The Impact of Greenery on Improving Thermal Performance of Historic Housing in Hot-Arid Climate

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This study examines the impact of courtyard vegetation, particularly Neem trees, on outdoor thermal comfort within the courtyards of three houses in Bahrain, characterized by a hot-arid climate. Radiation dynamics—including Incident Radiation, Mean Radiant Temperature (MRT), and Universal Thermal Climate Index (UTCI)—were assessed under two simulated scenarios: one without Neem trees and the other with Neem trees in the courtyards, evaluating their cooling effect on the microclimate. Conducted on July 27th, the hottest day of the year in the region, the simulations demonstrate a substantial reduction in incident radiation across the three case studies. For instance, House C exhibits an annual reduction of incident radiation up to 30% with trees compared to scenarios without trees. Significant reductions in MRT and correlated drops in UTCI—up to 3.5°C in House A—underscore the microclimate influence of courtyard trees, emphasizing their role in enhancing the thermal performance of the courtyard.

Keywords: Thermal comfort, microclimate modification, Mean Radiant Temperature, Incident radiation, Universal Thermal Climate Index.

1. Introduction

Traditional courtyard houses in the region have been designed to improve energy efficiency and sustainability, showcasing the impact of courtyards as microclimate modifiers [1][2]. Research in tropical regions has also highlighted that shaded areas within courtyards enhance comfort and contribute to sustainable environments [3]. Studies have shown that urban vegetation, including trees, can regulate microclimates by influencing various atmospheric parameters like air temperature, humidity, and radiation components, ultimately affecting human thermal comfort [4]. However, tree shade has a notable impact on the radiant environment but minimal effects on air temperature and humidity in the surrounding area [5]. This has also been demonstrated in a simulation study conducted in schoolyards, where trees substantially improved the microclimate by reducing direct radiation by over 90% [6].

In this research, the main parameters to be measured to quantify the cooling effect of trees in the courtyard microclimate of the three case study houses are incident radiation, Mean Radiant Temperature (MRT), and the Universal Thermal Climate Index (UTCI). Incident radiation refers to the solar flux that falls on building surfaces, impacting their thermal behaviour [7][8]. This radiation is crucial for understanding energy efficiency and bioclimatic design, as it varies based on factors like orientation and urban geometry [9][10]. Mean Radiant Temperature (MRT) is a critical parameter in assessing heat stress and outdoor thermal comfort, integrating the impact of all radiation fluxes received by the human body. It represents the average temperature of all the surfaces surrounding a person, taking into account both shortwave and longwave radiation emitted by these surfaces [11]. The Universal Thermal Climate Index (UTCI) is a comprehensive thermal comfort index that considers various meteorological elements such as air temperature, humidity, wind speed, and radiation to assess the impact of ambient conditions on human comfort [12][13].

This paper investigates the impact of courtyard trees on incident radiation and various thermal comfort metrics, including Mean Radiant Temperature (MRT), Universal Thermal Climate Index (UTCI), air temperature, and relative humidity in hot-arid residential buildings.

2. Case studies: courtyard homes in hot-arid climate

This research focuses on three typical courtyard houses (House A, House B, and House C) located within the historic core of Bahrain, each over 120 years old (see Figure 1). The selection criteria for these houses included easy access to data, the ability to study them within the research timeframe, and the presence of a courtyard. The gross floor areas for House A, House B, and House C are 100m², 206m², and 130m², respectively. Originally designed to rely on natural ventilation strategies, these houses utilized courtyards as climate modifiers. Natural cooling techniques included shaded corridors and courtyard vegetation, which collectively contributed to evaporative cooling and solar control.

Figure 1 illustrates the base case of the courtyards for the three houses. Currently, the courtyards contain small trees with little foliage that provide minimal shading and solar control. To enhance thermal comfort, these trees are proposed to be replaced in Scenario 2 with strategically selected trees, with superior shading and solar control capabilities.


House A House B House C

Figure 1: Pictures of the three case study houses.

3. Selection of tree species for simulations

In hot arid climates, the choice of tree species influences thermal comfort. Research shows that evergreen trees can effectively cool building walls and enhance urban pedestrian comfort all year round[14][15]. Deciduous and coniferous trees near internal thermal zones can significantly reduce energy demand and discomfort hours from April to October, improving overall thermal comfort and energy efficiency in courtyard buildings [16][17]. Mature trees and grass in semi-enclosed spaces lower thermal stress, especially with added shading [4], reducing air and surface temperatures and limiting excessive solar radiation [18][19]. Therefore, incorporating trees can be a sustainable strategy to mitigate urban heat island effects and create more comfortable outdoor spaces.

The Neem tree (Azadirachta indica) was selected due to its tolerance to dry conditions and minimal water needs, making it suitable for arid climates [20]. Its roots pose minimal risk to structures, unlike other common tree species in Bahrain like Conocarpus erectus, which can damage underground structures [21].

The number of trees per courtyard was based on typical Neem tree dimensions and courtyard area: House A had one centrally positioned tree, House B had two trees, and House C had three trees, as detailed in Table 1. The trees have been modelled according to the minimal dimensions characteristic of a mature Neem tree. These dimensions encompass a height ranging from 5 to 6 metres, a trunk diameter measuring 30 centimetres, and a canopy diameter spanning between 5 to 8 metres.

Table 1. Modelling input data for House A, House B, and House C.

	House A	House B	House C
Courtyard area	37 m^2	84 m^2	35 m2 + 62 m^2
Quantity of trees	1	2	3
Quantity of sensors	72	104	151

4. Methodology

Rhino and Grasshopper, augmented with Ladybug and Honeybee plugins are selected for their ability to handle complex parametric models, enabling a thorough evaluation of multiple strategies. Simulations were conducted using OpenStudio-EnergyPlus and Radiance engines. Virtual models of three courtyard houses in Muharraq City, Bahrain, were created to compare thermal performance across different scenarios using local weather data in EPW (EnergyPlus Weather) format. As illustrated in Figure 2, the study investigated two scenarios: Scenario 1, the base case for a courtyard without trees, and Scenario 2, with Neem trees incorporated into the courtyards. The objective is to investigate the cooling effect of the trees on outdoor thermal metrics, including incident radiation, Mean Radiant Temperature (MRT), and the Universal Thermal Climate Index (UTCI).

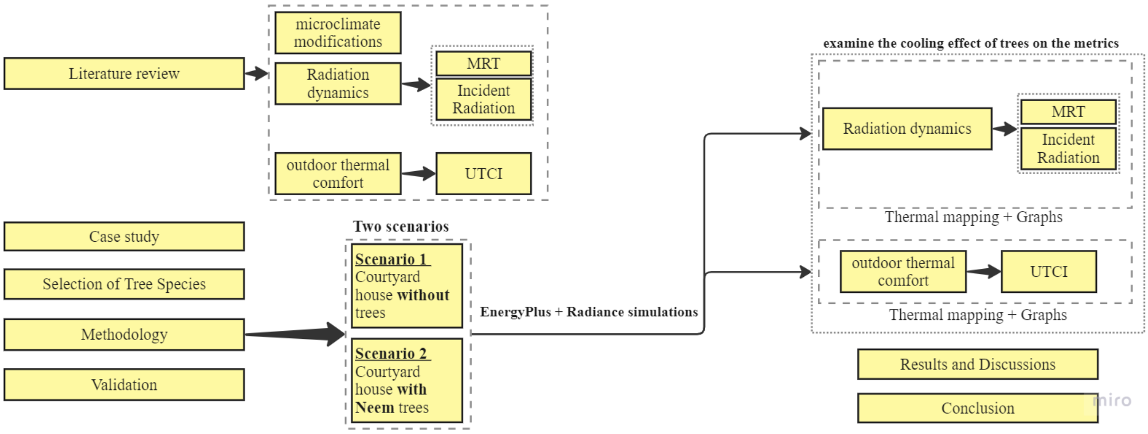

Figure 2: Research workflow.

4.1. Incident Radiation Analysis.

Radiance sensor grids were utilized to map thermal dynamics, defining building surfaces and contextual factors such as the presence of trees. A sky matrix represented sky conditions across the hemisphere. Incident radiation on building surfaces, expressed in kWh/m², was analysed to evaluate tree shading effectiveness in mitigating solar heat gain.

4.2. Mean Radiant Temperature (MRT) and Outdoor Thermal Comfort.

MRT and UTCI, represented in °C, were calculated using an evaluation surface at a height of 1.5 meters. Standardized sensor grids with dimensions of 1 meter by 1 meter were deployed in House A (72 sensors), House B (104 sensors), and House C (151 sensors).

In Grasshopper, MRT simulations included both longwave and shortwave radiation using Ladybug Tools and Honeybee plugins. These plugins enabled comprehensive environmental analyses by defining parameters such as geographic location, time, and surface properties. The simulations calculated the combined effects of shortwave radiation from direct sunlight and longwave radiation emitted and absorbed by surfaces. Simulations were conducted for scenarios with and without trees to quantify the cooling effect of trees on the outdoor radiant environment.

The UTCI values have been categorized into comfort and stress levels, some recent studies have done adjustments based on regional climatic conditions and local populations' thermal perceptions[22]. However, for the scope of this research, the universal scale of UTCI will be used to compare the simulation results to ensure a standardized comparison, as illustrated in Table 2.

Table 2: Universal Thermal Climate Index (UTCI) scale.

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

4.3. Simulation Period.

The simulation period was aligned with the peak heat of the year, focusing on the hottest day and time of the Typical Meteorological Year (TMY), July 27th, from 13:00 to 14:00. Additionally, the total annual incident radiation was calculated. This methodology provided a detailed assessment of tree shading's impact on thermal comfort and energy efficiency in hot-arid climates.

5. Validation

The validation of simulation results involved a comparative analysis of the simulated average air-bulb temperatures over a 24-hour period on the hottest day of summer, specifically July 27th. To ensure precision in assessing the simulated data, the average dry-bulb temperatures for the same date over the past five years were obtained from the Bahrain weather history [23].

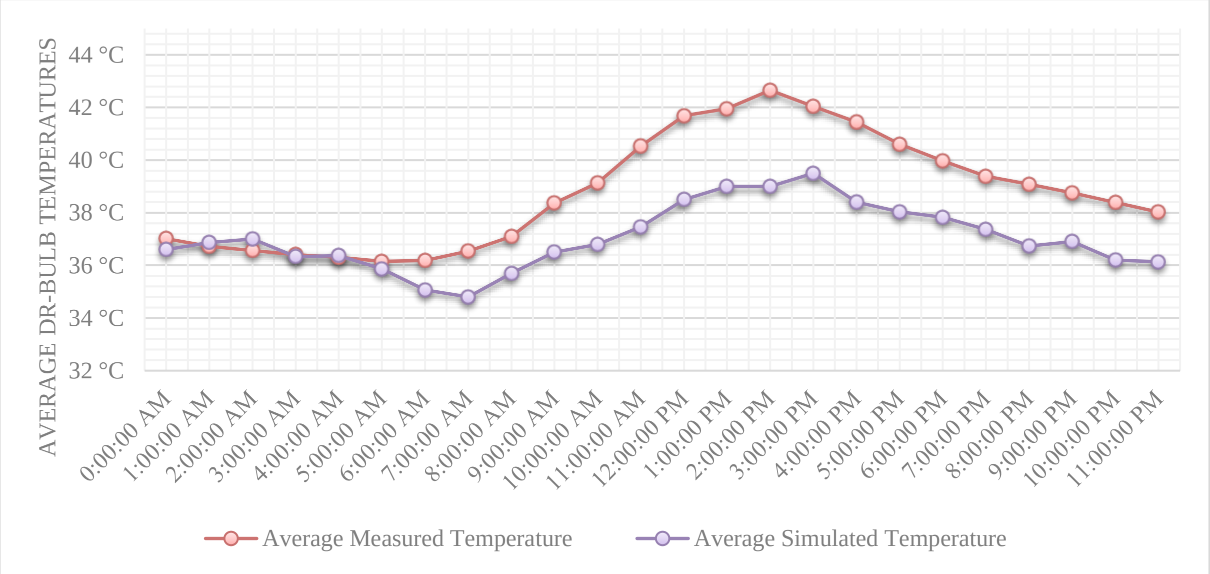

Figure 3: Comparison of Average Measured Dry-Bulb Temperatures with Simulated Results for Validation of Modeling and Simulation.

Both the monitored data and simulated data for the three case study houses were plotted on a graph, as illustrated in Figure 3. To quantify the agreement between the measured and simulated data, the absolute error was calculated for the dry-bulb temperatures. This involved subtracting the simulated data from the measured data as stated in equation (1), providing insights into the magnitude and direction of discrepancies between the two datasets (Table 3). The sum of the absolute errors for the entirety of the 24 time steps is 47.3.

$$\text{Absolute Error} = |\text{Predicted Value} - \text{Actual Value}| \qquad (1)$$

Table 3: The absolute errors between the average measured and simulated datasets across the three case study houses during a 24-hour period on July 27th.

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
Absolute error	-0.4	0.1	0.4	-0.1	0.1	-0.3	-1.1	-1.7	-1.4	-1.9	-2.3	-3.1	-4.2	-4.3	-4.5	-3.4	-3	-2.6	-2.1	-2.0	-2.4	-1.9	-2.2	-1.9

Furthermore, to provide a measure of overall accuracy, the Mean Absolute Error (MAE) is calculated via equation (2); Therefore, MAE equals ≈ 1.97

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n} |\text{ Predicted Value}_i - \text{Actual Value}_i| \qquad (2)$$

Where: n is the total number of data points, Predicted Value$_i$ is the predicted value for the i^{th} data point, and Actual Value$_i$ is the actual value for the i^{th} data point, $|\cdot|$ denotes the absolute value.

The Mean Absolute Error (MAE) measures the average magnitude of discrepancies between simulated and measured values. In urban heat studies, an MAE of around 1-2˚C is generally considered reasonably accurate [24]. Thus, an MAE of 1.97˚C indicates that the simulation results are accurate and the level of error is acceptable.

6. Results and Discussions

The study examines changes in radiation dynamics and evaluates courtyard thermal comfort in three baseline houses without trees and with the addition of Neem trees. It analyses incident radiation and mean radiant temperature (MRT), in addition to assessing outdoor thermal comfort using the Universal Thermal Climate Index (UTCI). The results are presented using graphs and thermal maps.

6.1. The Incident Radiation.

This analysis aims to understand the impact of courtyard vegetation, specifically the Neem tree, on incident radiation levels.

Table 4 presents the simulation results detailing the reduction of incident radiation on building surfaces facing the courtyard. Incident radiation was calculated for a single hour on the hottest day, revealing reductions of 19.6% for House A, 43.6% for House B, and 20.4% for House C compared to scenarios without Neem trees. These differences in percentage reductions are due to the proportion of the exposed wall surfaces to direct sunlight. These results underscore the significant impact of tree shading in diminishing incident radiation on surfaces, thereby mitigating heat transfer into buildings.

Table 4. Simulation results of the Incident radiation for scenario 1: without trees in the court and scenario 2: with trees in the court.

	Scenario 1	*Scenario 2*	
Case study	Incident radiation on 27th July at 14:00 kWh/m^2	Incident radiation on 27th July at 14:00 kWh/m^2	*Total reduction (%)*
House A	0.56	0.45	19.6%
House B	0.39	0.22	43.6%
House C	0.49	0.39	20.4%

6.2. *Mean Radiant Temperature (MRT).*

The simulation results of scenario 1 revealed consistently high MRT values across all sensors. In scenario 2, MRT demonstrated greater variability around the trees, with the maximum MRT recorded within the sensor grid remaining lower than the lowest MRT observed in scenario 1, which demonstrates the cooling impact of green cover on the radiation dynamics on the surrounding environment. Figure 4 represents the MRT reduction percentage over the sensor grid.

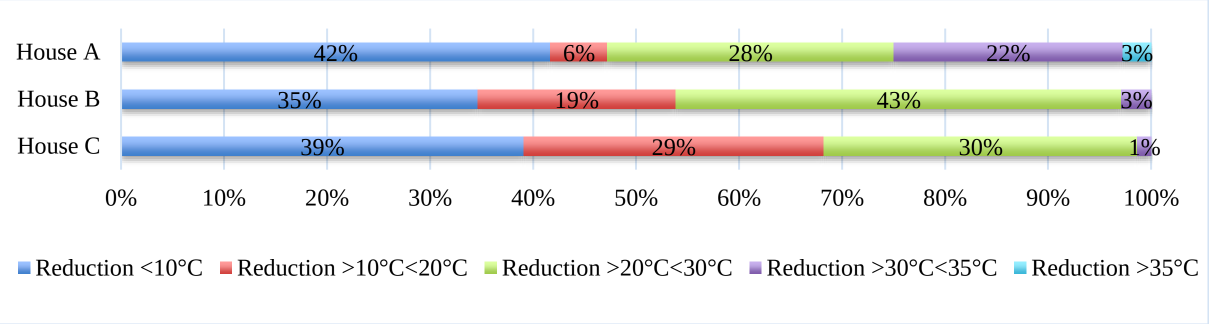

Figure 4: MRT (Mean Radiant Temperature) reduction between scenarios 1 and 2 on July 27th at 14:00 for houses A, B, and C.

Table 4 shows that in Scenario 2, the Mean Radiant Temperature (MRT) remains relatively constant (51 to 51.8°C), regardless of the number of trees. The greatest MRT reduction occurred in House A (18.8°C), while House C had the smallest reduction (13.4°C). This indicates that the number of trees does not directly correlate with lower MRT.

The MRT reduction occurs because shaded surfaces receive less solar radiation, lowering the temperatures. Shading also influences nearby surfaces by reducing the re-radiation of longwave heat absorbed during the day. Therefore, the highest proportion of House C's courtyard area receives direct sunlight compared to House A and House B in Scenario 2, leading to smaller reductions in MRT for House C (see Table 5).

Table 5. Average Mean Radiant Temperature (MRT) for Scenario 1 and Scenario 2 on July 27th at 14:00.

Case study	*Scenario 1* Average MRT without trees in the court *(°C)*	*Scenario 2* Average MRT with trees in the court *(°C)*	The percentage of the courtyard that receives direct sunlight in Scenario 2 *(%)*	*Total reduction (°C)*
House A	70.7	51.9	17	18.8
House B	67.3	51.4	27	15.9
House C	64.5	51.1	30	13.4

6.3. *Outdoor Air Temperature and Relative Humidity.*

Simulation results show that outdoor air temperature and relative humidity remained consistent across the scenarios for the three case study houses. For example, the air temperature in House A remained at 37.5°C and relative humidity at 56% in both scenarios. This supports previous findings [5] that tree shading within a confined area has minimal impact on these variables. Significant changes in air temperature and humidity require larger-scale modelling, potentially over four city blocks of trees [25].

6.4. *Outdoor Thermal Comfort.*

Table 5 compares the average Universal Thermal Climate Index (UTCI) in degrees Celsius (°C) for the two scenarios. The results indicate a decrease in UTCI values across all three case study houses. House A experienced the most significant reduction with a drop of 3.5°C, followed by House B with a decrease of 2.9°C, and House C with the least reduction of 2.5°C. The degree of reduction in the (UTCI) was highest for House A and lowest for House C, which aligns with the reduction in Mean Radiant Temperature (MRT) observed in scenario 2 across the three case studies, suggesting a direct correlation between MRT reduction and UTCI values. This highlights the importance of considering MRT and other environmental factors when assessing outdoor thermal comfort, with UTCI providing a measure of thermal conditions.

Table 6. Average Universal Thermal Climate Index (UTCI) for Scenario 1 and Scenario 2 on July 27th at 14:00.

Case study	*Scenario 1* Average UTCI without trees in the court *(°C)*	*Scenario 2* Average UTCI with trees in the court *(°C)*	*Total reduction (°C)*
House A	45.7	42.2	3.5
House B	45.1	42.1	2.9
House C	44.4	41.9	2.5

Comparing the simulated results of Scenario 2 to the Universal Thermal Climate Index (UTCI) scale in Table 2, the average UTCI in Scenario 2, with trees in the courtyard, ranges from 41.9°C to 42.2°C (see Table 6). This range is considered to indicate very strong heat stress. Therefore, further cooling strategies are needed to improve outdoor thermal comfort during peak heat times.

The simulation results of the UTCI for the three case study houses are visually represented through thermal mapping within the courtyards, demonstrating the cooling effect of tree shading on the context, illustrated in Figure 5 (a, b, and c).

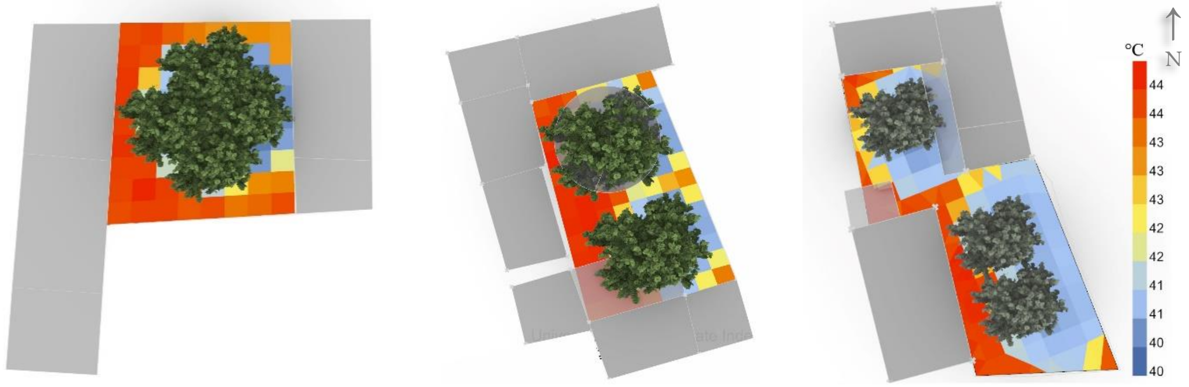

Figure 5 (a): House A **Figure 5 (b):** House B **Figure 5 (c):** House C

Figure 5 : Universal Thermal Climate Index (UTCI) thermal map distribution in °C for July 27th at 14:00.

7. Conclusion

The simulation results demonstrate the impact of tree shading on the radiant environment, notably demonstrated by the reduction in incident radiation when trees are present. This cooling effect on the surroundings plays a crucial role in mitigating heat transfer through buildings.

The impact of tree shading on Mean Radiant Temperature (MRT) and Universal Thermal Climate Index (UTCI) is related and crucial for understanding thermal comfort in outdoor environments. Tree shading reduces MRT by blocking direct solar radiation and preventing surfaces from absorbing excessive heat. Lower MRT values in shaded areas result in reduced radiant heat load on occupants, contributing to a more comfortable thermal environment. The cooler microclimate created by shading leads to lower air temperatures, which in turn lowers UTCI values, indicating improved thermal comfort for occupants.

Nevertheless, even with the decrease in the Universal Thermal Climate Index (UTCI), the prevailing values persist above the recognized comfort range between 9°C and 26°C (see Table 2). Consequently, additional passive cooling strategies are needed to improve thermal conditions and enhance outdoor comfort, particularly during the peak periods of extreme heat in such climatic conditions.

The simulation findings suggest that tree shading within residential settings yields marginal impacts on both air temperature and relative humidity. Consequently, achieving substantial modifications in these parameters requires simulation on a larger urban scale, integrating a more extensive vegetation cover.

8. References

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