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Assessing the Impact of Urban Canyon Geometry on Outdoor Thermal Comfort: A Case Study in Marrakech, Morocco

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Abstract

The rapid urbanization of cities, combined with the challenges of climate change, has made managing outdoor thermal comfort a priority in urban planning. As cities experience rising temperatures, strategies to mitigate the Urban Heat Island (UHI) effect and enhance outdoor thermal comfort are becoming essential for enhancing the quality of life and promoting sustainable, healthy urban environments. This study investigates the impact of urban form features on UHI intensity and outdoor thermal comfort in Marrakech, Morocco. The UHI effect and thermal comfort, quantified using the Universal Thermal Climate Index (UTCI), were simulated across various urban canyon design scenarios using the Urban Weather Generator and Ladybug Tools. Five simulation experiments analyzed the effects of altering street aspect ratios, building heights, and street orientations within urban canyon geometry. The results show that compact urban canyons can increase air temperature by up to 6°C but offer significant benefits for thermal comfort during winter nights and spring and summer days. Street orientation had the greatest impact on thermal comfort, with UTCI variations reaching up to 15°C. The northeast-southwest orientation proved optimal across all seasons and building heights had a limited effect, except during winter. This study highlights the importance of urban design in mitigating UHI and enhancing outdoor thermal comfort, providing key insights for sustainable urban planning in hot climates. Overall, a compact urban canyon with a northeast-southwest street orientation is identified as the most effective design for improving outdoor thermal comfort in Marrakech.

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Keywords

Outdoor Environment; Urban climate; Urban heat island; Urban forms; Urban planning; Public Space; Ladybug Tools; Marrakech

1. Introduction

Urbanization and climate change are among the most defining issues of our time (Dreyfus, 2015). The Urban Heat Island (UHI) effect exacerbates the impact of rising temperatures in cities due to global warming (Dogan et al., 2019; Ramamurthy & Bou-Zeid, 2017), which has led to growing interest in studies of outdoor thermal comfort. Over the past decade, this field has gained significant importance, becoming a key indicator of urban space quality and a crucial factor in designing climate-adapted and healthy urban environments (Elnabawi & Hamza, 2020; Lachir, 2022). Poor outdoor thermal comfort can adversely affect human health and well-being while also reducing social and commercial outdoor activities. High temperatures and humidity can make working or spending time

outdoors difficult (Smith et al., 2014). Ensuring appropriate thermal comfort can extend the duration of outdoor activities, enhance urban life and vitality, and decrease energy consumption in built environments (El-Bahrawy, 2023).

The planning and design of urban spaces has been shown to significantly impact outdoor thermal comfort (Targhi & Van Dessel, 2015; Yahia et al., 2018). Effective strategies, including optimizing urban geometry, incorporating vegetation, using appropriate materials, and considering street orientation, can significantly enhance outdoor thermal comfort in urban areas. (Bedra et al., 2023; Hedayatnia et al., 2023; Korkut & Rachid, 2024) In particular, urban morphology,—including the compactness and layout of buildings, as well as the presence of open spaces—, has been shown to cause significant variations in microclimatic conditions, affecting thermal comfort differently across various urban settings. For instance, a study in Isfahan demonstrates that different block designs lead to varying microclimatic and thermal comfort outcomes (Sadeghian et al., 2024). Therefore, urban design must account for local microclimatic conditions to enhance thermal comfort, fostering more sustainable cities and improving urban quality of life.

Assessing thermal comfort in outdoor environments is highly complex due to the interplay of various environmental, personal, psychological, and cultural factors. Key environmental parameters, such as solar radiation, air temperature, wind speed, and relative humidity, significantly influence thermal comfort and are strongly altered by urban microclimate processes (Shooshtarian & Ridley, 2016; Zhang et al., 2022). The heterogeneity of urban geometry and surface characteristics leads to high spatial variability in thermal comfort within urban areas, highlighting the need for micro-scale models focused on the neighborhood scale to accurately depict interactions between buildings and their surroundings. Several studies have developed and used micro-scale models for outdoor thermal comfort, aiming to provide insights for sustainable urban design and decision-making, emphasizing the importance of considering microclimate factors for improving outdoor thermal comfort (Aghamolaei et al., 2023; Jänicke et al., 2021; Lam et al., 2021). Available simulation tools include ENVI-met (Huttner & Bruse, 2009), RayMan (Matzarakis et al., 2007), and Ladybug (Sadeghipour Roudsari & Pak, 2013). These tools quantify outdoor environmental conditions by estimating thermal comfort indices. The most frequently used indices are the Physiologically Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI). Both PET and UTCI were specifically developed for measuring thermal comfort in outdoor environments and have shown reliability and potential as useful tools in urban planning (Staiger et al., 2019).

In the Moroccan context, few studies have addressed outdoor thermal comfort. Ouali et al., (2020) showed that urban design choices, such as the shape, size, and spacing of buildings, can significantly improve outdoor thermal comfort in moderate climates. A study in Fez, Morocco, found that urban geometry plays a crucial role, with deep street canyons offering better comfort in hot climates but necessitating wider streets or open spaces for solar access during colder seasons (Johansson, 2006). Jihad & Tahiri (2016) investigated the influence of the aspect ratio in Agadir, Errachidia, and Fez. Existing literature demonstrates the importance of outdoor thermal comfort in the Moroccan context and highlights the significance of urban design in enhancing this comfort. However, there is still a significant knowledge gap in this field, particularly regarding how different design options influence thermal comfort. Studies in various climatic regions demonstrate that effective urban design must be tailored to local conditions (Ruefenacht et al., 2022). This case study in Marrakech, Morocco, examines key design parameters related to urban forms that impact the microclimate and provides guidelines to assist architects and urban planners during the early design stages of new districts in a city where extreme temperatures are a significant concern.

This paper aims to contribute to existing knowledge by analyzing how various urban form features impact the urban microclimate and thermal comfort. We investigate three urban form features: building height, street aspect ratio, and street orientation, and quantify their effects on the urban heat island and thermal comfort in the climate context of Marrakech, Morocco. These urban form features are identified as key geometrical characteristics influencing outdoor microclimate conditions. Previous research indicates that their interactions with air temperature and thermal comfort can vary, with some outcomes being debated in the literature. For example, compact urban areas may reduce daytime temperatures and improve thermal comfort by providing shading and limiting direct solar exposure, which is beneficial during warmer periods. However, these same features can also retain heat at night, thereby

intensifying the UHI effect and reducing nighttime cooling (Cha & Oh, 2020; Hedayatnia et al., 2023). This paper provides valuable insights for urban planners aiming to enhance thermal comfort and mitigate urban heat through effective design strategies. To achieve this goal, we analyze various design scenarios of an urban canyon, focusing on key geometrical characteristics and using validated simulation models to estimate their impacts on the urban heat island effect and thermal comfort within the canyon.

2. Materials and Methods

2.1. Climate Data

The study is conducted in the climatic context of Marrakech, a semi-arid city known for its dry and extremely hot summers, with temperatures often exceeding 40°C. To characterize Marrakech's climate, we used hourly climatic data in Energy Plus Weather (EPW) format. These data, commonly used for simulating building energy requirements, represent a typical year's climate and are derived from observations at the Marrakech Menara A.P. 602300 station between 2004 and 2018.

In this study, we focus on analyzing thermal comfort during the summer, spring, and winter seasons. For each season, we selected a representative day on which simulations were conducted in Marrakech. The hourly climatic data for the selected days are shown in Figure 1.

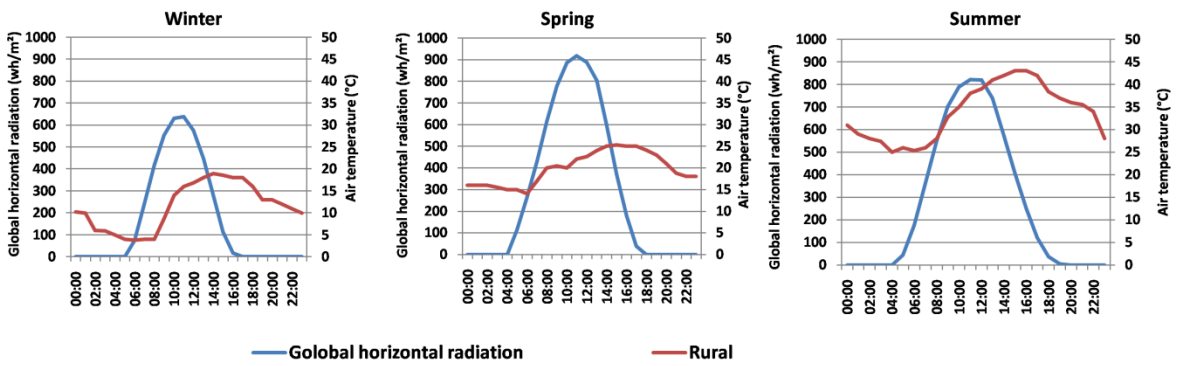

Figure 1: Air temperature and global horizontal radiation for the selected study days.(Source: by authors)

2.2. The Urban Canyon Design Scenarios

The study is conducted for a simplified urban canyon with varying geometrical features. These are as follows:

Buildings height: this is indicated by the number of the buildings' stories (3.2m height for each story). We considered building heights of 3 stories, 6, 15 and 30 stories;

Street aspect ratio (building height-to-street-width): four cases of H/W are considered; 1/3, 1/2, 1, 2 and 4;

Street orientation: Four cases are considered: East-West (EW), Northeast-Southwest (NESW), North-South (NS), and northwest-southeast (NWSE).

The buildings within the urban canyon are assumed to be air-conditioned, with a 30% glazing ratio and a well-insulated envelope. The streets are considered to be asphalt-covered with no vegetation, and traffic heat release is estimated based on urban density. A reference design scenario, shown in Figure 2, is defined with a street aspect ratio of 1, three-story buildings, and an East-West street orientation.

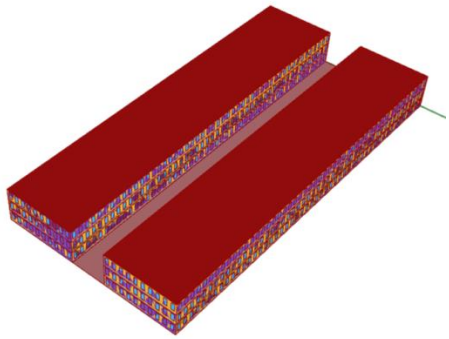

Figure 2: Reference Scenario 3D model.(Source: by authors)

2.3. Simulation Tools

In this study, the outdoor thermal comfort is evaluated using the UTCI. This indicator is developed to fully reflect the real heat exchange processes within the human body when it is in contact with ambient conditions (Blazejczyk et al., 2013). It is based on an advanced multi-node model of human thermoregulation (Fiala et al., 2012) coupled with a model of adaptive clothing choice in urban populations (Havenith et al., 2012). The UTCI index has the advantage of universal applicability and is validated for different climatic conditions (Bröde et al., 2013; Quadros & Mizgier, 2023).

The UTCI provides an equivalent temperature for a given combination of wind, radiation, humidity and air temperature (Table 1). This is defined as the air temperature that would result in the same comfort sensation as the actual conditions, assuming a reference scenario where the air velocity (Va) is 0.5 m/s, relative humidity (Rh) is 50%, and the mean radiant temperature (MRT) is equal to the air temperature (Ta) (Bröde et al., 2011).

The UTCI is calculated under two assumptions. The first uses climate data from a weather station that is free from urban heat island effects. The second uses a morphed weather file where air temperature and relative humidity are modified to include the urban heat island effect for each urban design scenario. These synthetic weather files are produced for different urban settings using the Urban Weather Generator (UWG)(Bueno et al., 2013). This model uses a neighborhood-scale surface energy balance to estimate hourly urban canopy air temperature and humidity, based on weather data from a rural weather station and the characteristics of the urban canyon. The model has been evaluated against field measurements from various urban sites and has shown high accuracy in predicting urban temperatures (Salvati et al., 2016).

Table 1: The Universal Thermal Climate Index (UTCI) assessment scale

UTCI (°C) range	Stress Category	UTCI (°C) range	Stress Category
above +46	extreme heat stress	+9 to 0	slight cold stress
+38 to +46	very strong heat stress	0 to -13	moderate cold stress
+32 to +38	strong heat stress	-13 to -27	strong cold stress
+26 to +32	moderate heat stress	-27 to -40	very strong cold stress
+9 to +26	no thermal stress	below -40	extreme cold stress

The simulations are conducted using Ladybug Tools (Ladybug Tools, L.L.C., 2021), a suite of applications integrated into the Grasshopper plug-in for Rhinoceros, a computer-aided design (CAD) software. These tools enable the generation of 3D urban models, the definition of input parameters, and the execution of simulations to estimate the urban heat island effect and thermal comfort for each design scenario.

2.4. The simulation experiments

The UTCI is simulated assuming a walking human subject at street level within the urban canyon under study. Calculations are performed on a 2m x 2m grid at an hourly time step for selected days, capturing spatial, temporal, and seasonal variations in thermal comfort. Five simulation experiments were conducted as follows:

- Experiment 1: UTCI is simulated for the reference urban canyon design scenario using a weather file with meteorological data from a rural station, excluding the UHI effects.
- Experiment 2: The UHI is simulated for the reference design scenario using the Urban Weather Generator (UWG). This UHI-inclusive weather file is then used to simulate UTCI for the reference design.
- Experiment 3: The UHI and UTCI are simulated for a set of scenarios where the reference design is altered by varying street aspect ratios.
- Experiment 4: The UHI and UTCI are simulated for a set of scenarios with modifications to building heights in the reference design.
- Experiment 5: The UHI and UTCI are simulated for a set of scenarios with different street orientations applied to the reference design.

For experiments 3, 4, and 5, the hourly UHI effect is calculated as the temperature difference between UWG-generated weather data (incorporating the UHI effect) and UHI-free meteorological data from a rural station. Hourly UTCI maps are produced using the UHI-inclusive UWG data, and average UTCI values across the street are computed for each time step. Additionally, statistics on the minimum, maximum, and average hourly UHI and UTCI are calculated for the various canyon design scenarios.

3. Results

3.1. Impact of Urban Heat Island Consideration on Outdoor Thermal Comfort Calculation

Figure 3 presents examples of simulation results from Experiment 1, highlighting significant spatial variation in UTCI across the urban canyon open space, particularly during the daytime. Spatial differences in UTCI can reach up to approximately 10°C at 8 a.m. and 11 a.m. during spring, and at 8 a.m. in summer, with slightly smaller differences observed later in the day. These substantial variations are primarily due to solar exposure, with sun-exposed areas exhibiting the highest UTCI values. This underscores the strong influence of solar exposure on UTCI during daytime hours. During summer and spring, shading has a positive impact, enhancing thermal comfort. In spring, even though the air temperature does not exceed 25°C, the UTCI calculation indicates that pedestrians will experience moderate heat stress in most of the studied areas throughout the day. At 11:00, the simulated UTCI can reach up to 34°C, indicating strong heat stress, while the air temperature is 22°C. During summer, results indicate moderate heat stress in shaded areas early in the morning, while very strong to extreme heat stress is observed otherwise. During winter, Results indicate a slight to moderate cold stress. The low solar altitude increases the shaded area, significantly decreasing thermal comfort (up to 15°C at 11:00). At night, UTCI calculations show minimal spatial variation with differences below 2°C. The lowest values are simulated at the extremes of the urban canyon.

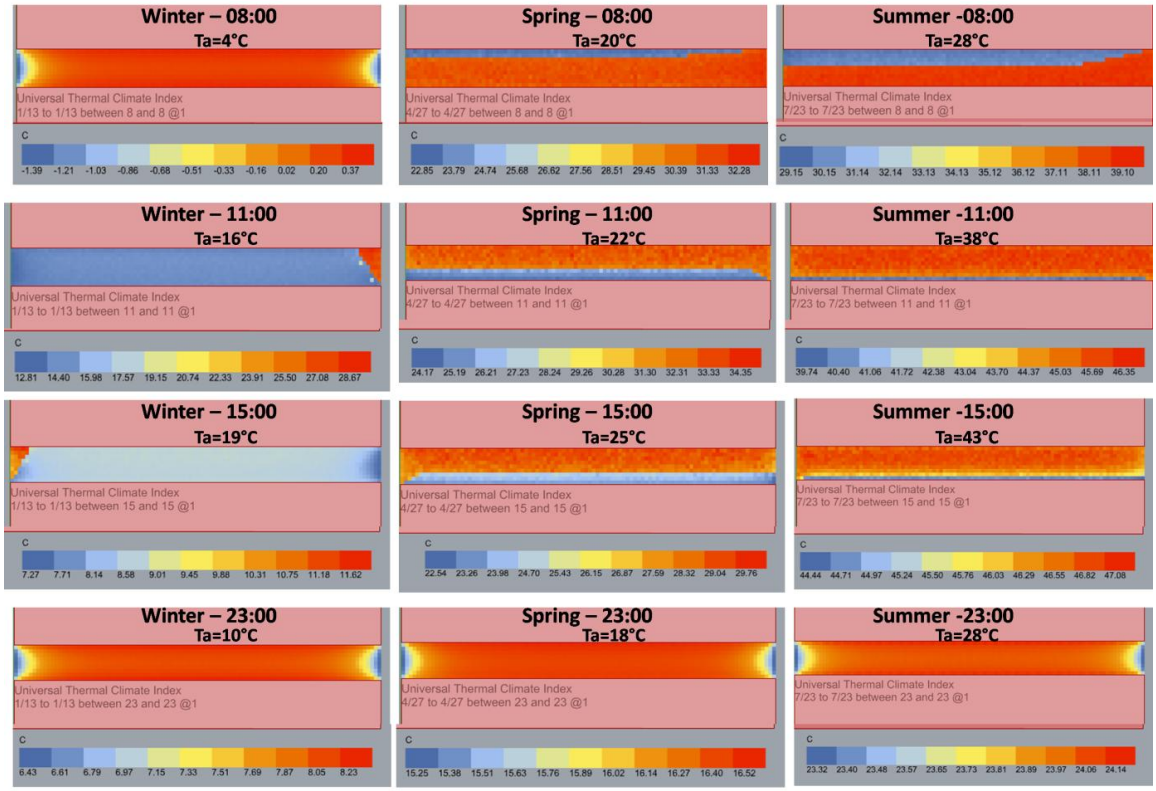

Figure 3: Examples of Universal Thermal Climate Index (UTCI) maps for the reference design scenario on the three selected days in winter, spring, and summer, with corresponding air temperature (Ta) provided for each time step.(Source: by authors)

Figure 4 presents the results of Experiment 2, illustrating the impact of the UHI on air temperature and UTCI. These indicate that the built-up can increase air temperature by up to 6°C, 1.6°C, and 5°C during the selected winter, spring, and summer days, respectively. The increase in air temperature is simulated during nighttime, with maximum values occurring before sunrise. During the daytime, a slight decrease in air temperature is observed. By incorporating weather data that accounts for the UHI resulting from the urban environment, the UTCI calculations offer a more realistic assessment of thermal comfort compared to those based on rural weather data. When accounting for the UHI effect, UTCI values increase by up to 5.5°C, 1.5°C, and 4.5°C during the selected winter, spring, and summer days, respectively.

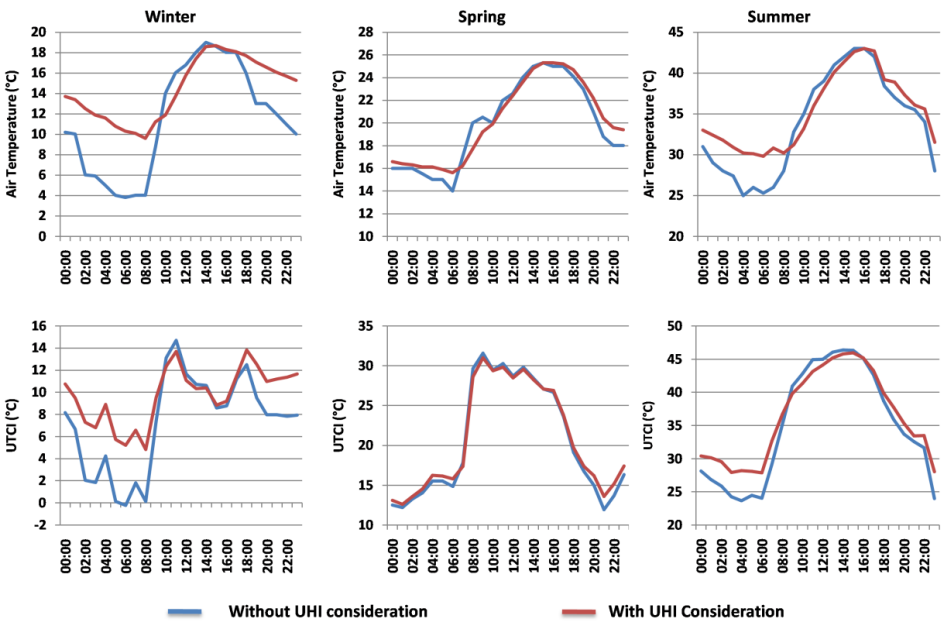

Figure 4: Hourly air temperature and the Universal Thermal Climate Index (UTCI) for the reference urban canyon design scenario, calculated with and without the urban heat island effect, during the selected days.(Source: by authors)

3.2. Impact of urban canyon geometry on UHI and outdoor thermal comfort

The results of experiment 3, presented in Figure 5, show that the street aspect ratio (H/W) significantly impacts the UHI effect across all seasons, particularly affecting the maximum UHI intensity at night. Specifically, the UHI intensity increases by 1.4°C in winter, 0.6°C in spring, and 1.3°C in summer when the street aspect ratio changes from 0.33 to 4. The cooling effect during the day is less sensitive to variations in street aspect ratio, with a maximum difference of 0.4°C.

The UTCI analysis shows that increasing the street aspect ratio enhances thermal comfort during the day in spring and summer. The maximum UTCI values decrease by 6°C and 1.7°C, respectively, when the H/W ratio increases from 0.33 to 4. At night, the minimal UTCI values increase by 2.5°C and 3°C, making cool spring nights more comfortable. In winter, compact urban canyons positively impact night-time UTCI, with an increase of 5°C in the minimum UTCI values. However, during the day, a decrease of 4.8°C in UTCI is observed.

The results of experiment 4, presented in Figure 6, indicate that building height has a minimal impact on UHI and thermal comfort, with the exception of winter. In this season, the maximum UTCI increases by 10°C when the building height increases from 3 to 30 stories. This can be attributed to the greater solar access provided by wide streets and tall buildings (with a street aspect ratio of 1) compared to shorter buildings and narrower streets, particularly given the low solar altitude during winter. In contrast, during summer, the higher solar position reduces the shading effect of buildings, diminishing the impact of building height.

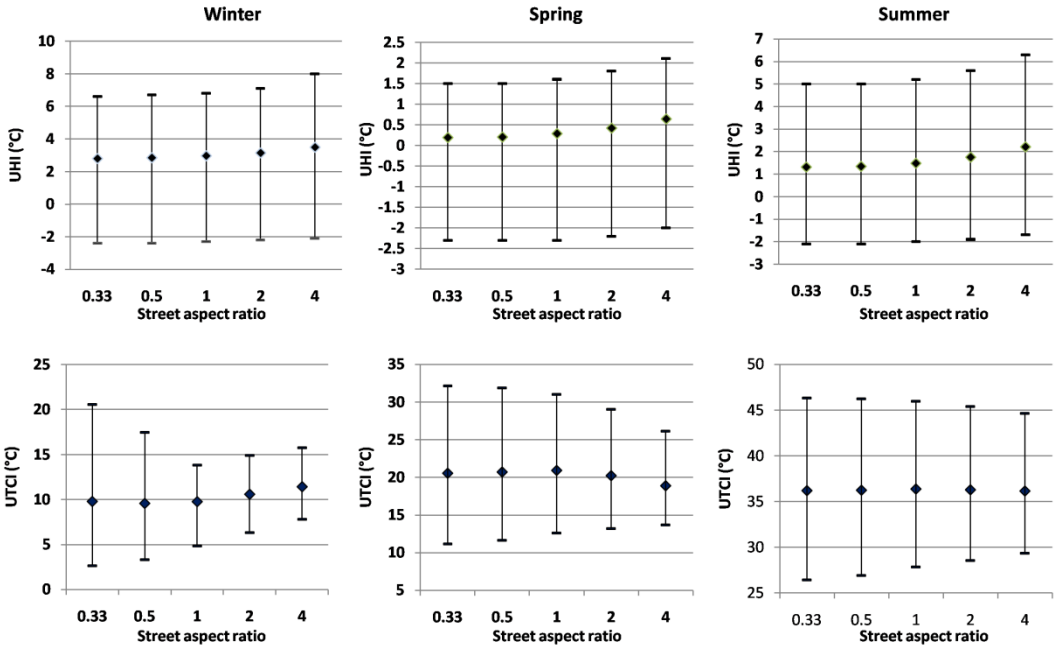

Figure 5: Impact of street aspect Ratio (H/W) on urban heat island (UHI) and the Universal Thermal Climate Index (UTCI) during the three selected days in winter, spring, and summer. .(Source: by authors)

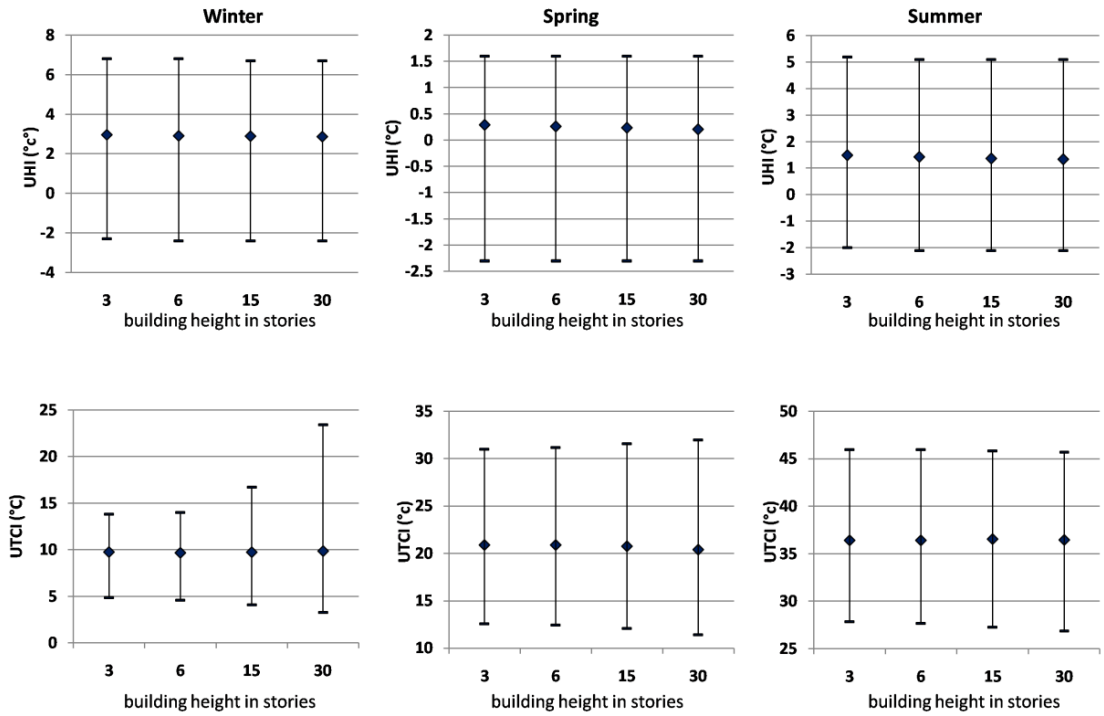

Figure 6: Impact of building height on urban heat island (UHI) and the Universal Thermal Climate Index (UTCI) during the three selected days in winter, spring, and summer. .(Source: by authors)

The results of experiment 5, as shown in Figure 7, suggest that street orientation has a minor effect on UHI intensity, but a significant impact on outdoor thermal comfort. The most favorable street orientation across all seasons is the northeast-southwest (NE-SW). Compared to the less favorable east-west (E-W) orientation, the daily average UTCI increases by 3.5°C in winter and decreases by 2.5°C in summer, thereby enhancing thermal comfort in both seasons. During winter, the NE-SW orientation provides better solar access than the E-W orientation, leading to a 15°C increase in maximum UTCI. However, in summer, solar access is reduced, resulting in a 4.5°C decrease in maximum UTCI. Additionally, the NE-SW orientation improves outdoor thermal comfort at night, with a rise in minimum UTCI of up to 5°C during winter and a decrease of 2°C in summer compared to the E-W orientation.

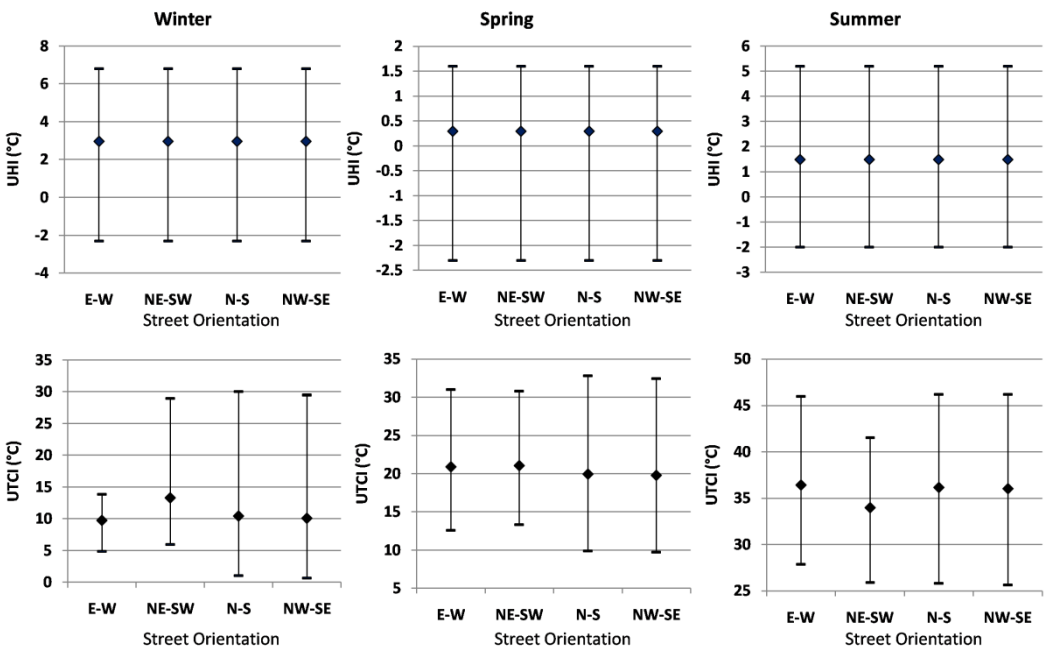

Figure 7: Impact of street orientation on urban heat island (UHI) and the Universal Thermal Climate Index (UTCI) during the three selected days in winter, spring, and summer. .(Source: by authors)

4. Discussion

The urban environment is widely recognized for its substantial impact on microclimatic conditions, particularly air temperature (Lachir, 2022; Lachir & Nia, 2023). The results of this study reinforce this understanding, showing that the UHI effect significantly increases nighttime air temperatures while having a comparatively smaller, slightly cooling, effect during the daytime. This diurnal temperature pattern is attributed to the heat storage capacity of buildings and the shadowing effect from surrounding buildings, which reduces daytime solar gains. Conversely, the intensified nighttime UHI effect is primarily explained by the release of stored heat from buildings, along with the reduced sky view factor and lower wind speeds in urban canyons, which limit the radiative and convective cooling of the area (Svensson, 2004; Yang et al., 2017).

Incorporating UHI effects into the estimation of the UTCI offers a more accurate and context-specific evaluation of outdoor thermal comfort. This study reveals that UHI exacerbates thermal discomfort for outdoor occupants, a finding consistent with other studies conducted in Rome (Battista et al., 2016) and Kuala Lumpur (Fong et al., 2023). Multiple studies suggest that effective mitigation strategies, such as increasing urban greenery, applying cool materials, and promoting urban designs that improve ventilation and shading, can reduce UHI intensity and enhance outdoor thermal comfort (Evola et al., 2017; Jia & Wang, 2022; Morini et al., 2016; Wang et al., 2016).

In this study, we focused on three key geometrical features of urban form to assess their impact on both UHI intensity and outdoor thermal comfort. The analysis of urban canyon geometry reveals that wider canyons, with a higher sky view factor, can mitigate UHI intensity by facilitating more efficient radiative cooling at night. In contrast, deep urban canyons trap heat within the canopy, reducing convective cooling due to lower wind speeds in more compact areas (Kolokotsa et al., 2022; Theeuwes et al., 2014). However, the impact of the street aspect ratio on UTCI indicates that compact urban canyons contribute to improved thermal comfort during the day, particularly in spring and summer, by reducing solar exposure and increasing shading (Salleh, 2007). Thermal comfort is also enhanced during colder nights in winter and spring, as the reduced sky view factor in deep canyons limits heat loss from the human body to the sky. Overall, in the context of Marrakech, a compact urban canyon design proves to be more advantageous for thermal comfort. The average UTCI throughout the day suggests enhanced comfort in winter and spring, with minimal impact during summer. A similar case study in Fez, Morocco, revealed that while deep canyons provide thermal comfort during the summer, shallow canyons are more comfortable during winter (Johansson, 2006).

Street orientation emerges as a significant factor influencing thermal comfort, primarily due to its effect on solar access, which is a critical determinant of outdoor thermal comfort. For instance, a study in Liverpool, Australia, highlighted street orientation as the most influential factor affecting outdoor thermal comfort (Abdollahzadeh & Biloria, 2021). In the current study, we found that northeast-southwest (NE-SW) orientations are particularly favorable for enhancing outdoor thermal comfort. However, optimal orientations are likely to vary depending on the climate context and their combination with the street aspect ratio (Abdelhafez et al., 2022; Elkhayat et al., 2024).

5. Conclusion

Urbanization and climate change have amplified the Urban Heat Island effect, making outdoor thermal comfort a critical aspect of urban design. In Marrakech, Morocco, our study shows that pedestrians may experience slight to moderate cold stress during winter nights, while heat stress is prevalent at most other times, especially during summer and spring, where strong to extreme heat stress can occur even at air temperatures around 22°C due to significant solar exposure. Among the tested urban design features, street aspect ratios (H/W) have a greater impact on UHI compared to building heights and orientation, but strategies to reduce UHI don't always align with those that enhance thermal comfort. While compact urban canyons tend to increase UHI, they are effective in improving outdoor thermal comfort, particularly during winter cold nights and hot days. Conversely, open urban canyons offer better comfort during summer nights and cold winter days. Street orientation, particularly a northeast-southwest (NE-SW) alignment, proves most favorable for outdoor thermal comfort across all seasons, providing optimal solar exposure in winter and reduced exposure in summer. Ultimately, the best urban design strategies should be adapted

to the intended use of outdoor spaces, while also considering other factors like the impact of building energy efficiency for a more sustainable urban environment.

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Ethics approval

Not applicable.

Conflict of interest:

The author(s) declare that there is no competing interest.

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