Linking Insolation Shadow Ratio with UTCI: Morphological Insights into Outdoor Thermal Comfort

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Abstract

Outdoor thermal comfort is strongly influenced by solar exposure, yet few simple metrics effectively quantify shading performance. Building upon previous research that introduced the Insolation Shadow Ratio (ISR), this study extends its application by linking ISR to outdoor thermal comfort and urban morphology. Eighty residential sites in Xi'an were surveyed, and parametric models were generated in Rhino/Grasshopper. The Universal Thermal Climate Index (UTCI) was simulated using the Fiala multi-node model, while ISR was derived through Ladybug-based sun-path analysis. Five morphological indicators (BD, FAR, OSR, BGSC, BSC) were correlated with ISR and the proportion of comfortable UTCI hours (UTCI%). Results show that ISR negatively correlates with BD ($r = -0.64$ to -0.80) and exhibits opposite seasonal effects: positive ISR–UTCI% relationships in winter/spring and negative ones in summer/autumn. The findings validate ISR as a simple and robust proxy for evaluating shading–comfort relationships and provide a quantitative framework for climate-responsive urban design.

Keywords: Outdoor Thermal Comfort; Outdoor Space; Insolation Shadow Ratio(ISR); Universal Thermal Climate Index(UTCI); Morphological indicators

1. Introduction

Outdoor thermal comfort in urban environments has a significant impact on public health, well-being, and energy consumption(Elnabawi and Hamza, 2020; Huo et al., 2025; Ren et al., 2021). Prolonged exposure to extreme thermal conditions has been linked to adverse health outcomes and elevated cooling demands, particularly during periods of intensified urban heat island effects (Santamouris., 2014) (Zhan et al., 2024). Among various climatic drivers, solar radiation plays a dominant role in shaping outdoor thermal conditions by influencing mean radiant temperature (MRT) and thermal indices such as the Universal Thermal Climate Index (UTCI). Effective solar shading strategies have demonstrated substantial potential to reduce MRT and improve thermal comfort levels in outdoor spaces. For instance, Lam et al. demonstrated that shading devices could lower MRT by approximately 25 ℃ and UTCI by around 5.9 ℃(Bian et al., 2023; Lai et al., 2019; Wai et al., 2020). In addition, various studies have established strong correlations between urban morphological indicators and UTCI(Song et al., 2025), including Floor Area Ratio(FAR), Open Space Ratio(OSR), Building Density(BD), and impervious surface ratio(Yi et al., 2023). Extended shading periods are associated with reduced UTCI values, while larger OSR tends to increase UTCI(Nicholson et al., 2024), providing critical guidance for the design of thermally comfortable urban and architectural environments(Alharthi et al., 2025). And Extended shading duration often corresponds to reduced UTCI values, while increased openness may elevate thermal stress under high-radiation conditions(Elrefai and Nikolopoulou, 2023; Sun et al., 2023). These findings highlight the necessity of integrating morphological parameters into design guidelines for thermally comfortable environments (Elnabawi and Hamza, 2020).

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Beyond individual components, geometric shadow descriptors have been formalized to quantify spatio-temporal shading. Recent work has examined the Insolation Shadow Ratio (ISR) and related shadow indices as concise measures of shading potential across seasons and morphologies, and has reported systematic relationships with urban-form indicators(Song et al., 2025a; Wang et al., 2025; Y. Xu et al., 2025). Field and simulation studies in diverse climates further demonstrate the thermal efficacy of shading from trees, buildings, and devices—lowering MRT and, in many cases, UTCI—thereby supporting the use of shadow-based indicators in outdoor comfort assessment(Lam et al., 2023). Although previous studies have emphasized the importance of shading and morphological characteristics in influencing outdoor thermal comfort(Ibrahim et al., 2021) , there remains a lack of simple and direct indicators capable of quantifying the relationship between variations in solar shading and thermal comfort. For architectural and urban designers, a straightforward method for evaluating the thermal performance of design alternatives would greatly improve efficiency, particularly in early-stage planning. Despite these advances, a fundamental gap remains in the availability of simple yet robust indicators that can directly quantify the relationship between solar shading dynamics and outdoor thermal comfort. Existing studies have explored the optimization of urban design and complex environments through digital workflows(L. Xu et al., 2025); however, most existing methods rely on computationally intensive simulations or fragmented datasets, limiting their practicality and applicability in early-stage design and urban planning. A practical tool capable of linking shading variations to thermal performance could significantly improve efficiency, enabling designers and planners to integrate comfort considerations into decision-making from the outset. Addressing this gap, the present study proposes the concept of the Insolation Shadow Ratio (ISR) as a quantitative metric. The study aims to investigate the quantitative relationship between ISR and outdoor thermal comfort as measured by UTCI, and to examine the associations between ISR and key morphological indicators such as BD, FAR, OSR, Building Group Shape Coefficient(BGSC) and Building Surface Complexity(BSC)(Wang et al., 2025; Yang and Li, 2015).

Guided by these advances, the present study investigates ISR as a temporally resolved geometric proxy that can be paired with UTCI to evaluate seasonally varying outdoor comfort in residential environments. Two research questions are addressed: (1) What is the quantitative relationship between ISR and outdoor thermal comfort as measured by UTCI when both vary across space and time? and (2) How does ISR and UTCI% relate to key morphological indicators (BD, FAR, OSR, BGSC, and BSC)? To capture diurnal activity periods and seasonal solar geometry, analyses are performed on four typical solar-term days (spring equinox, summer solstice, autumn equinox, winter solstice). For each day, ISR is averaged over 08:00–18:00, and thermal comfort is summarized by UTCI%, defined as the proportion of hours between 08:00 and 18:00 in which UTCI lies within the comfortable range (9–26 ℃). This joint ISR–UTCI% framing enables a consistent comparison across seasons and morphologies and is intended to support climate-responsive design and planning decisions.

Building on prior research, this study utilizes the Insolation Shadow Ratio (ISR), a geometric indicator previously employed to characterize spatio-temporal variations in solar access and shading across urban morphologies(Song et al., 2025)(Xu et al., 2025; Wang et al., 2025)(Gai et al., 2025), and ISR is extended to examine its relationship with outdoor thermal comfort . To capture comfort conditions more consistently, the analysis further incorporates UTCI%, a percentage-based index of comfortable hours that has been applied in outdoor microclimate studies to reflect diurnal comfort duration(Thorsson et al., 2014; Johansson et al., 2018). The research is guided by two central questions: (1) What is the quantitative relationship between ISR and outdoor thermal comfort, as measured by UTCI, when both vary across space and time? and (2) How does ISR relate to key morphological indicators such as building density (BD), floor area ratio (FAR), open space ratio (OSR), building group shape coefficient (BGSC), and building surface complexity (BSC)? To address these questions, analyses are conducted for four representative solar-term days (spring equinox, summer solstice, autumn equinox, and winter solstice). For each day, ISR is averaged over 08:00–18:00, while outdoor comfort is expressed by UTCI%, defined as the proportion of hours within this period in which UTCI falls between 9 ℃ and 26 ℃.

This integrated ISR–UTCI% framework enables consistent seasonal comparisons and provides a systematic basis for linking solar exposure, morphology, and comfort outcomes. By situating ISR within a thermal comfort context, the study advances its application from a shading descriptor toward a practical, design-oriented metric capable of supporting climate-responsive architectural and urban planning strategies.

2. Methodology

This study adopted a multi-stage methodology designed to establish and validate the quantitative and interpretable relationships between urban morphology, solar dynamics (ISR), and outdoor thermal comfort (measured by

UTCI%). The framework integrated field surveys, parametric modeling, dynamic thermal simulations, and multi-level statistical analyses to ensure robustness and reproducibility. The following subsections describe the study area, data acquisition, morphological metrics, solar and thermal simulations, and statistical modeling procedures.

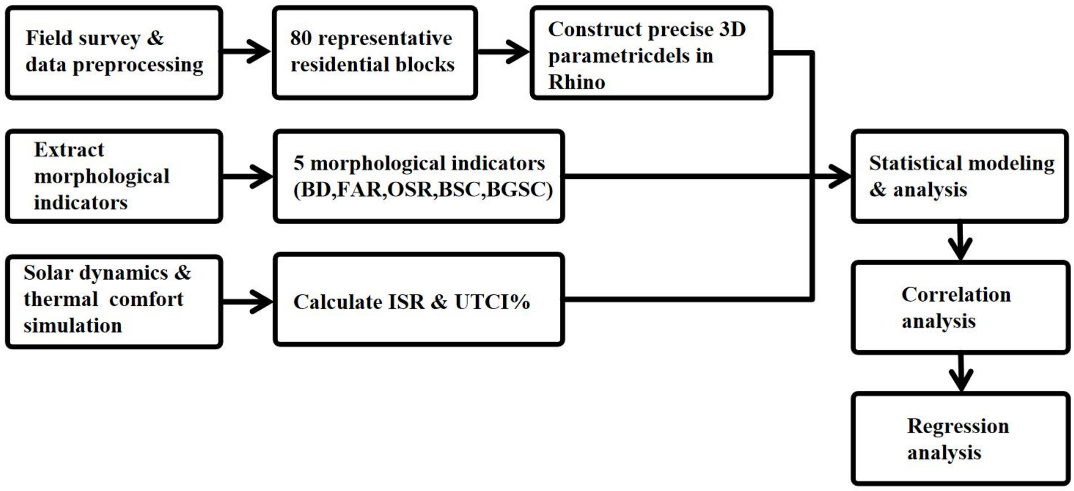


Fig. 1 Research Workflow Diagram.

2.1 Study Area and Data Collection

The empirical analysis was conducted in Xi'an, China, which features a temperate continental monsoon climate with hot summers and cold winters, providing a suitable context for examining seasonal variations in solar radiation. Eighty representative residential blocks were selected to capture a broad range of morphological conditions, including differences in building density, spatial openness, and layout patterns.

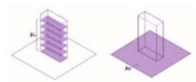
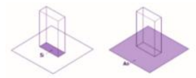
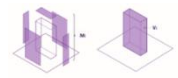
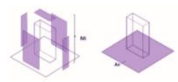
High-resolution spatial information, including building footprints, heights, and orientations, was obtained through on-site surveys. These data were used to construct detailed 3D parametric models of each block in Rhino/Grasshopper, ensuring that site-specific morphological characteristics were accurately represented.

Meteorological conditions were represented using a typical meteorological year (TMY, .epw) file for Xi'an, which provided hourly data on air temperature, relative humidity, wind speed, and solar radiation. By combining these climatic inputs with site-specific morphological models, the study was able to simulate seasonal variations in solar exposure and assess their impact on outdoor thermal comfort. This approach enables a systematic exploration of how spatial configuration interacts with climatic conditions to shape the seasonal distribution of comfort and heat stress in urban residential environments.

2.2 Morphological Indicators

To quantify the geometric characteristics influencing the microclimate, five key morphological indicators were derived from the 3D parametric models constructed in Rhino/Grasshopper. These indicators capture multiple dimensions of the built environment, including density, spatial distribution, and openness, and provide a framework for systematically linking urban form to thermal conditions, and reflect different dimensions of built form and have been extensively applied in urban climate studies(Qian and Li, 2017; Xu et al., 2024). Among these, building density (BD), floor area ratio (FAR), and open space ratio (OSR) were calculated for each residential block to reflect the intensity of development and the availability of outdoor space. By analyzing these indicators in relation to thermal indices such as UTCI, the study explores how variations in spatial configuration affect seasonal comfort levels. This approach not only facilitates the identification of patterns between morphological traits and microclimatic responses but also provides actionable insights for climate-sensitive urban design, emphasizing how careful management of density and open space can mitigate heat stress and enhance outdoor comfort across different seasons (Alharthi et al., 2025; Yi et al., 2023; Yuan et al., 2023).

Table. 1: Extraction of key morphological indicators

Morphological indicators	Abbreviations	Calculation formula	Definition	Diagram
Floor Area Ratio	FAR	$FAR = \frac{\sum_{i=1}^{n} F_i}{A_0}$	The ratio of the building's above-ground floor area to the land area of the site.	
Building Density	BD	$BD = \frac{\sum_{i=1}^{n} S_i}{A_0}$	The percentage of the total building footprint area relative to the land area, essentially representing the building coverage ratio.	
Open Space Ratio	OSR	$OSR = \frac{A_1}{\sum_{i=1}^{n} S_i}$	The ratio of the area of open space of its building site.	
Building Group Shape Coefficient	BGSC	$BGSC = \frac{\sum_{i=1}^{n} M_i}{\sum_{i=1}^{n} V_i}$	The ratio of the total exterior surface area of a building group to its total volume.	
Building Surface Complexity	BSC	$BSC = \frac{\sum_{i=1}^{n} M_i}{A_0}$	The ratio of the total exterior surface area of a building group to the site area.	

2.3 Solar Dynamics and Thermal Comfort Simulation

The dynamics of solar exposure in urban residential blocks were quantified to assess their impact on outdoor thermal comfort and their relationships with morphological characteristics. ISR was employed to represent solar access, defined as the ratio of sunlit area (Ai) to total site area, with shaded regions (As) corresponding to building-cast shadows on the ground under solar irradiation(Fig 2). ISR captures spatial variations between sunlight and shadow across outdoor spaces, reflecting how urban form modulates solar exposure. Calculations were performed using the Ladybug Tools suite, incorporating sun-path and solar radiation analyses. Simulations were conducted for four representative solar-term days — winter solstice, spring equinox, summer solstice, and autumn equinox — between 08:00 and 18:00, capturing both seasonal and diurnal variations in shading patterns. The ISR is calculated as follows:

$$ISR = \frac{Ai}{As+Ai} \quad \text{(eq. 1)}$$

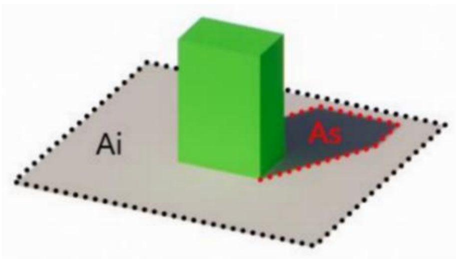


Figure. 2 Schematic diagram of the ISR(Song et al., 2025b)**.**

Outdoor thermal comfort was assessed through the Universal Thermal Climate Index (UTCI), which integrates air temperature, mean radiant temperature, relative humidity, and wind speed into a physiologically based comfort index. UTCI values were computed using the Fiala multi-node model(Fiala et al., 2012). To account for temporal variability, the UTCI% metric was introduced, defined as the proportion of daytime hours when UTCI fell within the comfort range of 9–26 °C. Simulations were implemented in Rhino/Grasshopper using Ladybug and Honeybee plugins, enabling a detailed analysis of how morphological indicators interact with solar dynamics. This approach provides a systematic framework for exploring the seasonal distribution of comfortable and heat-stressed conditions, offering insights into the influence of urban form on outdoor thermal environments.

2.4 Statistical Modeling and Analysis

The relationships among urban morphology, solar exposure, and outdoor thermal comfort were examined using a two-stage statistical approach. Spearman's rank correlation was first applied to assess monotonic associations between morphological indicators and ISR. This non-parametric method was chosen for its robustness in handling non-linear relationships and variables that do not follow normal distributions, allowing reliable identification of underlying trends between urban form and microclimatic conditions.

Both linear and quadratic models were tested for each representative solar-term day to capture potential non-linear responses in thermal comfort to variations in solar exposure. The coefficient of determination (R^2) was used to evaluate the goodness of fit and to compare model performance across seasons. This process enabled the identification of season-specific patterns, revealing how the same morphological or solar parameter can have contrasting effects under different climatic conditions. The derived regression functions provide interpretable metrics that can inform climate-responsive urban design, linking spatial configuration to expected thermal outcomes. Overall, this analytical framework facilitates a systematic exploration of the complex interactions between built form, solar dynamics, and outdoor thermal comfort, offering insights into design strategies that optimize comfort across seasonal conditions.

3. Results

3.1 Correlations Between Morphological Indicators and ISR

Spearman's rank correlation analysis was conducted to examine the relationships between ISR and five morphological indicators (BD, FAR, OSR, BSC, and BGSC) across four representative solar-term days (winter solstice, spring equinox, summer solstice, and autumn equinox). The results reveal clear seasonal variability and systematic links between shading dynamics and urban form (Figure 3).

During the winter solstice, ISR was moderately negatively correlated with BD ($r=–0.434$, $p<0.01$) and FAR ($r=0.114$), while showing no significant associations with OSR, BSC, or BGSC. These results suggest that compact morphologies limit solar access in winter, thereby reducing shading ratio values. Similar findings were reported by Elnabawi and Hamza, who emphasized that high-density configurations restrict insolation in cold periods, potentially constraining thermal benefits(Elnabawi and Hamza, 2020; Elnabawi and Jamei, 2024).

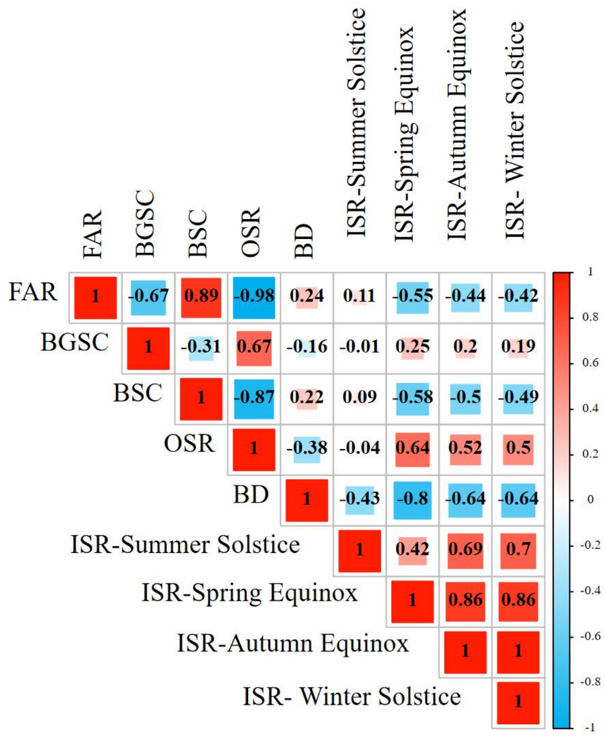


Figure. 3 Correlation heat map between morphological indicators and ISR.

At the spring equinox, ISR was strongly negatively correlated with BD ($r = –0.635$, $p < 0.01$) and FAR ($r=–0.440$, $p<0.01$), and positively correlated with OSR ($r=0.515$, $p<0.01$). BSC also exhibited a significant negative correlation ($r=–0.503$, $p<0.01$). These associations reflect the role of more open and less compact layouts in allowing increased solar penetration during transitional seasons. Studies on urban canyons have similarly shown that lower density and higher openness improve shading–sunlight balance during equinox periods (Lam et al., 2023). The results highlight the influence of spatial openness on solar accessibility in outdoor environments. More open and less compact spatial layouts were associated with higher ISR, indicating that outdoor areas benefit from greater solar penetration during transitional seasons. Such patterns suggest that adjusting the degree of openness in residential blocks may be an effective seasonal design strategy to regulate daylight access and outdoor comfort.

The summer solstice exhibited the strongest correlations among the four solar-term days. ISR was strongly and negatively correlated with building density ($r = -0.796$, $p < 0.01$), floor area ratio ($r = -0.549$, $p < 0.01$), and building surface complexity ($r = -0.582$, $p < 0.01$). Conversely, it showed a strong positive correlation with open space ratio ($r = 0.643$, $p < 0.01$) and a moderate positive correlation with building group shape coefficient ($r = 0.253$, $p < 0.05$). These results suggest that open and less compact urban forms substantially increase solar exposure during summer. This finding highlights the potential need to balance openness with effective shading strategies in order to mitigate the intensification of thermal stress under high-radiation conditions.(Jin and He, 2025).

During the autumn equinox, ISR was again negatively correlated with BD ($r=-0.636$, $p<0.01$), FAR ($r=-0.425$, $p<0.01$), and BSC ($r=-0.487$, $p<0.01$), while showing positive associations with OSR ($r=0.501$, $p<0.01$). This pattern suggests that areas with lower building density and greater openness allow more solar radiation to reach outdoor spaces, potentially amplifying heat exposure during this season. The findings highlight how urban form can shape seasonal variations in outdoor thermal conditions, pointing to the need to consider both spatial configuration and solar exposure in the design of comfortable residential environments.

Overall, the findings demonstrate that ISR is systematically constrained by compact morphologies such as BD, FAR, and BSC, while it is enhanced by open-space characteristics including open space ratio and, to a lesser extent, building group shape coefficient. The seasonal reversal between winter–spring and summer–autumn underscores the dual function of urban morphology: compact forms reduce excessive solar exposure and help alleviate thermal stress in hot periods, whereas more open configurations facilitate beneficial solar access during colder months. This duality suggests that morphological design should not be guided by uniform principles, but rather by adaptive strategies that align spatial form with seasonal thermal requirements.

3.2 Seasonal Correlations Between ISR and UTCI%

Spearman’s rank correlation analysis was conducted to assess the relationship between e ISR and UTCI% across four representative solar-term days (winter solstice, spring equinox, summer solstice, and autumn equinox). The results reveal pronounced seasonal variability.

During the winter solstice, UTCI% exhibited a significant positive correlation with ISR ($r = 0.637$, $p < 0.01$), indicating that higher levels of solar exposure increased the proportion of comfortable hours. This suggests that insolation plays a key role in mitigating cold stress in outdoor environments.

At the spring equinox, the positive correlation between ISR and UTCI% was even stronger ($r=0.783$, $p<0.01$), implying that transitional seasons benefit substantially from moderate solar exposure. Small increases in sunlight during spring can meaningfully extend the duration of comfort hours, emphasizing the potential of solar access in improving outdoor thermal conditions.

Table. 2 Seasonal Correlations Between ISR and UTCI%

		UTCI%-Winter Solstice	UTCI%-Spring Equinox	UTCI%-Summer Solstice	UTCI%-Autumn Equinox
ISR-Winter Solstice	r	0.637**	0.783**	-0.207	-0.728**
	p	0.000	0.000	0.070	0.000
ISR-Spring Equinox	r	0.589**	0.619**	-0.679**	-0.762**
	p	0.000	0.000	0.000	0.000
ISR-Summer Solstice	r	0.314**	0.322**	-0.704**	-0.491**
	p	0.005	0.004	0.000	0.000
ISR-Autumn Equinox	r	0.589**	0.623**	-0.672**	-0.762**
	p	0.000	0.000	0.000	0.000

By contrast, the summer solstice showed a significant negative correlation between ISR and UTCI% (r = –0.679, p < 0.01). Excessive solar radiation during hot periods reduced the proportion of comfortable hours, highlighting the importance of shading and other cooling strategies to mitigate heat stress in outdoor spaces.

A similar trend was observed during the autumn equinox, with UTCI% strongly negatively correlated with ISR (r =–0.762, p<0.01). Late-season solar exposure appears to exacerbate heat stress, indicating that interventions such as shading may still be necessary until ambient temperatures decline further.

The ISR–UTCI% relationship varies seasonally, being positive in cooler periods (winter and spring) and negative in warmer periods (summer and autumn). This highlights the dual role of solar access in outdoor thermal comfort—enhancing comfort under cold conditions while increasing heat stress in hot periods. The findings emphasize the need for seasonally responsive urban design: winter planning should prioritize solar exposure, whereas summer and autumn strategies should focus on shading to optimize outdoor thermal conditions throughout the year.

3.3 Regression Analysis between ISR and UTCI% across Solar-Term Days

Least-squares regression was employed to characterize the relationship between ISR and the proportion of hours within the comfortable Universal Thermal Climate Index range (UTCI%) across 80 residential districts on the spring equinox, summer solstice, autumn equinox, and winter solstice. Both linear and quadratic models were tested for each dataset, and the model with the highest coefficient of determination (R^2) was selected. The results are summarized as follows (Fig. 4).

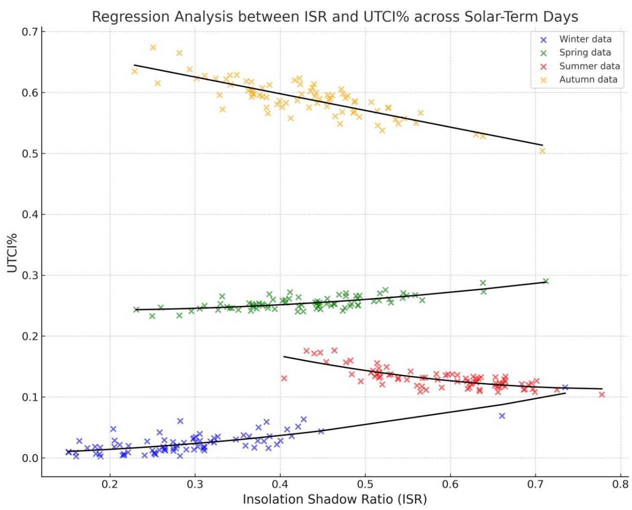


Figure. 4 The fitting relationship between ISR and UTCI%

The analysis revealed that during the spring equinox, ISR exhibited a significant positive non-linear association with UTCI%, with the quadratic model providing the best fit ($R^2 = 0.520$). This indicates that higher solar exposure effectively prolongs the proportion of comfortable hours during transitional seasons, when additional radiation helps to alleviate mild cold stress.

$$y = 0.147x^2 - 0.045x + 0.246, R^2 = 0.520 \quad \text{(eq. 2)}$$

In contrast, the summer solstice demonstrated a strong negative non-linear relationship, with the quadratic model again selected as optimal ($R^2 = 0.573$). Increased ISR was associated with marked reductions in UTCI%, emphasizing the importance of shading strategies for mitigating heat stress in hot periods.

$$y = 0.343x^2 - 0.547x + 0.331, R^2 = 0.573 \quad \text{(eq. 3)}$$

For the autumn equinox, a negative linear trend was identified, with the linear model outperforming the quadratic alternative and yielding the highest explanatory power among all seasons ($R^2 = 0.675$). The regression equation was:

$$y =- 0.274x + 0.708,\ R^2 = 0.675 \quad \text{(eq. 4)}$$

This result suggests that, even as ambient temperatures begin to decline, persistent solar intensity continues to exert a significant influence on outdoor comfort, reinforcing the role of shading in maintaining acceptable conditions during early autumn. By contrast, the winter solstice displayed a strong positive non-linear relationship, with the quadratic model achieving the best fit ($R^2 = 0.612$). Increased ISR was associated with higher UTCI%, confirming the decisive role of solar access in improving outdoor thermal comfort in cold seasons and supporting opportunities for wintertime outdoor activities.

$$y = 0.175x^2 + 0.009x + 0.005,\ R^2 = 0.612 \quad \text{(eq. 5)}$$

Taken together, these findings demonstrate a clear seasonal reversal in the ISR–UTCI% relationship. During colder periods (winter and spring), higher levels of solar exposure contribute positively to thermal comfort, whereas in warmer periods (summer and autumn), increased exposure leads to a reduction in comfortable hours. This duality underscores the necessity of seasonally adaptive, climate-responsive design strategies, in which the provision of shading and solar access must be carefully balanced to align with seasonal thermal requirements.

These findings are consistent with previous studies that identified the dual role of solar exposure in outdoor thermal environments. In hot-humid and subtropical climates, excessive insolation has been shown to elevate mean radiant temperature and exacerbate heat stress, reinforcing the importance of shading interventions during summer (Lam et al., 2019; Bian et al., 2023). Conversely, in cold and transitional seasons, enhanced solar access is beneficial, supporting outdoor activity and mitigating cold discomfort (Elnabawi and Hamza, 2020; Alharthi et al., 2025). The seasonal reversal observed in this study provides quantitative evidence that shading strategies must be seasonally adaptive rather than uniform, integrating both solar access in winter and shading provision in summer. From a planning perspective, this suggests that morphological guidelines should consider dynamic ISR–UTCI% relationships to optimize comfort year-round, thereby advancing climate-responsive and health-oriented design of residential environments.

4. Conclusion

4.1 Key findings

The results demonstrate that multiple urban morphological parameters are significantly associated with ISR. BD shows a strong negative correlation with ISR during the spring equinox, autumn equinox, and winter solstice ($r=-0.80, -0.64, -0.64$), and a moderate negative correlation during the summer solstice ($r=-0.43$). FAR and BSC exhibit moderate negative correlations with ISR in spring, autumn, and winter, whereas BGSC and OSR display moderate positive correlations during the same periods. These findings indicate that higher building density and surface complexity reduce solar access, while greater openness and lower ground shading enhance solar exposure.

Regression analyses between ISR and UTCI% reveal distinct seasonal variations. During the winter solstice, ISR is positively associated with UTCI%, with the quadratic model achieving the best fit ($R^2=0.612$), suggesting that increased solar exposure substantially improves thermal comfort in cold seasons. In contrast, during the summer solstice, ISR shows a negative relationship with UTCI%, with the quadratic model providing the best fit ($R^2=0.573$), highlighting that excessive insolation diminishes summer comfort. A weak positive quadratic relationship is observed in spring ($R^2 = 0.520$), whereas a strong negative linear relationship is identified in autumn ($R^2 = 0.675$), demonstrating that higher solar exposure in transitional cool periods still reduces comfort duration.

This study elucidates the mechanisms through which urban morphology influences solar accessibility and outdoor thermal comfort, offering quantitative evidence for climate-responsive urban design, and provides quantitative evidence linking ISR, urban morphological indicators, and outdoor thermal comfort. Key findings indicate that ISR correlates negatively with building density, floor area ratio, and surface complexity, while showing positive associations with green space and open space ratios. Seasonal regression models reveal that ISR enhances outdoor comfort in winter and spring but reduces comfort in summer and autumn. These results validate ISR as a practical and geometry-based metric for assessing shading potential and its implications for outdoor thermal comfort.

4.2 Limitations

The analysis was limited to representative residential blocks in Xi’an, which may constrain the generalizability of the findings to other climatic zones and urban contexts. Moreover, the reliance on simulation-based methods restricted the incorporation of subjective human perceptions of comfort.

4.3 Future Research Directions

Cross-climatic and morphological validation. The ISR – UTCI% relationship should be tested across multiple climate zones—including hot-humid, hot-arid, and tropical regions—as well as under varied urban morphologies such as gridiron layouts and organic street patterns. This is essential for establishing ISR as a universally applicable design tool.

Advancement of interpretable modeling approaches. Future studies should explore interpretable methods such as generalized additive models and explainable neural networks to develop robust, accurate, and transparent predictive frameworks for urban design applications.

Integration of human subjectivity. Future research should combine objective indices such as UTCI% with subjective assessments of thermal sensation and behavioral responses, providing a more comprehensive understanding of outdoor comfort that accounts for both physical conditions and human perception.

5. Acknowledgments

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