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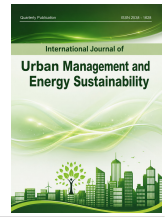

ORIGINAL RESEARCH PAPER

Comparative Assessment of Climate-Responsive Characteristics of Residential Southern Facades in Mashhad: The 600 Dastgah and High-Rise Apartment Complexes

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ABSTRACT

Climate change and rising energy consumption highlight the need to reconsider building envelope design. However, many contemporary residential facades in Mashhad prioritize formal aesthetics over climatic responsiveness. This study compares the climate-responsive design characteristics and solar exposure of the southern facades of two representative late Pahlavi-era residential complexes in Mashhad: the 600 Dastgah Complex and the High-Rise Apartment Complex. Using a descriptive-analytical method with a mixed approach, the cases were modeled in Rhinoceros 7 and evaluated via Ladybug Tools 1.7.1. and EPW weather data based on four components: geometry, openings, shading, and materials. The results indicate, the southern façade of the 600 Dastgah Complex receives approximately 16% less incident solar radiation than that of the High-Rise Apartment Complex. However, self-shading in the former also reduces solar radiation received during the colder months. This difference highlights a seasonal trade-off in façade design between reducing solar exposure in summer and maintaining access to beneficial solar radiation in winter. Furthermore, the Window-to-Wall Ratios were calculated at 47% and 17%, respectively, both falling outside the 25–30% reference range considered in this study. Additionally, the material characteristics of both building envelopes, including the absence of thermal insulation, were examined as part of the comparative facade assessment. Ultimately, the findings highlight the role of facade geometry, openings, shading, and material characteristics in differentiating the architectural and environmental features of the two residential complexes, demonstrating the importance of considering these elements in comparative facade assessment.

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INTRODUCTION

In recent decades, the intensification of climatic instabilities in the arid and cold cities of Iran, particularly Mashhad (with a Köppen climate classification of BSK), has posed major challenges to the efficiency and durability of residential buildings. Observed trends in the regional climatic data indicate that rising average temperatures, decreasing annual precipitation, and a significant increase in the number of dry days have altered the historical climate patterns of this city, imposing substantial thermal stress on residential buildings (Sadeghinia et al., 2023). Future projections also point to the exacerbation of these instabilities; extreme precipitation fluctuations and prolonged dry periods are expected to further challenge material durability and the performance of building envelopes (Afsari et al., 2024).

In this context, facade design, as one of the most fundamental components of residential architecture, gains double importance. Building facades act as the primary boundary between the indoor and outdoor environments, playing a pivotal role in confronting these challenges. They directly influence solar heat gain, ventilation, thermal comfort, and protection against weather conditions (Rababa and Asfour, 2024). Recent studies have shown that many common facade design patterns in cold and arid regions fail to respond effectively to changing climatic conditions, having often been developed based on past climate data (Kuda et al., 2025). Consequently, buildings designed without considering future climatic conditions face high energy consumption, thermal instability, and a reduced lifespan of the envelope.

Globally, extensive efforts have been made to develop climate-responsive facades, adaptive envelope systems, and climate-oriented technologies. These systems can synchronize with variations in solar radiation, temperature, and pollution levels to dynamically regulate the indoor environment (Matin and Eydgahi, 2021). However, the implementation of these technologies in many Iranian cities, including Mashhad, faces economic barriers, technical complexities, and maintenance constraints, which challenge their widespread application (Matin et al., 2017). Furthermore, although global experiences in developing climate envelopes are valuable, many of them cannot be directly transferred to the residential fabric of Mashhad without considering local characteristics, construction culture, and regional execution capacities.

Alongside these climatic shifts, research has demonstrated that the building envelope and facade, as the first layer of encounter with the outdoor environment, play a primary role in controlling thermal exchange, daylight distribution, ventilation, and protection against future climatic conditions. The significance of the facade in studies related to climate resilience has been repeatedly emphasized, with many researchers asserting that enhancing envelope performance can significantly reduce energy consumption and increase building resistance to climate change. Reviewing facade retrofitting strategies in hot and dry climates indicates that the utilization of thermal insulation, shading systems, high thermal mass materials, and Low-Emissivity (Low-E) glazing can be highly effective in reducing cooling loads and improving occupant comfort (Lassandro and Di Turi, 2017). Moreover, studies emphasize that parameters such as the Window-to-Wall Ratio (WWR) and shading depths are the most decisive variables in managing the radiant load of the facade, and their optimization through parametric simulation tools is an essential step in sustainable housing design (Alwetaishi, 2019).

In the residential sector, research particularly highlights that smart envelope design and redesign can mitigate the negative impacts of climatic anomalies, given that many existing buildings were designed for past climatic conditions and remain inefficient in the face of new realities (Dehghan and Porras-Amores, 2025). Additionally, the development of novel technologies has positioned dynamic and responsive facades (Kinetic/Responsive Facades) as a key approach in future

architecture. Investigations into these systems show that the continuous regulation of openings and shading devices can optimize the thermal and luminous performance of buildings under changing climatic conditions (Matin and Eydgahi, 2021). In this regard, evaluations of dynamic and smart shading systems on southern orientations have demonstrated significant potential in providing adequate daylighting while preventing visual discomfort and glare, particularly when integrated with regional architectural patterns (Elmkhah and Eiraji, 2022).

A review of technologies employed in dynamic facades also reveals that advancements in electromechanical control, advanced materials, and artificial intelligence have rendered these systems more adaptive to environmental changes, allowing them to play a greater role in reducing energy demand (Matin et al., 2017). Nevertheless, implementing these complex systems in developing countries is frequently hindered by economic barriers and maintenance challenges; hence, focusing on passive strategies, such as modifying facade geometry and proportions, represents a more logical and sustainable approach for these societies. On the other hand, traditional Iranian architecture possesses a coherent, principle-based system rooted in climate responsiveness, where the principle of "Parhiz-az-Bihoodeghi" (avoiding futility) holds a special place in facade design. Introduced and analyzed by Pirnia, this principle signifies the avoidance of any decorative or non-functional element in architecture, emphasizing functionalism, material efficiency, and climate adaptation (Ghobadian, 1998).

Research carried out specifically within the context of Mashhad reveals that contemporary buildings in this city, contrary to the region's vernacular architecture, exhibit weaker performance in many cases regarding energy consumption, opening ratios, material types, and wall thicknesses (Mirshojaeian Hosseini et al., 2020). Thermal behavior analysis of common walls in Mashhad has confirmed that certain conventional materials lack an appropriate thermal response and require a serious reconsideration in facade construction technology (Maddahi and Abbasi, 2019). Even studies focusing specifically on optimizing facade parameters in Mashhad's high-rise buildings state that the correct combination of window systems, careful management of the Window-to-Wall Ratio (WWR) and use of fixed shading devices can minimize energy consumption without reducing indoor lighting quality (Mirshojaeian Hosseini et al., 2021).

This is aligned with broader comparative studies in similar arid climates, which indicate that the concurrent optimization of opaque building envelopes and transparent walls integrated with shading devices can significantly drop primary energy consumption and annual operation costs (Tafreshi and Alemi, 2023). Furthermore, a systematic review of climate-adaptive measures in housing has shown that a combination of passive strategies, novel envelope technologies, and the application of performance assessment and energy simulation tools can play a crucial role in enhancing housing resilience (Rañeses et al., 2021). Additionally, analyzing the impact of climate change on the durability of facade materials indicates that rising temperatures and moisture fluctuations substantially increase maintenance costs, which doubles the necessity of selecting climate-compatible forms and materials (Grøntoft, 2011). In conclusion, despite the abundance of research in the field of climate change and facade energy optimization, a literature review reveals a distinct research gap in the integrated and comparative performance evaluation of existing built typologies in the metropolis of Mashhad. The bulk of previous research has focused on abstract models or newly constructed buildings, and few studies have systematically compared envelope components simultaneously across established housing patterns. Accordingly, the primary gap and innovation of the present study lie in formulating a comprehensive analytical framework for the quantitative and comparative evaluation of climatic facade performance in two

landmark and historical residential projects in Mashhad (600 Dastgah Complex and High-Rise Apartment Complex). To address this, comprehensive research was conducted in Mashhad in 2026 to evaluate the climatic performance of southern facades in these prominent residential patterns. Utilizing Ladybug computational tools within the Grasshopper environment, this study quantitatively evaluates solar radiation received and sunlight hours to ultimately provide executive principles for improving southern facade performance under current and future climatic conditions based on computational simulations.

MATERIALS AND METHODS

The current study was conducted with the aim of investigating the climate-responsive characteristics of residential building facades in Mashhad and extracting climatic retrofitting strategies for contemporary housing facades. The nature of the research problem necessitated a simultaneous investigation of the physical characteristics of the facades and an assessment of their climatic performance; therefore, a descriptive-analytical research method with a hybrid (qualitative-quantitative) approach, based on architectural analysis and computer-based solar analysis, was selected. The quantitative analysis was limited to incident solar radiation and Direct Sun Hours. The research process was organized into three main phases: theoretical studies, comparative analysis of case studies, and the extraction of retrofitting strategies (Fig. 1). In the first phase, the theoretical foundations and previous research related to climate-responsive facade design, building envelope thermal performance, solar radiation control, and energy retrofitting in residential buildings were reviewed. Based on the literature review analysis, a set of components influencing the environmental characteristics of the facade-comprising geometry and orientation, opening characteristics, shading and radiation control, and envelope materials and structure-was extracted and formulated as the analytical framework of the study. In the second phase, two prominent examples of residential complexes from the late Pahlavi era in Mashhad, the 600 Dastgah Residential Complex and the High-Rise Apartment Complex, were selected as case studies. The criteria for selecting these cases included their prominence in Mashhad's urban landscape, their contemporary architectural value, the availability of precise physical documents and records, and their comparative architectural and solar analysis.

In the third phase, to increase the accuracy of the analyses and reduce reliance on purely descriptive evaluations, a portion of the research components was assessed quantitatively based on simulations. To this end, 3D models of the case studies were developed in the Rhinoceros7 environment, and solar analyses were conducted using Ladybug Tools 1.7.1. Climatic data were imported into the computational system via the EPW file IRN_KV_Mashhad.Intl.AP.407450_TMYx.epw. The file identifies the location as BSk among its probable Köppen climate classifications. The simulations focused on extracting quantitative data, such as the amount of incident solar radiation on the facade surfaces (kWh/m2) and the analysis of Direct Sun Hours on the southern facades. The analysis focused on the southern facades of the two residential blocks, with each block modeled as a representative residential block from each complex. January and July were selected to compare facade solar exposure during representative cold and warm season conditions, respectively. To account for differences in facade geometry, area-weighted averages were calculated for both incident solar radiation and Direct Sun Hours. In the final step, the results from the qualitative analyses and the numerical simulation outputs were integrated to identify the strengths and weaknesses of each case in relation to the climatic conditions of Mashhad. Ultimately, based on the findings, a set of practical design strategies was proposed to guide improvements to contemporary residential façades in Mashhad.

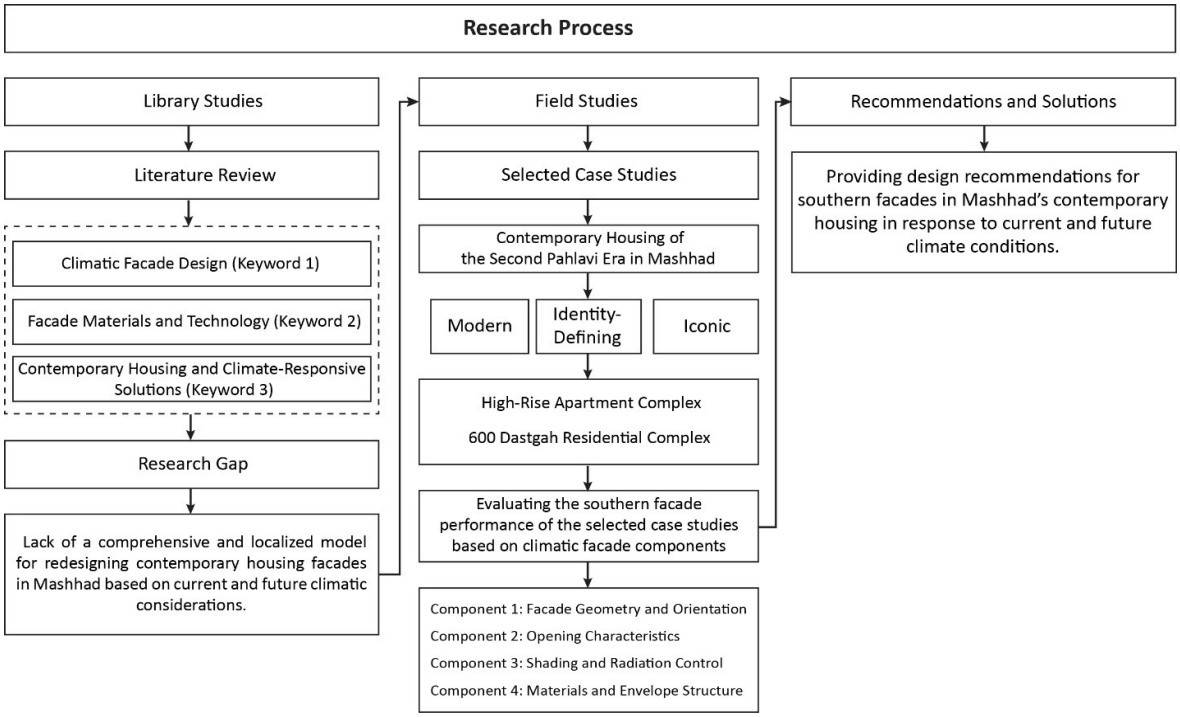

Figure 1: The conceptual framework and research process

CLIMATIC ANALYTICAL FRAMEWORK

In this study, the components for analyzing the building facade were not selected by default, but were extracted through an inductive analysis of previous literature. Accordingly, a selection of national and international studies related to the climatic performance of facades was chosen and analyzed as baseline research. In this process, each study was categorized based on its primary research axis, investigated variables, and key findings. Subsequently, indicators and parameters that directly or indirectly influenced the climatic performance of the facade were extracted. The following table presents the baseline studies, their analytical axes, and the components derived from them, establishing the theoretical foundation for selecting the facade analysis components in this research. (Tab. 1)

Table 1: The climatic analysis framework of the facade and the extraction of evaluation components

Article	Primary Research Axis	Analytical Focus	Extracted Component
(Sadeghinia et al., 2023)	Determining the optimal orientation of residential buildings in Mashhad to achieve thermal comfort and reduce energy consumption in a cold and semi-arid climate.	Analysis of climatic conditions in Mashhad and their impact on the thermal requirements of buildings.	Orientation
(Mirshojaeian Hosseini et al., 2020)	Finding an optimal combination of wall materials and opening sizes in residential facades in Mashhad to reduce energy loss using computer simulation.	Analyzing the impact of wall material types and opening percentages on energy consumption and thermal comfort to provide an optimal pattern.	Material type; Opening characteristics

(Khodakarami & Nouri, 2020)	Investigating the role of common facade materials (e.g., brick, travertine, marble) in altering the thermal comfort conditions of urban outdoor spaces in hot and dry climates.	Analyzing the effect of vertical envelope materials on air temperature, mean radiant temperature (MRT), and thermal comfort indices.	Material type
(Maddahi and Abbasi, 2019)	Investigating and comparing the thermal performance of building outer envelopes to achieve an appropriate pattern for reducing energy consumption and enhancing thermal comfort.	Identifying common walls in Mashhad and simulating them using building performance simulation tools.	Material type
(Mirshojaeian Hosseini et al., 2021)	Investigating the optimal window-to-wall ratio to achieve adequate natural daylight and reduce energy consumption.	Analyzing the effect of window size and ratios on energy performance and indoor lighting quality using algorithmic simulation.	Opening ratio and characteristics
(Ghobadian, 1998)	Providing climate-responsive design principles focusing on determining proper building orientation and optimal shading depth to reduce energy consumption.	Analyzing climatic data and calculating solar energy received by walls in different seasons to determine optimal building orientation and shading depth.	Orientation; Shading and radiation control
(Nohi Bezanjani and Nikpour, 2022)	Determining the optimal building orientation in Mashhad based on solar radiation and prevailing winds to improve thermal comfort and reduce energy consumption.	Analyzing solar radiation, climatic data, and prevailing wind directions to identify favorable building orientations in Mashhad.	Orientation
(Behzadianmehr et al, 2017)	Determining the best orientation for buildings and streets in Mashhad based on solar radiation to achieve thermal comfort and minimize energy use.	Analyzing climatic data to identify the most optimized orientation options.	Orientation
(Akbari and Hosseinejad, 2021)	Determining the optimal aspect ratio and orientation of buildings across different climatic zones of Iran based on solar energy gain.	Comparing square and rectangular forms with different aspect ratios and geographical orientations using cosine law calculations to identify the best combination in each climate.	Geometry and orientation
(Lassandro and Di Turi, 2017)	Selecting appropriate and sustainable materials for the external envelope of residential buildings in hot and dry climates.	Identifying criteria and sub-criteria affecting material selection (such as durability, cost, environmental impacts, aesthetics, and recyclability).	Material type
(Dehghan and Porras-Amores, 2025)	Determining the appropriate form, aspect ratio, and orientation of buildings based on solar radiation to achieve climate-responsive design and reduce energy consumption.	Comparing various geometric forms (square, rectangle, polygons) and their aspect ratios using radiation data to maximize winter solar gain and minimize summer absorption.	Geometry and orientation
(Matin et al., 2017)	Evaluating the impact of building orientation, facade material types, and construction methods on the annual cooling and heating loads of residential buildings.	Simultaneously measuring orientation, facade materials, and execution methods to extract an optimized model for energy reduction.	Material type; Orientation

(Rababa and Asfour, 2024)	Investigating the impact of various shading devices on the aesthetic perception of building facades versus their energy efficiency using augmented reality and energy simulation.	Comparing user aesthetic preferences across eight shading typologies while simultaneously analyzing their thermal performance.	Shading
(Kuda et al., 2025)	Determining allowable ranges for changing the orientation of large-scale residential buildings in hot-arid climates to maintain thermal comfort without altering facade design features.	Analyzing parametric simulations of energy and thermal comfort considering glazing types, window-to-wall ratios, and shading systems.	Shading; Opening ratio and characteristics
(Matin and Eydgahi, 2021)	Investigating the optimization of responsive façade configurations based on indoor illuminance and daylight patterns.	Parametric simulation of facade configurations, orientations, and louver angles across different climate zones using hourly illuminance data.	Openings and solar-control elements / shading configuration
(Alchapar et al., 2025)	Investigating the influence of façade thermal mass and surface albedo on urban microclimatic conditions across different climatic zones.	Simulating traditional, lightweight, and external thermal insulation composite façade technologies under different albedo levels to assess their effects on outdoor thermal conditions.	Material properties (thermal mass and albedo)

The results of this analysis indicate that the primary focus of previous literature has been heavily concentrated on factors such as facade geometry and orientation, opening characteristics and ratios, shading and radiation control strategies, and envelope material types and structure. This persistent recurrence establishes the scientific justification and baseline for selecting these specific four core components as the analytical framework for the present study.

FINDINGS AND DISCUSSION

Following the extraction of the primary analytical components from the literature review, this section examines the degree of compliance of the selected case studies' facades with climatic imperatives. The objective of this phase is to analyze the facade's performance under the climatic conditions of Mashhad and to identify the strengths and weaknesses of each sample regarding energy efficiency, thermal comfort, and climatic responsiveness. Accordingly, four core components including facade geometry and orientation, opening characteristics, shading and radiation control, and materials and envelope structure—are analyzed through a set of physical and performance indicators to enable a comparative evaluation and extract effective patterns for improving contemporary housing facade design in Mashhad.

Analysis of Facade Geometry and Orientation

Facade geometry and orientation are considered among the most fundamental components of climate-responsive building design, as the mass's positioning relative to the solar path, prevailing wind direction, and direct radiation absorption directly impacts the thermal performance of the external envelope. Appropriate orientation can enhance indoor thermal comfort by controlling unwanted radiation, reducing cooling and heating loads, and improving energy efficiency; conversely, inappropriate form selection and building placement will increase energy loss and degrade indoor thermal quality (Behzadianmehr et al., 2017). In Mashhad's cold and dry climate,

the southern and south-eastern facades are identified as the most suitable orientations for building placement; this orientation maximizes winter solar gain while preventing the thermal load increases associated with intense summer radiation (Nohi Bezanjani and Nikpour, 2022). In addition to orientation, the overall geometry of the building mass plays a decisive role in controlling the building's thermal conditions. An appropriate aspect ratio, mass elongation, facade depth, and volumetric setbacks can improve the envelope's climatic performance by reducing critical surfaces exposed to direct radiation, creating self-shading, and enhancing natural ventilation (Akbari and Hosseinejad, 2021). Studies indicate that rectangular forms with an east-west elongation, particularly in the cold and dry climates of Iran, perform better in terms of controlled solar energy reception and reduce the building's reliance on mechanical systems (Hoseinabadi et al., 2012). Hence, analyzing geometry and orientation in the studied samples can more accurately specify their compliance with Mashhad's climatic design principles. (Fig. 2, 3 and Tab. 2).

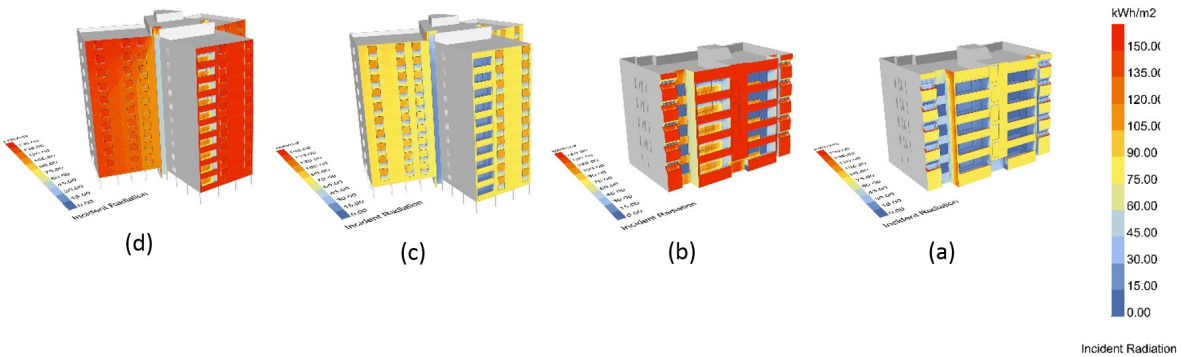

Figure 2: Solar incident radiation analysis of the southern facades of the studied cases; the 600 Dastgah Complex in July (a) and January (b), the High-Rise Apartment Complex in July (c) and January (d).

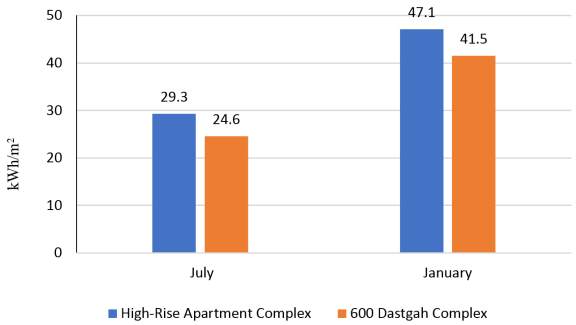

Figure 3: Solar incident radiation chart of the southern facades of the studied cases.

An examination of facade geometry and orientation in the studied samples demonstrates that the organization of the building mass and its placement relative to the solar path are important aspects to consider when interpreting differences in solar exposure and envelope characteristics. In both investigated samples, differences in mass elongation, facade depth, and the extent of volumetric setbacks coincide with variations in their solar exposure patterns (Tab. 2). As shown in Figure 2, the presence of deep balconies, recesses, and volumetric setbacks in the 600 Dastgah Complex creates conditions for self-shading across parts of the façade. In July, the mean incident solar radiation on the south façade of this complex is 24.6 kWh/m², approximately 16% lower than the 29.3 kWh/m² recorded for the High-Rise Apartment Complex (Fig. 3). This indicates lower solar radiation exposure on the studied façade during the summer. In January, the 600 Dastgah Complex also receives approximately 12% less solar energy, with an incident solar radiation value of 41.5 kWh/m² compared with 47.1 kWh/m² for the High-Rise Apartment Complex. Consequently, although reduced solar radiation in summer can help limit excessive solar heat gains, the lower solar exposure in winter may be a disadvantage in

Table 2: Analysis of facade geometry and orientation in the studied samples

Case Study	Mass Elongation	Facade Depth	Volumetric Setbacks	Climatic Evaluation
High-Rise Apartment Complex	Lacks clear elongation along the optimal climatic axis	Shallow depth with a relatively flat envelope	Limited setbacks and relative uniformity of the facade	Increased surfaces exposed to direct radiation and reduced envelope thermal efficiency
600 Dastgah Complex	Appropriate elongation along the East-West axis	Adequate facade depth due to balconies and projections	Effective volumetric setbacks and creation of self-shading	Optimal performance in radiation control, thermal mitigation, and cooling load reduction

Mashhad's cold semi-arid (BSk) climate, where solar energy can contribute to the passive heating of buildings.

In contrast, the High-Rise Apartment Complex, characterized by greater building height, a relatively uniform façade, and limited façade depth, exhibits a different pattern of solar radiation exposure (Fig. 2). Although the building's greater height may cause inter-floor self-shading at certain times of the day, the results indicate that its south façade receives more incident solar radiation than that of the 600 Dastgah Complex in both months examined (Fig. 3). Overall, the findings show that the south façade of the 600 Dastgah Complex receives less incident solar radiation than that of the High-Rise Apartment Complex in both July and January. This comparison highlights the relationship between façade configuration and the distribution of incident solar radiation.

Analysis of Opening Characteristics

Openings are considered one of the most effective components of the building's external envelope in regulating natural light, ventilation, thermal comfort, and energy consumption rates. In Mashhad's climate, the proper design of windows plays a vital role in reducing heat loss during the cold season and controlling unwanted heat during the hot season; thus, the ratio, placement, and type of openings are primary determinants of the facade's climatic performance (Hosseini et al., 2023). Increasing the window area, while improving natural daylight, can escalate the building's cooling and heating loads if not properly controlled. Maddahi and Tavanaiee (2022) evaluated the optimal opening-to-facade ratio in Mashhad's residential buildings to be between 25% and 30%, stating that exceeding this amount diminishes energy efficiency. Furthermore, Hosseini et al. (2023), in their research on the Window-to-Wall Ratio (WWR) in Mashhad's buildings, state that although the 32% to 40% range is suitable for providing useful illuminance, utilizing the lower limit of this range is more logical for achieving better energy performance. These results indicate that the opening ratio must be regulated simultaneously based on lighting needs and thermal control requirements. In addition to the opening area, the type of glazing and frame significantly impacts the facade's thermal performance. Utilizing double-glazed windows, Low-Emissivity (Low-E) glass, and thermally broken frames can reduce energy loss and enhance thermal comfort conditions (Mirshojaeian Hosseini et al., 2021). Additionally, placing openings on the southern and south-eastern facades yields better performance in Mashhad's climate compared to western and eastern facades (Behzadianmehr et al., 2017).
Accordingly, in the analysis of the studied samples, opening characteristics were evaluated based on indicators including the Window-to-Wall Ratio (WWR), opening proportions and placement, glass and frame types, and their compliance with Mashhad's climatic conditions. (Tab. 3)

Table 3: Analysis of opening characteristics in the studied samples

Case Study	Southern Facade WWR	Opening Proportions	Glass and Frame Type	Climatic Evaluation
High-Rise Apartment Complex	17%	Horizontal openings	Single-glazed with metal frames; limited use of UPVC windows in recent renovations	Reduced thermal exchange due to less transparent surfaces, coupled with potential natural light limitations
600 Dastgah Complex	47%	Expansive openings combined with balconies and setbacks	Single-glazed with metal frames; partially featuring UPVC windows in recent renovations	Adequate daylighting accompanied by an increased probability of radiation reception and heat transfer

An examination of opening characteristics in the studied samples reveals that the Window-to-Wall Ratio (WWR), opening placement, and technical specifications are important aspects of the building envelope's environmental performance. To quantitatively evaluate this component, the southern facade WWR for both samples was calculated based on the 3D building model. The results show that the window-to-wall ratio (WWR) is 47% for the 600 Dastgah Complex and 17% for the High-Rise Apartment Complex. These values fall on opposite sides of the recommended range of 25-30% for residential buildings in Mashhad (Maddahi and Tavanaiee, 2022), indicating two distinct approaches to building envelope design Table 3. The larger glazed area in the 600 Dastgah Complex offers greater potential for daylight admission and visual connection with the outdoors. However, this feature may also increase solar radiation gains and heat transfer through the façade. In contrast, although the smaller glazed area of the High-Rise Apartment Complex may limit solar energy gains and heat transfer through the glazed portions of the façade, it may also reduce the potential for daylight admission and increase reliance on artificial lighting. Therefore, a lower window-to-wall ratio does not necessarily indicate a better façade design; it should be evaluated alongside other factors, including building orientation, façade depth, glazing properties, and shading conditions. In both cases, the openings are predominantly located on the south façade, an arrangement suited to Mashhad's climate that allows for solar gains during winter. Field observations indicate that both complexes use single-glazed windows with metal frames, which can facilitate relatively high heat transfer through the openings and limit the thermal benefits associated with their window placement and façade configuration. Field observations also indicate that UPVC windows have been introduced mainly in individual cases during renovations carried out by residents, rather than being part of the buildings' original design. In the 600 Dastgah complex, balconies and recessed building volumes provide shading for glazed surfaces. In contrast, shading is limited in the high-rise apartment complex, where the windows are fitted with single glazing. Compared with double-glazed windows, single-glazed windows offer lower thermal resistance and consequently contribute to greater heat loss during colder periods.

Analysis of Shading and Radiation Control

Shading is considered one of the most important strategies for controlling direct solar radiation in a building, playing an effective role in reducing cooling loads, controlling glare, and enhancing thermal comfort. In Mashhad's climate, the proper design of shading devices must prevent intense summer radiation while preserving the ability to harness solar energy during the cold

season; thus, shading type, depth, and coordination with facade orientation are primary indicators for evaluating the envelope's climatic performance (Nohi Bezanjani and Nikpour, 2022). Studies show that adequate shading depth on the southern facade can reduce undesirable summer radiation without blocking winter gain (Hoseinabadi et al., 2012). Furthermore, Behzadianmehr et al. (2017) state that utilizing shading devices on the southern and south-eastern facades in Mashhad yields better thermal performance compared to other orientations, bringing indoor conditions closer to the comfort zone. On the other hand, research by Ibrahim et al. (2023) demonstrates that horizontal louvers, kinetic shading devices, and integrated systems are evaluated more favorably not only in reducing energy consumption but also in terms of visual quality and aesthetic perception. This indicates that radiation control is not solely a functional issue but also part of the facade's architectural quality. Accordingly, in analyzing the studied samples, shading and radiation control were examined based on indicators such as the presence of shading devices, their type and depth, and their effectiveness in controlling direct radiation. (Fig. 4, 5 and Tab. 4)

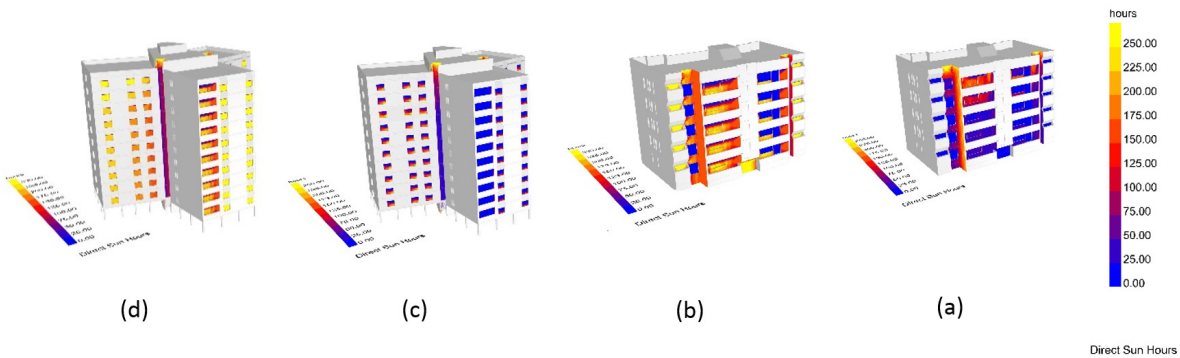

Figure 4: Direct sun hours analysis of the southern facades of the studied cases; the 600 Dastgah Complex in July (a) and January (b), the High-Rise Apartment Complex in July (c) and January (d).

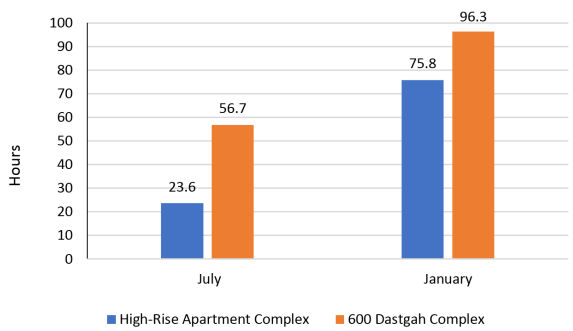

Figure 5: Direct sun hours' chart of the southern facades of the studied cases.

To quantitatively evaluate the shading performance of the façade, a Direct Sun Hours analysis was conducted for the southern façades of the studied samples during July and January, representing summer and winter conditions, respectively. This analysis indicates the number of hours the façade surface is exposed to direct solar radiation and enables a comparison of direct solar exposure patterns between the two samples. At first glance, the results indicate that the south-facing façade of the 600 Dastgah complex receives direct sunlight for longer periods, with 96.3 hours in January and 56.7 hours in July, compared with 75.8 hours in January and 23.6 hours in July for the High-Rise Apartment Complex (Fig. 5). However, comparison with the incident radiation analysis shows that longer exposure to direct sunlight does not necessarily correspond to a higher cumulative amount of solar radiation received by a façade. Although the 600 Dastgah complex experiences more hours of direct sunlight, the solar

Table 4: Analysis of shading and radiation control in the studied samples

Case Study	Type of Shading Elements	Shading Efficiency	Climatic Evaluation
High-Rise Apartmen Complex	Cement sunshades, balconies	Relative radiation control on certain facades	Reduced direct sun hours, but relatively high radiant energy reception due to the flat envelope
600 Dastgah Complex	Deep balconies, volumetric setbacks, and facade fractures	Effective performance in reducing direct solar radiation	Better radiation distribution and decreased received energy intensity through self-shading

energy received by its south-facing façade is lower in both months than that received by the High-Rise Apartment Complex (Fig. 5). This difference indicates that the cumulative solar energy received also depends on the intensity of solar radiation throughout the exposure period. Therefore, the duration of direct sunlight exposure alone does not determine the total incident solar radiation on a façade. In the 600 Dastgah Complex, balconies and façade indentations create self-shading across parts of the façade. This feature contributes to spatial variations in solar exposure across the façade surface. Conversely, although the High-Rise Apartment Complex receives fewer sun hours, its relatively uniform façade and limited volumetric setbacks coincide with higher incident solar radiation in July (Fig. 4). Overall, the analysis results suggest that evaluating shading performance based solely on Direct Sun Hours is insufficient; incident solar radiation should also be considered. The comparison shows that the southern façade of the 600 Dastgah Complex combines longer direct-sun exposure with lower incident solar radiation than the High-Rise Apartment Complex during both examined months. This finding underscores the importance of considering façade configuration and the distribution of solar exposure when evaluating shading performance.

Analysis of Materials and Envelope Structure

In Mashhad's climate, the selection of external envelope materials must be done in a way that, while reducing temperature fluctuations, allows for the gradual storage and release of heat; hence, thermal mass, thermal transmittance, insulation capacity, and facade execution methods are among the most critical indicators for evaluating envelope performance (Maddahi and Abbasi, 2019). Selecting external wall materials is not merely an aesthetic decision but a multidimensional process that simultaneously encompasses climatic, functional, economic, and environmental aspects. The inappropriate use of materials can reduce the envelope's thermal quality and increase energy consumption, whereas selecting climate-compatible materials significantly improves the building's energy performance (Akoochekian and Khalatbari, 2018). Studies by Maddahi and Tavanaiee (2022) show that utilizing walls with AAC blocks alongside a polystyrene insulation layer provides better performance than conventional clay walls, leading to a noticeable reduction in energy loss. Furthermore, Maddahi and Abbasi (2019) state that using dry facade systems and lightweight materials combined with thermal insulation can reduce the building's thermal load and yield a more appropriate response to climatic conditions.

Conversely, more recent research indicates that material lightness alone is not an adequate criterion, and controlled thermal mass also plays a vital role in envelope thermal performance. Alchapar et al. (2025) note that facades with higher thermal mass and controlled albedo perform better in mitigating urban heat stress, whereas excessively increasing surface reflectance can raise the radiant temperature and reduce thermal comfort. This implies that material selection must be considered simultaneously at both the building and urban microclimate scales. Accordingly, in analyzing the studied samples, materials and envelope structure were evaluated

based on indicators including dominant facade material types, surface color and texture, and compliance with Mashhad's climatic conditions. (Fig. 6 and Tab. 5)



Figure 6: Southern facade materials of the studied cases; (a) the High-Rise Apartment Complex, (b) the 600 Dastgah complex.

Table 5: Analysis of materials and envelope structure in the studied samples

Case Study	Dominant Facade Materials	Material Density (kg/m³)	Surface Color and Texture	Climatic Evaluation
High-Rise Apartment Complex	Brick and cement render	High (Brick: 1500, Cement: 1900); lacks effective insulation layer	Beige brick and red cement render	Good heat storage capacity, but energy loss due to the lack of thermal insulation
600 Dastgah Complex	Brick and cement render	Similar thermal capacity coupled with greater envelope depth and effective volumetric setbacks	Beige brick and brown cement render	More optimal thermal performance and greater temperature stability

In both studied samples, the dominant façade materials consist of brick and cement render, which, due to their relatively high density (approximately 1500- 1900 kg/m³) and thermal storage capacity, fall into the category of materials with medium to high thermal mass (Tab. 5). This characteristic enables these materials to store heat and release it over time, potentially moderating indoor temperature fluctuations depending on the wall assembly, insulation, and climatic conditions. An examination of the façade wall assemblies indicates that neither of the two case studies incorporates effective thermal insulation layers. This may facilitate heat transfer through the building envelope, suggesting that thermal mass alone does not ensure satisfactory thermal performance. Rather, achieving better thermal performance depends on an appropriate combination of thermal mass, insulation, construction quality, and façade geometry.

Comparative Summary and Extraction of Findings

The comparative review of façade geometry and orientation, opening characteristics, shading and solar radiation control, and materials and envelope structure indicates that the façades in the studied samples should be assessed in relation to the combined characteristics of these factors rather than the performance of any single component in isolation. The quantitative and qualitative analyses provide a comparative assessment of incident solar radiation, Direct Sun Hours, window-to-wall ratio (WWR), and envelope characteristics, highlighting their relevance to the environmental performance of the studied façades. Incident Radiation analysis results show that the southern façade of the 600 Dastgah Complex receives less incident solar radiation during both July and January than that of the High-Rise Apartment Complex. Furthermore, Direct Sun Hours analysis indicates that although the southern façade of the 600 Dastgah

Complex is exposed to direct sunlight for longer periods, its cumulative incident solar radiation is lower. This contrast highlights the importance of considering both direct-sun exposure duration and incident solar radiation when comparing façade solar performance. In terms of façade openings, the 600 Dastgah complex has a higher window-to-wall ratio (WWR) of 47%, compared with 17% in the High-Rise Apartment Complex. This indicates a greater proportion of glazed surfaces on the façade of the former and, consequently, greater potential for access to natural daylight. Both case studies feature single-glazed windows with metal frames lacking a thermal break, resulting in lower thermal resistance than that of windows with better insulation performance. In terms of façade materials and envelope construction, both case studies incorporate materials with relatively high thermal mass, including brick and cement plaster. However, thermal mass alone does not ensure optimal climatic performance, as other factors, such as thermal insulation, envelope configuration, and building operation, also play a role. Overall, these findings underscore the importance of an integrated approach to façade design, in which geometry, openings, shading, and material properties are considered in relation to one another. In Mashhad's BSk climate, the two cases exhibit distinct patterns of solar exposure associated with differences in façade characteristics and envelope configuration.

Climatic Retrofitting Strategies for Contemporary Residential Facades in Mashhad

As previously noted, a significant portion of the existing challenges in contemporary residential facades in Mashhad stems from the need to better align building envelope design with local climatic requirements. In many instances, the facade has devolved into a purely formal surface independent of the building's thermal performance, rather than functioning as a regulatory layer for environmental conditions. This has caused components such as openings, shading devices, volumetric organization, and materials to operate in isolation, thereby reducing the envelope's overall climatic efficiency. Conversely, analysis results demonstrate that the more successful typologies exhibited a degree of integration among mass geometry, radiation control, opening organization, and material thermal properties, a concept strongly emphasized in recent studies as a fundamental principle of climate-responsive design (Ascione et al., 2019). Accordingly, the climatic retrofitting of contemporary residential facades in Mashhad should extend beyond isolated technical interventions to consider the façade as an integrated environmental system. Within this framework, the strategies proposed in this study are derived from the comparative findings and the façade characteristics examined in the case studies, alongside relevant principles of climate-responsive design. They aim to address Mashhad's current climatic conditions while supporting the adaptation of existing residential buildings to changing climatic conditions.

Regarding geometry and orientation, the findings indicate that recessed building volumes and deep balconies offer opportunities for self-shading and reducing solar radiation exposure. Accordingly, retrofit strategies may include introducing appropriately designed shading devices, increasing façade depth where feasible, and considering building orientation and massing when interventions involve more extensive renovation. These measures can help regulate solar exposure, particularly during summer. The design and proportion of façade openings should also be considered in relation to orientation, shading conditions, and seasonal solar requirements. Regarding openings, the comparison of the two cases highlights the importance of evaluating WWR alongside other façade characteristics rather than treating it as an independent indicator of climatic performance. Therefore, the WWR of southern façades should be determined by balancing daylight provision, solar control, and thermal considerations in ac-

cordance with the specific conditions of each building. Relevant design measures include Low-Emissivity (Low-E) glazing, thermally broken frames, and appropriate external shading systems. In areas affected by outdoor particulate pollution, opening design should also account for indoor air quality through suitable filtration and ventilation strategies. In terms of shading and radiation control, the Direct Sun Hours analysis revealed differences in direct solar exposure between the two studied façades; considered alongside the Incident Radiation results, these differences demonstrate the value of assessing exposure duration and incident solar radiation together. Accordingly, potential retrofitting measures include appropriately designed horizontal shading devices, perforated screens, and other external shading systems selected according to façade orientation and seasonal solar angles. Double-skin façades may also be considered where their technical feasibility, maintenance requirements, and overall performance justify their use. Concerning materials and envelope structure, the findings indicate that both samples use brick and cement render and that their thermal performance also depends on the construction of the envelope and the presence or absence of effective insulation. In this regard, adding suitable thermal insulation and improving envelope detailing can help limit unwanted heat transfer. The selection of insulation and its placement should account for existing wall construction, moisture risks, and the requirements of the retrofit project. Furthermore, applying materials with controlled albedo and lighter colors on surfaces subjected to intense radiation can effectively lower the facade's surface temperature and mitigate microclimatic heat stress (Alchapar et al., 2025). In conclusion, the comparison of the two residential complexes highlights the importance of an integrated approach to façade retrofitting in Mashhad. Mass geometry, solar radiation control, opening organization, and material properties should be considered in relation to one another rather than addressed as isolated components. From this perspective, façade retrofitting can form part of a broader architectural response to current climatic conditions and future climate change. (Tab. 6)

Table 6: Climatic retrofitting strategies for contemporary residential facades in Mashhad

Component	Research Finding	Identified Challenge in Cases	Climatic Consequence	Proposed Strategy
Geometry and Orientation	The 600 Dastgah Complex received approximately 16% less incident solar radiation in July than the High-Rise Apartment Complex.	Shallow facade depth and envelope uniformity	•Increased direct radiation reception •Increased summer cooling load	•Increasing facade depth and volumetric setbacks •Reinforcing east-west elongation. •Increasing facade depth and volumetric setbacks •Reinforcing east-west elongation.
Openings	Superior performance observed in the 600 Dastgah Complex	•Imbalance between daylighting and thermal control •Reliance on single-glazed windows and metal frames •High thermal loss and direct radiation reception •Infiltration of dust and air pollution	•Increased thermal loss and potential glare •Elevated heat exchange rates •Decreased indoor air quality	•Adjusting the WWR corresponding to the orientation •Utilizing Low-E glass and thermal break frames •Implementing multi-layered opening designs •Installing filtered window screens

Shading and Radiation Control	Superior performance in the sample featuring deep balconies and volumetric setbacks	•Insufficient shading depth •Weak or absent radiation control elements.	•Increased cooling loads •Reduced overall climatic efficiency of the facade.	•Adding horizontal louvers and form-integrated shading devices •Utilizing semi-transparent double-skin facades and perforated screens
Materials and Envelope Structure	Presence of adequate thermal mass, yet lacking effective thermal insulation	Unhindered heat transfer and reduced energy efficiency	Increased indoor temperature fluctuations and higher facade surface temperatures.	•Adding lightweight thermal insulation layers and adopting multi-layered envelopes •Utilizing materials with controlled albedo

RESULTS AND CONCLUSION

This study aims to revisit residential façade design in Mashhad through a comparative analysis of the south-facing façades of two representative residential developments from the Second Pahlavi era: the 600 Dastgah complex and the High-Rise Apartment Complex. The synthesis of findings from digital simulations and physical analysis indicates that façades serve a role beyond that of the building's external envelope, playing an important part in how buildings respond to climatic conditions.

According to the solar radiation simulation results, the south-facing façade of the 600 Dastgah complex receives approximately 16% less solar radiation in July than that of the High-Rise Apartment Complex. This difference suggests that the flat, uniform façade of the High-Rise Apartment Complex is associated with greater solar radiation exposure, whereas the recessed volumes, projections, and deep balconies of the 600 Dastgah complex create self-shading effects that reduce solar radiation received by the façade. Therefore, the climatic performance of a building envelope cannot be assessed solely in terms of direct sunlight hours. Despite receiving more hours of direct sunlight on its south-facing façade, the 600 Dastgah complex receives less solar radiation during the summer period due to the physical characteristics of its façade. In January, the 600 Dastgah complex also receives less solar radiation (41.5 kWh/m²) than the High-Rise apartment complex (47.1 kWh/m²). This finding points to a seasonal trade-off between reducing solar radiation exposure and benefiting from useful solar heat gains during winter. A considerable difference exists between the two case studies and the window-to-wall ratio (WWR) range recommended in previous studies for the climatic context under investigation. The 600 Dastgah complex, with a south-facing WWR of 47%, has a relatively large glazed area, which increases the surface exposed to solar radiation and may allow greater access to natural daylight. However, depending on the thermal properties of the windows and building operating conditions, this may also increase heat transfer through the building envelope. In contrast, the High-Rise Apartment Complex, with a WWR of 17%, has a more limited glazed area and potentially less access to natural daylight, which may increase the need for artificial lighting. Therefore, façade opening design should strike a balance between providing adequate daylight and controlling solar radiation. An examination of the predominant façade materials in both complexes, mainly brick and cement render, indicates that their relatively high density and thermal mass have the potential to moderate daily temperature fluctuations under Mashhad's climatic conditions. However, thermal mass alone does not guarantee effective building envelope performance. Therefore, the interaction between thermal mass, thermal insulation, envelope construction, and façade

geometry should be considered when evaluating building façades.

From a holistic perspective, the findings indicate that the climatic performance of building façades is influenced not only by their individual components but also by the interactions among building geometry, the arrangement of openings, material properties, and solar exposure. Therefore, the design and retrofitting of façades in contemporary housing in Mashhad should move beyond a purely formal and visual approach towards the development of an integrated environmental envelope. This approach requires strategies such as increasing effective façade depth to enhance shading, establishing an appropriate balance between glazed and opaque areas, improving the thermal performance of walls with lightweight insulation layers, and incorporating shading devices. These strategies should be evaluated in terms of both solar radiation control during summer and the retention of beneficial solar heat gains during winter.

Nevertheless, several limitations should be acknowledged. The analysis was confined to the southern façades, and other building orientations were not quantitatively evaluated. Furthermore, the study focused on incident solar radiation and Direct Sun Hours rather than whole-building energy or thermal simulations. Accordingly, actual heating and cooling loads, thermal comfort, and total energy consumption could not be determined from the present analysis. The simulation results were also not validated or calibrated against field measurements from the studied buildings. In addition, the comparison involved only two case studies that differed simultaneously in building height, window-to-wall ratio (WWR), façade depth, articulation, and other geometric characteristics. Consequently, the findings do not establish the isolated causal effect of any single façade component and should be interpreted within the context of the two cases examined. Future studies could extend the investigation to additional residential typologies in Mashhad and evaluate façades across all building orientations. Field measurements could be incorporated to validate and calibrate simulation results. More comprehensive building-performance simulations integrating solar radiation, thermal comfort, heating and cooling loads, and energy consumption could further clarify the implications of façade design strategies. Future research could also incorporate future climate scenarios and economic assessments to support a more comprehensive framework for designing and retrofitting climate-responsive residential façades in Mashhad.

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