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Research Paper

Daylight and Thermal Performance Evaluation of Orosi; Traditional Colored Window (Case study: Kazeruni House in Shiraz)

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Abstract
The incorporation of various openings that permit daylight into interior spaces significantly influences thermal comfort. In the central region of Iran, Orosi windows are a prevalent architectural feature in courtyard buildings. These latticed door-windows are embellished with colorful glass pieces arranged in geometric patterns. This study aims to evaluate the impact of glass color in Orosi windows on their thermal and daylight performance. The primary objective is to determine the thermal comfort and daylight performance of a typical Qajarian Orosi with different glass colors (colorful, red, blue, yellow, green, colorless) and to identify the optimal glass color for Orosi windows. The findings reveal that the glass color of Orosi windows not only affects thermal comfort but also has a significant impact on daylight performance. Yellow glass offers the most favorable thermal conditions, irrespective of the season. In terms of daylight performance, all glass colors perform adequately; however, the Orosi with yellow glass achieves the highest values for spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). The next preferred options, in descending order, are colorless, green, and blue glass. Considering both daylight and thermal performance, it is recommended to use Orosi windows with yellow glass due to the 22% improvement in annual thermal comfort and satisfactory daylight performance.

Keywords: *Orosi, Colored glass, Daylight, Thermal comfort, Traditional house.*

ABBREVIATIONS

PMV	predicted mean vote
sDA	spatial Daylight Autonomy
ASE	Annual Sunlight Exposure
UDI	Useful Daylight Illuminance

1. INTRODUCTION

Daylighting is a crucial passive strategy for achieving energy efficiency in buildings, with the potential to reduce energy consumption by up to 45% in both residential and commercial structures (Du et al., 2014). Windows play a dual role by not only allowing natural light to brighten indoor spaces and create a pleasant atmosphere, but also by providing occupants with a visual connection to the outdoors (Li, 2010). However, the design of daylighted spaces must address concerns such as heat gains, visual discomfort, and glare. Balancing visual comfort with the benefits of daylight requires a comprehensive examination of the relationship between human needs and natural lighting, taking into account factors such as light quantity and uniformity, color rendering quality, and the risk of glare (Hosseini et al., 2019). The positive effects of daylighting on occupant comfort, health, well-being, and productivity are well documented (Yu and Su, 2015). Historical architecture demonstrates a positive correlation

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between the built environment and traditional buildings, which were designed with careful consideration of climatic requirements and socio-cultural contexts. Iranian vernacular architecture employs a variety of design strategies to provide comfort to residents (Hourigan, 2015). Traditional courtyard houses in the hot-dry region of Iran are exemplary of climate-responsive architecture, effectively addressing the harsh environmental conditions (Soflaei et al., 2016). Conversely, light and color have historically been powerful elements that inspired architects to blend creativity and aesthetic sensibility, thereby connecting inhabitants with their environment. The Orosi window exemplifies this fusion, showcasing the wisdom of ancient Iranian architects in creating a constant interplay of light and color. An Orosi is a latticed door-window featuring colorful glass pieces set in geometric patterns. Typically, the lower part of the main facade facing the courtyard is adorned with sets of seven, five, or three Orosi windows, which can be opened and closed vertically (Pirnia, 2011). While glass production for architectural purposes increased in Central Europe between 1250 and 1500 (Adlington et al., 2019), the emergence of the Gothic style in the 13th century marked the extensive use of colored glass and large windows in church facades (Simmons and Mysak, 2012). In Iranian architecture, the use of colored glass began in the 10th and 11th centuries Hijri and became widespread during the Safavid era, with the Orosi window becoming particularly prominent during the Qajar period (Hosseini et al., 2019).

In recent years, there has been increasing interest in examining the characteristics of Orosi and daylighting openings in vernacular buildings. Makani (2012) highlighted that in hot-dry climates, the use of natural light in traditional houses transcends technical aspects, significantly contributing to creating healthier living environments. Vaafi (2001) studied the features of windows in residential architecture from the Safavid period in Isfahan, concluding that windows and doors possess aesthetic value based on their specific locations. The study found that adjustable doors and windows allowed for controlling natural light according to the varying daylight conditions throughout the year. Nabavi, Yahaya, and Goh (2012) analyzed architectural elements in twenty traditional Iranian houses, discovering multiple approaches to integrating daylight into these structures. Traditional Iranian architecture boasts a variety of openings and apertures. Tahbaz and Moosavi (2009) examined six types of windows in Iran's traditional architecture, noting that climate-responsive architecture in Iran offers a wide selection of windows, each designed for specific purposes such as ventilation, lighting, visibility, privacy, and heat control. Field measurements and natural daylight analysis conducted in traditional houses in Kashan and Kerman by Kazemzadeh and Tahbaz (2013) and Tahbaz et al. (2014) revealed a diversity of lighting elements influenced by factors like location, room depth, geometry, and adjacent spaces.

Previous research has extensively evaluated various types of Orosi windows, examining their structural, functional, and environmental characteristics (Shafipour, 2006). Beyond their contributions to daylighting and thermal performance, Orosi windows also serve a decorative purpose. Alipour (2011) investigated the designs and motifs of Orosi windows in the Tehran Palace and their influence on other art forms, such as gilded carpets. Studies have emphasized that the colorful glass used in Orosi windows serves functions like light control, aesthetic enhancement, and insect repellence (Nabavi et al., 2012). Moreover, these studies have indicated that Orosi windows positively affect human personality and behavior (Jalili and Sefidi, 2016).

Atrvash and Fayaz (2015) conducted a study to analyze the impact of Orosi windows on indoor airflow. Their research revealed that the placement and opening of Orosi windows can induce changes in the airflow within a room, leading to improved air circulation over a larger area of the space.

There has been a dearth of research addressing the quantitative evaluation of daylight performance concerning Orosies adorned with colorful glass. Haghshenas and Ghiabaklou conducted a study to explore the effects of tinted glazing on daylight and energy transmission within nine Orosies located in vernacular houses. Their investigation revealed a significant alteration in reflected energy from windows due to tinted glass. By impeding high-frequency waves, the transmitted energy experienced a reduction of approximately one-third when compared to standard float glass (Haghshenas and Ghiabaklou, 2008). In a subsequent study, they evaluated the solar transmittance of stained glasses utilized in Safavid Orosies. The outcomes demonstrated a diminution in the transmission of visible light and wavelengths detrimental to human skin and materials. Nonetheless, it was observed that employing a minimal percentage of color, particularly yellow, proved efficacious in diminishing harmful wavelengths without compromising visible light and energy. Conversely, the utilization of blue coloration was discouraged as it permitted significant harmful wavelengths to traverse despite reducing visible light and energy (Haghshenas et al., 2016). Gorji Mahlabani and Mofrad Boushehri (2017) scrutinized twelve instances of Orosies within Qajar houses in

Qazvin. Their findings indicated that between 28% and 52% of the sun's visible radiation was either absorbed or reflected by the Orosies. Simple and yellow glasses facilitated a higher percentage of light transmission compared to blue, red, and green variants. Wahdattalab and Nikmaram (2017) conducted a study focusing on the arrangement and placement of red coloration in the upper segments of Orosies within historical residences in Tabriz. Their investigation revealed red as the predominant color choice for Orosies. Mousavi, Mahmodi, and Tahbaz (2019) delved into the influence of skylight positioning, room configuration, and its placement within the courtyard on the daylight performance of traditional dwellings in Yazd. Their findings unveiled a correlation between the window-to-wall ratio, window elevation, room depth, and sky visibility. The results suggested that the incorporation of numerous small frames with colored glass facilitated a more even distribution of light and mitigated glare.

Diverse geometric configurations utilized in Orosi windows yield varying effects on daylight performance. Furthermore, the amalgamation of geometric patterns and hues impacts the quantity of admitted daylight. Consequently, the geometry and thickness of Orosi windows wield substantial influence on daylight performance (Hosseini et al., 2020). In a study conducted by Hosseini et al. (2018), the efficacy of colorful glass in regulating direct sunlight in Orosi windows was explored. The results underscored the significance of a judicious combination of lattice frames, Iranian-Islamic motifs, and colored glass, contingent upon factors such as functionality, climatic conditions, and occupant behavior. More recently, the integration of a kinetic façade featuring colored glasses inspired by Orosi windows was investigated. Simulations of this interactive façade, considering sun positioning and occupants' locations, underscored the pivotal role of colored glass in lighting management. Blue and red hues were identified to ameliorate daylight performance by mitigating glare, whereas yellow, green, and transparent glasses optimized the ingress of daylight into interior spaces (Hosseini et al., 2020). In a recent examination of visual comfort, Orosi windows were juxtaposed with Orosis lacking frames, colors, and conventional windows. The findings suggested that tinted glasses possess the potential to regulate the quality of transmitted light but may augment the demand for lighting energy. Orosi frames augmented Useful Daylight Illuminance (UDI), and the integration of glass and frame configurations diminished illuminance differentials between central, frontal, and lateral zones. Among the three components scrutinized, glass color emerged as the most influential factor (Omidi et al., 2022).

Upon reviewing prior investigations, it becomes evident that while Orosi geometry and the light transmittance characteristics of its colorful glass have been examined, a comprehensive analysis of the thermal and daylight performance of Orosi windows is lacking. Consequently, there exists a research gap concerning the concurrent evaluation of the thermal and daylight effects of glass colors employed in Orosi windows. This study endeavors to address this gap by assessing the impact of glass coloration in Orosi windows on the thermal and daylight performance of Qajar houses in Shiraz (Table1).

2. METHODOLOGY

The present study investigates thermal comfort and daylight performance of glass colored Orosi window in vernacular house in Shiraz. The main objectives of the present study are as follow:

- Defining thermal comfort and daylight performance of a typical Orosi
- Investigating the effect of glass colors (red, green, blue, yellow) on thermal and daylight performance of Orosi
- Defining optimum glass colors for Orosi based on thermal and daylight performance

The Kazeruni house in Shiraz has been chosen as the focal point for this case study, featuring minimally altered Orosi windows. Illustrated in Figure 1, the methodology is structured around three key phases: 1) Literature review, 2) Case study, and 3) Modeling and simulation. The initial phase involves a comprehensive review of previous studies on Orosi windows to delineate their various functions, thereby identifying research gaps. Subsequently, traditional houses in Shiraz are identified as the statistical samples, from which a dwelling with limited modifications to its Orosis over time is selected. Field measurements are conducted to formulate research scenarios. In the third phase, modeling and simulation of the case study are executed to ascertain the impact of glass colors on the thermal and daylight performance of Orosi windows (Figure1).

Table 1. Summary of Literature review

No	Author	Year	Methodology	Climate	Parameters
1	Vaafi	2001	LS/CS	BSk	FB/PD/O
2	Shafipour	2006	LS/DA	-	G/O/C/P
3	Haghshenas & Ghiabaklou	2008	LS/FS/CS/SA/LM	-	AG/C
4	Tahbaz&Moosavi	2009	LS/SA/FM	-	O/G/AG
5	Alipour	2011	LS/ DA	BWh	P
6	Makani et al	2012	LS	B	BF/O/PD/C
7	Nabavi et al	2012	LS/CS	B	BF/G
8	Zarei	2013	LS/DA	BSk	G/M/P
9	KazemZade&Tahbaz	2013	LS/SA	BWk	O/G/BF
10	Tahbaz et al	2014	LS/SA/FS	BWh	O/PD/WWR/M/C
11	Atrvash & fayaz	2015	LS/CS/SA	BWh	O/ PD
12	Madhoushiannezhad &Alamooti	2016	LS/DA	BSk	G/PD/WWR/M/C
13	Haghshenas & et al	2016	LS/FS/LM	BWh	AG/C
14	Jalili&Nazari	2016	LS/CS/DA	BWh	C/PsE
15	GorjiMahlabani & MofradBoushehri	2017	LS/CS/LM	BSk	C/AG
16	Wahdat talab & Nikmaram	2017	LS/CS/FS	BSk	C/G/P
17	Hosseini et al	2018	LS/SA	BWh	G/O/WWR/C
18	Khamechian et al	2018	LS/FS/CS	BWh	BF/PD/G
19	Mousavi et al	2019	LS/CS/NA	BWh	G/PD/O/WWR
20	Hosseini et al	2020	LS/SA	B	C/G/P
21	Hosseini et al	2020	LS/SA	BWh	G/P
22	Omidi at al	2022	LS/CS/LM	BWh	C/G/P

Methodology: *LS:* Library Study, *CS:* Case Study, *FS:* Field Survey, *SA:* Simulation Analysis, *LM:* Laboratory Measurements, *DA:* Descriptive Analytics, *NA:* Numerical Analysis; Climate: *BWh:* Hot Desert, *BSk:* Cold Semi-arid, *BWk:* Cold Desert, *B:* Arid and Semi-arid; Parameters: *DP:* Daylight Performance, *DR:* Decoration Role, *TP:* Thermal Performance, *NV*: Natural ventilation; Effective Architectural Elements: *G:* Geometry, *O:* Orientation, *AG:* Albedo of Glass, *M:* Material, *PD:* Proportion and Dimension, *BF:* Building Form, *WWR:* Window-to-wall Ratio, *C:* Color, *P:* Pattern.

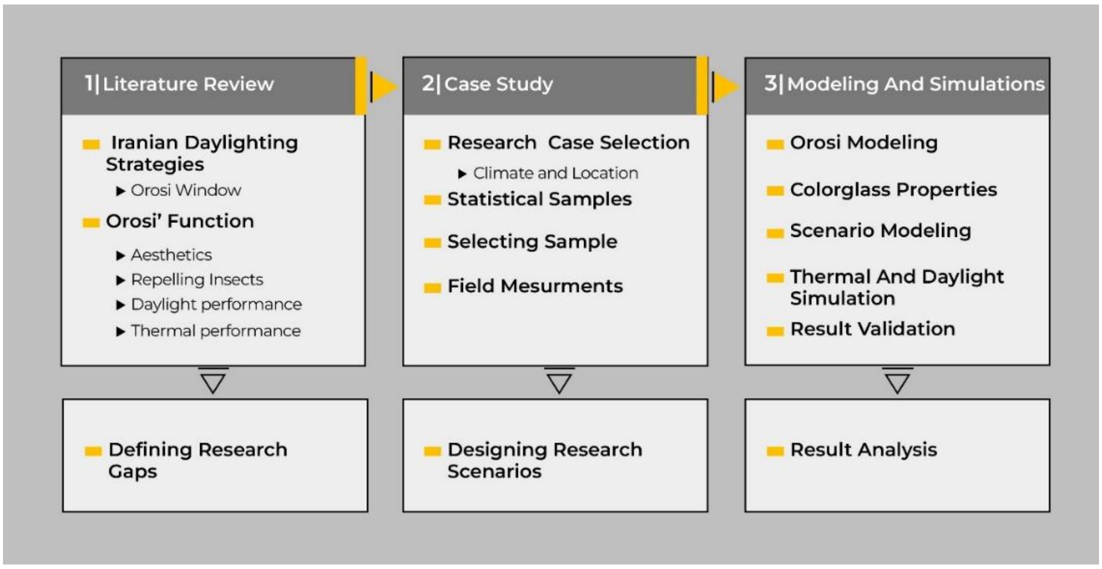


Fig 1. Research steps

2.1. Location and Climate

Shiraz is located at 29.53 degrees north latitude and 52.53 degrees east longitude, categorizing it as a city with a hot-dry climate. Table 2 depicts the average monthly weather conditions in Shiraz. The warmest months, as indicated, are June through September, while January, February, and December experience the lowest temperatures. Figure 2 illustrates the monthly solar radiation levels in Shiraz, showcasing an annual average of around 500 Wh/sq.m per hour.

Table 2. Shiraz weather data (website, wunderground.com, weather information for 2022)

Month	Avg Dry Bulb Temp ©	Min Avg Dry Bulb T ©	Max Avg Dry Bulb T ©	Avg Rel Humidity (%)	Min Avg Rel Humidity (%)	Max Avg Rel Humidity (%)	Avg Wind Speed(m/s)
January	5.8	0.3	11.8	62.0	35.0	85.5	1.3
February	7.2	1.4	13.1	57.2	32.6	81.8	2.2
March	11.6	5.3	17.7	48.3	26.8	71.0	2.3
April	17.0	9.4	23.9	40.4	23.1	60.9	2.8
May	23.2	14.9	30.5	29.1	16.2	46.3	3.3
June	28.0	18.8	35.8	19.4	9.2	33.6	2.7
July	29.5	20.5	37.1	22.1	13.0	36.2	2.9
August	29.1	19.9	36.7	24.2	10.6	40.5	2.4
September	24.8	14.4	33.9	22.9	8.7	41.8	1.7
October	18.6	8.9	27.3	31.5	10.9	57.4	1.9
November	12.7	4.8	20.9	40.6	20.3	60.0	1.3
December	6.4	0.5	13.0	61.1	37.9	82.1	1.7

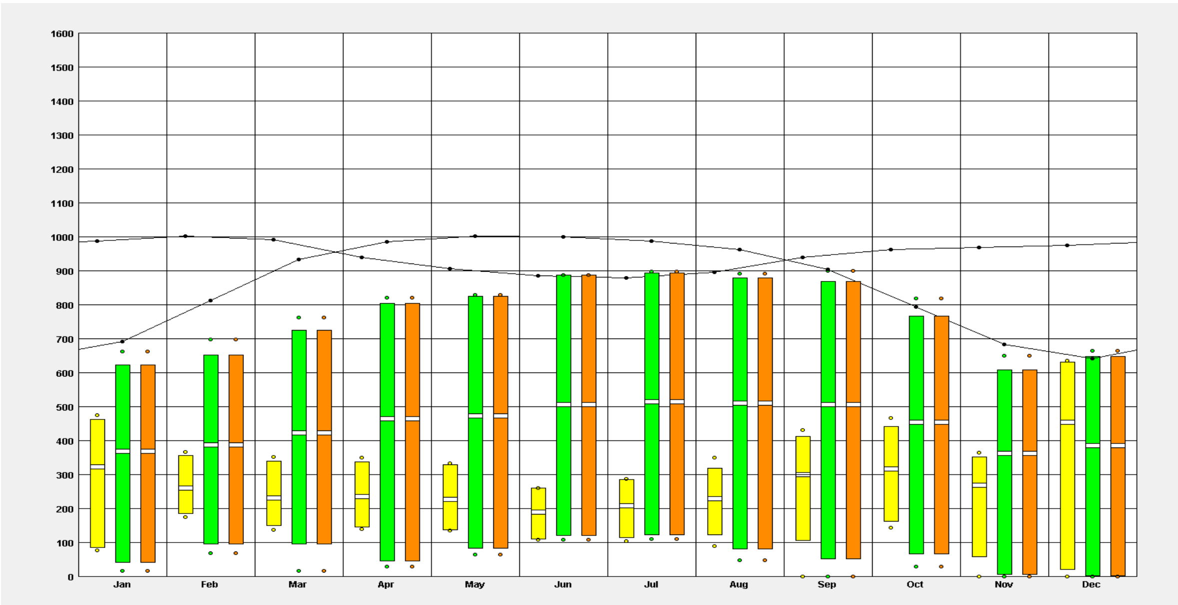


Fig 2. Monthly solar radiation in Shiraz (epw weather data file extracted from climate consultant).

2.2. Case study

In traditional Iranian housing layouts, a prevalent arrangement involves organizing rooms around a rectangular courtyard. In this configuration, summer quarters are commonly positioned to face north, while winter chambers are located on the opposite side. The central axis of the courtyard typically features the main room, known as Shahneshin or Talar, which serves as a focal point for hosting guests and is embellished with various decorative elements. The façade of this main room, facing the courtyard, is adorned with three, five, or seven Orosies (window-door combinations) (refer to Figure 3, part e). In fact, rooms may even be named after the number of Orosies they feature, such as Panjdari, denoting a room with five door-windows. Within the historical context of Shiraz, there are approximately two thousand residences dating back to the Qajar era, each showcasing distinctive architectural characteristics. However, only a handful of these houses have received official recognition as cultural heritage sites. The Orosi window stands out as one of the most significant elements in typical Qajar houses in Shiraz. Nonetheless, in recent years, many of these residences have undergone substantial alterations. Therefore, to select an appro priate sample of a Qajar house in Shiraz, the Kazeruni house was chosen due to its minimal modifications in Orosi design. This particular house stands apart from others in Shiraz owing to its unique mezzanine talar room, as depicted in the provided illustration (Figure 3).

In figure 4, colorful glasses in the Orosi window are illustrated in separated pictures. Using field study, the current Orosi has been modelled and the area of colored and colorless glass calculated in Table3. As it is shown, the most part of Orosi is covered by clear glass (37.68%), while the area for other four colors are almost the same (14.31-16.37%).

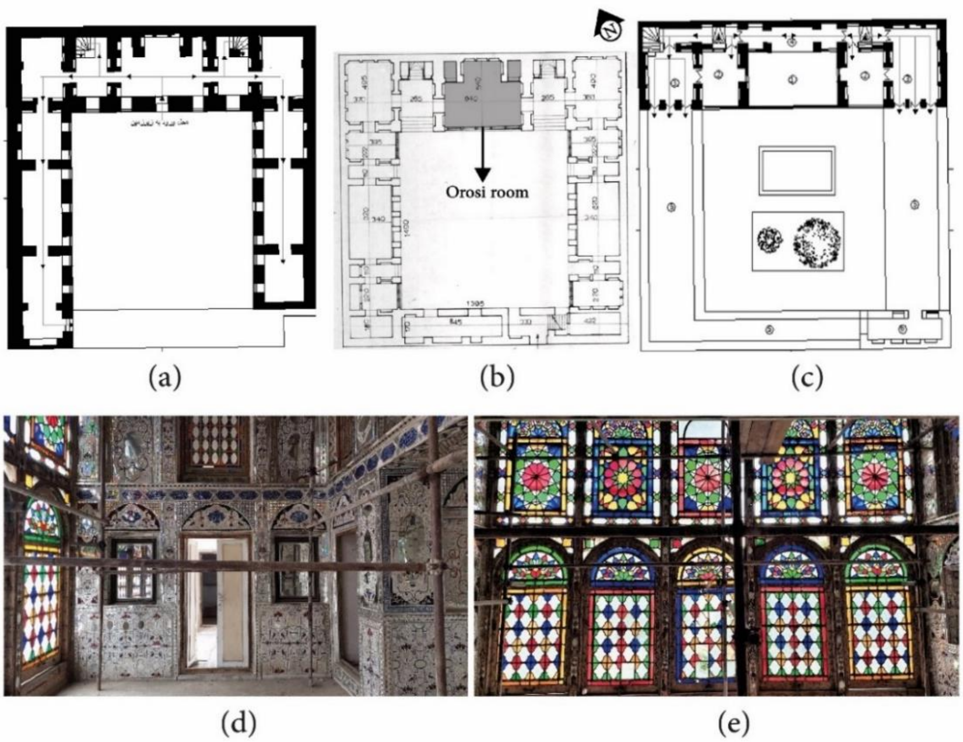


Fig 3. Orosi window in Kazeruni house: (a) Basement plan (b) Ground floor plan (c) First floor plan, (d) Shahneshin (e) Orosi window from inside.

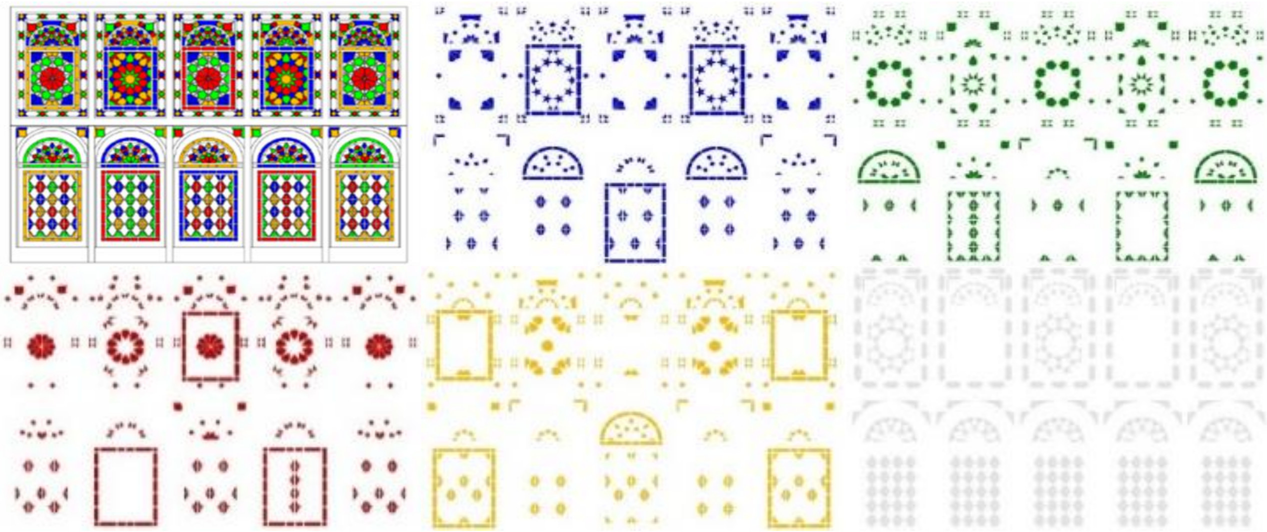


Fig 4. Colorful glasses in the Orosi window shown in separate pictures.

Table 3. Area of different glass colors used in the current Orosi

Color glass	Area	Percentage
All colors	12.7512 m2	100%
Blue	2.0548 m2	16.12%
Red	1.9792 m2	15.52%
Yellow	2.0863 m2	16.37%
Green	1.8253 m2	14.31%
Colorless	4.8056 m2	37.68%

2.3. Simulation scenarios and software

To explore the influence of various glass colors, six distinct scenarios were devised for Orosi windows. These scenarios encompassed the current configuration alongside five monochromatic colors: blue, red, yellow, green, and colorless. The existing scenario was also utilized to validate the findings. For thermal and daylight analysis, Design Builder software was utilized, renowned for its robust capabilities in assessing building environmental performance.

Thermal comfort was evaluated utilizing the Predicted Mean Vote (PMV) index, while spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and Useful Daylight Illuminance (UDI) indices were employed for the assessment of daylight performance. UDI, sDA, and ASE represent dynamic climate-based metrics widely utilized in daylight evaluation and are attainable through lighting simulation software as indicated by Reinhart and Wienold (2011). UDI denotes the proportion of the area receiving adequate daylight within the acceptable range of 300-2000 lux. Conforming to Leadership in Energy and Environmental Design (LEED) guidelines, attainment of 2 or 3 points necessitates sDA values of no less than 55% or 75% for sDA300/50%, respectively, while ASE (ASE1000, 250h) should remain below 10%. These specified values align with recommendations by the Illuminating Engineering Society (IES) for year-round illumination (from 8 A.M. to 6 P.M.). Thus, the simulations were configured to meet these specified thresholds.

The Predicted Mean Vote (PMV) model, recognized in international standards such as ANSI/ASHRAE 2020, Comité Européen 2007, and AC08024865 2005, was utilized for the assessment of thermal comfort. PMV serves as an indicator of thermal comfort, accompanied by the Predicted Percentage of Dissatisfied (PPD) which quantifies dissatisfaction expressed as a percentage. Thermal comfort simulations were executed for a standard year as well as for the hottest and coldest days of the year to yield comprehensive findings.

2.4. Building model and input parameters

Figure 5 (a) and (b) depict the physical model of the room with Orosi windows located on the south façade (Shahneshin). The Orosi frame (c) and its current state (d) are simulated using Design Builder software. The calculations are performed for a typical year, specifically from 9:00 A.M. to 4:00 P.M., with the work plane set at a height of 0.8 meters.

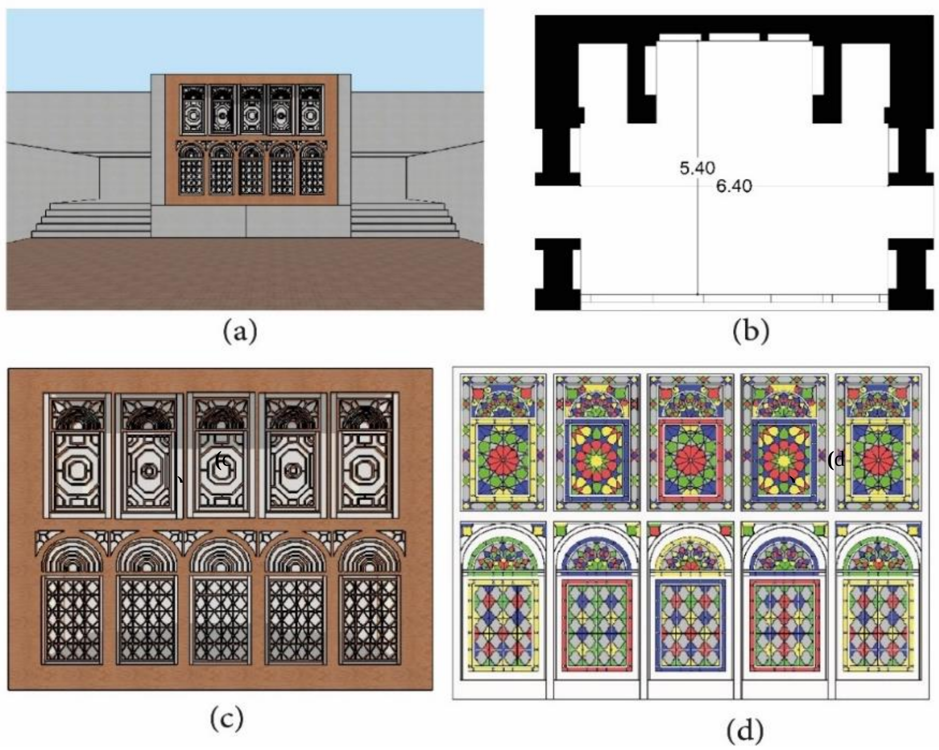


Fig 5. Simulation of Kazeruni house (a), plan of Shahneshin (Orosi room) (b) the Orosi frame simulation (c) the Orosi current state (d).

The input parameters for simulations, representing the characteristics of building materials, are displayed in Table 4. It should be noted that certain materials commonly employed in traditional Iranian architecture for walls, roofs, and floors are not available in the software's construction library. Consequently, these properties are determined based on laboratory tests and previous research (Haghshenas et al, 2016). Table 4 provides the specifications of the colored glass utilized in the simulation scenarios, specifically chosen to reflect the colored glass found in Qajar buildings.

2.5. Field Measurements and Validation

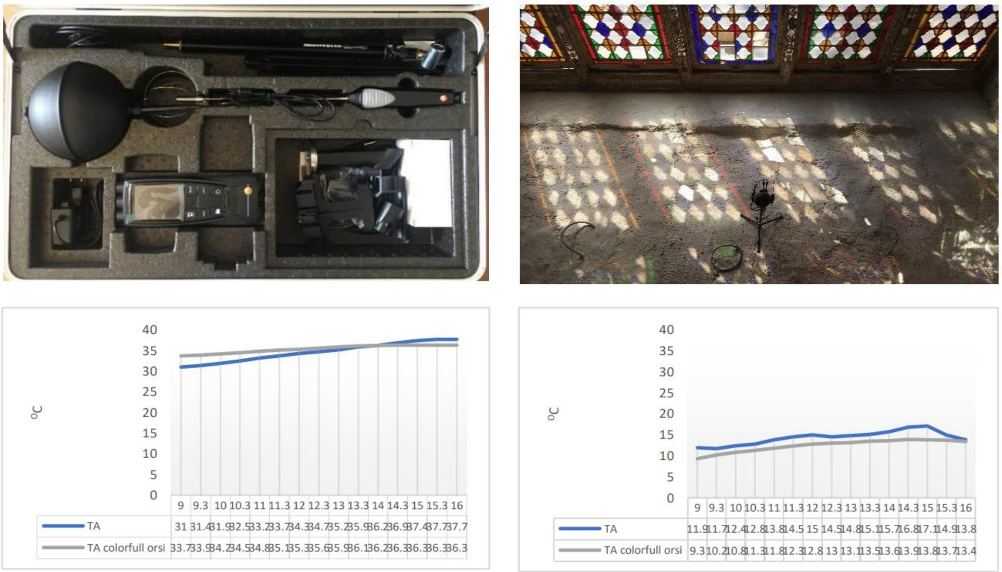
In order to verify the accuracy of the thermal comfort findings, a multifunction data logger device (Testo 480 – AG 501 1ST, 0563 4800) was employed to measure various parameters, including air temperature (TA), relative humidity (RH), and wind velocity (WV) (see Figure 6). Data was collected on both the hottest day (July 5th, 2022) and the coldest day (December 21st, 2022) of the year. The data logger was strategically placed at the center of the Orosi room to record bihourly readings from 9:00 AM to 4:00 PM. The validation results can be observed in Figure 6.

Table 4. Characteristics of building materials

Layer	Layer No.	material	thickness	Conductivity ($Wm^{-1}k^{-1}$)	Specific heat ($jkg^{-1}k^{-1}$)	Density(kgm^{-3})
Roof	7					
	1	Wood	0.012 m	0.09	1880	460
	2	Thatch	0.01 m	1.1	840	1500
	3	Khak Keshi	0.02 m	1.1	840	1770
	4	Ghore Gel	0.12 m	1.1	840	1770
	5	Straw	0.003 m	0.19	2390	700
	6	Parvazbandi Va Beams	0.03 m	0.19	2390	700
	7	Tofal Kobi	0.02 m	0.19	2390	700
External wall	3					
	1	Gypsum plaster	0.01 m	0.4	1000	1000
	2	Brick	0.27 m	0.72	840	1920
	3	Gypsum plaster	0.02 m	0.4	1000	1000
Inner wall	3					
	1	Gypsum plaster	0.02 m	0.4	1000	1000
	2	Adobe	0.21 m	1.1	840	1770
	3	Gypsum plaster	0.02 m	0.4	1000	1000
Floor	7					
	1	Cast concrete	0.012 m	1.4	840	2100
	2	Khak Kobide	0.02 m	1.1	840	1770
	3	Ghel Bam	0.12 m	1.1	840	1770
	4	Straw	0.003 m	0.19	2390	700
	5	Beams	0.02 m	0.19	2390	700
	6	Takhte Kobi	0.03 m	0.19	2390	700
	7	Brick	0.15 m	0.72	840	1920
Wall Orosi	1					
	1	Wood	0.08	0.17	1880	700

Characteristics of colored glass (from the studies of Haghshenas et al (2016) and the software material library WINDOW and Design Builder

Color	Thickness	SHGC	Light transmission	U-value ($wm^{-2}k^{-1}$)
Blue	0.045 m	0.681	0.361	5.813
Red	0.045 m	0.703	0.234	5.818
Yellow	0.045 m	0.787	0.852	5.818
Green	0.045 m	0.813	0.627	5.813
Colorless	0.03 m	0.861	0.637	5.894



(a) (b)

Fig 6. Testo (480 – AG 501 1ST, 0563 4800) in Orosi room with result validation for: a) the hottest day, b) the coldest day

3. RESULT ANALYSIS

The analysis of simulation results for Orosies with different colored glass are divided into two categories of thermal comfort and daylight evaluation.

3.1. Thermal comfort analysis

Thermal simulations were conducted across three distinct timeframes: an annual analysis representing typical conditions, as well as assessments on the hottest and coldest days of the year. Orosi windows remained shut to regulate natural ventilation. Figure 7 depicts the distribution of hours among various thermal states. The baseline scenario, featuring vibrant Orosi windows, recorded the lowest number of hours within the thermal comfort range. Conversely, marginal discrepancies were noted in the thermal comfort hours across the other scenarios, with the exception of the yellow Orosi case. Notably, the scenario employing yellow glass Orosi yielded the highest count of comfort hours, characterized by PMV values ranging from -1 to 1.

Table 5 presents an overview of the duration spent within different thermal conditions. In the instance of yellow Orosi, the count of comfort hours was 22% greater compared to the baseline scenario. Similarly, the yellow and colorless scenarios exhibited nearly identical values, demonstrating a 1.5% increase in comfort hours. Following these, the instances involving blue (8779 hours) and red (8776 hours) glass Orosis were observed. Consequently, Orosi windows featuring yellow-colored glass offered the highest number of thermal comfort hours, while the base case with colorful glass presented the lowest. Additionally, the findings indicated a notably higher count of hours within the PMV range of -2 to 2 in the yellow Orosi scenario compared to all other cases.

Figure 8 illustrates the examination of PMV values on the hottest day of the year, indicating that Orosi with yellow glass offers the highest level of thermal comfort throughout the entire day. Table 6 delineates the most significant divergence in PMV values between Orosis of varying colors occurring on the hottest and coldest days of the year. Thermal conditions in Orosis with blue, green, and red hues exhibit similar patterns, with comparable fluctuations throughout the day. Notably, the discrepancies between the highest and lowest PMV values are less pronounced in colorful Orosi, followed by the colorless variant. On the coldest day of the year, thermal fluctuations remain consistent across all Orosis except for the yellow one, where the PMV differences throughout the day are notably lower. This suggests that the thermal conditions in the yellow case are more stable during winter days, offering greater thermal comfort. Similarly, on the coldest day of the year, Orosi with yellow glass provides enhanced thermal comfort. While none of the colors fall within the thermal comfort range according to the PMV index on both the coldest and hottest days of the year, the yellow Orosi demonstrates relatively better performance (Figure 9). In a typical year, Orosi with yellow glass maintains thermal comfort for more extended periods compared to other variants, thus making yellow the preferred color choice for enhanced thermal comfort for residents.

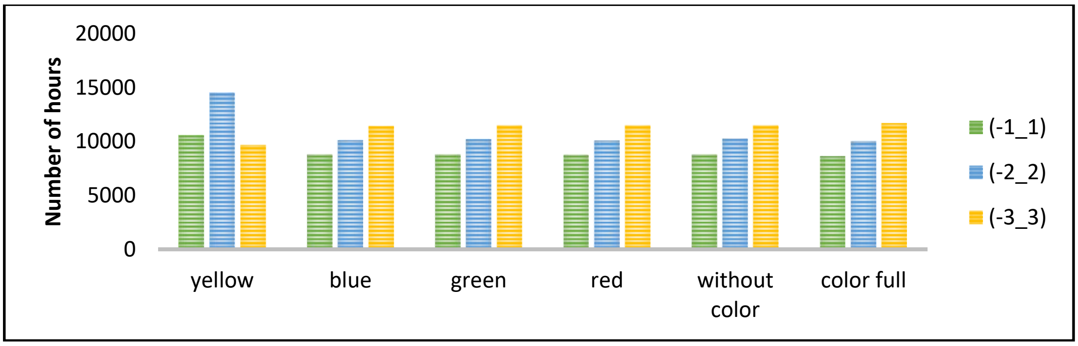


Fig 7. Annual simulation result for number of hours in different thermal conditions

Table 5. Number of hours in different thermal conditions

Glass color	Number of hours				
	(-1_1)	(-2_2)	(-3_3)	> (-3_3)	Improved hours%
yellow	10574	14528	9691	1917	22
blue	8779	10120	11452	122	1.4
green	8780	10226	11513	134	1.5
red	8776	10116	11491	119	1.3
Colorless	8791	10294	11487	134	1.5
Colorful	8657	10048	11706	-	-

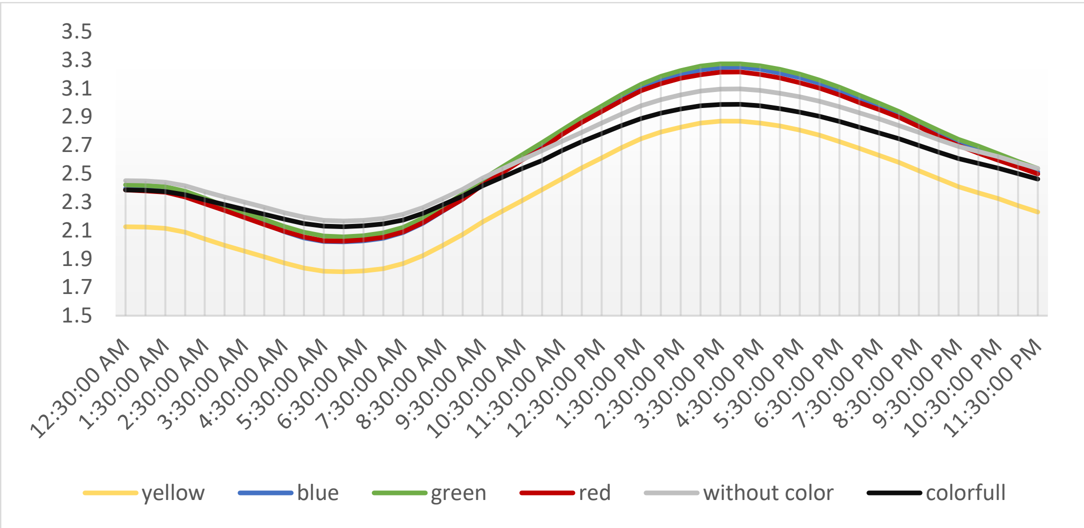


Fig 8. Simulation results on the hottest day of the year

Yellow glass offers the highest level of thermal comfort, with a maximum PMV ranging from 2.87 to 1.81 on the hottest day and a minimum PMV ranging from -2.96 to -1.87 on the coldest day. Conversely, blue glass presents the least favorable thermal comfort conditions, exhibiting only marginal differences compared to other colors. It records a maximum PMV of 3.25 on the hottest day of the year and a minimum PMV of -3.94 on the coldest day. The substantial PMV difference signifies notable fluctuations in thermal comfort during the hottest day of the year (1.23) for blue glass and the coldest day (1.52) for colorful glass. In summary, the PMV difference is more pronounced on the coldest day of the year compared to the hottest day.

Due to Shiraz's hot-dry climate, the average PMV values do not align with the comfort range on either the hottest or coldest day of the year. Table 7 outlines the average PMV values and the preference for Orosi colors on these extreme days, highlighting a preference for yellow-colored Orosi. Furthermore, the colorless Orosi emerges as the second most suitable option for the coldest day of the year, whereas the colorful Orosi ranks as the second-best option for the hottest day of the year.

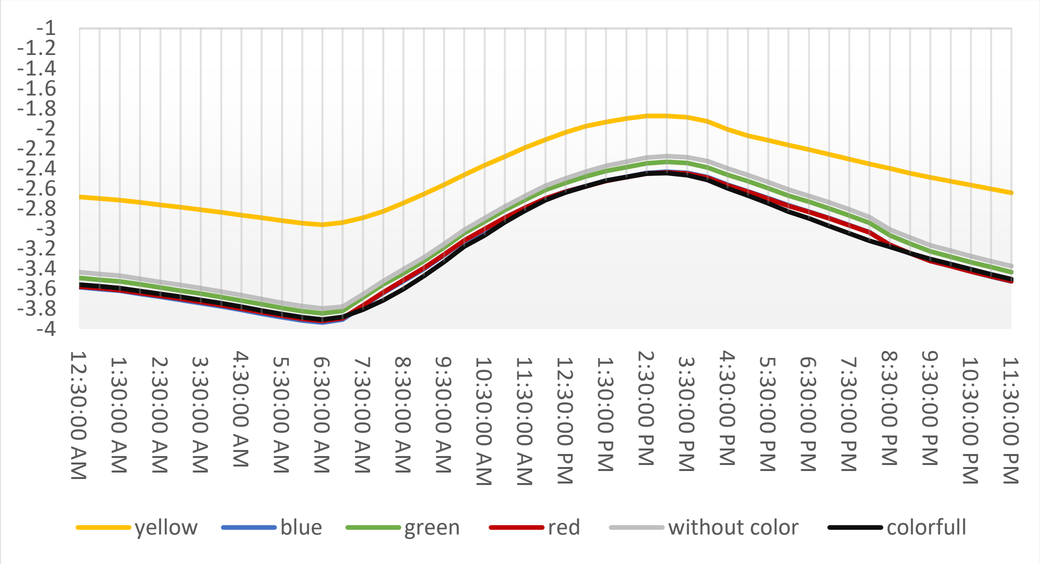


Fig 9. Simulation results on the coldest day of the year

Table 6. PMV values in the hottest and coldest days of the year

color glass	The hottest day of the year			The coldest day of the year		
	Max	Min	difference	Max	Min	difference
yellow	2.87	1.81	1.06	-1.87	-2.96	1.09
red	3.22	2.02	1.19	-2.44	-3.92	1.48
blue	3.25	2.02	1.23	-2.43	-3.94	1.51
green	3.27	2.05	1.22	-2.33	-3.84	1.51
color full	2.99	2.13	0.86	-2.44	-3.91	1.52
without color	3.10	2.17	0.93	-2.28	-3.80	1.46

Table 7. PMV in the hottest and coldest day of the year

color glass	The hottest day of the year		The coldest day of the year	
	Prioritize	Average	Prioritize	Average
yellow	1	2.34	1	-2.45
color full	2	2.56	6	-3.22
red	3	2.62	4	-3.2
without color	4	2.63	2	-3.06
blue	5	2.64	5	-3.21
green	6	2.67	3	-3.11

3.2. Air Temperature

The assessment of air temperatures on the hottest and coldest days of the year indicates that the thermal performance of Orosis with various glass colors is largely consistent. However, the maximum difference in average air temperatures between different cases is more pronounced on the coldest day of the year (0.8°C). Conversely, on the hottest day, Orosis with different colors exhibit similar performance. Specifically, on the hottest day, the average temperature ranges from 34.26 to 34.39°C, while on the coldest day, it is 11°C in the colorless Orosi and 10.2°C in the colorful variant (Table 8) (Figure 10 & 11).

3.3. Daylight analysis

Daylight performance was assessed utilizing the ASE, sDA, and UDI indices. Table 9 showcases the annual hours during which UDI values fall within the range of 100 to 3000 lux for Orosies with various glass colors: (a) yellow, (b) blue, (c) green, (d) red, and (e) colorless. Results indicate that blue glass demonstrates superior performance compared to other colors, with a majority of values falling within the specified lux range. However, it's imperative to recognize that the prioritization of Orosi glass colors should not be solely determined based on UDI values due to the lower threshold of 100 lux. Additionally, Table 9 presents the sDA and ASE values for each case. In alignment with LEED requirements for daylighting performance (option 1), the daylight quality of all cases is considered acceptable. Nonetheless, yellow, green, and colorless glasses emerge as the most favorable options. The highest sDA value of 98.6% is attained with yellow glass, while the case with red glass demonstrates the lowest sDA value of 57.7%. Based on sDA values, the daylight performance of colorless and green Orosies is nearly equivalent, followed by blue glass orosi with an sDA of 88%. Therefore, the prioritization of glass colors based on sDA values is as follows: yellow, green or colorless glass, and blue glass, with red glass not recommended due to its performance. Regarding ASE, the lowest value of 1.44% is observed in Orosies with green, blue, and colorless glass. Orosi with red glass exhibits an ASE of 4.33%, while Orosi with yellow glass demonstrates the highest ASE value of 5.96%, indicating weaker performance in terms of glare control. Overall, all cases with different glass colors provide an acceptable amount of light while effectively managing glare.

Table 8. Air temperatures in the hottest and coldest days of the year

color glass	The hottest day in summer				The coldest day in winter			
	Max	Min	temperature difference	Average	Max	Min	temperature difference	Average
yellow	36.01	32.49	3.52	34.26	13.36	8.17	5.19	10.59
red	36.17	32.35	3.83	34.27	14.13	7.05	7.08	10.42
blue	36.27	32.34	3.93	34.32	14.17	6.99	7.18	10.41
green	36.33	32.43	3.9	34.38	14.55	7.37	7.18	10.78
color full	36.39	32.4	3.99	34.39	13.9	7.09	6.81	10.2
without color	36.45	32.5	3.94	34.46	14.78	7.57	7.21	11

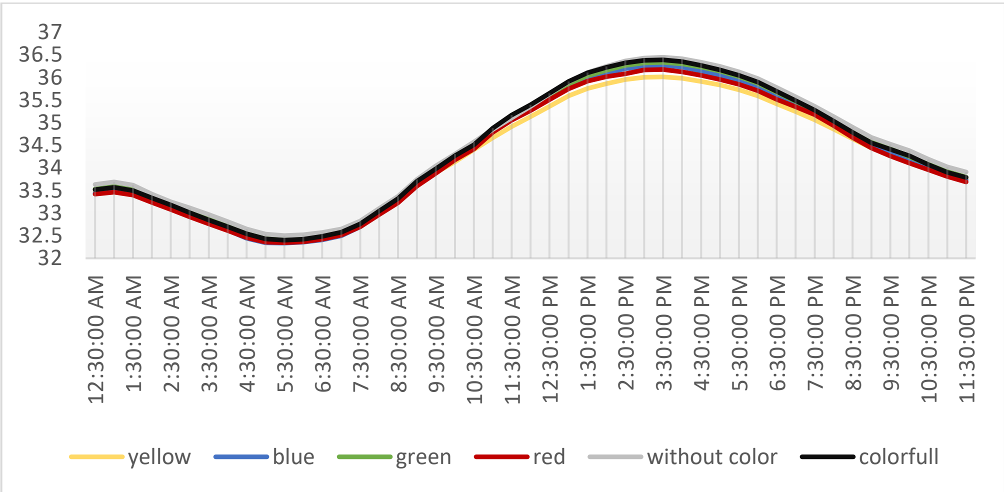


Fig 10. Air temperatures on the hottest day

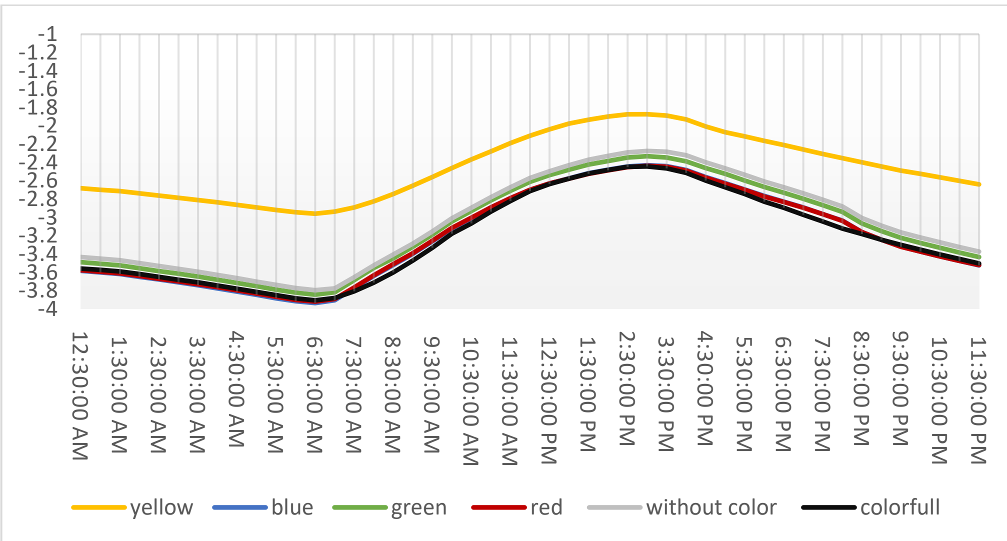
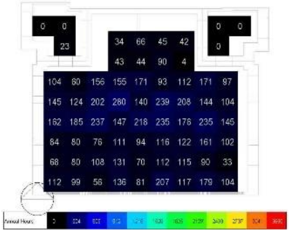
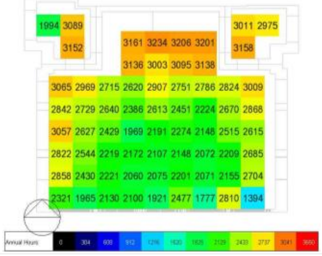
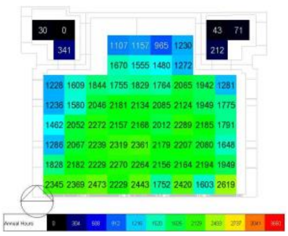
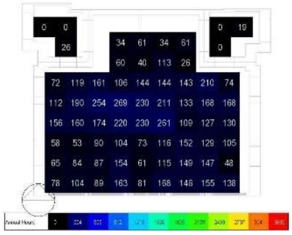
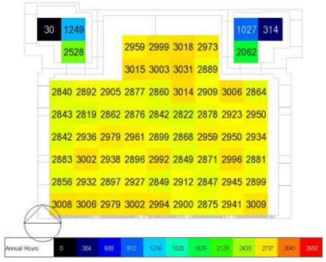
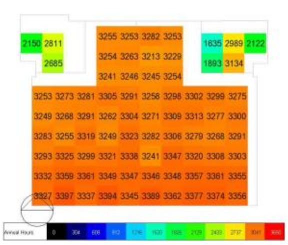
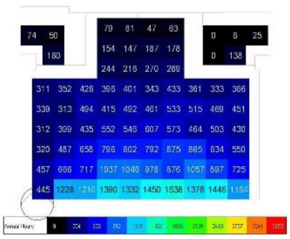
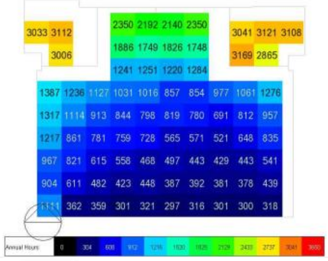
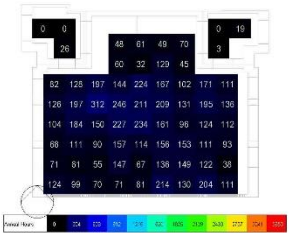
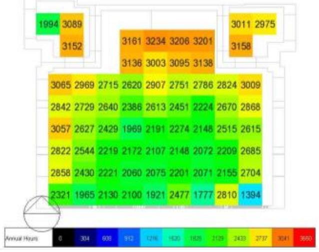
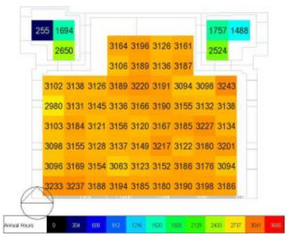
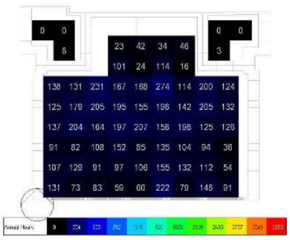
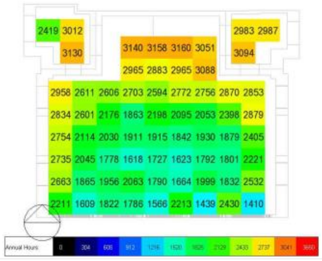
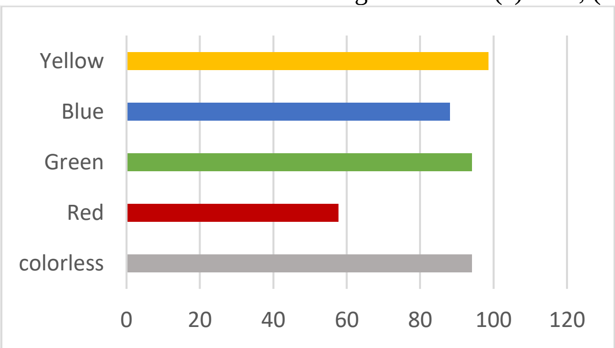


Fig 11. Air temperatures on the coldest day

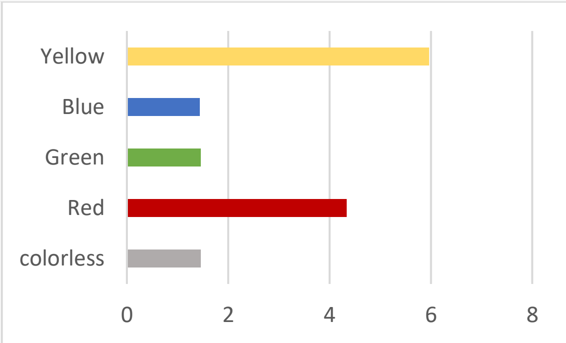
Table 9. Daylight analysis of Orosies with different glass colors

Colored glass	sDA (%)	Figure	ASE (%)	Figure	UDI
Blue	88.042		1.44		
Red	57.732		4.33		
Yellow	98.61		5.96		
Green	94.021		1.45		
colorless	94.034		1.45		

Values for orosies with different glass colors: (a) sDA, (b): ASE



(a)



(b)

The findings suggest that the influence of Orosies glass color on thermal comfort in the adjacent room is minimal, whereas its impact on daylight performance varies significantly. Concerning thermal comfort, yellow glass presents the most favorable conditions in both summer and winter. Noticeable differences in air temperatures and PMV are observed between yellow glass and colorless Orosi, while the variations in thermal performance among other cases are negligible. Regarding daylight performance, the preferred glass colors for Orosies are yellow, followed by green and colorless, with the former option exhibiting a 4.51% higher ASE. Despite all cases achieving acceptable daylight performance, the Orosi with red glass scores 2 points (LEED option 1) compared to the others scoring 3 points. These findings are consistent with a prior study by Haghshenas, Bemanian, and Ghiabaklou (2016), which advocated for the use of yellow color in Orosies to mitigate the transmission of harmful wavelengths without significantly compromising visible light transmission. Furthermore, it is noted that energy transmission is more efficient in the case of yellow glass compared to colorless glass.

4. DISCUSSIONS

The article presents findings from a thermal comfort and daylight analysis conducted on Orosi windows with varying glass colors, focusing on their impact within a hot-dry climate. The study aimed to assess how glass color affects thermal comfort and daylight performance. Thermal comfort analysis encompassed three periods: annual, hottest, and coldest days of the year. Results revealed that Orosi with yellow glass offered the highest number of thermal comfort hours throughout the year, contrasting with the colorful base case which exhibited the lowest comfort hours. Notably, the yellow Orosi demonstrated a 22 percent increase in comfort hours compared to the base case. Additionally, the yellow Orosi showed a significantly higher number of hours within the thermal comfort range (PMV value -2 to 2) compared to other cases.
On the hottest day of the year, the Orosi with yellow glass consistently provided superior thermal comfort throughout the day. Similarly, on the coldest day, thermal fluctuations among Orosies were comparable except for the yellow one, which displayed a more stable thermal condition. Therefore, the orosi with yellow glass color provided greater thermal comfort on both the hottest and coldest days of the year. Although none of the glass colors fell within the thermal comfort range of the PMV index on these extreme days, the yellow Orosi exhibited better performance compared to other colors. In a typical year, the Orosi with yellow glass color remained within the thermal comfort range for more hours compared to other cases, making it the preferred option for ensuring thermal comfort for residents. Regarding air temperatures on the hottest and coldest days, the thermal performance of Orosies with different glass colors was nearly identical, with a slightly higher maximum difference in average air temperatures observed on the coldest day compared to the hottest day. In terms of daylight analysis, Orosi with blue glass color demonstrated superior performance in UDI values, with the majority falling within the desired range. However, it's important to note that the prioritization of glass colors should not be solely based on UDI values due to the lower threshold utilized in the analysis. Considering LEED requirements for daylighting performance, all cases were found to maintain acceptable daylight quality.
The Orosies with yellow, green, and colorless glasses emerged as the optimal choices based on sDA values, with the yellow glass orosi achieving the highest sDA value of 98.6%. Conversely, the Orosi with red glass displayed the lowest sDA value, indicating inferior daylight performance. Regarding ASE, Orosies with green, blue, and colorless glasses exhibited the lowest values, indicating superior glare control. Conversely, the orosi with yellow glass demonstrated the highest ASE value, suggesting weaker performance in glare control. Overall, the study highlighted that the glass color of Orosi windows had minimal impact on thermal comfort in the adjacent room but significant differences in daylight performance. The Orosi with yellow glass offered the most favorable thermal conditions in both summer and winter. Regarding daylight performance, the priority of glass colors would be yellow, green, and colorless, with the Orosi with yellow glass slightly outperforming others in ASE value. These findings corroborate with prior research advocating for the use of yellow glass in Orosi windows to mitigate the passage of harmful wavelengths without substantially affecting visible light transmission. Additionally, energy transmission was found to be more efficient with yellow glass compared to colorless glass.

5. CONCLUSIONS

This study investigates the influence of various glass colors used in Orosi windows on the thermal and daylight performance of Qajar houses in Shiraz. The study aims to evaluate the thermal comfort and daylight performance of a typical Orosi window in a Qajar house and explore how different glass colors (red, green, blue, yellow) affect these aspects to determine the optimal glass color. The findings reveal that while glass color choice impacts thermal comfort, its effect on daylight performance is noteworthy. Yellow glass offers the best thermal conditions year-round, ensuring optimal thermal comfort. Concerning daylight performance, all glass colors demonstrate satisfactory performance, but Orosi with yellow glass achieves the highest values for spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). Following yellow, colorless, green, and blue glass are preferred options. Although Orosi with red glass meets LEED daylight requirements, its lower sDA value makes it less desirable. Considering both daylight and thermal performance, Orosi with yellow glass emerges as the recommended choice, offering a 22% enhancement in annual thermal comfort alongside acceptable daylight performance. Future research should explore the influence of Orosi proportion, lattice pattern, and orientation on thermal and daylight performance, as well as consider aesthetic factors.

COMPETING INTERESTS

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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