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Orginal Article

Evaluation of the orientation of residential buildings in Mashhad based on direct solar radiation reception

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Abstract: Reducing energy consumption and developing renewable energy sources are key strategies for addressing the environmental issues caused by fossil fuels. Cities consume 75% of the world's energy, with residential buildings being among the most energy-intensive sectors and offering significant potential for energy reduction. This paper evaluates the orientation of residential buildings in Mashhad based on direct solar radiation using EnergyPlus software. The analyses indicate that a vertical surface oriented at 220 degrees receives the highest radiation, while a vertical surface at 90 degrees receives the least annual direct radiation in Mashhad. During the hot seasons in Mashhad, south-facing façades receive 23% of the direct solar radiation received by horizontal surfaces, the lowest amount. Conversely, during the cold period, south-facing façades receive the highest direct solar radiation, 38% more than horizontal surfaces. Therefore, a south-facing orientation is the most effective during both the hot season (June, July, and August) and the cold period (November to March). Despite this, only 24% of Mashhad's residential buildings are oriented towards the south, while the majority face southwest. After the south, the southwest orientation is the most suitable for Mashhad's dominant cold periods. The southeast orientation, the second most common in Mashhad, is better suited for the hot seasons.

Keywords: building orientation, direct solar radiation, simulation, residential buildings, renewable energy

1. Introduction

Fossil fuels and deforestation are the primary contributors to the increase in carbon dioxide levels in the Earth's atmosphere (Peters et al., 2012). Carbon dioxide is a major driver of climate change and global warming (Wang et al., 2014). The rise in greenhouse gases leads to an increase in the average air temperature and sea levels. The environmental challenges posed by carbon dioxide emissions, alongside the depletion of fossil fuel resources, highlight the urgency of identifying alternative energy sources and solutions. Iran's urban population has been growing in recent years. According to the 2016 population and housing census, approximately 74% of the country’s population lived in cities. This urban population growth has led to increased energy consumption and higher greenhouse gas emissions in urban areas.

City energy consumption is typically divided into five main sectors: industry, transportation, residential, public/commercial services, and agriculture (Aghakarimi et al., 2024; Poggi & Amado, 2024). Among these, transportation and buildings are the most influential in urban energy consumption (Sharbafian et al., 2024). According to published statistics, buildings accounted for 30% of global energy consumption and 15% of CO_2 emissions in 2021 (Li et al., 2024). Residential buildings represent one of the most energy-intensive sectors in cities (Azizibabani et al., 2022; Yuan et al., 2024). In Iran, residential buildings contribute significantly to energy demand, making research in this area a priority.

The implementation of passive cooling and heating strategies in urban buildings is an effective approach to reducing fossil fuel consumption (Aghakarimi et al., 2023; Azizibabani & Dehghani, 2017). The geographical orientation of buildings, particularly in regions with predominantly sunny conditions, plays a crucial role in enhancing indoor comfort using passive heating and cooling techniques. This study evaluates the orientation of residential buildings in Mashhad based on direct solar radiation and determines the optimal orientation angle for developing new residential urban fabrics in accordance with the city's climatic characteristics.

2. Literature review

Numerous studies have examined the relationship between urban structure, buildings, and the use of renewable energy. This research focuses specifically on the orientation of buildings and the amount of solar energy they receive. Zafari Jurshari et al. (2024) investigated residential buildings in Rasht to determine the optimal proportions and orientation for energy efficiency. Their findings indicate that buildings with a 1:4 ratio and an east-west elongation exhibit the most efficient energy consumption. Additionally, they found that buildings oriented at zero degrees to geographic north with an east-west elongation produce the least carbon dioxide and have the lowest annual energy consumption. Sabah Haseeb et al. (2023) analyzed the environmental performance of a ten-story building to identify the optimal form and orientation for minimizing energy consumption. Their results indicate that a T-shaped model, rotated at 285˚, had the lowest energy consumption, providing valuable insights for designing energy-efficient buildings in Kirkuk. Beninca et al. (2023) evaluated the shape and orientation of large-scale social housing multifamily buildings in southern Brazil to identify the best solar positioning for reducing both cooling and heating demands. Their findings reveal that optimizing solar orientation could lower total energy demand by 4% for the "H" shape and 22% for linear buildings in isolated conditions. In a condominium setting, energy demand was reduced by 2% for the "H" typology and 8% for the linear shape. Elaouzy and El Fadar (2022) argue that optimizing building orientation can lead to significant energy savings, particularly in arid and cold climates. Similarly, Shareef (2021) found that orientation is the most influential factor affecting cooling loads and energy consumption in urban blocks, as it directly determines the amount of solar radiation and buildings' solar gain. Li et al. (2020) examined key determinants influencing urban building energy usage and concluded that orientation is among the most significant factors affecting energy consumption.

Watson and Labs (1983) proposed solutions for optimising building orientation to mitigate the effects of summer radiation. Kasmaei (2013), after analysing factors influencing building orientation, recommended suitable directions for various climate zones in Iran.

Lashkari et al. (2011) examined the optimal orientation of buildings in Ahvaz based on climatic conditions. They mapped different building types onto the sun path diagram, considering Ahvaz's latitude. Their findings indicate that the most favourable building orientation is northeast, with a north-south elongation. Rafiyan et al. (2011) argued that modifying the form, density, orientation, and height of residential buildings alone could reduce energy consumption by 45%. HosseinAbadi et al. (2012) studied the climatic design of residential buildings in Sabzevar, focusing on building orientation and canopy depth. They identified the best orientation for both single-sided and double-sided buildings based on solar radiation levels. Barzegar and Heidari (2013) investigated the impact of solar radiation on building façades and its effect on energy consumption in Shiraz. Their results indicate that buildings with a climate-adaptive orientation consume less energy. Similarly, Zarghami et al. (2016) analysed non-rectangular building forms and energy consumption, simulating various orientations to determine the most efficient direction for Semnan's hot and dry climate. Fallahtafti and Mahdavinejad (2015) studied the optimal shape and orientation of buildings in Tehran to enhance energy efficiency, recommending an orientation between 298 and 318 degrees. Zamani et al. (2016) explored the best building orientation in Zanjan based on solar radiation. Aksoy and Inalli (2006) suggested that proper orientation and form could reduce a building's energy consumption by 34–36%. Morrissey et al. (2011) identified building orientation as the most critical factor in passive design for energy reduction. Pacheco et al. (2012) highlighted orientation, shape, and the ratio between the external shell and volume as key determinants in lowering energy demand. Xu et al. (2012) examined energy savings related to building orientation in Chinese cities using EnergyPlus software. Abanda and Byers (2016) estimated that adopting an appropriate climate-responsive orientation could save £878 in energy costs over 30 years.

The literature review highlights the growing recognition of building orientation as a crucial factor in promoting sustainability in architecture and reducing energy consumption. With rising energy costs, it has become increasingly important for builders to orient buildings to maximise the benefits of solar energy. Many studies identify building orientation as the most critical factor in climatic design. Proper orientation offers several advantages, including improved energy efficiency, enhanced thermal comfort, better natural lighting, and reduced HVAC demands. These benefits underscore the necessity of studying building orientation across various climatic and geographical conditions.

3. Research methodology

The computer simulation method is employed in this research. Using climatic data from Mashhad and EnergyPlus software, the city's climate has been simulated, and the orientation of residential buildings has been analysed. The data analysis was conducted in three stages:

In the first stage, Mashhad's climatic data was extracted, and the heating and cooling requirements of residential buildings were analysed across different months. To enhance accuracy, input data related to solar radiation was collected through field studies and incorporated as primary data in the simulation software. In the second stage, information regarding the residential blocks of Mashhad was obtained from the Mashhad Geospatial Database. After analysing the orientation of these buildings, statistical charts illustrating the distribution of residential building orientations were generated. In the third stage, the amount of direct solar radiation received was simulated using EnergyPlus software, based on the building orientations identified in the second stage. Following validation of the simulation results, the findings were assessed using climate analysis and are presented in the research findings section.

4. Results and discussion

4.1. Climatic information of Mashhad

Mashhad is located at 36.16°N latitude and 59.38°E longitude, at an elevation of 999 meters above sea level. According to data from the Mashhad Synoptic Station, between 1951 and 2005, the average annual dry-bulb temperature in Mashhad was 14°C. The lowest average temperature occurs in January at 1°C, while the highest is recorded in July at 27°C. The average annual relative humidity during this period is 55%, increasing in the colder months and decreasing in the hotter months. Temperature and relative humidity data are presented in Fig. 1.

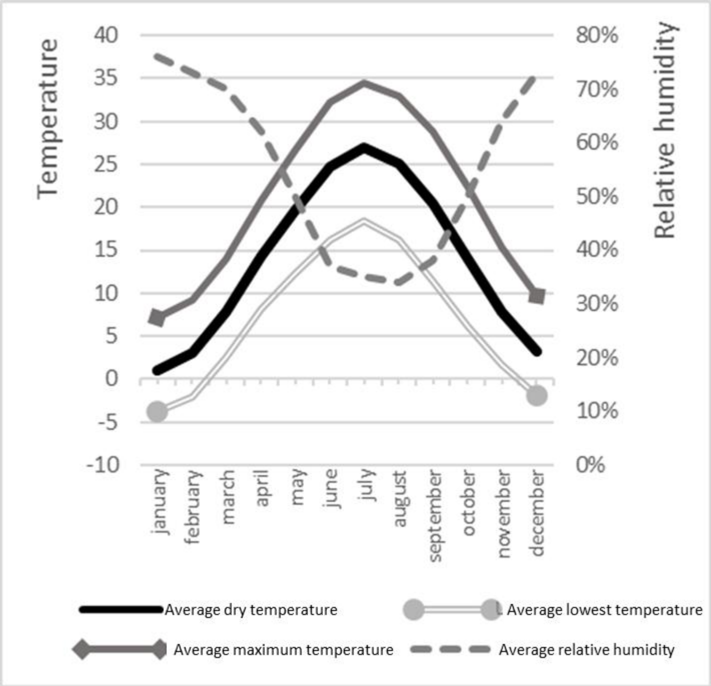

Fig. 1. Average temperature and relative humidity in Mashhad. Derived from (IRIMO, 2024)

To analyse the impact of air temperature on fuel and energy consumption, two indices – heating degree days (HDD) and cooling degree days (CDD) – are defined. Heating degree days measure the extent (in degrees) and duration (in days) for which the outside air temperature remains below a specified threshold, while cooling degree days measure how much and for how long the temperature exceeds a certain level. These thresholds are set at 18°C for the cold season and 21°C for the hot season. The monthly average degree day data for Mashhad, covering the period from 1951 to 2005, is presented in Fig. 2. The total annual heating degree days in Mashhad amount to 2,223.3 units, while the total annual cooling degree days are 439.6 units, highlighting the city's predominant heating requirements.

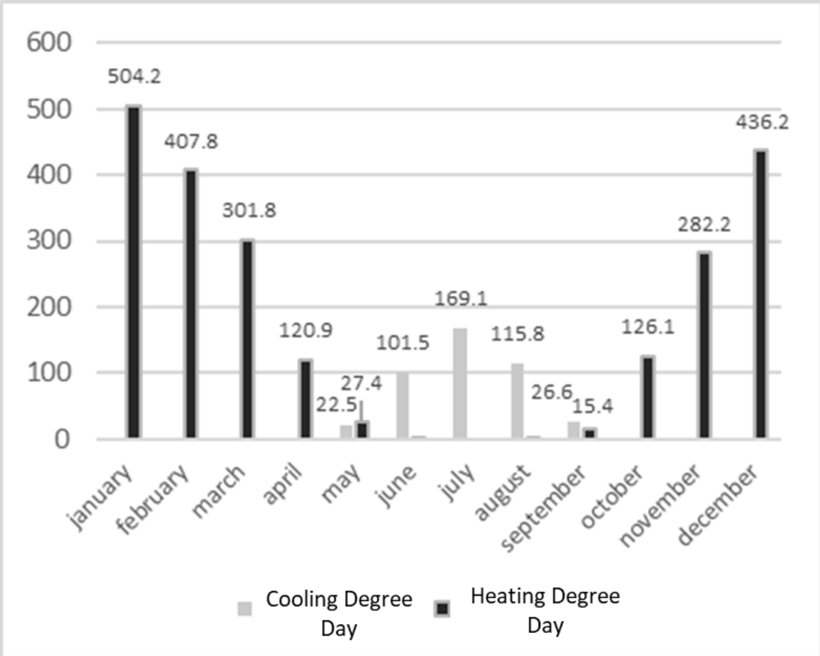

Fig. 2. Monthly average degree day data for mashhad. Derived from (IRIMO, 2024)

Solar radiation intensity is another key parameter used in the analysis. It is typically expressed in watts per square meter per hour (W/m²), representing the amount of solar energy received per unit area in one hour. The intensity of solar radiation varies based on geographical location, time of day, weather conditions, and season. The solar radiation received on horizontal surfaces in Mashhad has been measured by radiation monitoring stations, and the recorded data is presented in Tab. 1.

Table 1. Solar radiation on horizontal surfaces in Mashhad (W/m²). Derived from (PBO, 1997)

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Total radiation	94.41	123.56	149.85	201.37	247.17	277.09	282.61	253.85	228.67	160.41	116.83	89.81
Direct radiation	56.18	74.75	86.91	134.92	181.67	220.29	226.09	208.16	185.23	121.91	83.53	52.09
Diffuse radiation	38.24	48.81	62.94	66.45	65.50	56.80	56.52	45.69	43.45	38.50	33.30	37.72

4.2. Orientation of residential plots in Mashhad

This study focuses on buildings that receive light from two directions, as they constitute a significant portion of the residential structures in Mashhad. A total of 446,908 plots of land in Mashhad have been analysed. The orientation analysis was conducted in 5-degree intervals, with the results presented in Figs 3 and 4. In this survey, the axis angle of each residential plot was measured relative to the north direction, ranging between 90 and 270 degrees for different plots.

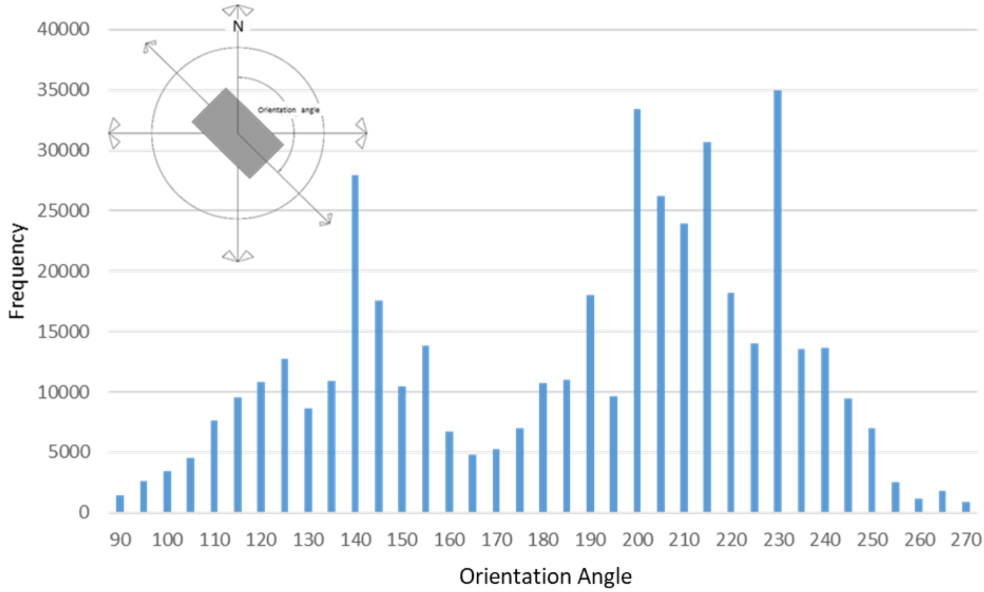

Fig. 3. Frequency of residential plots by geographical orientation in Mashhad. *Source*: Authors

The results indicate that the highest frequencies of residential plot orientations in Mashhad are at 230, 200, 215, and 140 degrees.

4.3. Analysis of direct solar radiation based on different orientations in Mashhad

To calculate the amount of direct solar radiation received by vertical surfaces at various angles, EnergyPlus simulation software (version 8.4) was used. This software processes weather data in a comprehensive file to perform precise calculations. A reliable weather file was generated using Meteorama software, as recommended by the EnergyPlus website (NREL, 2017). The Meteorama database for the Mashhad station contains only temperature data. Since the accuracy of initial radiation data significantly impacts simulation results (Mateus et al., 2014), field-measured data were integrated into the software to improve precision. These data include average, minimum, and maximum temperatures, precipitation levels, and both total and diffuse radiation. Temperature and precipitation data were sourced from Mashhad Synoptic Station records (1951–2005), while radiation data were extracted from the Mashhad Radiometric Station database (1985–1991). After generating the Mashhad weather file, a vertical surface was imported into EnergyPlus to calculate the amount of direct solar radiation received across different months and orientations. Since residential plot orientations in Mashhad were analysed at 5-degree intervals, the direct radiation analysis followed the same approach. Simulations were conducted from 90 to 270 degrees in 5-degree increments, resulting in a total of 36 models tested at different angles. The findings of this simulation are presented in Fig. 4.

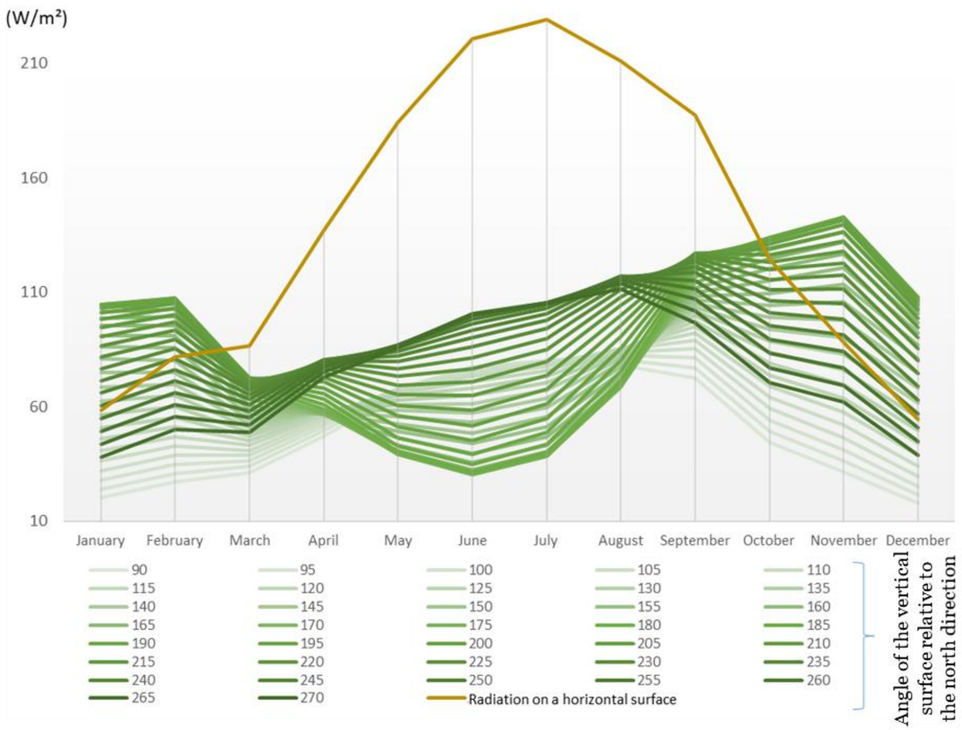

Fig. 4. Average monthly direct radiation at different angles in Mashhad (W/m²). *Source*: Authors

Annual average energy received from direct solar radiation for different orientations (Fig. 5).

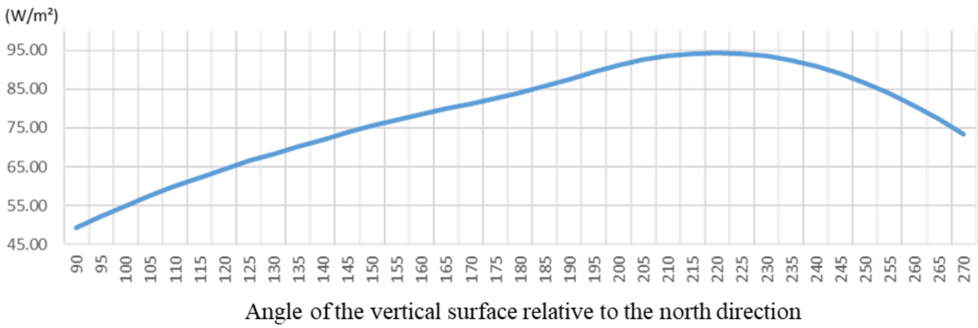

Fig. 5. Annual average direct radiation received for different orientations in Mashhad. *Source*: Authors

4.4. Validation of simulation results

To ensure the accuracy of the simulation data, the results for direct radiation received on horizontal surfaces were compared with measurements taken at the Mashhad Radiometric Station. The comparison between the simulated results and the measured data is presented in Fig. 6.

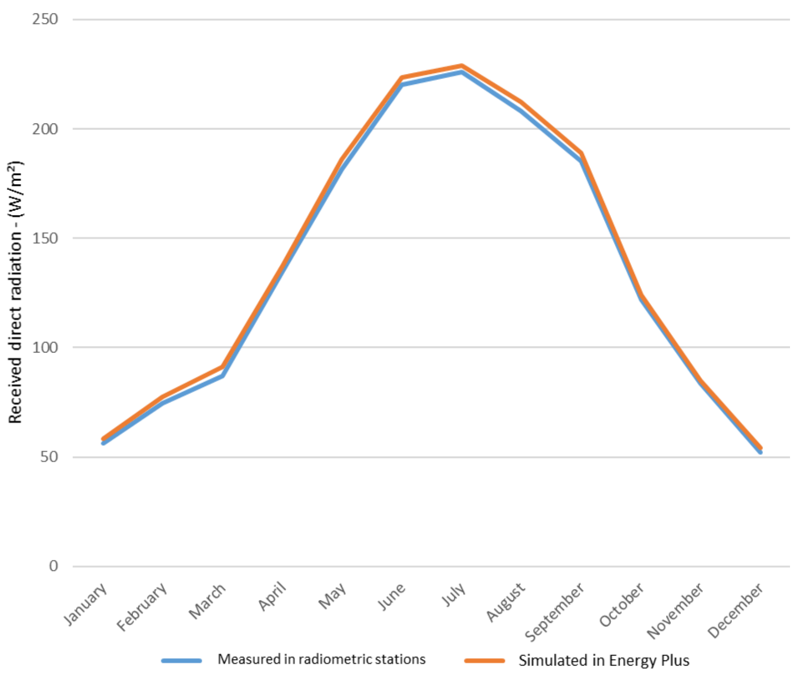

Fig. 6. Comparison of simulated and measured radiation data on a horizontal surface. *Source*: Authors

The normalized root-mean-square error (NRMSE) is 1.78%. According to Abanda & Byers (2016), the acceptable percentage error between computer simulation results and empirical or measured data should be within ±15% for the software to be considered accurate. Therefore, the simulation data are deemed reliable.

4.5. Analysis of simulation results

To evaluate radiation across different orientations, the interval orientations were grouped into five geographical directions: east (90–110°), southeast (115–155°), south (160–200°), southwest (205–245°), and west (250–270°). The results of this classification, along with the amount of radiation received on horizontal surfaces and the degree day data for Mashhad, are presented in Fig. 7.

The simulation results were analysed across two distinct temperature periods in Mashhad. The first period, from November to March, is characterised by high heating demand and is referred to as the cold period. The second period, from June to August, is termed the hot period. For optimal building performance, direct solar radiation should be minimised during the hot period and maximised during the cold period.

During the cold period, the dominant season in Mashhad, the south and southwest orientations perform best. During this time, vertical surfaces receive more direct radiation than horizontal surfaces. The south-facing orientation receives approximately 38% more radiation, while the southwest-facing orientation receives about 23% more than horizontal surfaces. The eastern orientation performs the worst in the cold period, receiving only 45% of the radiation received by a horizontal surface and 33% of the energy received by the south-facing orientation.

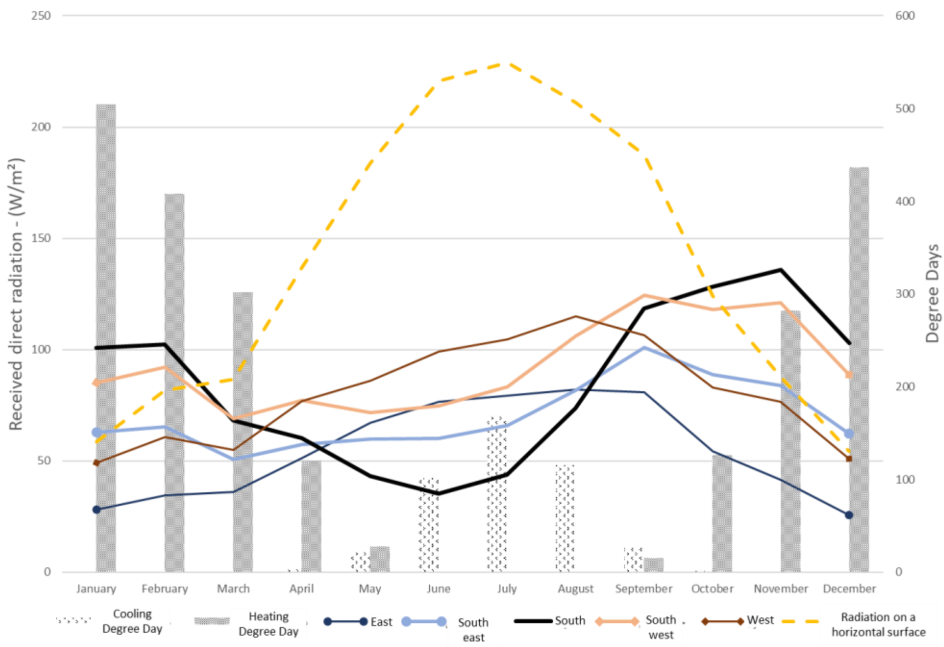

Fig. 7. Monthly average direct radiation received in geographical directions in mashhad and heating and cooling degree days. *Source*: Authors

During the hot period, the south-facing orientation performs best, receiving only 23% of the radiation received by a horizontal surface. After the south orientation, the southeast and east orientations are the most effective, with the southeast receiving 31% and the east receiving 36% of the radiation received by a horizontal surface. The southwest and west orientations perform poorly in hot periods, receiving 40% and 48% of the radiation received by a horizontal surface, respectively. The west-facing orientation also receives more than twice the energy received by the south-facing orientation during the hot period.

The analysis of the annual average direct radiation on a vertical surface indicates that an orientation of 220 degrees receives the highest amount of direct radiation, equivalent to 68% of the average direct radiation received by a horizontal surface. In contrast, an orientation of 90 degrees receives the lowest amount of direct radiation, amounting to 36% of the average direct radiation received by a horizontal surface.

5. Conclusions

The results indicate that the majority of residential plots in Mashhad are oriented at 230 degrees (the method for determining the angle is shown in Fig. 3). The southwest orientation, accounting for 41%, is the most common among residential buildings in the city. Following this, the southeast and south orientations are the next most frequent, while the eastern and western orientations are the least common. The frequency of residential plot orientations in Mashhad can be summarised as follows, where a greater number of “>” signs indicates a larger difference in frequency:

Southwest (205°-245°) >> Southeast (115°-155°) > South (160°-200°) >>> East (90°-110°) > West (250°-270°)

The analysis of absorbed direct radiation across different orientations shows that surfaces oriented at 220 degrees receive the highest amount of direct radiation. In contrast, vertical surfaces with an eastern orientation receive the least direct radiation throughout the year. When categorising the results based on general geographical directions, it was determined that the southern orientation performs best during the cold period in Mashhad (November to March). The ranking of the best orientations for maximising direct radiation during the cold period is as follows:

South (160°-200°) >>Southwest (205°-245°) >>Southeast (115°-155°) >West (250°-270°) >>East (90°-110°)

During the hot season (June, July, and August), the south orientation remains the most effective, followed by the southeast orientation. The best orientations for minimising direct radiation absorption in the hot period are ranked as follows:

South (160°-200°) >>Southeast (115°-155°) >>East (90°-110°) >Southwest (205°-245°) >>West (250°-270°)

The south orientation is the most suitable for receiving direct radiation throughout the year. Given the high number of heating degree days and the predominant heating demand in Mashhad, the best year-round orientation for direct solar radiation absorption aligns with the optimal orientation for the cold period. However, the results indicate that only 24% of residential plots in Mashhad have the proper orientation to effectively receive direct solar radiation (Tab. 2).

Table 2. Frequency of residential building orientations in Mashhad and priority of orientation in different periods**. *Source*: Authors

Frequency of residential building orientations in Mashhad		Optimal orientation for receiving direct radiation in Mash	
		Cold Months (Dominant period in Mashhad)	Hot Months
41%	Southwest	South	South
28%	Southeast	Southwest	Southeast
24%	South	Southeast	East
4%	East	West	Southwest
3%	West	East	West

The findings of this research can offer valuable strategies for urban designers, planners, and architects to incorporate direct solar radiation considerations into urban development plans and architectural design. Naturally, additional factors should be examined to determine the optimal climatic orientation, which could be explored in future studies. Furthermore, similar research can be conducted for other cities to contribute to the advancement of sustainable development.

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