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Article

Effect of Sustainable Cities on the Urban Heat Island and Human Thermal Comfort-Dubai Sustainable City as A Case Study

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Abstract: Due to the adverse effects that rising air temperatures have on urban dwellers' health and thermal comfort, the urban heat island phenomenon (UHI) is a global problem that worries architects. The high energy consumption of buildings, particularly in hot, arid areas, to maintain comfortable indoor temperature conditions for users, is one of the primary causes of UHI. Because of the rise in carbon dioxide levels, urban heat islands are becoming more common, especially in urban areas. Urban geometry is a key factor affecting the intensity of the UHI phenomena. As a result, the aim of this study is to evaluate and contrast the impact of sustainable cities and conventional urban forms on lowering outdoor air temperatures, reducing UHI effects, and improving human thermal comfort in the United Arab Emirates (UAE). Specifically, this research aims to assess how the urban form and layout of Dubai's Sustainable City compare with a conventional residential district in Ajman, focusing on their influence on microclimate and thermal comfort. The study uses a qualitative approach, employing ENVI-met urban microclimate simulation software to assess the UHI effects in both districts. The findings revealed that lower air temperatures were observed in the sustainable district, particularly between the hours of 10 a.m. and 6 p.m. On August 21, at 1 p.m., the sustainable district exhibited air temperatures 1.11 °C to 2.90 °C lower than those in the conventional district. The average air temperature at 1 p.m. was 40.52 °C, which was 2.02 °C cooler than in the conventional district. Additionally, the sustainable district showed lower levels of Predicted Mean Vote (PMV), indicating improved human thermal comfort. This discrepancy was attributed to the courtyards and semi-attached buildings in the sustainable district, which enhanced shading and reduced variables affecting sky views. This study aims to demonstrate the beneficial effects of passive design strategies associated with sustainable urban forms, such as compact layouts and courtyards, in lowering outdoor air temperatures and improving thermal comfort in hot, arid climates.

Keywords: urban heat island; human thermal comfort; sustainable cities; sustainability; urban configuration; hot-arid climate; UAE

1. Introduction and Literature Review

As global populations grow and cities expand, the necessity for towering large cities and urbanization becomes evident. While urbanization generally offers advantages, such as improved living standards and contributing to over 90% of global gross value added (Anderson et al., 2013), it also introduces adverse environmental, social, and economic impacts. One of the significant environmental aspects is the formation of urban heat islands (UHI). The UHI phenomenon occurs when built-up urban areas experience higher temperatures compared to the surrounding rural countryside. This is mainly attributed to man-made materials absorbing and storing a larger proportion of incident solar energy (Phelan et al., 2015; Kolokotroni, Giannitsaris, and Watkins, 2006). According to Wanphen and Nagano (2009), the temperature difference between rural and urban areas can range from 5 to 15 °C, significantly impacting human thermal comfort. According to the United Nations (UNITED NATIONS, 2018), it is projected that by 2050, 68% of the global population will reside in urban regions, compared to the current 55%. Urbanization is expected to result in an additional 2.5 billion people living in urban areas by 2050. As this process continues, the UHI effect will become more widespread and severe.

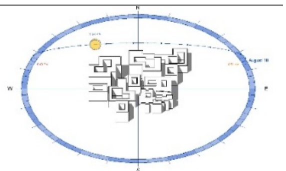
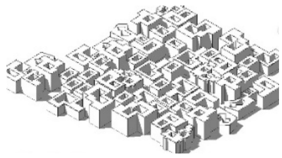
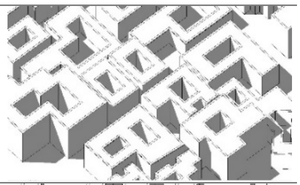
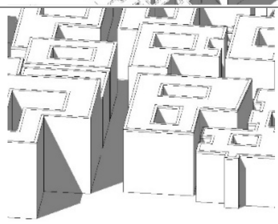
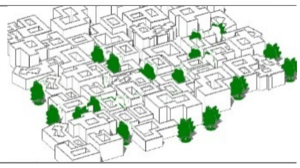
Taslim et al. (2015) stated that in cities characterized by hot and arid climates, UHI effect is expected to lead to a range of challenges, including cold and heat stress, excessive sun exposure, insect infestations, air and water pollution, waste accumulation, noise pollution, and heightened energy use, as well as an increased risk of fires. According to Phelan et al. (2015) the UHI effect directly influences both daytime and night-time temperatures and leads to various indirect impacts, such as heightened air conditioning demands, worsened air and water quality, decreased pavement lifespans, and intensified heat waves. Litardo et al. (2020) found that cooling energy consumption of residential and commercial buildings in the UHI area is 30–70% higher and 10–20% higher than buildings in rural areas. Similar conclusion resulted by Elmarakby (2022) and Nuruzzaman (2015) in Cairo, Qaid et al. (2016), Ameen and Mourshed (2017), and Sodoudi (2014) in Middle Eastern countries. While, Li et al. (2019) reveled that the UHI in warm climate regions can lead to a 19% in cooling energy consumption but it can also reduce heating energy consumption by the same proportion. Kolokotroni et al. (2007) conducted an analysis of the UHI effect in London, revealing that the city's cooling load was 25% higher than in rural environments, while the heating load decreased by 22%. Similar conclusion resulted from Salvati et al. (2017) in Spain. Therefore, researchers in recent years around the world have tried to find effective strategies to mitigate the intensity of UHI. These strategies can be implemented during the project design phase of urban planning, directly influencing city temperatures on a local scale (Gago et al., 2013). Altan et al. (2016), Nenadović and Milošević (2022). Faragallah (2022) stated that creating passive buildings will have a great effect on the local micro-climate and then to UHI by improving the indoor thermal condition without using any mechanical cooling and heating system. The effect of passive buildings will increase significantly if natural-based mitigation measures is used in the buildings, such as green roof and wall, exterior tree, etc. (Golany, 1996). Salameh and Touqan (2022) found that within hot and arid regions, traditional passive design architecture stands out for its capacity to create comfortable indoor spaces and shaded outdoor areas, diverging from the prevalent use of energy-intensive air conditioning systems in contemporary architecture. Some examples include courtyard, vegetation, shading devices, compact urban design, wind catchers, and orientation. Also, the UHI effect significantly by urban form, which includes building shape and orientation, courtyards, and street patterns and width, as shown in Table 1.

The building shape and orientation can influence heat absorption, retention, and airflow within urban areas. Tall buildings with compact arrangements can create "canyon effects," where streets are flanked by high structures. These can limit natural ventilation, trap heat, and intensify the UHI effect due to reduced air circulation. Additionally, building orientations can impact the amount of sunlight absorbed and heat generated. Buildings with large surfaces facing the sun can absorb more heat, contributing to elevated temperatures (Friess and Rakhshan, 2017; Riham Nady Faragallah, 2022). Elkhazindar et al. (2022) investigated the impact of the urban form on the UHI in the hot arid region via using ENVI met software. The researchers highlighted that the Compact traditional urban layouts have the potential to improve thermal conditions and sustainability in hot, arid regions, irrespective of population density. Since it has compacted urban form, high height-to-width (H/W) ratio that provides more shaded areas, low sky view factor (s.v.f), which means less surfaces are exposed to the solar radiation, and narrow streets and alleyways that results in a temperature decrease. Jamei et al. (2020) and Al Tawayha et al. (2016) found that the effectiveness of shading and/or urban ventilation has is higher than the extensive vegetation, water bodies, or albedo modifications for reducing air temperatures. Similar conclusion resulted from Kolokotsa et al. (2022), (Galal, Sailor and Mahmoud, 2020), and Yahia et al. (2018).

The courtyard stands as the foremost technique for utilizing indoor building space, exerting a substantial influence on the local microclimate and contributing to environmental enhancement. (Mushtaha et al., 2021), assessed the hierarchy of UHI factors within an existing courtyard. Proposed scenarios were developed and evaluated using the ENVI-met simulation software to determine the impact of each factor. The results revelad that raising the aspect ratio through an increase in the height of adjacent buildings 15 m and 30 m, in contrast to the base case's 8m, leads to a decrease in air temperature by 0.35 °C and 1.25 °C, respectively. Notably, the aspect ratio emerged as the most influential factor, succeeded by vertical greenery and building materials, a green roof, and finally, the configuration.Hence, the outdoor surface temperature was reduced by 2.45 °C. According to Thapar and Yannas (Thapar and Yannas, 2008), in their study exploring the impact of diverse urban layouts on temperature fluctuations, observed that courtyards exhibited the lowest air temperatures attributed to enhanced shading. Furthermore, their research indicated that pedestrians might find higher air temperatures acceptable when there is substantial wind movement.

Cui (2023) conducted a study to investigate the impact of H/W ratio and vegetation ratio on the UHI phenomena. Field measurements and ENVI met simulations were performed to find the optimum microclimate. The outcomes indicated that the Physiological Equivalent Temperature (PET) achieved its optimum value in streets featuring an aspect ratio of 0.5, where trees covered 50% of the outdoor space along the N–S and S–N directions. In cases with similar vegetation distribution and street orientation, the most energy-efficient streetscape was achieved with aspect ratios of 0.9 and 0.7 in both scenarios. Alobaydi et al. (Alobaydi, Bakarman and Obeidat, 2016) examined the influence of various urban configurations on the urban heat island (UHI) effect within the city center. This investigation encompassed modern detached, modern attached, and traditional compact urban forms. The study revealed that the compact urban form with a high H/W (height-to-width) ratio exhibited the lowest air temperatures, emphasizing the significance of maximizing shaded spaces and minimizing solar radiation exposure. Conversely, the highest air temperatures were recorded in shallow urban canyons associated with both modern attached and detached urban forms. Bakarman and Chang (Bakarman and Chang, 2015) investigated the impact of two urban canyons, shallow modern (H/W = 0.42), and deep traditional (H/W = 2.2) canyons in Saudi Arabia as a hot and arid city. The study's outcome indicated decrease in UHI intensity as the H/W ratios decreased. In contrast to rural surroundings, the air temperature within deep and shallow urban canyons exhibited respective increases of 5% and 15%. This elevation in temperature in the shallow canyon was notable due to its extensive exposure to intense solar radiation.

Table 1. Illustrations of passive design strategies.

Passive Design Strategies	Explanation	Image
Orientation	The orientation of the building and the location of the walls and openings based on the climatic conditions determine the amount of solar gain and the prevailing cool winds enhances cross ventilation. (Friess and Rakhshan, 2017), (Riham Nady Faragallah, 2022)	
Compacted urban form	The compacted urban form increases the outdoor shading areas, and minimizing the number of surfaces exposed to the solar radiation, thus decrease the heat gain, and enhance the human thermal comfort. (Al Tawayha, Bragança and Mateus, 2016), (Elkhazindar, Kharrufa and Arar, 2022),and (Jamei et al., 2020).	
Courtyard	Courtyards hold significance in facilitating ventilation, daylight penetration, ensure comfort by reducing temperatures, they function as climatic moderators, gathering cool air during the night and offering shade throughout the day.(Thapar and Yannas, 2008),(Lu et al., 2016), (Mushtaha et al., 2021)	
Street pattern	Urban canyons that are deep and narrow, featuring a high H/W ratio and a low sky view factor (SVF), exert a more pronounced influence in lowering air temperatures, expanding shaded zones, and improving human thermal comfort and enhance the energy-efficiency. (Bakarman and Chang, 2015), (Cui et al., 2023), (Alobaydi, Bakarman and Obeidat, 2016).	
Vegetation	The implementation of urban greening can effectively alleviate UHI intensity, leading to a notable reduction in global air temperature and mean radiant temperature. It prove\ides more shaded areas and utilize evaporative cooling techniques. (Aflaki et al., 2017),(Spyrou et al., 2023).	

To evaluate the effect of outdoor air temperature on the human comfort, there are may criteria can be uses such Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), the Predicted Mean Vote (PMV) is used to reflect how outdoor microclimate conditions impact human comfort and perception. This, in turn, influences user satisfaction and productivity within outdoor urban spaces (Elshater et al., 2022). PMV is typically associated with outdoor microclimate elements like air temperature, wind speed, mean radiant temperature, and humidity along with human-related factors such as gender, metabolism, and age of the users (ENVI-met, 2023). PMV method is effective in representing human thermal comfort. The PMV method is commonly used to assess how people perceive thermal conditions in indoor or outdoor environments. Abd Elraouf et al. (2022) and Lam et al. (2023) studies support the suitability of the PMV method in evaluating and understanding human comfort in various settings and help guide decisions related to design, urban planning, and environmental management to create more comfortable and livable spaces for individuals.

The originality of this study resides in its specific focus on passive design techniques intended to reduce the UHI effect in hot, dry climates—a setting that is frequently overlooked in the body of current UHI research. This study fills a vital gap by combining traditional architectural components with contemporary urban planning strategies to solve region-specific difficulties, even though urban heat mitigation has been a well-researched topic globally. As an illustration, earlier research has shown how vegetation and compact urban forms affect urban microclimates (Elkhazindar, Kharrufa and Arar, 2022); Cui et al., 2023). In order to improve thermal comfort and lower energy needs in harsh climates, our study methodically assesses how passive features like courtyards, green roofs, and urban canyons might be enhanced.

By leveraging advanced simulation tools such as ENVI-met, this research goes beyond empirical observations to provide a quantitative analysis of how specific design interventions—like increasing the height-to-width ratio or integrating vertical greenery—can significantly lower outdoor surface temperatures and improve microclimate conditions. For instance, (Mushtaha et al., 2021) identified aspect ratios and greenery as key factors, but our study further investigates their combined impacts in diverse urban configurations, offering a more comprehensive framework for sustainable urban design.

Furthermore, although the contribution of traditional architecture to UHI mitigation has been recognized (e.g., Thapar and Yannas, 2008; (Salameh and Touqan, 2022), this study emphasizes how these tactics can be successfully modified and expanded in modern urban design. This study gives priority to solutions that are specifically tailored to the thermal dynamics of dry regions, in contrast to general UHI mitigation efforts that frequently concentrate on temperate or tropical climates. By incorporating novel measures like the Physiological Equivalent Temperature (PET) to assess human thermal comfort holistically, our findings complement and expand upon the work of (Alobaydi et al., 2016), who highlighted the significance of optimizing shaded areas in compact urban structures.

While previous studies have explored strategies to mitigate the UHI effect in hot and arid regions, this study distinguishes itself by adopting a multi-scalar approach that integrates passive design strategies across various urban scales—building, neighborhood, and city levels. Unlike earlier research, which often isolates the effects of individual strategies, such as vegetation, urban canyons, or building orientation, this study systematically examines the compound impact of multiple interventions when applied simultaneously.

Ultimately, this study adds to the body of knowledge by offering urban planners region-specific, practical insights that highlight creative uses of passive design techniques to produce sustainable, energy-efficient urban settings in hot, arid climates. In addition to addressing current urbanization issues, this furthers international efforts to counteract the negative impacts of the UHI phenomena.

Research-Gap

However, despite the extensive exploration of different passive design solutions that could mitigate the UHI phenomena and contribute to the advancement of sustainable contemporary architecture and urban environments. There remains a notable gap in research addressing the specific challenges posed by the hot, arid climate of the UAE and the impact of the various passive design solution in mitigating the UHI, and establishing a robust groundwork in this realm. Thus, this study seeks to narrow this gap by comparing sustainable and regular districts in Dubai as an example of urban forms in hot arid climate to evaluate the viability of passive and sustainable solutions in enhancing UHI impact and thermal conditions within hot regions. The study also aims to extract valuable urban design concepts from the sustainable city to be implemented in forthcoming urban designs. Utilizing the ENVI-met software, the research adopts a qualitative methodology. In order to address climate change and mitigate the effects of UHI, it is imperative to grasp insights from passive and sustainable design solutions that have been implemented in Dubai sustainable city and integrate effective, climate-responsive strategies into contemporary architecture and urban planning.

2. Methodology

The research adopted a qualitative methodology to compare microclimates and thermal comfort levels in hot arid regions of the UAE, evaluating regular rsidential district and sustainable city configurations in Dubai via the ENVI-met software. The purpose of this comparison is to identify the impact of utilizing the passive design solutions and climate responsive strategies in the sustainable cities on the UHI phenomena and the human thermal comfort that could be integrated into forthcoming modern urban developments. Figure 1 illustrates the research methodology and tools utilized to analyze the impact of different uran forms and design strategies on UHI intensity at the local scale of chosen locations.

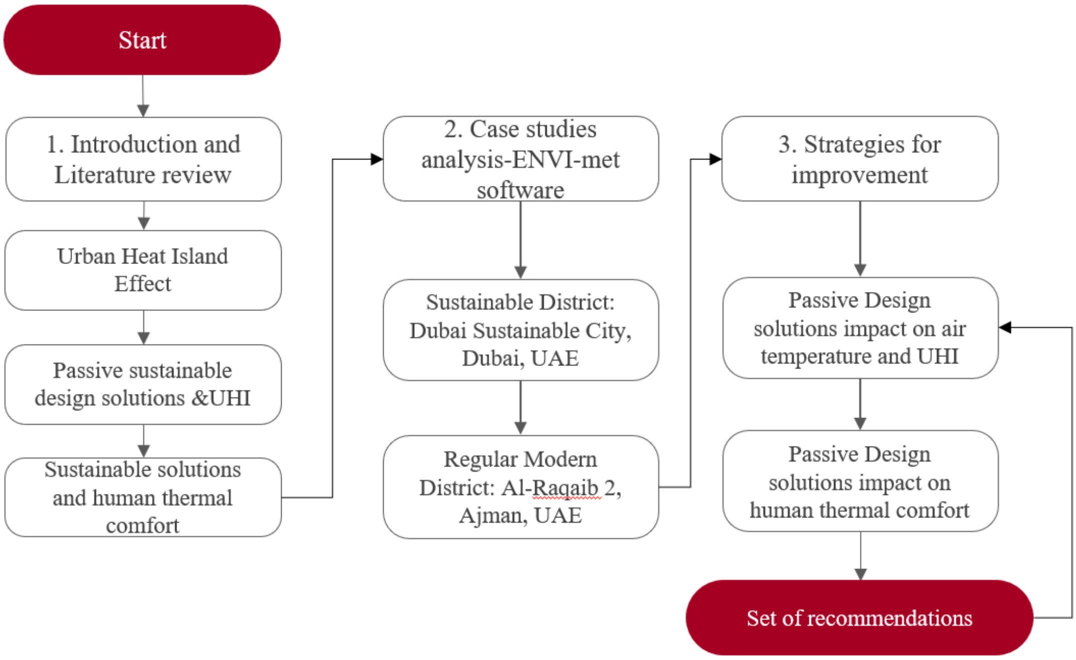


Figure 1. Research methodology framework.

2.1. Case Studies

This study examines the impact of two distinct residential urban forms on microclimate, UHI, and human thermal comfort in the UAE, focusing on Dubai and Ajman. The two sites were selected to compare contrasting urban designs, offering valuable insights into how different urban forms affect UHI intensity and thermal comfort in arid, rapidly urbanizing regions. Key factors considered in the selection included urban density, building form, green infrastructure, and climate responsiveness, all of which are crucial for understanding their influence on both environmental and human comfort. The two case study sites were carefully selected to provide a comparative analysis:

1. **Dubai Sustainable City (DSC):** A sustainable and climate-responsive urban district in Dubai, known for its energy-efficient design, green building technologies, and passive cooling strategies. It represents an environmentally-conscious approach to urban planning, chosen to assess how sustainable design mitigates UHI effects and enhances thermal comfort.
2. **Al Raqaib 2 (AR2):** A modern, conventional residential development in Ajman, affiliated with the Sheikh Zayed Housing Project. It features standard building forms and limited green infrastructure, providing a contrast to DSC and highlighting the impacts of traditional urban design on UHI and human comfort.

The selection of these sites (Figure 2) was justified by their contrasting urban forms, which enable an in-depth evaluation of how sustainable and traditional urban designs affect UHI intensity and human comfort in hot, arid climates. Data was collected using microclimatic measurements (temperature, humidity, wind speed) and human comfort indices (PMV, PET). Simulations using ENVI-met software helped analyze the impact of urban form and green infrastructure on microclimate and thermal comfort. This comparative approach provides new insights into the role of urban design in mitigating UHI effects.

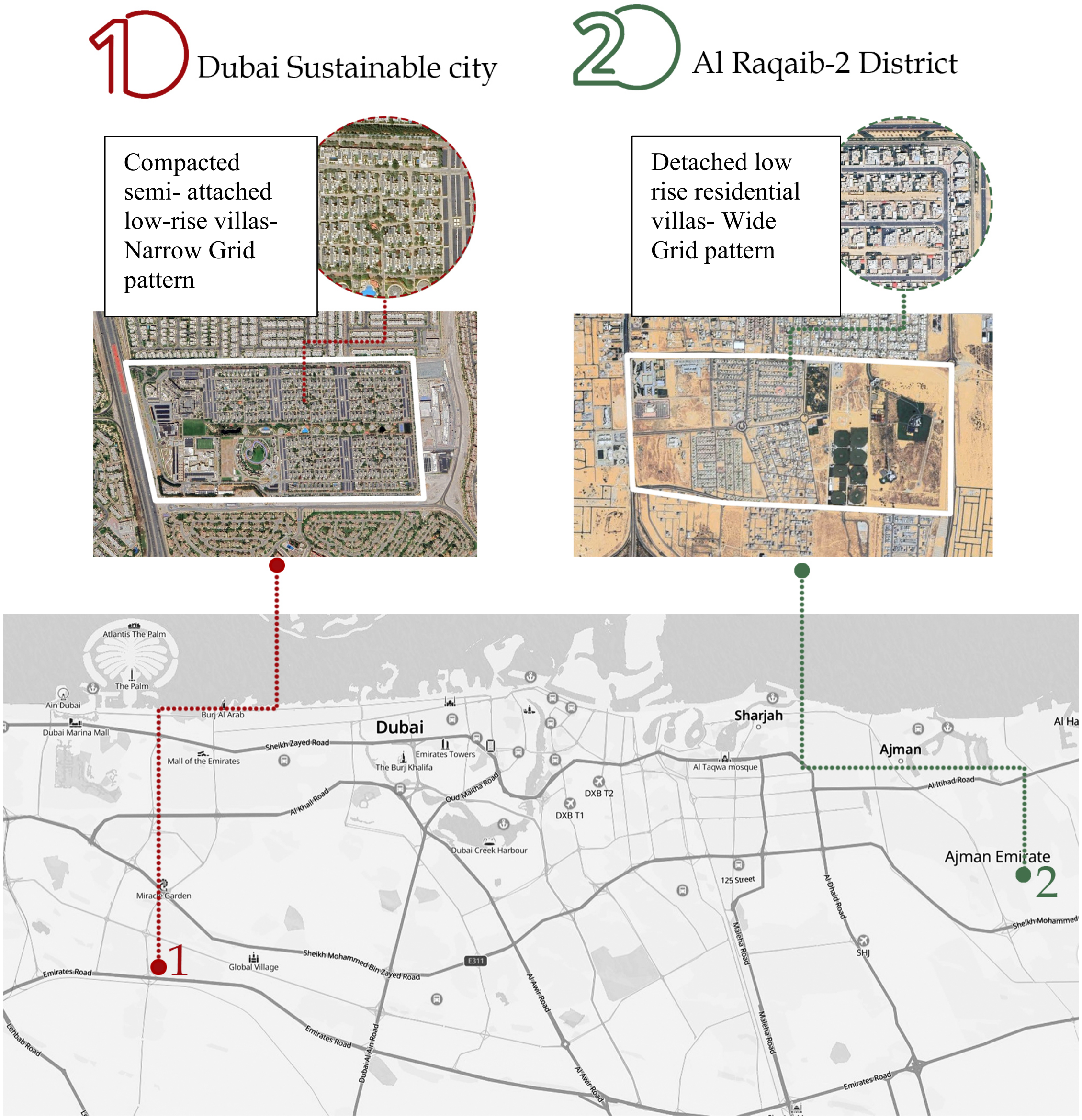


Figure 2. Geographical locations and urban configurations for selected sites.

2.1.1. First Case Study: Dubai Sustainable City-DSC

The sustainable city in Dubai (TSC) was launched in 2016 and considered to be the first sustainable city designed to achieve the net-zero energy in the middle east. TSC Dubai accommodates around 2700 residents, offering them a comprehensive array of services and amenities that facilitate a seamless integration of living and work experiences (Figure 3). The design of this city focuses on minimizing the need for residents to travel outside its boundaries, thereby reducing carbon footprints (Davidson-huxley, 2021). Located in Dubai Land and covering an area of more than 460 hectares (El-jisr, 2016). The TSC has various land uses as residential zones, diamond innovation centre, educational establishments, vibrant urban green spaces, commercial hubs, essential healthcare facilities, leisure, urban farming zones, and other important services. Within TSC, the residential area is organized into five distinct clusters, each comprising 100 villas or townhouses. Additionally, within the mixed-use precinct, a limited number of rental flats (91 units) are available, varying in built-up area from 40 m² to 170 m² (Juaidi et al., 2019). The urban setting is meticulously planned to house a community of 2,700 residents, complemented by a daily influx of 6,000 individuals. The city boasts a remarkable 10 MW peak solar energy generation capacity while ensuring a sustainable supply of organic produce from its farms and biodomes to all its residents. Mobility within the city revolves around a central ring road that accommodates private vehicles, leading to photovoltaic-covered parking facilities strategically positioned within a 90-meter walking radius from the farthest villa. From these parking zones, individuals have the choice to traverse by foot or opt for the electric carts thoughtfully provided by the city (El-Bana, 2015).

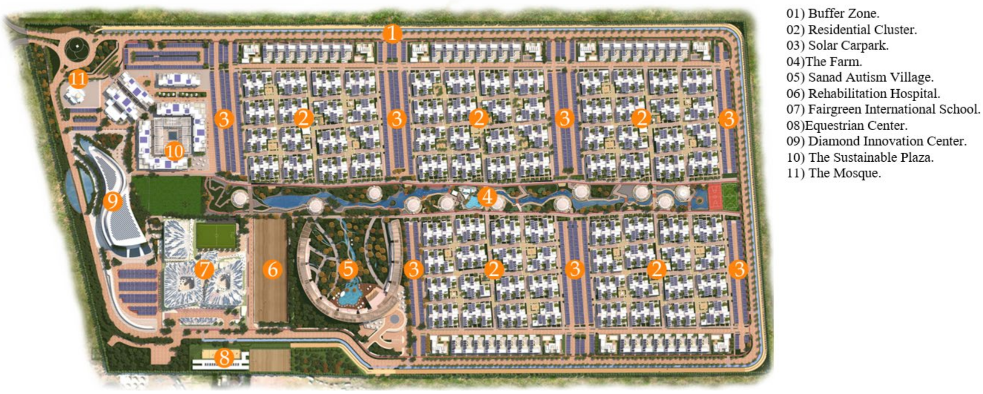


Figure 3. Master plan of the sustainable city in Dubai (Diamond Developers, 2023).

The Sustainable City in Dubai is dedicated to embracing the principles of the Triple Bottom Line (TBL) sustainability framework which are environmentally, socially, and economically. In terms of environmental considerations which is the focal point of this study.

Environmental sustainability:

A fundamental pillar of sustainability evident in TSC is its strong emphasis on the environment. The city's design is dedicated to minimizing its impact on the natural world, achieved through the incorporation of eco-friendly materials in residential construction, the integration of renewable energy sources, and the promotion of resident-led waste recycling initiatives. The development underscores its commitment to environmental sustainability through a combination of passive and active design strategies, coupled with strategic collaborations (Table 2). Considering its Middle Eastern location with its arid and hot climate, a key priority was the implementation of design elements to mitigate heat accumulation in living, commercial, and outdoor spaces. Various innovative design strategies were employed to accomplish this, ensuring both environmental friendliness and affordability for residents (Diamond Developers, 2023).

Table 2. Dubai Sustainable city Environmental sustainability solutions. Images from (Google, 2023).

	Design Solutions	**Explanation**	**Image**
Residential Clusters	Residential units		
	Orientation		
	Building form	L-Shaped, Semi-attached forms with semi closed courtyard.	
	Materials	-Highly insulated UV of reflective windows, walls, and roofs. -External walls: anti-reflective light-colored paint.	
	Solar Panels	Transform the heat of the day into solar energy to power the grid. Thus, significantly reduce energy costs by producing off-grid power for consumption.	
	Wind tower (Barjeel)	5 wind towers, one in each cluster, fostering a cooler micro-climate, serving as a natural ventilation system, guide higher altitude air into the residential cluster, boosting wind speed and enhancing comfort within each area. It aims to provide a cooling effect within approximately 7 to 8 meters in radius.	
	Street network		

	Pattern	The clusters are car-free zones, and have narrow shaded sikkas (streets) designed to provide shade, coolness, and reduce physical exposure from their narrow paths and the presense of the villas on both sides.	 
	Materials	Light-coloured paving materials create a cooler micro-climate rather than the asphalt.	
Other TSC strategies			
	Landscape and greenery	TSC has buffer zone comprising five layers of trees, functioning as a protective barrier that prevents dust penetration, reduces air and noise pollution, and enhances air quality standards within the city. Moreover, TSC's 'Central Green Spine' or 'The Farm' spans the community, offering green spaces, water features, gardens, paths, animal sanctuaries, and ten biodomes. These controlled ecosystems enable urban farming of plants in the UAE's challenging climate. Each cluster provides shaded communal garden with children playground and seating areas.	  
	Energy efficiency	Energy efficient air conditioning, LED lighting, solar water heaters, and energy-rated appliances.	
	Waster and solid Waste	Every household reduces potable water usage by 40% compared to other communities. Water consumption is divided into two networks: grey water and black water. Grey water recycled and reused for irrigation. Each unit is equipped with its own set of recycling bins, complementing the communal waste bins situated along each street, which are sorted into various categories such as glass, plastics, biomass, paper, metal, cardboard, and organic compounds at the source to minimize their environmental impact.	
	Solar Car parking	Solar shaded parking bays produce additional electricity which supply common areas including street lights, bio domes, water features, wind towers, and public amenities.	

2.1.2. Second Case Study: Regular Modern Urban Neighborhood

The Al-Raqaib neighbourhood in Ajman, UAE, represents a contemporary residential urban layout which is part of the Sheikh Zayed Housing Programme (SZHP). This neighborhood contains 306 two-story detached villas and follows grid pattern structure which is characterized by organized rows of residential units aligned along straight horizontal and vertical streets (Figure 4). The development comprises 11 open streets and various outdoor spaces of different sizes and shapes, designed to encourage neighbourhood gatherings and safe social interaction away from busy traffic routes, especially for children and young adults. Surrounding the housing units are 11 communal outdoor areas, some as wide as 15 meters. However, the existing design with broad roads and low-rise buildings has led to insufficient shade, causing higher outdoor temperatures and discomfort for residents.

(**a**) Proposed 3D master plan and urban fabric for Al-Raqaib 2 in Ajman, UAE (SZHP) (iskanZayed, 2015).

(**b**) Existing master plan and layout for the modern reguler urban fabric, Al-Raqaib 2,Ajman Google, 2023).

(**c**) Shared open areas and playgrounds within the residential units (Google, 2023).

(**d**) Existing detached residential villas (Google, 2023).

Figure 4. Al-Raqaib 2 residential district in Ajman, formed by (SZHP).

2.2. Software for the Research Simulation Model

The analysis of urban areas was conducted using ENVI-met software. This software has demonstrated its reliability in previous research focused on urban microclimates and human thermal comfort (Salata et al., 2016). ENVI-met excels at assessing extensive urban micro-climates and contrasting various urban layouts. It computes factors such as humidity, temperature fluctuations, radiation influx, wind patterns, and physiologically equivalent temperature (PET) values. This tool enables users to model complex building and vegetation geometries, incorporating detailed material properties and calculating energy fluxes between soil, vegetation, the atmosphere, and buildings (Crank et al., 2018).

While ENVImet has shown strong performance in predicting air temperature (Ta), especially during day and night in summer, with R^2 values ranging from 0.62 to 0.99 and RMSE between 0.44 and 3.05 °C, there are still gaps in its validation for other climate variables. Studies on Mean Radiant Temperature (Tmrt), relative humidity (RH), and wind velocity (Va) remain limited (Crank et al., 2020; Salata et al., 2017; Sinsel et al., 2022; Aleksandrowicz, Saroglou and Pearlmutter, 2023). In particular, the model's ability to simulate the effects of solar radiation on heat stress, especially under high-temperature conditions, has raised concerns.

Some of the potential sources of simulation bias identified include misalignments in radiation flux calculations (Acero and Arrizabalaga, 2018), turbulence overestimation (Toparlar et al., 2017), and air temperature underestimation (Heris, Middel and Muller, 2020).

(Krayenhoff et al., 2021) emphasize the importance of validating models through in-situ measurements of atmospheric variables to improve confidence in predictions and provide more reliable insights.

Essential input parameters include wind speed and direction, average air temperature, and relative humidity (RH) for the specific location were provided. The input data used in the ENVI-MET software were sourced from Dubai Airport, which provided a consistent and unified dataset. Notably, there were no differences in the input data applied for both the Dubai and Ajman sites. This uniformity in data ensures that the environmental conditions modeled for both sites are based on the same set of meteorological variables, allowing for a fair and consistent comparison between the two areas. Additionally, ENVI-met is proficient in simulating urban thermal conditions in both two-dimensional (2D) and three-dimensional (3D) formats (Miao, Chen and Yu, 2022; Alyakoob et al., 2023; Thomas et al., 2023; Sinsel et al., 2022; Simon, 2016). ENVI-met will primarily focus on examining the following key parameters:

- The outdoor potential air temperature, wind speed, mean radiant temperature, and the humidity for both urban layouts.
- Thermal comfort assessment using the predicted mean vote (PMV). ENVI-met will analyze various factors that influence thermal comfort.

ENVI-met's PMV computation will encompass a scale from -4 to +4, as illustrated in Figure 5. Values approaching zero indicate enhanced human thermal comfort conditions. As per ASHRAE Standard 55 (2022), the PMV scale suggests an ideal thermal range between -0.5 and 0.5 (Taleghani et al., 2013).

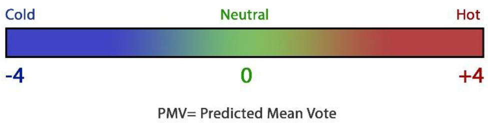
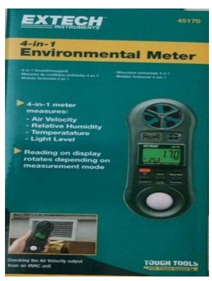
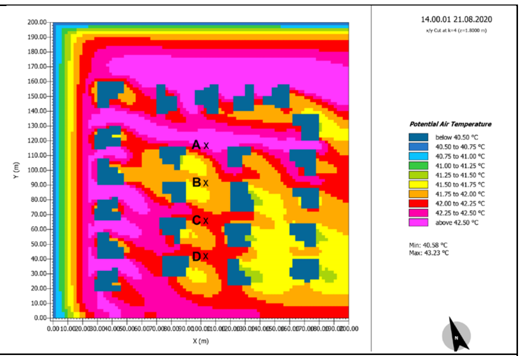


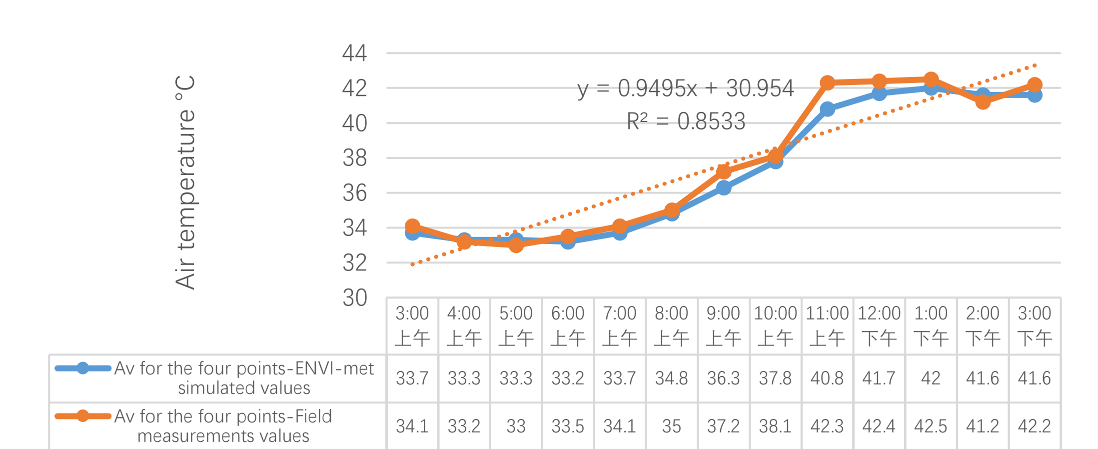
Figure 5. Classification of PMV levels based on nine comfort scales. Image generated by the author from reference (Ahmed, 2003).

Salameh et al. (Salameh, Mushtaha and El Khazindar, 2023) validated the ENVI-met simulation model for Al-Raqaib city (second case study) by comparing the average air temperature data (Figure 6A) obtained from measurements using an Extech meter (Figure 6b) at four points (A, B, C, and D) with the corresponding average air temperature data generated by the ENVI-met simulation on August 21, 2020 (Figure 6c). Despite minor variations between the datasets due to the precision of the field measurement meter, the correlation between the measured and simulated air temperature data was strong, with an R^2 score of 0.85 as shown in (Figure 6d) (Salameh, Mushtaha and El Khazindar, 2023). This model is used in this study.





(**a**) Four points field measurements in Al Raqaib housing district 2021 (Google, 2023).	(**b**) Extech 45170 meter (Extech, 2021).	(**c**) Four points ENVI-met simulation at 2 pm on August 21.



(**d**) Correlation between measured and simulated temperature data

Figure 6 Validation information from (Salameh, Mushtaha and El Khazindar, 2023).

2.3. Simulation Sittings

UAE is situated along the shores of the Arabian Gulf, experiencing a hot, moderately humid, and sunlit climate. The data depicted in Table 3 illustrates the maximum and minimum monthly average air temperatures based on (Energy, NASA Prediction Of Worldwide, 2023). The peak temperatures are typically observed in June, July, and August, ranging from 42–44 °C. Conversely, the coolest temperatures tend to occur in December and January, averaging around 15–20 °C. The selected residential urban forms are investigated with ENVI-met simulations on August 21st by examining periods of 24 h. This specific date was selected because it corresponds to the day with the highest average air temperature, making it a critical point for assessing the urban heat island effect and thermal conditions. Also, the majority of wind speed falls within an average of ranging from 3.2–4.4 m/s, with occasional instances of stronger winds reaching up to 9 m/s. Prevailing winds in the region predominantly flow from the northwest (N-W) direction (Iowa State University, 2020), characterized by the highest speeds. Consequently, the simulations were conducted using this prevailing direction, ensuring consistent results, while variations in wind direction and the influence of sea breezes were intentionally downplayed. Throughout the year, Dubai maintains a relatively steady relative humidity (RH) range of 50–66%, as illustrated in Table 3. Notably, the lowest humidity levels are documented from April to August, whereas the highest levels are recorded from December to February (Energy, NASA Prediction Of Worldwide, 2023).

The selected residential urban forms are investigated with ENVI-met simulations on August 21st by examining periods of 24 h. This specific date was selected because it corresponds to the day with the highest average air temperature, making it a critical point for assessing the urban heat island effect and thermal conditions.

Table 3. Climatic conditions for the study areas (*Energy, NASA Prediction Of Worldwide*, 2023) Top of Form.

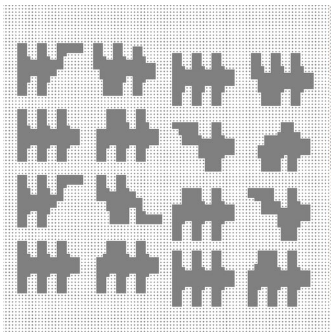
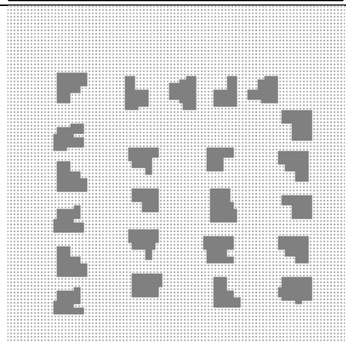
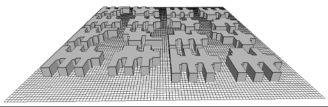
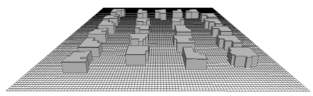
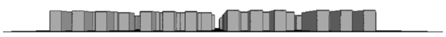
	AIR TEMPERATURE (°C)		**WIND SPEED (M/S)**	**RELATIVE HUMIDITY (%)**
	Maximum	**Minimum**		
JAN	26.4	14.9	3.8	57.6
FEB	29.3	16.8	3.7	66.2
MAR	35.3	17.4	4.4	57.4
APR	37.2	21.2	3.7	53.9
MAY	40.7	24.3	3.4	59.1
JUN	44.2	28.7	3.7	57.6
JUL	42.7	30.8	4.0	54.7
AUG	43.3	30.6	3.3	53.3
SEP	40.6	29.8	3.2	57.3

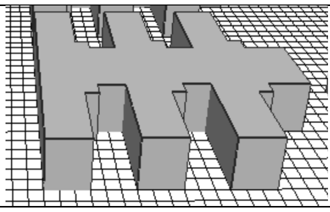
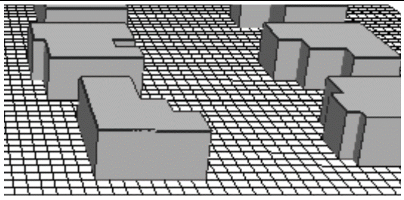
OCT	38.7	25.1	3.4	56.8
NOV	34.1	22.2	3.2	57.6
DEC	29.0	19.6	3.4	60.6

To facilitate environmental analysis, a square plot measuring 200 meters on each side was established for our case studies: the regular SZHP in Ajman and the sustainable city in Dubai, as shown in Table 4a. Each case was represented by two units within the ENVI-met software, where the parameters dx, dy, and dz were set to 2 meters. These simulations ran for a 24-hour duration, specifically on August 21st. Certain variables remained consistent across all urban fabrics in the case studies. These included building materials with their associated thermal properties such as conductivity and albedo, as outlined in Table 4b. Additionally, the geographic location remained fixed at Dubai, and meteorological data was uniform. It's important to note that factors like urban design, street width, geometry, orientation, built-up area-to-plot area ratio, building heights, and 3D configurations were unique to each case study.

Conversely, there were dependent variables – the outcomes of the modeling, such as potential outdoor air temperature – which varied based on the independent features of each case study.

Table 4. Case studies Model geometry and materials properties. (Salameh, Elkhazindar and Touqan, 2023).

a-Case studies model geometries		
Case studies		
Urban layout		
Built-up units		
		
District area	200 m × 200 m =40000 m^2	200 m × 200 m =40000 m^2
Built-up area	Around 25,0000 m^2	Around 11,500 m^2
Urban layout	Grid pattern layout	Grid pattern layout
Streets width	Narrow with maximum width 8m	Wide with maximum width 15m
Façade layout		
Buildings heights	8m	8m
Buildings type	Semi-attached units	Detached units

Houses geometry				
b-Unified Materials thermal Properties for All the Cases				
Thermophysical Properties	**Thermal Conductivity (W/m K)**	**Density (kg/m^3)**	**Specific Heat (kJ/kg K)**	**Albedo**
	1.37	2076	0.88	0.25–0.70
	1.4	2350	0.88	0.25–0.70

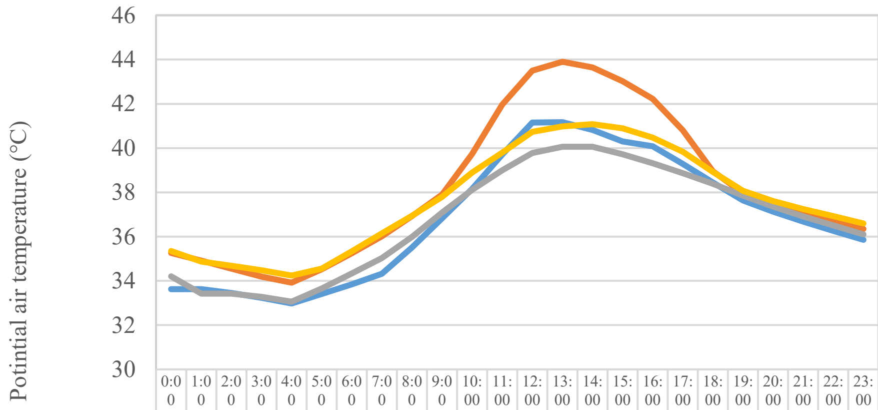
3. Results and Discussion

3.1. Thermal Conditions Comparison for the Regular and Sustainable Districts

Microclimatic elements such the humidity, wind speed, and temperature of the air help in understanding the Urban heat island -UHI effect's geographical variability. (Coutts, Beringer and Tapper, 2007; Yuan et al., 2023). Thus, this research used the air temperature as an indicator for the effect of the UHI.

The results of the simulation on August 21showed that the air temperature data between the regular and the sustainable districts case studies varied. In comparison to the regular district, the sustainable case study's area has lower air temperature readings for the min. and the max. readings, particularly between the hours of 10 a.m. and 18:00 p.m., as shown in Figure 7. The air temperature distribution at 13:00 p.m. on August 21 in the sustainable district is lower over the whole district than in the regular district, according to the scored hourly max and min air temperature through the day (Figure 8). The minimum and the maximum air temperatures in the regular district were 41.17 °C and 43.90 °C respectively, and for the sustainable district 40.06 °C and 40.98 °C, respectively. Consequently, the sustainable district minimum reading scored 1.11 °C lower than the minimum for the regular district, and the sustainable district maximum reading scored 2.90 °C lower than the maximum for the regular district. This is mostly due to the way the sustainable district was built, which had a more compressed layout, shaded streets, and semi-closed courtyards, which led to more shaded areas and lower air temperature.

Looking at the average readings for the air temperature for both districts (Figure 9), the sustainable districts recorded 40.52 °C as average air temperature on August 21 at 13:00 p.m.- hottest hour of the day- and that is lower by 2.02 °C than the regular district average temperature at the same time.



	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Min reguler district	33.6	33.6	33.4	33.2	32.9	33.4	33.8	34.3	35.5	36.8	38.1	39.7	41.1	41.1	40.8	40.3	40.0	39.2	38.4	37.6	37.1	36.6	36.2	35.8
Max reguler district	35.2	34.9	34.5	34.1	33.9	34.5	35.2	36.0	36.9	37.9	39.7	41.9	43.5	43.9	43.6	43.0	42.2	40.8	38.9	37.9	37.4	37.0	36.7	36.3
Min sustainble district	34.2	33.4	33.4	33.2	33.0	33.6	34.3	35.0	35.9	37.0	38.1	38.9	39.7	40.0	40.0	39.7	39.3	38.8	38.3	37.8	37.3	36.9	36.5	36.1
Max sustainble district	35.3	34.8	34.6	34.4	34.2	34.5	35.3	36.1	36.9	37.7	38.9	39.8	40.7	40.9	41.0	40.8	40.4	39.8	38.9	38.0	37.6	37.2	36.9	36.6

Figure 7. Max and min air temperature readings for regular and sustainable districts on August 21.

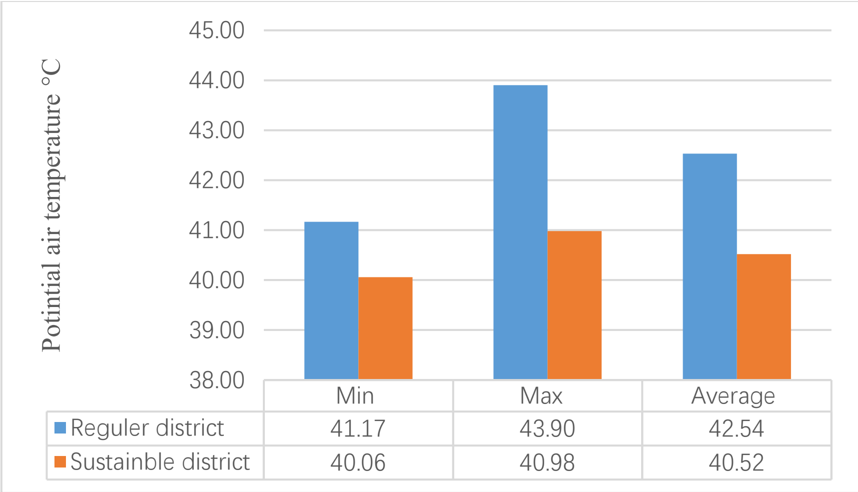


Figure 8. Max, min and average air temperature readings for regular and sustainable districts on August 21 at 13 p.m.

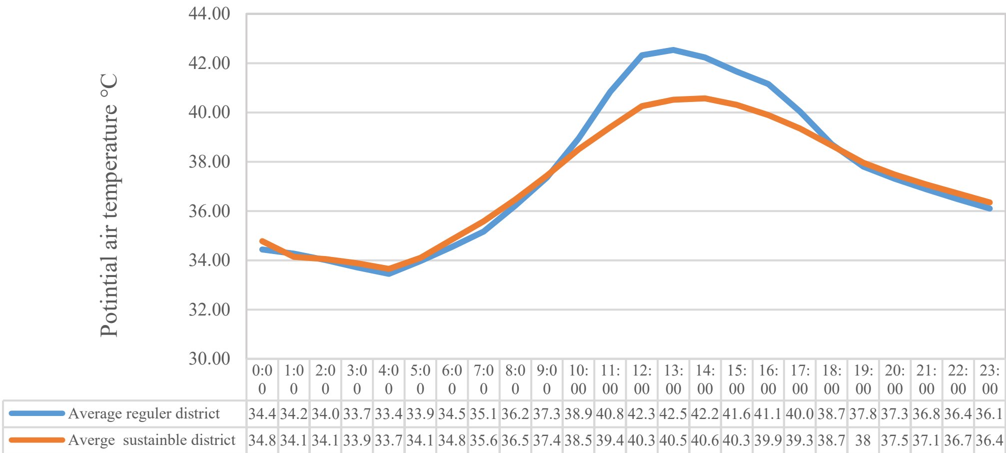


Figure 9. Average air temperature readings for regular and sustainable districts on August 21.

Figure 10a illustrates the air temperature distribution observed on August 21st at 13p.m. It is evident that the compacted layout in the sustainable district featured semi-attached buildings, forming a dense arrangement with a built-up area to plot area ratio of 64% (250000 m² out of 40000 m²). This compact structure resulted in more shaded regions, contributing to a reduction in the air temperature within the sustainable district. In contrast, the regular district had a different layout with detached buildings arranged in a grid pattern, leading to a lower built-up area to plot area ratio of 30% (11,500 m^2 out of 40000 m^2). Consequently, the regular district had less shaded areas. Furthermore, the streets in the sustainable district were designed to be narrow, with a maximum width of 8 m. These narrow streets increased the shaded areas and decreased solar gain, further influencing the thermal conditions. Conversely, the streets in the regular district were wide, reaching approximately 15 m in width.

Beside that the histogram in Figure 10b shows that most of outdoor air temperature of the sustainable district concentrated around 40.5 °C, while in the regular district it is concentrated around 42.5 °C.

The ratio of the visible sky area to the total viewable area is therefore known as the sky view factor (SVF), which is measured from certain ground positions and has consequences for air temperature changes. Figure 10c shows that the sustainable district with semi-attached buildings and courtyards had low sky view factor readings caused better thermal conditions. For example, the courtyard area's focused sky view ranged between 0.35 and 0.49 that cover around 8% of the cell distribution of the sustainable district, thus the quantity of solar radiation that reached the ground and urban masses in the sustainable district was reduced as a result. The regular district, which is distinguished by unattached structures, had a substantially less cells coverage around 1% of its area of sky view factor - between 0.35 and 0.49 - (as in Figure 10d). This difference in sky view factor resulted from the buildings' detached design, which raised the sky view factor and, as a result, the amount of solar radiation that reached the district's walls and the ground. This finding that connects the SVF with the thermal conditions is consistent with other research, including those by (Salameh, Elkhazindar and Touqan, 2023), (Ahmadi Venhari, Tenpierik and Taleghani, 2019) and, (Unger, 2009). These studies highlight the fact that lowering the SVF may result in a better thermal setting.

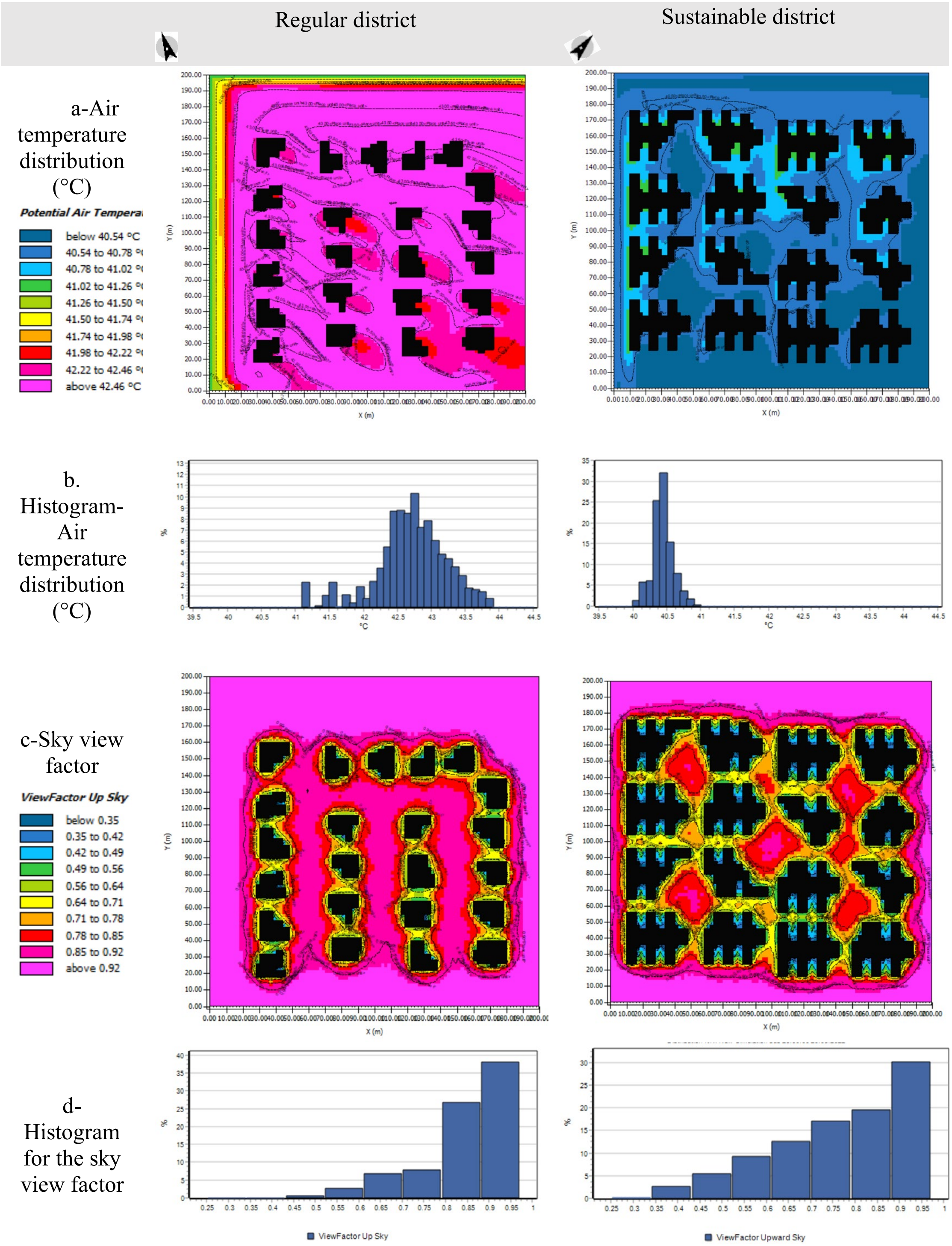


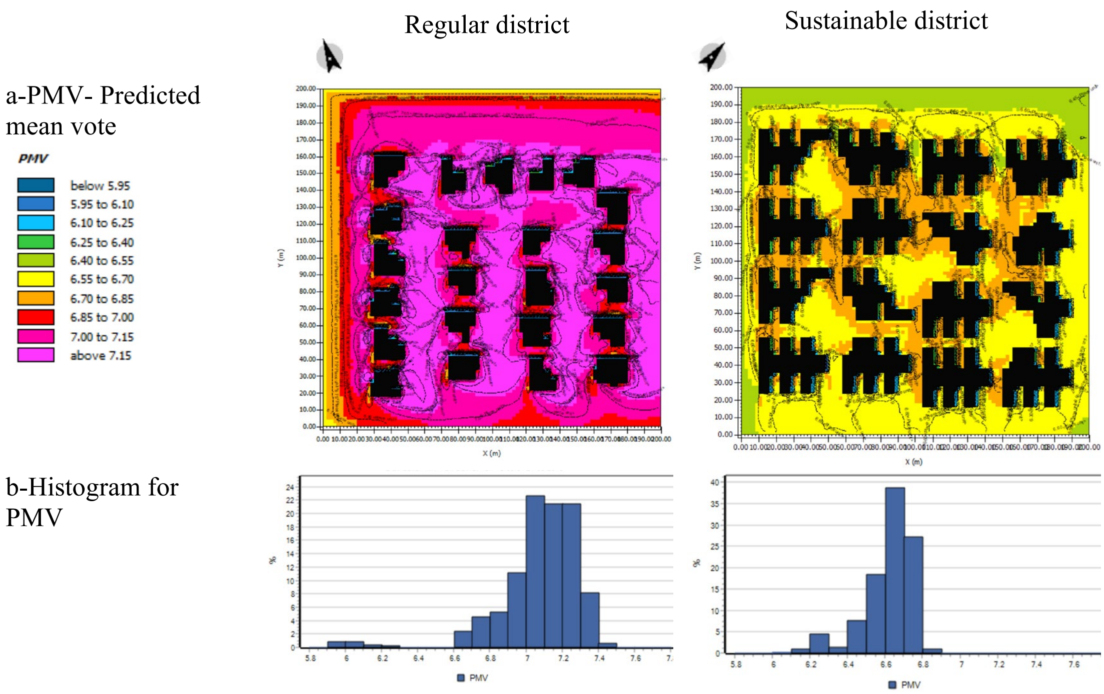
Figure 10. Air temperature distribution and histogram for the potential Air temperature and sky view factor for both districts- regular and sustainable - on the 21st of August at 13:00 p.m.

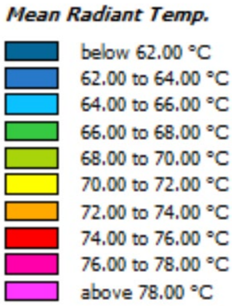
3.2 Thermal Comfort Comparison between the Regular and Sustainable Districts

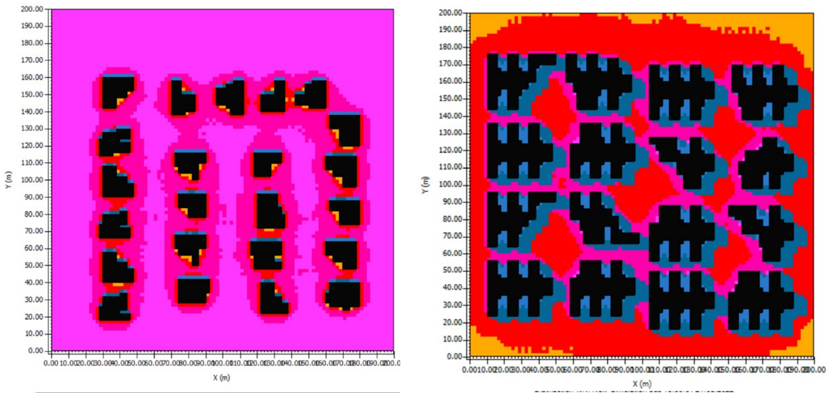
The ENVI-met Leonardo's depiction of heights progressively rises by 0.4 meters from the level of 0.2 meters, according to (Detommaso et al., 2021). The conventional PMV model is used in this study, which it is intended for a 35-year-old person who is 1.75 meters tall, weighs 75 kg, and moves at a speed of 4 kph (based on the ENVI-met software). Due to its near to 1.75 meters, the height of 1.8 meters is selected for the measurement of Predicted mean vote (PMV) values. Figure 11a shows that the sustainable district, produced better PMV levels than the regular district. The histogram plots in the Figure 11b shows that the sustainable district PMV values concentrated around 6.6 PMV level while the regular district readings are concentrated around 7.1 on August 21 at 13 p.m. Despite the fact that both districts exceeded the required −4 to +4 PMV range, however the sustainable district urban design is able to reduce the maximum PMV readings, especially in the semi-closed courtyards, by 0.7 compared to the regular district at 13 p.m., when the air temperature is at its peak. Also, the sustainable district has low Sky View Factor (SVF) which contributes to a reduction in outdoor PMV. Beside that the sustainable district has more clustered masses in the northwest side than the regular district and that helped in blocking the revealed hot wind and improved the PMV, which opposed the case in the regular district which has detached masses on its northern and western edges.

The Mean Radiant Temperature (MRT), shown in Figure 11c, demonstrates notable differences between the sustainable and regular districts. In the sustainable district, MRT values range from 57–64 °C, with only 0.5% cell coverage reaching the maximum MRT of 78–80 °C, as shown in Figure 11d. In contrast, the regular district records MRT readings mainly spanning 73–80 °C, with 32% cell coverage reaching the maximum MRT of 78–80 °C, as shown in Figure 11d. This disparity underscores how the sustainable district maintains lower MRT values over a larger area, contributing to improved thermal conditions and potentially more comfortable living environments compared to the regular district. The sustainable district exhibited slightly higher relative humidity levels (36–37%) compared to the regular district (34–35%) according to Figure 11e and 10f. This difference likely stems from factors like increased vegetation in the sustainable district.

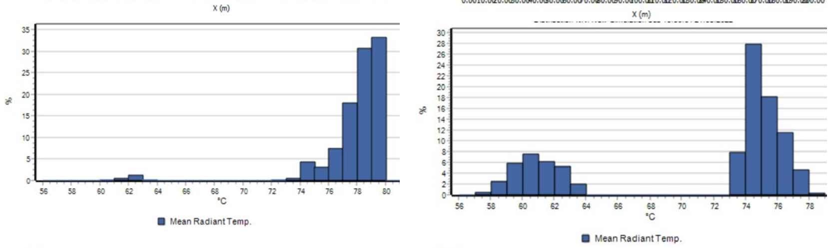
Looking at the maximum wind speed for both the sustainable and regular districts, as shown in Figures 11g and 10h, only 21% of the cells in the sustainable district encountered maximum wind speed 2–3 m/s, while 45% of the cells in the regular district did. As a result, the sustainable district had the lower wind speed readings at 13:00 p.m. This may be returned to that the sustainable district's design elements, which likely include well-planned urban layouts and natural barriers, contribute to reduced wind speeds compared to the regular district. Despite the sustainable district having the lowest wind speeds, this factor did not significantly impact the Predicted Mean Vote (PMV) values. This observation aligns with the findings of Salameh and Touqan (Salameh and Touqan, 2023), who noted that the PMV is primarily influenced by MRT and relative humidity.



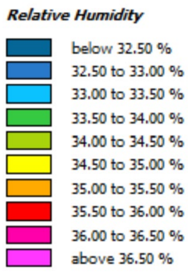


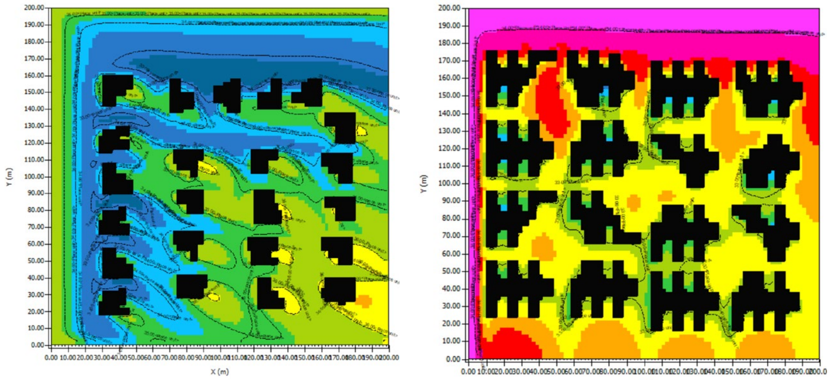


d-Histogram MRT

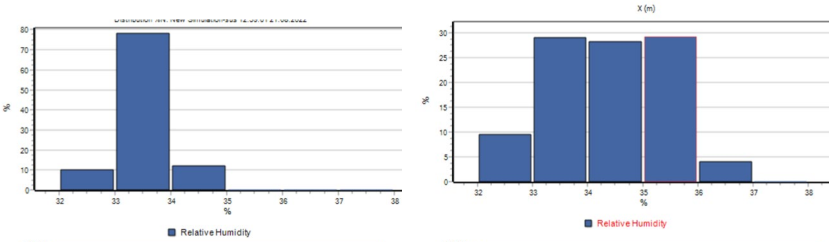


e-Relative humidity %

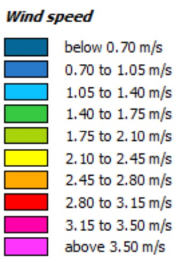


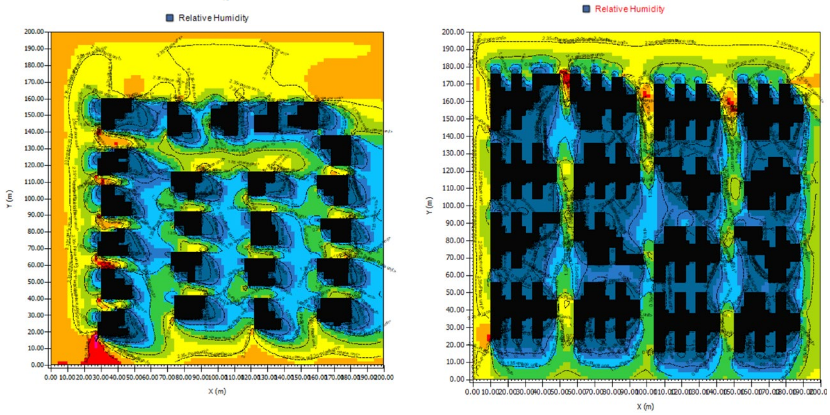


f- Histogram relative humidity %



g-Wind speed m/s





h-Histogram Wind speed m/s

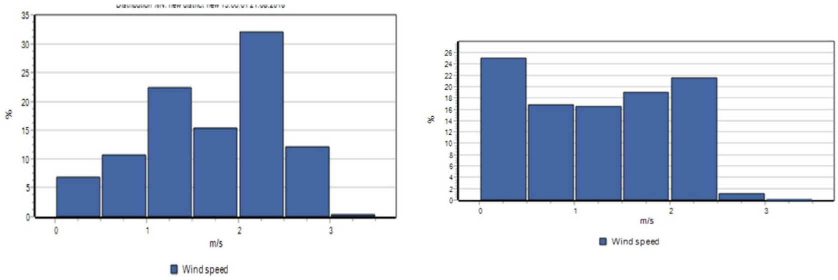


Figure 11. PMV, MRT, relative humidity and wind speed distribution and histogram for both districts-regular and sustainable - on the 21st of August at 13:00 p.m.

3.3 Thermal Analysis for Selected Points in the Open Spaces

For deeper understanding for the thermal conditions for both districts, a point named X is selected in the center of both districts in the open spaces, as shown in Figure 12. it is clear that the point X in the sustainable district recorded lower air temperature and MRT on the August 21, mostly from 10:00 a.m.–18:00 p.m. at the hottest hours of the day (Figure 13a and b), and that caused improvement in the thermal comfort PMV as in Figure 13c. The PMV reduction ranged between 0.2–3.1 on PMV scale between the hours 9:00 a.m.-17:00 a.m., this improvement was correlated with increasing in the relative humidity that ranged between 2–12 % and reduction of the wind speed around 0.07m/s–0.10m/s at the same time (Figure 13d and e).

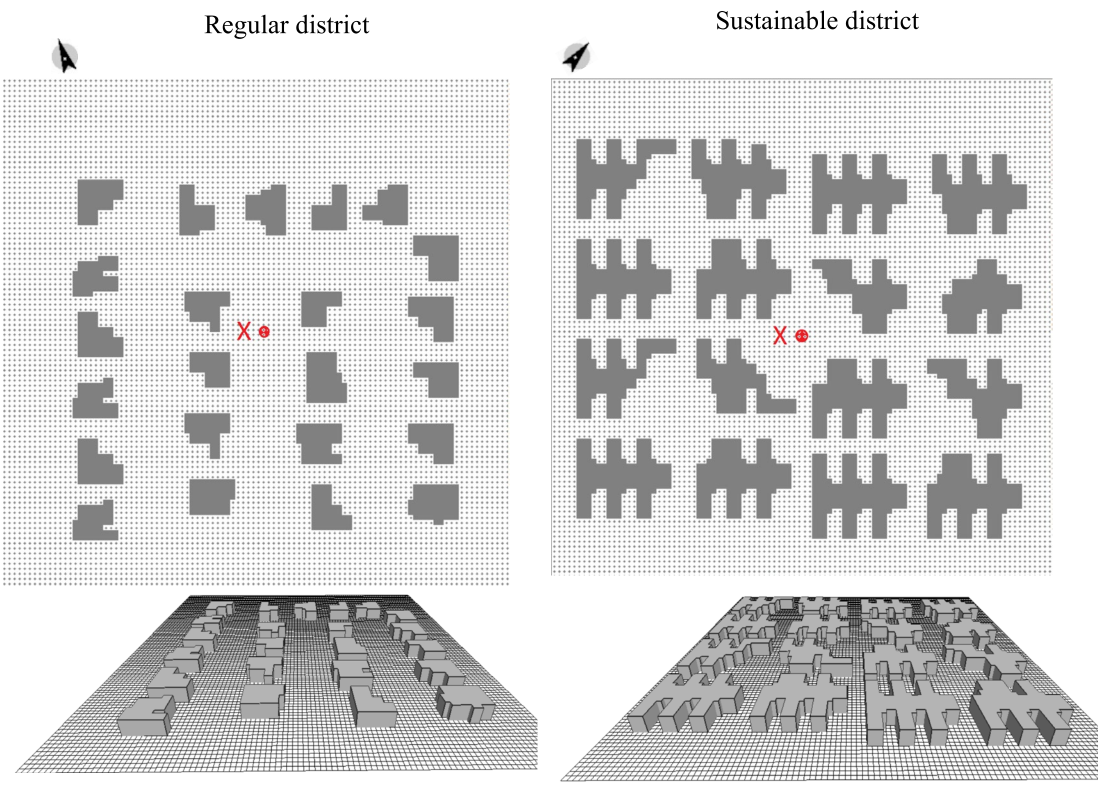
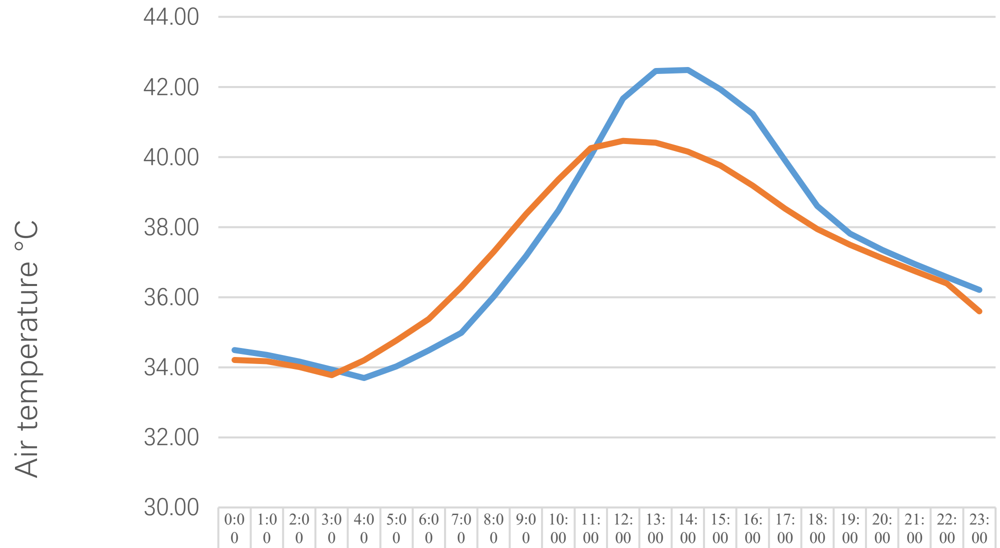


Figure 12. The selected points in the center of both districts – sustainable and regular – for the analysis of the thermal conditions in the open spaces.



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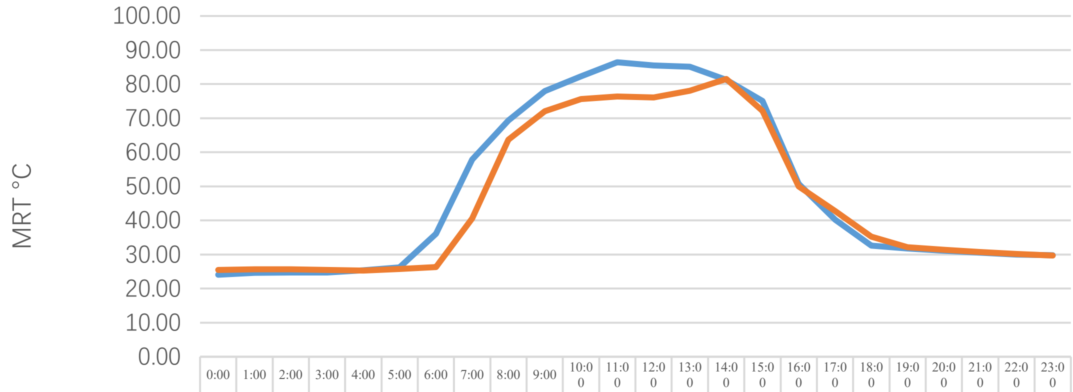
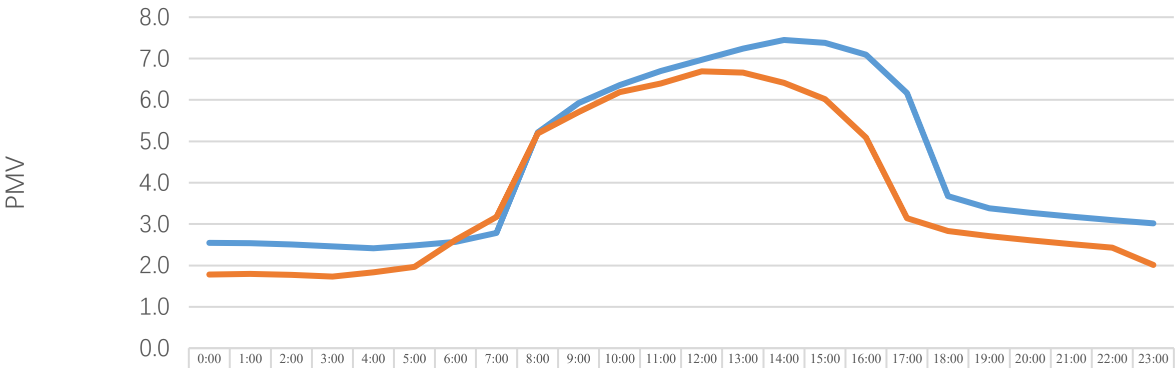
Reguler X-Potential Air Temperature (°C)	34.49	34.36	34.16	33.94	33.69	34.03	34.48	34.99	36.02	37.18	38.47	40.03	41.67	42.46	42.48	41.93	41.23	39.91	38.60	37.82	37.35	36.95	36.57	36.21
Sustainable X-Potential Air Temperature (°C)	34.21	34.17	34.00	33.78	34.20	34.76	35.38	36.29	37.29	38.37	39.36	40.25	40.46	40.41	40.15	39.76	39.19	38.53	37.94	37.50	37.11	36.75	36.40	35.60

a-Air temperature for Point X in the regular district and the point X in the sustainable district



	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Reguler X-Mean Radiant Temp. (°C)	24.07	24.61	24.76	24.73	25.42	26.21	36.08	57.91	69.37	77.93	82.33	86.42	85.50	85.12	81.25	75.11	50.78	40.20	32.57	31.73	31.07	30.51	30.00	29.80
Sustainable X-Mean Radiant Temp. (°C)	25.51	25.67	25.63	25.48	25.29	25.77	26.29	40.63	63.72	72.08	75.58	76.42	76.06	78.11	81.52	72.17	50.00	42.74	35.22	32.19	31.36	30.71	30.15	29.70

b-MRT for Point X in the regular district and the point X in the sustainable district



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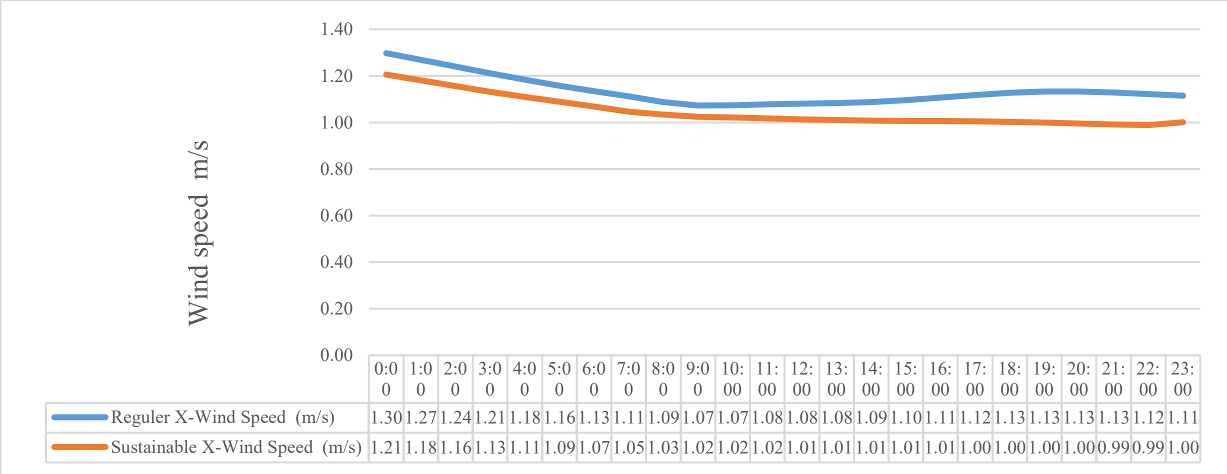
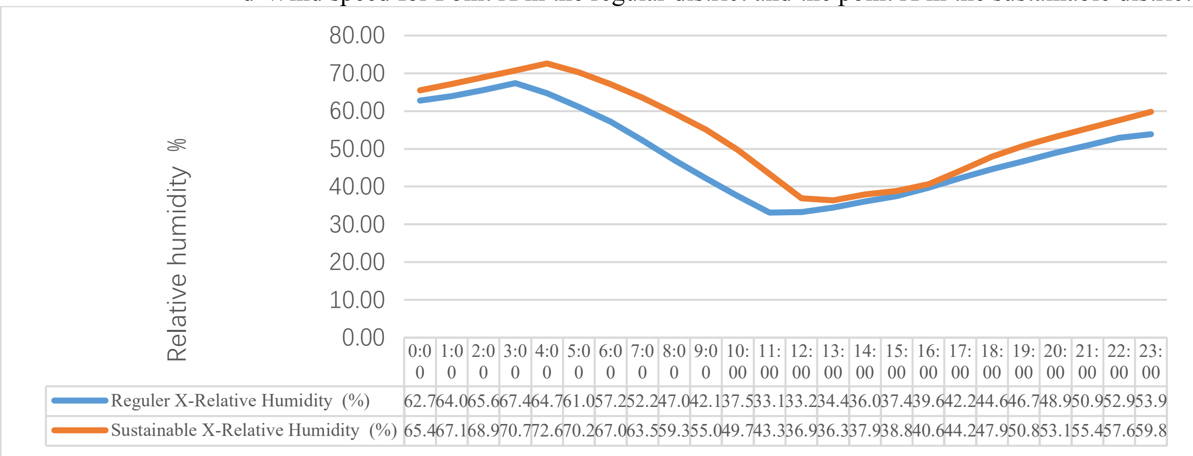
Reguler X-PMV	2.5	2.5	2.5	2.5	2.4	2.5	2.6	2.8	5.2	5.9	6.4	6.7	7.0	7.2	7.4	7.4	7.1	6.2	3.7	3.4	3.3	3.2	3.1	3.0
Sustainable X-PMV	1.8	1.8	1.8	1.7	1.8	2.0	2.6	3.2	5.2	5.7	6.2	6.4	6.7	6.7	6.4	6.0	5.1	3.1	2.8	2.7	2.6	2.5	2.4	2.0

c-PMV for Point X in the regular district and the point X in the sustainable district



d-Wind speed for Point X in the regular district and the point X in the sustainable district



e-Relative humidity for Point X in the regular district and the point X in the sustainable district

Figure 13. Air temperature, MRT, Wind speed and relative humidity for Point X in the regular district and the point X in the sustainable district on August 21.

3.4. Expanded Discussion and Analysis of Variables

The results illustrate how key urban design elements—vegetation, street width, building typologies, density, orientation, and glazing—collectively influence the microclimate, particularly air temperature. Below is a detailed discussion of these variables, validated by data and comparisons between the regular and sustainable districts

Impact of Urban Design on Air Temperature

1. **Vegetation**: The sustainable district includes vegetation, leading to slightly higher relative humidity levels (36–37%) compared to the regular district (34–35%). Vegetation contributes to evapotranspiration, which cools the environment and results in lower air temperature values. This is consistent with the 2.02°C reduction in average air temperature recorded in the sustainable district at 13:00 p.m. (40.52°C vs. 42.54°C in the regular district).
2. **Street Width**: Narrow streets (maximum width of 8 m) in the sustainable district enhance shading and reduce solar gain. These factors contribute to reduced air temperatures, especially during peak hours. By contrast, the regular district's streets (width ~15 m) expose more surface area to direct sunlight, resulting in higher air temperatures.
3. **Building Typologies (Attached vs. Semi-Attached)**:
    a. The semi-attached design in the sustainable district, with a built-up area to plot area ratio of 64%, creates a compact layout that minimizes solar exposure. The regular district, with detached buildings and a 30% built-up ratio, leaves larger areas exposed to direct sunlight, which increases air temperatures.
    b. Sky View Factor (SVF):
        i. Sustainable district: 8% of cells had low SVF values (0.35–0.49), reducing solar radiation.

ii. Regular district: Only 1% of cells had similar SVF values, allowing more solar radiation to reach the ground and building surfaces.

4. **Density and Orientation**: The dense clustering in the northwest of the sustainable district acts as a barrier against hot winds, effectively lowering air temperatures and improving Predicted Mean Vote (PMV) values. In the regular district, detached structures in the northern and western sections allow wind to flow freely, intensifying heat stress.

3.5. Integration of Qualitative and Quantitative Analysis for Validation

Integrating qualitative observations with quantitative data is essential for a comprehensive understanding of the study's findings. Qualitative insights derived from simulation visuals provide a contextual and intuitive interpretation of the thermal environment, enabling a clearer connection to real-world experiences. When combined with the precise numerical data extracted from simulations, this approach enhances the robustness of the analysis. By aligning these two perspectives, the research not only validates the quantitative results but also offers a richer narrative that bridges technical accuracy and practical relevance as below:

1. **Hourly Variations**: Air temperature measurements between 10:00 a.m. and 18:00 p.m. reveal that the sustainable district consistently recorded 1.11°C–2.90°C lower maximum temperatures than the regular district. These findings corroborate qualitative observations of improved thermal comfort across varied conditions.
2. **Thermal Comfort Metrics**:
   a. PMV values in the sustainable district concentrated around 6.6, compared to 7.1 in the regular district. This represents an improvement of 0.7 on the PMV scale during peak heat conditions, reinforcing qualitative insights on reduced discomfort during the hottest hours.
   b. MRT values (57–64°C) in the sustainable district are significantly lower than the regular district's MRT readings (73–80°C), emphasizing better thermal comfort, as noted in qualitative feedback.
3. **Selected Points (Point X Analysis)**:
   a. Air temperature: The sustainable district recorded a consistent reduction (0.5–2.0°C) at Point X during the hottest hours. This aligns with qualitative observations indicating enhanced user satisfaction.
   b. PMV: Improved by 0.2–3.1, correlating with increased relative humidity and lower wind speeds. These factors were qualitatively noted to contribute to better perceived comfort.
4. **Histograms for Air Temperature and SVF**: The sustainable district exhibited a narrower range of high temperatures, with most readings concentrated around 40.5°C. In qualitative terms, this suggests a more consistent and favorable thermal environment. The regular district showed a broader and higher range, concentrated at 42.5°C. Similarly, the sustainable district achieved a greater proportion of low SVF values, qualitatively reinforcing its effectiveness in mitigating urban heat.

By adding references to qualitative observations and emphasizing the synergy between qualitative insights and quantitative results, this revised section addresses the reviewer's comment and ensures the title reflects the integrated approach.

3.6. Comparison Between this Research and Relevant Studies on Urban Thermal Comfort and Passive Design Strategies

This study focused on the integration of passive design strategies at the urban level to combat the effects of climate change in hot arid climates, specifically in the UAE. The research compared a sustainable urban district in Dubai with a regular district, assessing the impact of strategies such as urban orientation, building form, materials, green infrastructure, and shading devices on outdoor thermal comfort. The results demonstrated a significant reduction in air temperature (up to 2.90°C), lower mean radiant temperature (MRT), and improved PMV (Predicted Mean Vote) values, highlighting the positive effects of passive strategies on urban microclimates.

Comparison with Other Studies:

1. (Battista et al., 2023) conducted a study on urban overheating in Rome examined strategies to mitigate heat stress in high-density neighborhoods. The research used ENVI-met software and found that interventions such as increasing vegetation and changing pavement albedo could reduce air temperatures by up to 2.5°C.
   Comparison: While Battista's study primarily focuses on localized interventions within a high-density urban setting, this research broadens the scope by addressing urban-level strategies (e.g., building orientation, wind towers, and energy-efficient infrastructure) in an arid climate. this study

offers a more comprehensive approach by incorporating various urban strategies, showing their potential to address broader urban heat island effects.

2. (Han et al., 2023) study included highlights strategies for mitigating the urban heat island (UHI) effect, focusing on cool materials, vegetation, water bodies, and optimizing urban geometry. They find that these strategies can reduce ambient air temperature by 1.4°C to 3.74°C. Comparison: Han's paper emphasizes general mitigation strategies, while this study applies these strategies to a specific urban context in Dubai, analyzing the actual thermal impact through simulation models. The findings in this study offer a quantitative measure of how passive strategies affect thermal comfort in an arid environment, thus providing a more context-specific and precise evaluation.
3. (Munaf et al., 2023) study focuses on the use of green roofs, façades, and urban greening strategies to mitigate UHI effects, emphasizing the role of green infrastructure in cooling urban areas. They highlight the importance of energy-efficient appliances and green installations. Comparison: Both studies agree on the value of greening strategies, but this research extends beyond green infrastructure to include a variety of passive design principles (e.g., wind towers, energy-efficient infrastructure) that impact urban microclimates. This study's detailed focus on outdoor thermal comfort using validated simulation models distinguishes it as a more focused and comprehensive examination of thermal performance in urban districts.
4. (Khare, Vajpai and Gupta, 2021) review emphasizes how urban geometry, vegetation, reflective surfaces, and water bodies affect the thermal environment in outdoor spaces. The study finds that compact urban spaces and vegetative strategies can significantly reduce urban temperatures. Comparison: Both Khare's research and this study emphasize the importance of vegetation and shading in reducing urban temperatures. However, this research goes further by evaluating a combination of passive design strategies at the urban level and assessing their direct impact on thermal comfort using PMV values. This provides a more detailed understanding of how integrated strategies can work synergistically to reduce UHI effects.

Significance and Contribution of this research:

This research stands out by offering a holistic, urban-level analysis of passive design strategies in a hot arid climate, contributing new insights into the role of sustainable urban planning in mitigating climate change. By comparing a sustainable district with a typical urban area, the study not only quantifies the thermal impact of these strategies but also provides practical evidence of their effectiveness in reducing urban heat island effects and improving outdoor comfort. The use of ENVI-met simulations to assess outdoor thermal comfort through PMV, combined with the examination of key climatic parameters, makes this research a valuable addition to the growing body of knowledge on urban resilience and sustainability.

In conclusion, while existing studies have contributed valuable findings on individual strategies or local interventions, this research significantly broadens the scope by assessing urban design on a macro level and providing a robust quantitative evaluation of passive design strategies in an arid climate. This work paves the way for future urban planning models that prioritize climate resiliency and sustainable development, offering a practical blueprint for cities globally.

4. Conclusion

In addressing the escalating challenges of climate change and global temperature increases, it is critical to extend passive design principles beyond individual buildings to encompass urban-scale planning. Urban-level passive strategies—including building orientation, form, materials, wind towers, green infrastructure, exterior shading, and energy-efficient infrastructure—play a pivotal role in mitigating the impacts of climate change. These measures are essential for combating the urban heat island effect, reducing outdoor temperatures, enhancing thermal comfort, and improving the overall well-being of metropolitan populations.

This study assessed the impact of passive strategies on urban thermal conditions in hot arid climates by analyzing two contrasting urban designs in Dubai: a sustainable city that employs diverse passive strategies and a regular urban district without these measures. The analysis conducted using a validated simulation model developed by Salameh, et al. (2023) with ENVI-met software, focused on outdoor thermal comfort using the Predicted Mean Vote (PMV) index and key climatic parameters, including air temperature, mean radiant temperature (MRT), relative humidity, and wind speed.

The findings demonstrate the quantifiable benefits of passive design:

- The sustainable district achieved a reduction in air temperature of up to **2.90 °C** compared to the regular district, underscoring the effectiveness of passive cooling strategies.
- The sustainable district showed significantly lower MRT values, with only **0.5% of cells** reaching the maximum MRT of 78–80 °C, compared to **32%** in the regular district.

- Relative humidity in the sustainable district was consistently about **2% higher** than in the regular district, contributing to enhanced microclimate conditions.
- Wind speed in the sustainable district was lower, with **21% of cells** experiencing maximum wind speeds of 2–3 m/s, compared to **45%** in the regular district.
- PMV values in the sustainable district were **0.5 lower** than in the regular district, reflecting better thermal comfort.

These results highlight how sustainable urban planning, rooted in passive design principles, can harmonize urban expansion with environmental preservation. By prioritizing shaded spaces, improving thermal comfort, and reducing the urban heat island effect, sustainable cities offer a model for resilient and ecologically conscious urban environments.

Future research will focus on assessing the impact of these improved urban thermal conditions on indoor thermal comfort, both under current and projected future climates, to provide a more comprehensive understanding of passive strategies' potential in urban sustainability

5. Recommendations for Urban Design to mitigate the urban heat island:

Based on the conclusions of this study, the following recommendations are proposed to enhance urban sustainability and thermal comfort in hot arid climates:

1. **Adopt Passive Design Strategies in Urban Planning:**
2. Urban planners and policymakers should prioritize incorporating passive design solutions such as building orientation, green infrastructure, and shading strategies. For instance, the study demonstrated that sustainable urban districts could reduce air temperature by up to **2.90 °C** compared to regular urban areas, emphasizing the substantial cooling potential of these strategies.
3. **Implement Measures to Minimize Mean Radiant Temperature (MRT):**

Reducing MRT is crucial for improving outdoor thermal comfort. The study found that only 0.5% of cells in the sustainable district experienced maximum MRT values of 78–80 °C, compared to 32% in the regular district. This underscores the importance of shading, reflective materials, and vegetation in minimizing heat absorption and radiation.

4. **Optimize** Urban **Microclimates with Green Infrastructure:**

Green spaces and vegetation should be integrated into urban designs to enhance relative humidity and create cooler microclimates. The sustainable district exhibited 2% higher relative humidity than the regular district, contributing to improved comfort and environmental quality.

5. Consider Wind Speed Management:

Passive design measures should account for optimizing wind flow. The findings indicate that wind speeds in the sustainable district were reduced, with 21% of cells experiencing maximum wind speeds of 2–3 m/s compared to 45% in the regular district. This suggests the need for balancing ventilation with thermal comfort in urban layouts.

6. **Use PMV Metrics to Evaluate Thermal Comfort:**

Urban developers should employ PMV values as a benchmark for outdoor comfort. The study highlighted that PMV levels in the sustainable district were 0.5 lower than in the regular district, indicating a significant enhancement in thermal comfort. Regular use of such indices can guide the effectiveness of implemented strategies.

7. **Promote Sustainable Urban Models as Standards:**

Sustainable cities exemplify effective urban adaptation to climate challenges, showcasing the benefits of passive solutions for reducing urban heat island effects and enhancing residents' quality of life. Policymakers should encourage the replication of sustainable city models in other urban areas, integrating lessons learned from the case study findings.

8. **Future Research and Policy Development:**

Further investigations should explore how improved outdoor thermal conditions influence indoor comfort under both current and projected climate scenarios. This could inform building codes and urban planning policies tailored for hot arid climates, fostering climate-resilient urban environments.

By adopting these recommendations, urban planners, policymakers, and designers can create cities that are not only more sustainable but also more livable and resilient to the challenges posed by climate change

Limitations of the Study

While this study provides valuable insights into the thermal performance of sustainable and regular urban districts, certain limitations should be noted. The research primarily focused on air temperature as an indicator of the Urban Heat Island (UHI) effect, which, although significant, represents only one facet of microclimatic variations. Other factors such as wind direction, surface albedo, and ground emissivity, which can also influence UHI dynamics, were not explicitly analyzed. Additionally, the simulations were conducted under specific seasonal and temporal conditions, limiting the generalizability of the findings to other times of the year or different climatic scenarios. Future research could address these aspects by incorporating a broader range of microclimatic elements and conducting multi-seasonal analyses to provide a more holistic understanding of urban thermal behavior.

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