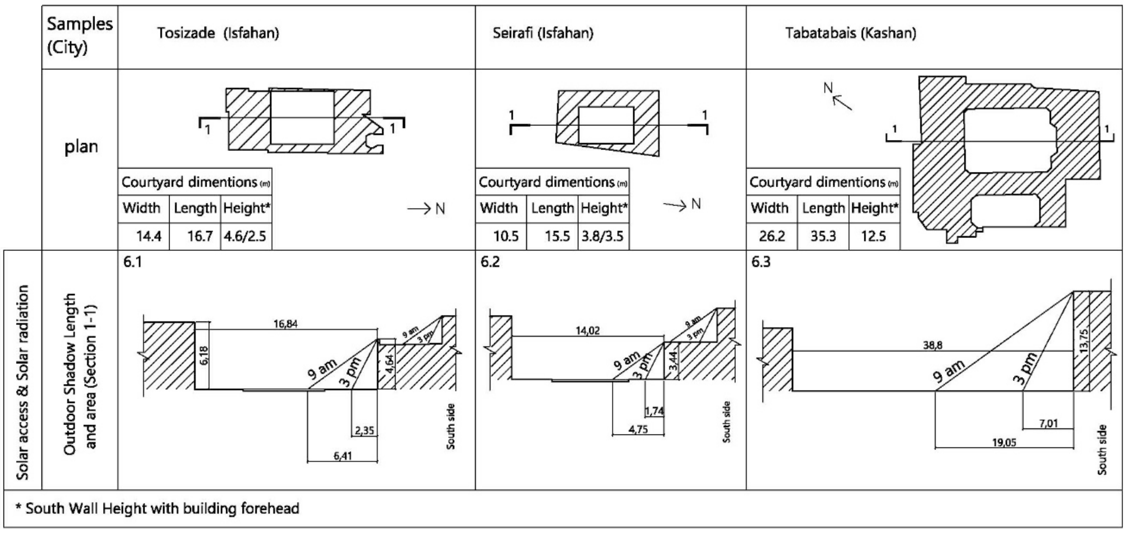


Figure 6. Outdoor shadow length (Source: Authors, based on Climate Consultant program) [4].

The outdoor shaded area within the internal courtyard has been calculated for each case study (see Tables 2–8):

Table 2. The Laris house: Outdoor shadow area calculation.

	The Laris House (Yazd)		
	9 am	12 pm	3 pm
Shadow length	13.4 m	5.8 m	2.7 m
Courtyard width	20 m		
Shadow area	13.4*20 = 268 m^2	2.7*20 = 54 m^2	5.8*20 = 116 m^2
Courtyard area	33*20 = 660 m^2		
Yard proportion in shadow	40%	8%	17%

Table 3. The Borojerdis house: Outdoor shadow area calculation.

	The Borojerdis House (Kashan)		
	9 am	12 pm	3 pm
Shadow length	12.4 m	2.9 m	4.5 m
Courtyard width	20 m		
Shadow area	12.4*20 = 248 m^2	2.9*20 = 58 m^2	4.5*20 = 90 m^2
Courtyard area	30*20 = 600 m^2		
Yard proportion in shadow	41%	10%	15%

Table 4. The Zehtab house: Outdoor shadow area calculation.

	The Zehtab House (Isfahan)		
	9 am	12 pm	3 pm
Shadow length	5.2 m	1.16 m	1.9 m
Courtyard width	8 m		
Shadow area	5.2*8 = 41.6 m^2	1.16*8 = 9.28 m^2	1.9*8 = 15.2 m^2
Courtyard area	8*11.5 = 92 m^2		
Yard proportion in shadow	45%	10%	17%

Table 5. The Samaeeyan house: Outdoor shadow area calculation.

	The Samaeeyan House (Isfahan)		
	9 am	12 pm	3 pm
Shadow length	5.9 m	1.3 m	2.16 m
Courtyard width	11.7 m		
Shadow area	5.9*11.7 ≈ 69 m^2	1.3*11.7 ≈ 15.2 m^2	2.16*11.7 ≈ 25.3 m^2
Courtyard area	15*11.7 ≈ 175 m^2		
Yard proportion in shadow	40%	9%	14%

Table 6. The Tosizade house: Outdoor shadow area calculation.

	The Tosizade House (Isfahan)		
	9 am	12 pm	3 pm
Shadow length	6.4 m	1.4 m	2.35 m
Courtyard width	14.4 m		
Shadow area	6.4*14.4 ≈ 92 m^2	1.4*14.4 ≈ 20 m^2	2.35*14.4 ≈ 34 m^2
Courtyard area	16.7*14.4 = 240 m^2		
Yard proportion in shadow	38%	8%	14%

Table 7. The Seirafi house: Outdoor shadow area calculation.

	The Seirafi House (Isfahan)		
	9 am	12 pm	3 pm
Shadow length	5.28 m	1.17 m	1.94 m
Courtyard width	10.5 m		
Shadow area	5.28*10.5 ≈ 55 m^2	1.17*10.5 ≈ 12.3 m^2	1.94*10.5 ≈ 20.4 m^2
Courtyard area	15.5*10.5 = 163 m^2		
Yard proportion in shadow	34%	8%	13%

Table 8. The Tabatabais house: Outdoor shadow area calculation.

	The Tabatabais House (Kashan)		
	9 am	12 pm	3 pm
Shadow length	17.3 m	4 m	6.4 m
Courtyard width	26.2 m		
Shadow area	17.3*26.2 ≈ 453 m^2	4*26.2 ≈ 105 m^2	6.4*26.2 ≈ 168 m^2
Courtyard area	35.3*26.2 ≈ 925 m^2		
Yard proportion in shadow	49%	11%	18%

The analysis of the seven houses indicates that at 9:00 am, between 34% and 49% of the courtyards of all the houses were covered in shadow. The proportion of the shaded area decreased to between 8% and 11% at 12:00 pm. In the afternoon, the area covered in shadow expanded to between 13% and 18% of the courtyard at 3:00 pm.

Earth coupling

In hot and dry climates with mild winters, the cool temperatures of the soil can provide passive cooling to the earth-covered parts of a building

[35]: "In regions with a temperate climate, the natural temperature of the soil in summer at a depth of 2–3 m may be low enough to serve as a cooling source" [35]. In the traditional houses of Iran's hot and dry regions, some rooms were built six to seven metres below the ground surface, where there is usually a steady annual temperature [6]. Empirical investigations showed that "these spaces can provide substantially cooler indoor temperatures in summer" [25]. This method has been used in Figures 7 and 8 except in the Zehtab house.

Some of the case studies discussed in this research include underground areas known as "Hozkhaneh" in Persian. These rooms benefit from the cooling effect of earth coupling. They usually include pools and wind catchers (see the "*Stack cooling*" Section for more details). Wind catchers redirect the wind into these underground rooms where the wind passes through the water and enters the interior spaces, cooling down the building's fabric [36].

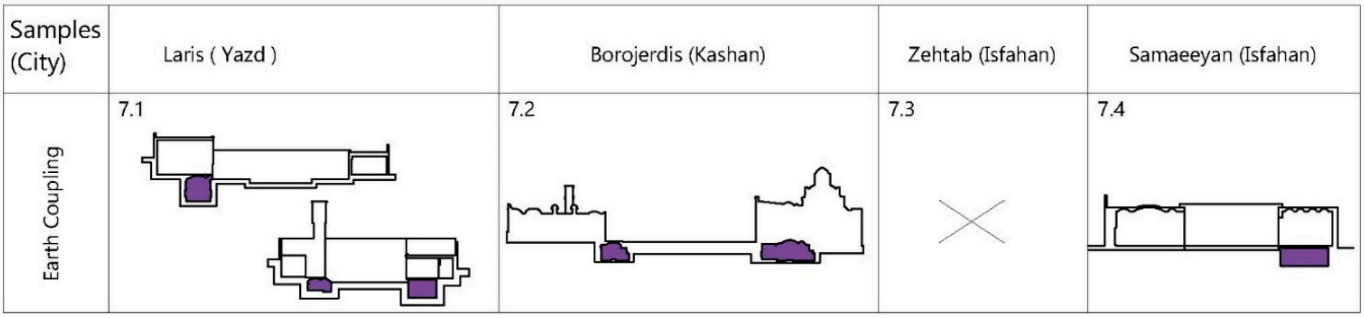


Figure 7. Earth coupling.

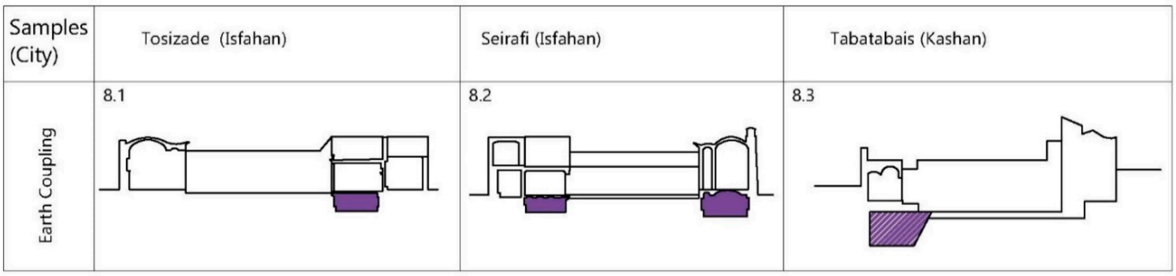


Figure 8. Earth coupling.

Natural ventilation

In traditional Iranian housing, privacy has always been considered as a significant factor in design because of cultural and religious beliefs [37]. This is one of the reasons why the rooms were designed to be inward facing and around a central courtyard [38]. As a result, the use of openings on the opposite sides of rooms was not always feasible for natural cross ventilation. One strategy to solve this problem was to use multiple wide windows on the same wall instead of providing a single opening on the wall adjacent to the courtyard. This helps the air to circulate through the house which is seen in all the seven buildings in this study.

In all seven houses, the openings were designed to facilitate the wind blowing freely from the courtyard through the house and back to the courtyard again. Thus, the wind was used for passive cooling and the provision of fresh air with the help of these openings (Figures 9 and 10).

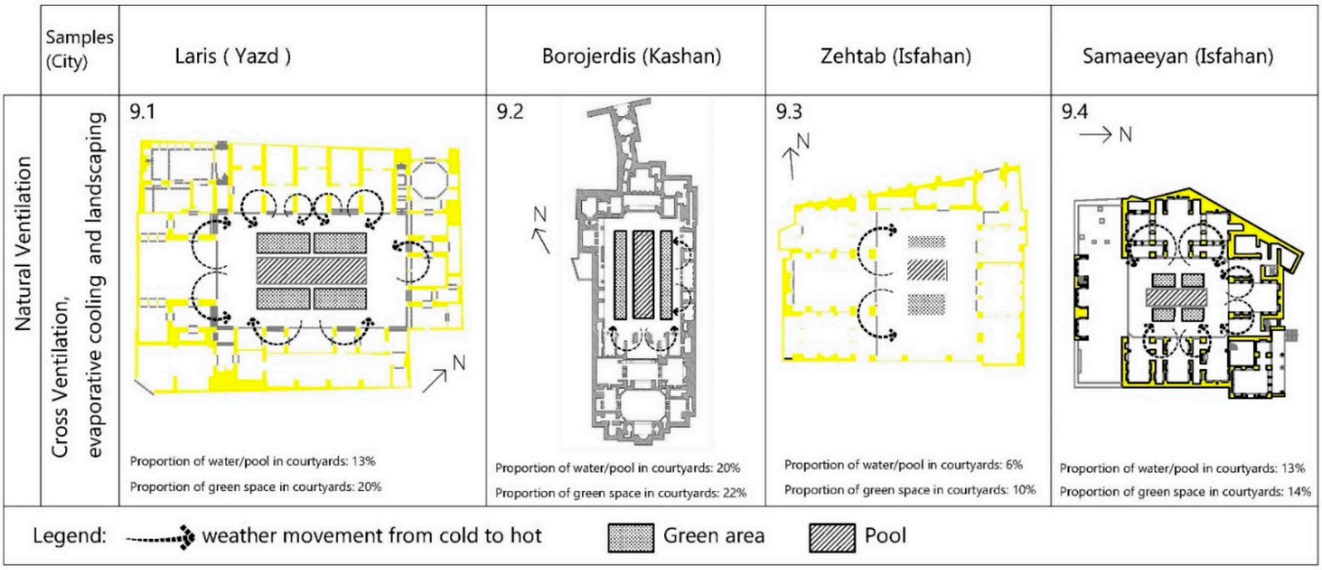


Figure 9. Natural ventilation.

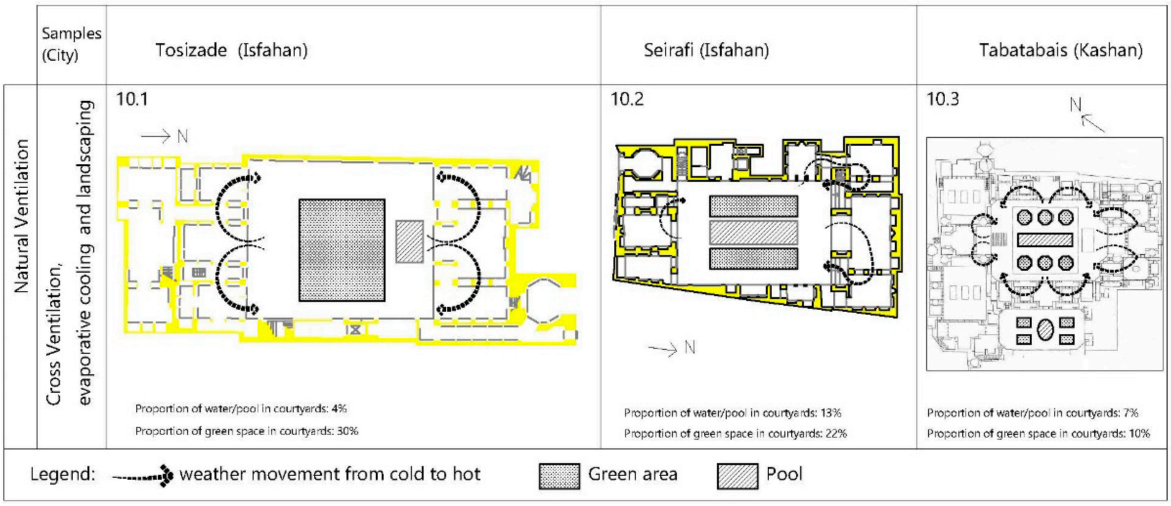


Figure 10. Natural ventilation.

Evaporative cooling

Most traditional houses with internal courtyards contain a shallow pool of water. This body of water not only contributes to the aesthetics of the courtyard, but also facilitates the evaporative cooling of the rooms surrounding the courtyard [39]. The pools covered 4% to 20% of the courtyard areas in the case studies investigated. These pools are designed to purify and cool the sandy hot wind that passes over them. The water in the pool adds some moisture to the air providing a desirable breeze to the interior spaces.

Trees and vegetation also improve the thermal and environmental conditions of buildings in summer [40–42]. Vegetation and landscaping in courtyards could play an important role in alleviating the heat over summer. By absorbing radiation, vegetation can transfer the sensible heat to latent heat, decreasing the temperature. The vegetation canopy covered 10% to 30% of the courtyard areas in the selected case studies.

Stack cooling

Cooling interior spaces was achieved by using passive stacks on hot summer days, providing a vertical exhaust path for the hot air. Further, ventilation towers (also known as solar chimneys and wind catchers) helped the building fabric to cool down during the night, owing to their thermally massive structures [43].

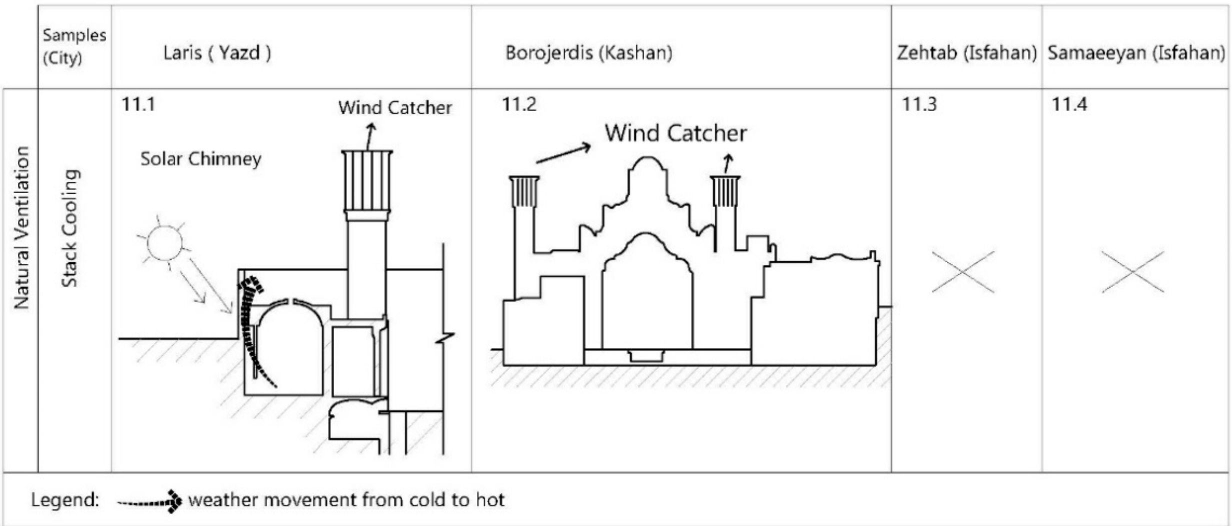


Figure 11. Stack cooling.

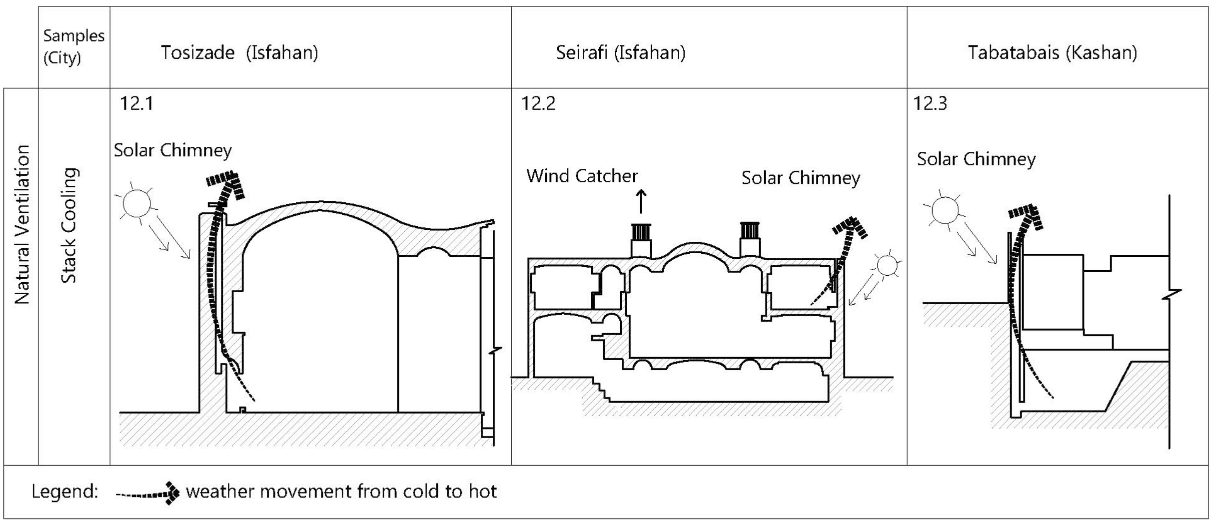


Figure 12. Stack cooling.

The movement of the air into and out of the building was analysed in the seven case studies (Figure 13). The Laris and the Seirafi houses (Figure 11, Section 11.1; Figure 12, Section 12.2) each have a solar chimney and a wind catcher, which contribute to the stack effect. The solar chimney is an architectural element of traditional Iranian houses that entices cool air to enter from the bottom and exhausts warm air through the vents at the top of the chimney. This flow decreases the temperature of the chimney which usually has thick brick walls and considered as a good thermal mass. The height of the wind catchers instigates the convection of the air and drives the hot air out of the building. Two other case studies, the Tosizade and the Tabatabais houses (Figure 12, Sections 12.1 and 12.3), have solar chimneys to improve natural ventilation through the convection of the heated air using passive solar energy. The Borojerdis' house only uses a wind catcher to create natural ventilation in the building (Figure 11, Section 11.2). Stack cooling was not used in the Zehtab and Samaeeyan houses. Overall, five out of seven case studies utilised stack cooling to improve the natural ventilation within the buildings.

Domes

Domes are one of the major elements of Iranian traditional structures, including residential buildings [44,45]. Five out of the seven houses have a dome designed to assist in passive cooling (Figures 13 and 14). This architectural element provides additional space for the heated air to move up to the ceiling, driving the cool, fresh air to enter from openings on the walls adjacent to the central courtyard. In the Borojerdis house (Figure 14.1), there were openings on the dome's surface that guided the hot air out of the building. Domes also increase the shaded area on ceilings in comparison with flat ceilings, decreasing the overall heat trapped in the thermal mass by solar radiation.

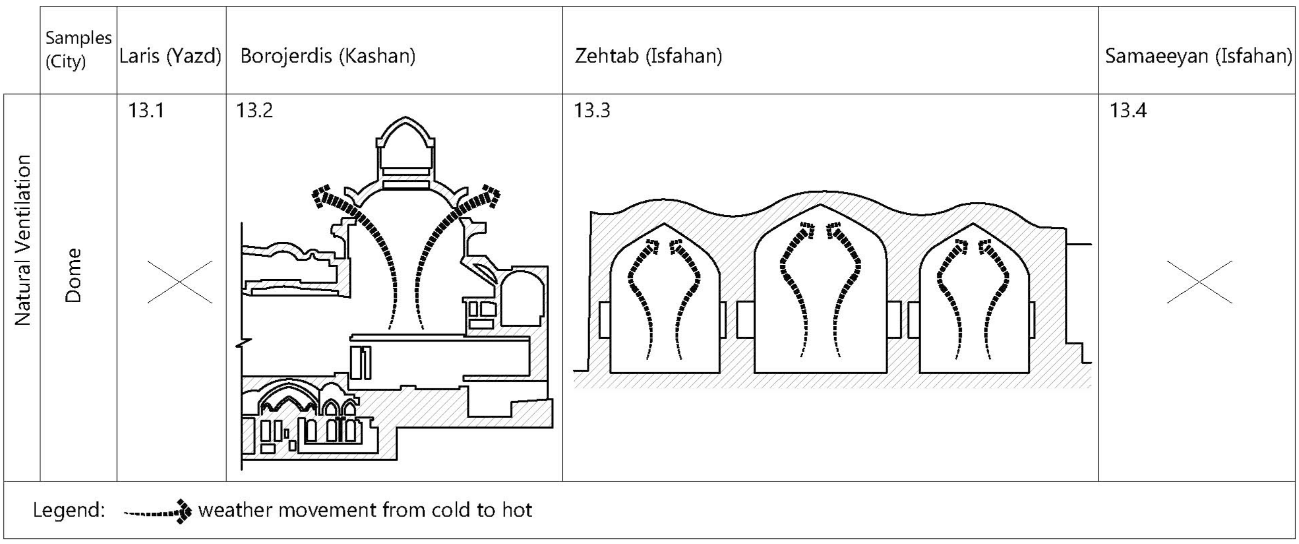


Figure 13. Dome.

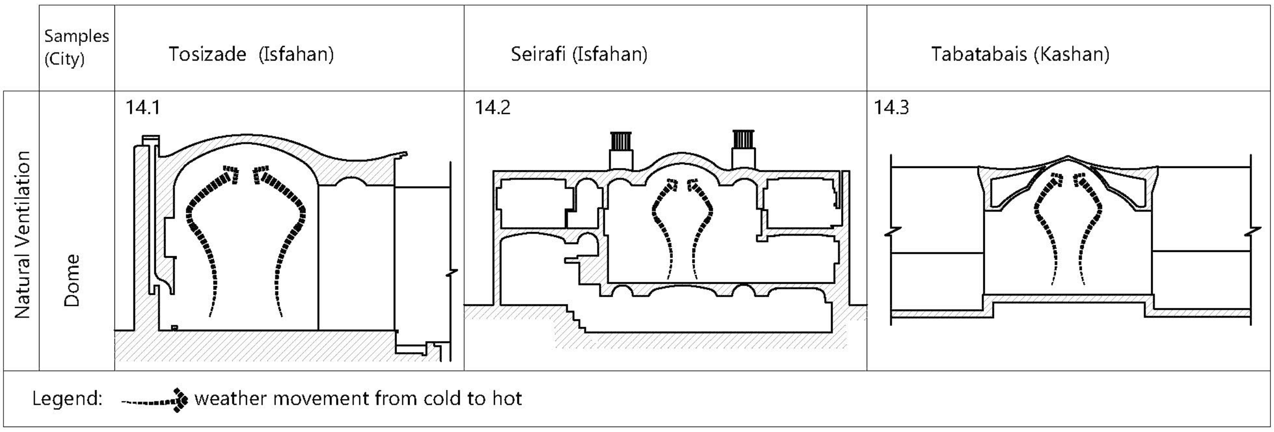


Figure 14. Dome.

Night purge ventilation/Night flushing

Night flushing is a passive cooling technique that uses the air movement to cool the building fabric at night time [46]. The building openings remain closed during the daytime so that the cool air from the night flushing can keep the building fabric cool during the day. Climate conditions have been shown to affect night purge ventilation. Higher differences between the outside temperature and the building fabric during the night can cause the mass cooling of the building [46]. This strategy was seen in five houses and only two houses (the Tosizades' and the Seirafis') were not sufficiently oriented towards the desirable wind to benefit from this natural ventilation method (Figures 15 and 16).

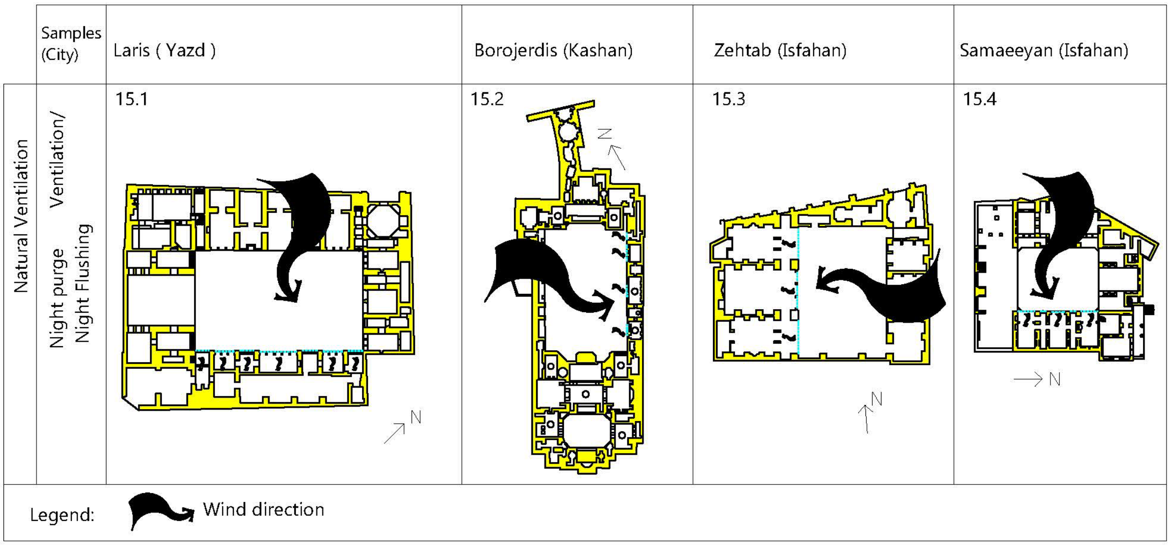


Figure 15. Night purge.

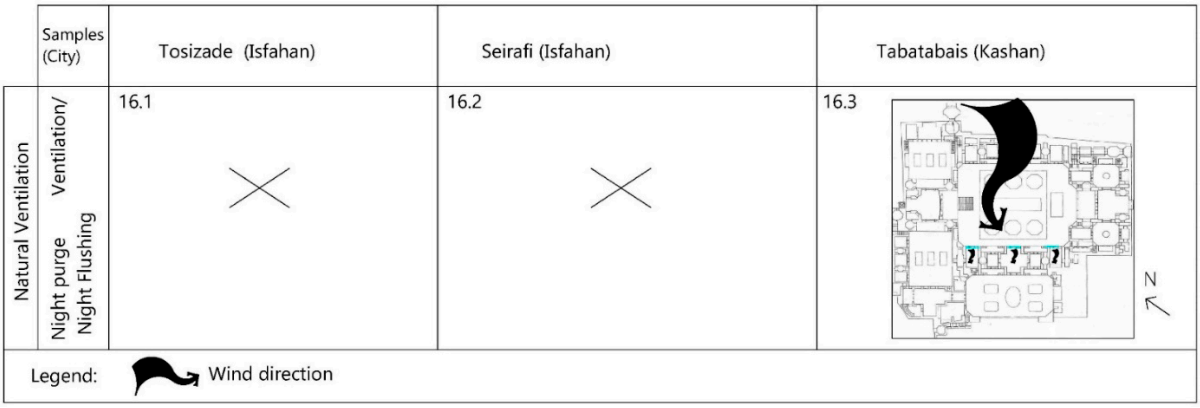


Figure 16. Night purge.

Seasonal relocations

The seasonal relocation between the summer and winter sections of the house was one of the most important responses to climate conditions in traditional Iranian houses [6,47]. Drawing on solar radiation, traditional Iranian houses were divided into summer (north-facing) rooms and winter (south-facing) rooms. Winter rooms were usually located in the northern and western parts of the courtyard where the sun enters during winter. Summer rooms were located on the western and southern sides of the courtyard, which are in shade during the summer [23,47]. These multi-functional rooms usually do not contain any heavy furniture and are covered with carpets or rugs. This makes it possible for the space to be used simultaneously or alternatively during the day and night, summer and winter, depending on the needs of its inhabitants and the changes in the weather [23]. The flexibility of these rooms allowed the inhabitants to use the thermal profile of each space for its use at any particular time of the day or year [48].

Material

Building construction is responsible for approximately 30% or more of the energy-related CO_2 emissions globally [49,50]. Therefore, the choice of material in building construction could make a huge difference for the environment.

In traditional houses located in hot and dry climates, thermally resistant materials, such as clay, mudbrick, stone, brick, mortar, lime and wood were used in building construction [51]. Earth in various forms, such as “unbaked bricks” (also known as “mud bricks” or “adobes”) has been used as the predominant construction material in this climate [52].

Adobe bricks are durable, recyclable and affordable material, but often neglected specially in the post-war period when concrete was mainly used in response to the massive housing demands. The main problem with materials such as concrete is having high-embodied carbon and not being recyclable or decomposable after disposal (Figure 17).

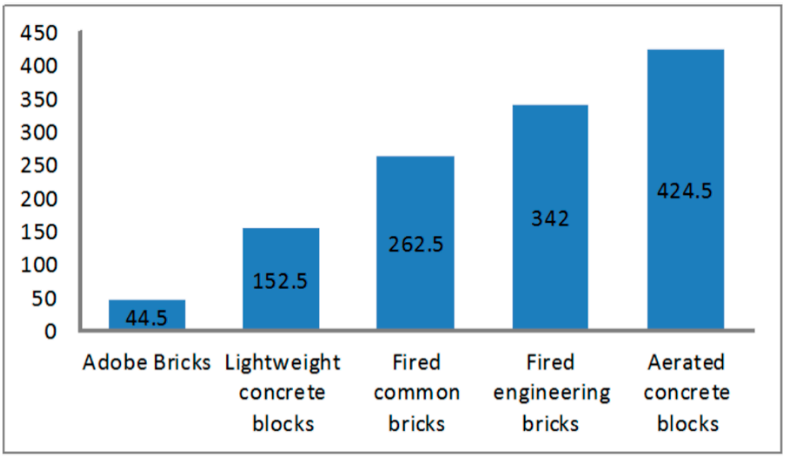


Figure 17. Embodied carbon (kgCO_2/kg)in different masonry materials [53].

Adobe bricks have high thermal mass performance, and they can last 400 years and more when they are maintained properly [54]. This material with a high heat capacity can help to reduce the speed of heat transfer from outside to inside the building through absorbing and retaining sun's radiation throughout the day, and preventing the heat from reaching interior spaces. As a result, adobe brick can offer steadier thermal conditions for indoor areas. At night, when the outside temperature drops, the external sides of the thermal mass, which had gained heat during the day, can gradually warm up the interior spaces, making them cooler and ready for the next day [31,55]. Hence, the choice of materials creates a "Flywheel effect" that mitigates the outside warmth and moderates the temperature within adobe buildings as a result of its high heat capacity [55,56].

Like any other material, adobe brick also has its own weaknesses such as moisture absorption, weathering, and shrinking cracks. Benghida suggests that the right proportion of the ingredients in adobe brick can resolve many of these weaknesses to a high extent [54]. He suggests the use of clay: 10–15%, silt: 10–15%, sand: 70–80% and water: 25–30% [54]. Shrinkage cracking can be mitigated by adding natural fibres like hemp and straw. Porosity problem and weathering can also be solved with mineral salts which behave as cementic agents like the carbonate mineral «calcite» $CaCO_3$ [57].

Material colours used on the sun-facing sides of the building are also important as they impact the reflection of the solar radiation and help to keep the building cooler [36].

Moreover, the thermal properties of courtyard pavement materials play an important role in passive cooling. The air trapped inside internal courtyards has a low thermal capacity, following the temperatures of the surrounding surfaces during the night and cooling the courtyard walls and floor mass via outgoing longwave radiation [6]. The specific properties for the adobe bricks mentioned above make them a good choice for the courtyard pavements as well.

Although common perception around construction time, or scarcity of professional brick layers may seem as drawbacks for the use of adobe brick, this locally sourced and produced material has less embodied carbon than many other construction materials.

Therefore, in order to make a positive shift towards more eco-friendly alternatives, this study suggests that adobe brick which has been predominantly used in vernacular architecture in Iran can be considered as one of the most sustainable materials for building construction in contemporary buildings.

DISCUSSION AND CONCLUSION

This paper investigates the sustainable features employed by seven traditional houses in Iran. The case studies were located in three cities—Esfahan, Yazd and Kashan—in hot and dry climates. The findings suggest that several passive techniques were used to cool down the buildings in summer, including the shadowing of outdoor areas, earth coupling, natural ventilation, evaporative cooling, the use of domes, and high heat capacity materials as well as seasonal relocations in the house. Each of these strategies was investigated in detail in relation to the geometry, form and characteristics of the buildings.

The findings indicate that taller walls on the south side of the courtyards provided expanded shaded areas and created thermally comfortable outdoor spaces for residents. For example, out of all seven studied houses, Tabatabais house had the tallest (13.75 m) north-facing wall in the courtyard, with the largest proportion of yard in shadow (49% at 9 am and 18% at 3 pm). Conversely, Seirafis house had the shortest (3.44 m) north-facing wall in the courtyard, providing the smallest proportion of yard in shadow (34% at 9 am, and 13% at 3 pm) among all the other houses. Therefore, this study suggests designing tall walls on the south side of the courtyards in northern hemisphere is a passive cooling strategy that contributes to the thermal comfort of the residents. This strategy is one of the most practicable passive solutions that can be incorporated in contemporary housing design. It is suggested that this strategy needs to be considered in building codes and regulations considering the geography and context of the building site.

Earth coupling was identified as another sustainable solution for creating thermally comfortable underground spaces. In most of the case studies, basement spaces were built six to seven metres below the ground surface. The steady annual temperature of these underground spaces helped them to be cooler than the courtyard and on-the-ground spaces and, therefore, they provided a thermally pleasant oasis for residents on hot summer days. Although earth coupling is a very effective passive cooling strategy, it is not applicable in every context in hot and dry climates, such as the sites with high level of water tables.

Further, natural ventilation was used as a passive method for air circulation around the house to reduce energy consumption for cooling.

Multiple openings on the courtyard-facing walls were seen in all the case studies. Although these openings were not on opposite sides of each room, multiple openings on the same wall could still facilitate the natural ventilation. In addition, openings oriented towards the prevailing wind facilitated night purging in most of the case studies. Shallow pools occupied 4% to 20% and green spaces 10% to 30% of the courtyard areas in the studied houses, both of which facilitated evaporative cooling. Stack cooling through wind catchers and solar chimneys and domes were other features used in 70% of the case studies. Regardless of the fact that whether contemporary housings have a courtyard or not, the natural ventilation strategy is still applicable. Natural ventilation is mainly driven by the correct positioning of the openings in walls which is easily addressed at the design phase of the buildings.

This study also investigated adobe brick as a local, and dominant material used in the traditional Iranian houses. Previous studies have shown that adobe brick is one of the most sustainable and thermally massive building materials with lowest amount of embodied energy (44.5 $kgCO_2/kg$) in comparison with engineering bricks and concrete. Research also has shown that there are simple and sustainable solutions to mitigate the weaknesses of this material, such as moisture absorption, weathering, and shrinking cracks [54].

Another passive cooling strategy discussed in this study was seasonal relocations in the house. Iranian traditional houses investigated in this study have north-facing rooms that were used in summer times and south-facing rooms that were used in winter times. This relocation was a simple response to the path and height of the sun in the sky and of course residents' thermal preferences in different seasons. This strategy might not be applicable in many cases in 21st century as we move on to live in denser cities and smaller living spaces, but can certainly be used in contemporary single detached houses.

Dome ceiling was also one of the popular geometries for the houses in hot and dry climate in Iran. Five out of the seven studied houses in this research had dome ceilings. This form facilitates the heat convection in the space and instigates the fresh air to enter from the openings on the walls below. Most of the domes have vents on top of them and therefore they can exhaust the hot air out of the building. Dome's geometry also increases the shaded area on ceilings which contributes to cooling down the building in hot summer days. Therefore, it is recommended to use domes where applicable to mitigate the heat.

The findings suggest that traditional design strategies used in Iranian houses can create a sustainable microclimate in residential environments with minimum access to electricity and gas. The underlying principles uncovered by this research can be adopted in many modern and contemporary houses with similar climatic condition to decrease energy usage, and create a more thermally comfortable environment without the use of mechanical services that are costly both for people and for the planet. However, it is important to note that not all of the discussed strategies are applicable to every housing in different geographies, such as earth coupling due to high water table level or pools due to water scarcity. Therefore, a case by case approach is recommended.

The next step would be to investigate the thermal comfort levels in traditional housing using on-site measurements.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

All three authors analysed the data and wrote the paper in collaboration with each other with equal contribution.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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