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Sustainable street architecture and its effects on human comfort conditions: Yazd, Iran

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Abstract

Sustainable development requires continual effort to create solutions for energy efficiency and air conditioning. In this study, we focused on the hot-arid city of Yazd in Iran as an eco-model city in terms of its architectural and design compatibility with the environment. We directed our focus to the orientation of the streets according to the sun and wind. Yazd was studied in terms of features at the urban scale and establishment of sustainability criteria. With its streets providing a natural air conditioning system and dense urban texture, Yazd implemented natural urban solutions allowing streets to reflect wind to increase air circulation and provide protection against the effects of the sun. In order to understand the characteristics of these streets, a case study is conducted in Lab-e Khandagh, Yazd historic district. In this site survey, thermal and humidity measurements were recorded at four points in the Historic City of Yazd, which are located on either Sabats, open streets or squares. The site study is conducted on 3 days apart in a week at summer, five different times in a day. The data is collected with a HTC 2 (Arcone, Made in PRC) device, 120 cm. above ground. The data obtained are evaluated and compared, and showed us traditional urban features provide a cooling effect notably in summer time.

Yazd, with its rare urban design features that provide solutions intended to create comfortable, healthy, and sustainable human settlements, is a model in terms of identifying architectural design standards for sustainability.

Keywords
Air-conditioning, Comfort cones, Sustainability, Sabat, Yazd.

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1. Introduction

From ancient settlements to modern buildings, although the formation and development of cities have mostly been based on sustainable design principles, the industrial revolution has led to the rapid growth of towns and uncontrolled rapid urbanization, resulting in unhealthy environments (Terio and Honkanen, 2013). As such, increased urbanization in our cities simultaneously threatened life on Earth due to extensive energy consumption and environment-polluting behaviour, which eventually made the architecture one of the main factors contributing to global warming (Edwards, 1999; Ozer and Turan, 2015). Since this unhealthy built environment, has increased greenhouse gas emissions, this situation led to a continuous climate change. An important source of these emissions comes from the generation and use of energy. Smarter passive energy solutions for buildings can be a way to achieve climate goals (Franzen, Nedar and Anderson, 2019).

Following the development of the concept of sustainability, humans have started to implement measures to mitigate aspects responsible for environmental pollution and energy loss using technology and modifying architecture. Today, humans are living in large anonymous cities in generic buildings that were identically fabricated all around the world after the industrial revolution.

Since the energy required to air-condition buildings is enormous, research on low-cost passive systems has focused on minimizing the need for air conditioning since the late 1980s. Minimazing the energy cost is in many government agendas, as an example; the goals of sustainable urbanization as stated on Global Report on Human Settlements are; to reduce greenhouse gas emissions, to built dense settlements due to land use, to use renewable energy, to produce less waste and to reduce the ecological footprint of towns and cities (Un-Habitat Global Report, 2009). Today, there are a lot of studies focusing on energy efficiency of buildings, determining the criteria using less energy (Leyzerovaa, Sharovarovaa and Alekhina, 2016; Dabaieh and Eybye, 2016).

While the importance of ecological settlements are on the agenda today, in some of the old settlements, there are ecological architectural solutions and the foundations of urban settlement conditions, since traditional structures are appreciated in terms of energy consumption and indoor air quality (Gallipoli et al., 2017). One of the cities where these principles are seen is Historic City of Yazd in Iran.

Therefore, this paper focuses on traditional urban fabric in order to provide air conditioning and cooling effect in hot arid climates. There are two appreciated solutions in Historic City of Yazd: [i] Sabat (semi-covered street), [ii] The orientation of the streets due to wind direction. In this case study, four points in the old city fabric is selected, temperature/ humidity data is collected in a week, and compared to each other. This research primarily focuses on the effect of traditional architecture on human comfort conditions. The findings are given so as to learn from traditional architecture and its cooling effects.

2. Material and method

In this study, we investigated the climatic conditions of the streets and a square of the Historic city of Yazd, Iran. For this purpose, we review related studies reported in the literature. Then, to evaluate thermal comfort conditions, climatic data were collected. The climatic data of the city and comfort conditions were compared, and comfort zones were determined throughout the year. The sun and wind directions are displayed on a map to understand the street settlement characteristics according to the wind and sun directions. To determine the urbanization conditions of the streets, thermal and humidity measurements were recorded at four points in the old city of Yazd, which are located on either streets or squares. The site study is conducted on 3 days apart in a week at summer, five different times in a day (July-2019). The data is collected with a HTC 2 (Arcone, Made in PRC) device, 120 cm. above ground. The data obtained are evaluated and compared.

3. Sustainable urban design and its features in the historic city of Yazd

Sustainable development should meet the needs of the present without compromising the ability of future generations to meet their own needs. Green architecture incorporates many factors, including approaches such as land-use planning, focusing on free environmental impacts at social and local scales, and generating solutions with the lowest possible negative impact on the environment and efficient energy use, which resulted in the creation of the concept of green building. This concept includes urban planning, environmental planning, architecture, landscape architecture, and urban structures.

Climate is strongly related to human thermal comfort and sensation. Accordingly, urban planning and architectural design are mostly shaped and affected by climatic factors like sunlight, air temperature, humidity, wind, and precipitation. Each region or geographic area has its own specific combination of conditions that restrict urban planning and motivate the development of different and unique solutions.

A city, including its ecological, cultural, political, institutional, social, and economic components, and without leaving a burden on future generations, should improve the quality of daily human life. Sustainability is the concept whereby sustainable community development provides the ability to make development choices by considering the relationship between the society, economy, ecology, and equity, which means that the relationship between economy, ecology, and equity should be considered when developing sustainable communities. In the following sections, the architectural and urban features are described in Yazd, which is a sustainable city.

Urban design in Yazd, Iran is traditional. The long and narrow streets of the city still maintain the cultural legacy of the region and provide various solutions to the climate. Registered on UNESCO's World Heritage List in 2017, the Historic City of Yazd is considered a living example of an ecocity. We firstly focused on the climate characteristics of Yazd, then examined the green design and architecture approaches used in this specific climate zone, and finally scrutinized Yazd's sustainability in harsh weather conditions and its compatibility with the environment achieved through its unique architectural and urban design.

For this purpose, we identified the geography and climate characteristics of the city were identified, then we examined the solutions created in the harsh desert environment to meet human needs.

3.1. Thermal comfort conditions in Yazd

Located east of Zagros Mountains, Yazd has relatively flat terrain. With a subtropical hot desert climate, the city is surrounded to the north by the Dasht-e Kavir desert and east by the Dasht-e Lut desert. Yazd has an average elevation of 850 m above sea level, with the nearby Mount Shīr Kūh rising to an altitude of 4075 m. From September to November and February to May (7 months), the weather is relatively cold at night but very cold in December and January. Thus, night temperature remains within a thermal comfort range only for three months of the year. From December to February, the weather is somewhat cold during the daytime.

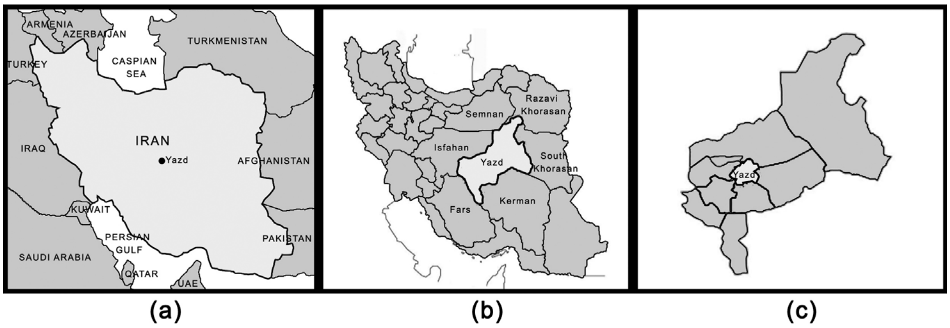

Figure 1. *Map of (a) Iran, (b) Yazd region, (c) historic city of Yazd.*

March, November, April, and October provide a favorable thermal environment during the daytime. Yazd copes with extreme hot weather through the rest of the year (Jahanbakhsh and Esmaeilpoor, 2004). The desert climate is characterized by drastic differences in day and night temperatures. Located east of Zagros Mountains, Yazd has relatively flat terrain.

The city of Yazd has a hot and arid climate. Dry warm desert and cold half-desert climatic types characterize Yazd district (Watson and Labs, 1983). The average rainfall is low in summer, resulting in drought conditions in some areas. The average annual precipitation is 50–100 mm. Temperature significantly fluctuates over the seasons from daytime to night-time temperature. Maximum temperatures of around 45 °C are typical, and minimum temperatures may drop to −20 °C. Average daily temperature ranges between 11/9 °C to 20/7 °C per year (day/night). The Elburz Mountains in Northern Iran act as a barrier to rain clouds. Over the city of Yazd, the sun's rays shine at a right angle, contributing to high temperatures. Scarce water increases the amount of dust in desert, resulting in poor vegetation and sandstorms. Providing the desired comfort levels for humans living in Iran's harsh climatic conditions requires particular methods and skills.

The concept of human comfort is a set of conditions suitable for at least 80% of people regarding the temperature state; people should neither have the sensation of being extremely cold nor extremely warm (Watson and Labs, 1983). Optimal thermal comfort is established when the human body functions appropriately and body temperature is maintained within a reasonable range, which is essential for human health and healthy living. Thermal comfort and thermal balance are essential in the built environment.

Factors impacting thermal comfort include air temperature, humidity, air flow rate, and thermal radiation. Figure 2a presents an acceptable combination of air temperature and humidity values as per the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 55-2010 PMV (predicted mean vote) / PPD (predicted percentage of dissatisfied) calculation method. In [Figure 2a], the thermal comfort zone displayed in blue indicates a 90% thermal acceptability. [Figure 2b] depicts comfort zones in Yazd according to climatic data. Ambient temperature does not depend on only one variable, it also depends on changes in humidity levels and air flow rate, increase or decrease the effect of temperature. As a result of a combination of these three variables, humans may feel the same sensation of warmth or have the same emotional/psychological response. For instance, at a temperature of 37 °C, a relative humidity of 10% and 3 m/s airflow may provide an equivalent sensation of warmth to a temperature of 27 °C, a relative humidity of 75%, and 0.1 m/s airflow. This means that under both conditions, human-perceived temperature is the same (ANSI/ASHRAE Standart 55, 2010).

As shown in [Figure 2], summer and winter conditions in Yazd fall considerably outside the thermal comfort zone and the climatic conditions in Yazd are unlikely to provide living comfort. Measures must be implemented to provide and maintain thermal comfort or establish energy use plans for heating or cooling purposes to meet human comfort requirements.

3.2. Sustainable architectural features of Yazd

Known for its unique architecture and urban texture, Yazd is inhabited by 450,000 people, the largest city in the region and the second oldest city in the world. The city was designed and planned from a unique and specific ecological perspective.

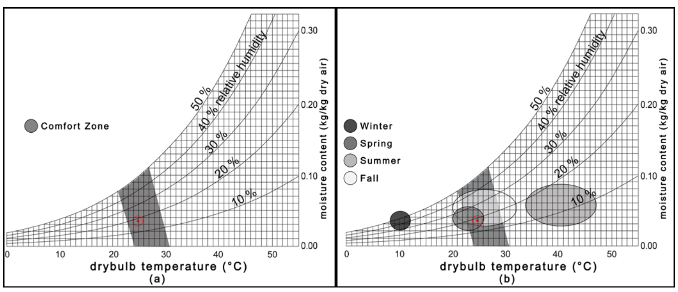

__Figure 2.__ (a) Thermal comfort conditions (Fanger, 1970); (b) human thermal comfort chart indicating Yazd's comfort zones identified by climate data analysis.

Yazd is known for its narrow alleys, houses, street orientation, and squares, as well as its specific environmental details and qualities in terms of architectural solutions. Mud-brick is the most common building material in Yazd; this building technique and material, which allows the construction of thick walls, is also ideal for hot and arid climates as it provides thermal insulation and comfort. In terms of architectural solutions, traditional houses in Yazd are air-conditioned with Badgir (wind-catchers) to protect the residents from the desert heat. These chimneys, creating unique scenery with their special designs, catch the cool breeze that blows at a higher level above the ground and direct it into the interior of the houses [Figure 3]. Wind chimneys are designed to bring the cool wind indoors into the structure and remove hot air; each chimney has a special design. The internal walls in all the chimneys regulate the inlet and outlet of the air. The divider walls in the chimney also increase the air flow rate by narrowing the inner section and forming channels. Air temperatures can be reduced from 40 to 30 °C using this method (Yardimli, Shahriary and Ozer, 2018).

Figure 3. *Domes and Badgirs (wind catchers).*

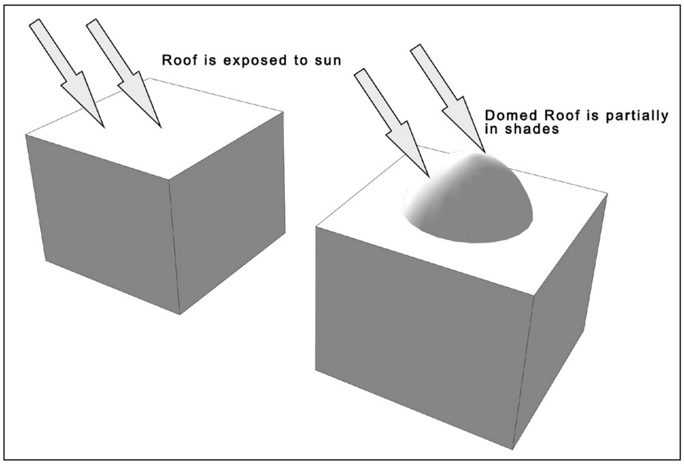

Figure 4. *(Left) A flat roof is fully exposed to sun, (Right) but domed roofs are partially in the shade, thereby providing a cooling effect.*

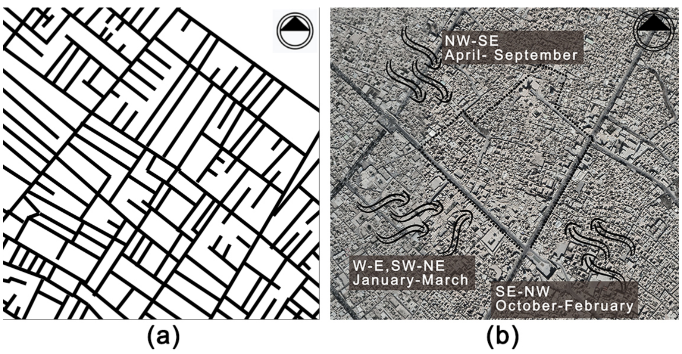

Figure 5. *(a) Historic City of Yazd street orientation and (b) wind directions shown on city map.*

To ventilate indoor rooms, parts of the houses that are used during summer are covered by dome-shaped roofs. Ventilation shafts are built at the peak of the domes to remove hot and stale air. Scattered throughout the city, these dome roofs preserve and enhance the scenic beauty of Yazd, dominating the city's silhouette for hundreds of years [Figure 3]. These domes also provide more protection from the sun than a flat roof. While a flat roof is exposed to all the sun, a dome roof is partially shaded behind the surface affected by the sun [Figure 4].

3.3. Sustainable urban features of Yazd

Yazd's old ruler, Amir Jalal-al-Din Chakhmagh, instigated a period of renewal in the 1400s. During this period, renewal projects were developed according to the geographical conditions and climatic characteristics. According to this project, solutions were produced for the city to meet the new structural and social needs. In this context, aqueduct water channels were installed in the houses and squares pools were created due to water channels; these pools were used to cool the environment. Public baths, water wells, and squares were built. These assets constructed in that period were recorded in national works. With this project, the water needs of the city were more than met.

Yazd's urban settlement also includes unique solutions according to these geographical conditions and these features are discussed below.

3.3.1. Streets of Yazd and axis directed toward the wind

Yazd and its elements are positioned based on weather and natural conditions to provide human comfort and use natural energy sources, forming a building method compatible with sustainability.

The area where traditional houses of Yazd are located was chosen as the object of our study. Streets of Yazd have a 45° angle (NE-SW) to protect people from warm northwest winds, sand, and dust storms. Likewise, urban blocks were designed and built facing the same direction or at a 90° angle to this axis [Figure 5] (Behranfar and Nurmohammadzad, 2011). The street settlements created on this angle allow to benefit from the wind breeze. In the streets that take advantage of the wind breeze, the hot air of summer provides a more comfortable condition when replaced by cool air.

3.3.2. Sun positions of streets in relation to seasonal variations in the sun's path

One of the methods used for reducing Yazd's energy consumption and offering convenient public transportation is providing dense texture and narrow and irregular streets. Yazd has a compact and dense texture, with narrow and long alleys (Figure 5), preventing desert heat and hot winds from entering urban spaces, and preserving coolness and humidity in the summer. The narrow streets and passages formed in perfect harmony with the urban texture act as an obstacle to desert winds, thus ensuring human comfort. With their high walls, the narrow streets of Yazd help maintain the sidewalks in shadows, reducing the ground warmth (Hashemi, 2013). With the street axes set to the north at 45°, the street orientation exposes them to the wind and both street walls create shade from morning to noon or afternoon.

The narrow alleys help to maintain humidity between houses. Scattered all over the city, Sabats, roofed structures with alleys beneath them, are used to cast shadow over the street network in the city [Figure 6]. The semi-covered passages in Yazd provide cooler weather during summertime, but warmer weather during winter by al-

Figure 6. *Aerial view of historical texture of Yazd.*

Figure 7. *Lab-e Khandagh District map of Yazd; Points A, B, C, and D indicate data collection locations.*

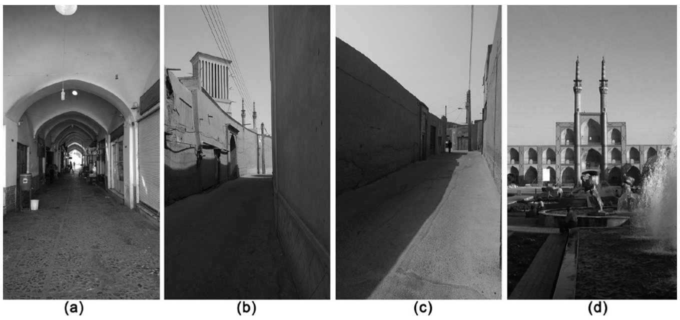

Figure 8. *The photographs of temperature and humidity data collection locations: (A) Sabat (Masjet Jame St.), (B) Narrow Street (Vaqt ol saat), (C) Wider street (other side of Vaqt ol saat), and (D) Amir Chaghmagh Square.*

lowing sunlight to enter the passage. This solution also enhances the structure of houses by connecting houses to each other. The construction against external weather conditions increases thermal comfort. These passages make pedestrian accessibility extremely easy and comfortable.

With its ancient architecture, the Lab-e Khandagh neighborhood contains some of the oldest cultural heritage in Yazd (Watson and Labs, 1983) [Figure 6]. The narrow streets in the formation of the city facilitate transportation and provide protection for buildings, ensuring human comfort without requiring energy.

Table 1. *Temperature (T) (°C) and Humidity (H)(kg/kg dry air) data measured for 3 days apart in a week: Sampling locations (A,B,C,D).*

		A		B		C		D	
	Time	T	H	T	H	T	H	T	H
Day1: 10.07.2019	07:00	34.1	0.015	33.9	0.015	35.1	0.014	37	0.016
	10:00	36.8	0.012	38.2	0.011	40.1	0.008	40	0.010
	12:00	39.1	0.010	41	0.009	42.5	0.009	42.2	0.010
	15:00	39	0.010	42	0.010	42.9	0.008	45	0.010
	20:00	37	0.014	39	0.019	38.5	0.019	36	0.023
Day 4: 13.07.2019	07:00	34.8	0.015	34	0.016	34.5	0.015	35.1	0.015
	10:00	37.5	0.011	38.5	0.010	39.2	0.010	38	0.011
	12:00	40.1	0.010	43	0.010	42.1	0.010	41.6	0.011
	15:00	45.1	0.008	45.5	0.009	46.1	0.010	45.3	0.010
	20:00	36	0.033	38.4	0.019	39	0.019	36.9	0.031
Day7: 16.07.2019	07:00	34	0.010	33.5	0.010	34	0.010	34.2	0.010
	10:00	37.1	0.009	38.5	0.008	38.5	0.010	38.9	0.010
	12:00	43.1	0.008	42	0.008	42.8	0.009	46	0.010
	15:00	46	0.010	47	0.008	48	0.009	49.1	0.011
	20:00	41	0.014	43	0.011	43.9	0.011	42.7	0.016

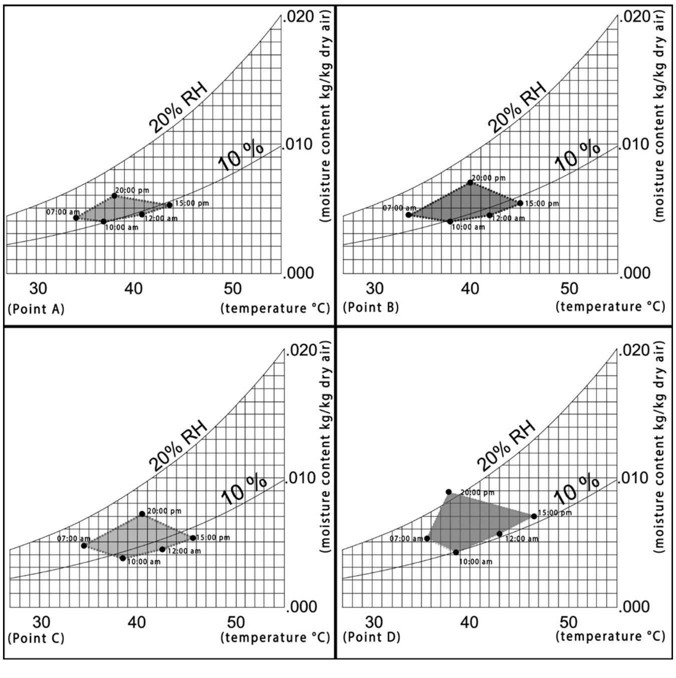

Figure 9. *(Point A-D) Temperature and humidity graphs on physiological chart for points A–D in the Lab-e Khandagh District, respectively.*

4. Case study within the old town in terms of comfort conditions

To determine thermal comfort levels, heat and humidity measurements were recorded at four different points of the city at different times during the day [Figure 7]. Point A is Sabat on Masjet Jame Street, B is a narrow street on Vaqt ol saat street, C is a wider part of the other side of Vaqt ol saat street and D is on the square of Amir Chaghmagh Complex [Figure 8]. The calculations are 120 cm. above ground.

Photographs of the streets and squares where the data were collected are provided in Figure 7. Measurements were also performed on four different days to obtain an average value. Measurements are listed in Table 1.

To evaluate the recorded measurements given in terms of acceptable heat and humidity for human comfort, these data were graphed as shown in [Figure 9]. When the measured data were examined, we found that the Sabat provides the conditions closest to human requirements; this effect is slightly more prominent in the narrow streets.

The average values were used for comparison of temperature and humidity measurements recorded over the four days at four different times of day. The results are provided in Table 1.

As a result, when we compare temperature data of four points (A-D), it is seen that point A (Sabat) is significantly have less temprature values (1-3°C) than other locations. This result shows us, having direct sunlight to a space, effects the temperature levels directly.

Comparing between points B-C, also shows us, narrow streets have a shading effect (point B), therefore the temperatures are lower than others. Another reason that point B has the lower temperatures is the orientation of the street, and letting summer breeze in NW-SE direction during summer time. Although Point C is in the same street as Point B, since the orientation is slightly different, the breezes doesn't have a cooling effect in the former.

Looking at humidity levels, they are not as significant as temperature levels. But still, Point A and Point B and Point C are measured with lowest humidity levels, compared to Point D. It shows us the pool in Amir Chaghmagh Square (Point D), is increasing humidity levels with evaporation.

To evaluate the measurements in Table 1 in terms of heat and humidity suitable for human comfort, these data were depicted in graphs as shown in [Figure 9]. When the measured data were examined, we found that the streets provided the conditions closest to the comfort range the people, whereas in narrow streets, the values are higher, but remain within the range for comfort, and in the square, temperature and humidity are above the upper limit for human comfort.

According to the measurements recorded at points A, B, C, the conditions were closer to the comfort line determined in the graph, whereas the measurements recorded at point D in the unprotected environment were the furthest from the comfort conditions line determined.

5. Results and discussion

In terms of evaluating the gaps in the city, narrow streets are used in the Mediterranean climate zone and in many hot regions around the world to protect inhabitants from heat and the sun. This feature is used extensively in Yazd. The placement of the street axes with angles of approximately 45° to the NE-SW orientation ensures that at least one wall of the street is shaded during the hot times of the day. This angular orientation not only ensures the comfort when traveling on the streets, but also protects those on the streets from the sun's burning effects by ensuring that one façade of each building remains in the shade. Some streets are covered (Sabat), providing summer and winter protection. These streets can be ventilated with the gaps left in the Sabat. Thus, comfortable conditions in buildings can be created without consuming energy. This angled orientation of the streets captures the wind, providing cooling from the wind. The large openings in the city squares were created to meet the religious and social needs of the inhabitants and the wind breeze is used in these sections.

Sustainability means meeting the needs of the present without compromising the ability of future generations to meet their own needs and without causing irreparable damage to the environment. The building features in Yazd were developed sustainably. The chimneys, which use the wind breeze in the city, are cooled without using energy. In places covered with a dome, part of the roof remains in the shade during the period when the sun is strongest, helping to cool the place. In some important buildings, wind chimneys carry the wind to the refreshing ponds in the basements, then disseminating the air throughout the interior to cool the building. To benefit from the cooling feature of the pools, structures with inner courtyards were developed in an attempt to create cool spaces with pools in these inner gardens. Thick masonry was used, which were mostly made of mudbrick and bricks for the façades. Thus, both humidity and thermal comfort conditions of the buildings were easily achieved. This usage also created a special texture in the city.

All these unique solutions have enabled the city and buildings to provide comfortable conditions without requiring energy. For this reason, Yazd is listed as an UNESCO World Heritage sites due to its historical and touristic city features, indicating its value as a unique ecocenter.

Yazd's urban architecture is a sensitive, unique, and creative solution to environmental issues. These solutions are so effective that they can overcome almost all unfavorable climate conditions in urban areas. The architectural solutions applied in Yazd include:

- Street orientation to the prevailing wind direction.
- Narrow and covered alleys and passages providing shaded areas and pedestrian zones protected from dust and sandstorms.
- Covered passageways providing comfortable and easy access for pedestrians during summer and winter.
- Areas where excessive light intensity affects pedestrian areas are controlled using narrow alleys.
- Dense urban texture provides energy savings.

- Construction of wind towers (Badgirs) to create natural ventilation in buildings.
- Parts of the houses used during summer are covered with dome-shaped roofs to lift the hot air away from the ground. Ventilation shafts are built at the peak of the domes to remove hot and stale air.
- Protection against harsh climatic conditions is created by enclosing the squares with buildings
- Sabats protect passages from sandstorms and the burning effects of the sun.
- Yazd minimizes energy consumption with its unique architectural construction techniques (Sabat, Badgir (wind catchers) etc.). The soil use, thick walls, and the system constructed below ground level reduce the energy consumption and improve human comfort.
- Solutions such as Badgir (wind chimneys) and Sabats help to provide comfort conditions without using energy or using less energy.

With these features, Yazd is a living example of a sustainable city. In this context, traditional practices in the city of Yazd have sustainable characteristics. As an ecocity with traditional architecture, Yazd, with an energy-efficient and environmentalist approach on both the urban and building scale, Yazd is focused on leaving a clean and healthy environment for future generations.

Our results showed us orienting the urban fabric due to wind direction and sun exposure of the streets are two important factors in air-conditioning, considering sustainable architecture. There are still a lot of traditional methods to learn, for design of urban fabric. Keeping in mind that, today's rapid urbanization causes a lot of troubles for human comfort, traditional methods should be taken into account again. These methods include, material studies, building techniques, passive systems and more sustainable city planning solutions. If the planning authorities focus on the bigger picture of how city planning serve more sustainable issues, the cities become more livable places. Therefore, further studies should include other aspects of traditional sustainable architecture to guide future city planning.

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