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Research Article

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A Design Methodology For Improving Outdoor Thermal Comfort In The Urban Space

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ABSTRACT

Improvement of outdoor thermal comfort is essential for achieving a livable and functional urban space and creating a thermally comfortable environment, so designers must think about developing solutions for landscape and urban design. The main problem is that urban developments in Egypt often overlook green design strategies, leading to an outdoor thermal discomfort environment for users. This paper introduces a simulation workflow utilizing the grasshopper interface with honeybee and ladybug plugins to determine the correlation between optimal tree shading ratios and the changing dimension proportions of a hypothetical central courtyard within the Cairo region. The Cassia nodosa tree model with maximum foliage (Seasonal leaf factor 1.0) has been simulated for a typical summer week from July 24th to July 30th to assess the impact of this correlation on outdoor thermal comfort. The simulation results indicate that the optimal tree shading percentage correlates with varying courtyard dimension proportions, keeping the height constant. This correlation leads to an optimum reduction in Mean Radiant Temperature (MRT) and Universal Thermal Climate Index (UTCI) values, as well as an enhancement in Outdoor Thermal Comfort Percentage (OTCP%) for the square-shaped hypothetical courtyards. Accordingly, a curve graph represents the correlation between the courtyard dimension proportions and the corresponding optimal tree shading ratio obtained. This curve enables both graphical and mathematical determination of this ratio.

Keywords:- Universal Thermal Climate Index (UTCI), Central Courtyards, Outdoor Thermal Comfort, Urban Spaces, Tree Shading.

1. INTRODUCTION

The role of tree shading in urban landscapes is not limited to being just an aesthetic appearance. It extends beyond that, as it acts as an essential element in promoting thermal comfort and human well-being. The effective integration of tree shading in outdoor urban areas and open courtyards has become known for enhancing the thermal comfort of the micro-climate [1]. Tree planting is one of the best strategies to combat urban heat islands and improve outdoor thermal comfort as a result of global warming and permanent urbanization. Furthermore, trees of different species and morphological characteristics can regulate solar radiation and achieve thermal comfort. Moreover, the shading effect generated by the surrounding buildings helps reduce the radiation load and improve the thermal comfort of pedestrians [2].The main effect of trees on thermal comfort lies in their shading effect, as trees work to reduce solar radiation through reflection and absorption. Trees can block a large amount of incoming short waves, in addition to decreasing longwave radiation due to the decrease in surface temperature values. Therefore, what distinguishes trees is their shape, location, and leaf density [3].

Focusing on the improvement of outdoor thermal comfort by examining the role of vegetation cover, where two main factors were investigated; tree species and layout. Microclimate data collected on a summer day for a street in a boulevard located in Guelma City, Algeria, results showed that Ficus Nitida is the most significant species that intercepts solar radiation and provides shade while providing the maximum reduction in (Ta) by 0.3°C and (UTCI)= 2.6 °C at 1:00 p.m. The layout of trees is also a pivotal factor in shading paths based on the quality of the shade cast by the trees. Also, planting Washingtonia palms along the middle of the street is the

best option to maximize the shade while achieving the maximum reduction in (Ta) by 1.8°C and (UTCI) = 3.5 °C at 4:00 p.m. [4].
Investigate the role of tree canopy coverage in improving thermal comfort in high-temperature and humidity urban areas, A study in Wuhan's shallow street canyon, China, found that higher tree canopy coverage significantly decreases (Ta) and (MRT) by up to 3.3°C and 13.9°C, respectively, in addition, shading and increasing wind speed are more effective strategies for thermal comfort than temperature and humidity control [5]. On the other hand, based on a study conducted in Thailand, trees and shrubs significantly enhance thermal comfort, particularly during the late afternoon, by examining various tree coverage scenarios:25%, 50%, 75%, and 100% found that 50% of tree coverage boosts eco-efficient than shrubs based on the change of (PET) relative to the cost of greenery [6]. A study within Egypt's hot arid climate was investigated to quantify the impact of different green design strategies on urban microclimate and human outdoor thermal sensation. The study revealed that significant thermal comfort was achieved by using the maximum tree coverage with a (PMV) value drop of 2.48 during peak hours compared with the base case scenario [7].

In addition to tree shading, the environmental features of courtyards are crucial, particularly in residential buildings, as it is an important factor in absorbing solar radiation on the courtyard surfaces. Thus, controlling the shading performance of thermal comfort is one of the most effective factors in reducing the ambient temperature. A study examining four traditional houses with courtyards in Iran's hot (Kashan) and cold (Ardabil) climates. The shaded areas for each case were analyzed using the Design Builder software. The results showed that the best shape for the courtyard in these climates is the rectangular shape. Moreover, increasing the length-to-width ratio (L/W) alongside the height (H) of the walls increases the shading ratio, the study concluded that there is a correlation showing that lower values of (MRT) improve the (PMV) index, indicating better thermal comfort [8]. The level of thermal comfort in residential courtyards in hot climates has been investigated in the City of Baghdad. The study develops a novel metric called Courtyard Thermal Usability Index (CTUI) and uses the Envi-met simulation tool to determine the annual thermal conditions and to quantify the ability of 360 tested courtyards to provide occupants with thermal comfort. (CTUI) represents the proportion of the thermally comfortable hours /total occupant hours. Results showed that courtyards offer up to 38% comfortable hours, and the rest of the time is not-comfortable due to overheating. When designing courtyards, the most effective geometric parameter for improving the thermal condition is the width to height ratio (W/H), and accordingly, the deeper the courtyard, the higher the shading level, the lower (MRT), and the lower the occupants' thermal sensation (Tg) [9]. Integrating courtyard dimensions with tree coverage to extreme environmental benefits includes considering many factors. The impact of tree species and configuration on the outdoor thermal comfort of a courtyard building was studied with numerical simulation validated by field measurement for two actual courtyard buildings, with and without trees, located at (IKIU) campus in Qazvin, Iran during (June 21st and Dec 21 st), the study showed that local trees provide the most protection of micro-climate in the courtyard with a significant improvement in (PET) during warm and cold periods [10]. Another study at Guangzhou University, China, investigated the impact of tree canopy coverage (TCC) on thermal comfort in two courtyards having different height-to-width (H/W) ratios examined using field data and Envi-met simulation. Increasing (TCC) enhances the cooling effect, particularly during peak hours, with courtyards having a higher (H/W) ratio showing a great cooling effect compared to those with a low (H/W) ratio, with the difference in (PET) up to 0.6°C. However, over the entire daytime, lower (H/W) courtyard have achieved more heat reduction than higher (H/W) courtyards up to 2500 J/m² [11].

The correlation between tree shading ratio and courtyard dimension proportions for outdoor thermal comfort in Egypt is crucial and requires further research, studies have implicated a correlation between the courtyard dimension proportions (L/W) and the optimal tree coverage ratio. A tree coverage ratio of 50% is optimal with a courtyard dimension proportion (L/W) of 3:1, conversely, a tree coverage ratio of 30% is optimal when the dimension proportion (L/W) is 1.5:1 [12], while the tree coverage ratio of 25% is optimal for a dimension proportion (L/W) of 1:1, to enhance outdoor thermal comfort by reducing (MRT) and (PMV) values [13], However, it is important to note that the height of the courtyard surrounding walls can significantly change these ratios. Furthermore, the orientation of the courtyard plays an effective role in mitigating the intensity of solar radiation [14]. In the role of mitigating heat stress at Aswan hot-arid climate, a study utilized field measurement and simulation to assess thermal comfort through (PET) index suggests that courtyards should be oriented at (N-S) direction to mitigate the impact of solar radiation so (SVF) can be reduced less than 0.2 with no heat-trapping issue. Additionally, providing green areas to courtyards can improve their thermal performance [15]. These results emphasize the importance of integrating tree coverage ratio with courtyard dimension proportions and orientation in urban design to improve outdoor thermal comfort in the Egyptian region.

The main objective of this study is to develop a design methodology that can enhance outdoor thermal comfort for occupants in urban spaces in Cairo's hot-arid climate, which involves examining the correlation between the optimal tree shading ratio and a hypothetical courtyard dimension proportions and orientation. By identifying a correlation curve, the research enables urban designers and architects to find the optimal ratio closest to achieving thermal comfort graphically and mathematically.

2. METHODOLOGY

This study presents a design methodology that investigates the correlation between the optimal tree shading ratio and the dimension proportion and orientation of the courtyard. The simulation process utilized Honeybee and Ladybug plugins within Rhino-Grasshopper. A hypothetical courtyard dimension proportions were analyzed: (L: W: H = 1:1:1, 2:2:1, 3:3:1, 4:4:1, 5:5:1 and, etc.), representing a gradually regular expanded square-shaped courtyard, while keeping the height (H) constant. Additionally, the multiples for dimension proportions possibilities of the courtyard simulated for the (North/South and East/West) orientations. The goal was to determine the optimal tree shading, which would allow for the optimal reduction in (UTCI) and (MRT) would be achieved with more shading.

2.1. Thermal performance measurement indicators.

2.1.1. Universal Thermal Climate Index (UTCI).

The Universal Thermal Climate Index (UTCI) is a metric strictly for outdoors that measures the physiological behavior of the human body under specific meteorological conditions and takes into account multiple climatic factors such as wind velocity (m/s), air temperature (Ta), mean radiant temperature (MRT) and, relative humidity (RH%). This index can be calculated based on this mathematical equation [16], [17]:

$UTCI = 3.21 + 0.872 . Ta + 0.2459 . Tmrt - 2.5078 . V - 0.0176 . RH\%$. [equ.1]

While (UTCI) is valid in all climates, seasons, and scales, it assumes that the human is a walking person and naturally adapts his clothes to the outdoor temperature. It is possible to categorize the thermal stress experienced by pedestrians according to (UTCI) values, as shown in **Table 1.**

- **Table 1.** (UTCI) assessment scales categorized in terms of thermal stress: [16]

UTCI range (°C)	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
+9 to 0	Slight cold stress
0 to −13	Moderate cold stress
−13 to −27	Strong cold stress
−27 to −40	Very strong cold stress
Below −40	Extreme cold stress

2.1.2. Mean Radiant Temperature (MRT).

The radiant temperature serves as the main indicator of the impact of radiation on the human body.

2.2. Cassia nodosa tree.

Cassia nodosa, as shown in **Figure 1**, is a tree species commonly used in the Cairo region, and it adapts well to hot climates. It is a deciduous tree and is extensively used in urban parks and open areas, as it provides sufficient shade in the summer and warm in the winter when its leaves fall. The specifications of the tree are listed in **Table 2**.

- **Table 2.** Cassia nodosa tree specification [18]:

Specification	Proposed tree species
Name	Cassia nodosa
Alternative name	Pink shower
Total height	7
Maximum LAD at height	5
Foliage height	3
Foliage Albedo	0.18
LAI Leaf Area Index	1.61

Figure 1: Cassia nodosa *[26]*

The seasonal leaf/foliage calendar, as presented in **Table 3**, enables for adjustments to the Leaf Area Density **(LAD)** throughout the year to simulate various stages of foliage growth for deciduous trees. Specifically, LAD values defined for the tree range from a maximum seasonal leaf factor of 1.0 (representing full shade during peak leafiness) to a minimum of 0.3 (accounting for branches that exists even in winter). Values above 0.2 are interpreted as leaves.

- **Table 3.** Cassia nodosa foliage calendar [19]:

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Seasonal leaf factor	0.3	0.3	0.3	0.4	0.7	1.0	1.0	1.0	0.8	0.6	0.3	0.3

2.3. Simulation tool.

Rhino-grasshopper is a computational program for parametric modeling and performance analysis in many fields. It combines the Rhino 3D interface with Grasshopper to create models based on specific algorithms.
The literature review indicated that the development of digital workflow incorporating to enhance thermal comfort Rhino-grasshopper with Honeybee and Ladybug plugins are reliable tools that can accurately determine the effect of vegetation and different infrastructures on outdoor thermal comfort by measuring the (UTCI) [20], besides the ability of these tools to create complex three-dimensional engineering models and the possibility of their application in architectural design [21]. By investigating and comparing the microclimate simulation results obtained from the validated and fully integrated program software Envi-met and Ladybug parametric tool, it found a high agreement in results for both simulation processes with too close calculation errors proximity, and also, results have shown that readings and thermal maps obtained from Ladybug tool workflow are significantly efficient in the outdoor microclimate parameters visually and numerically, hence they would have a design guideline in early design strategies helps the urban planners and architects to optimize the urban design thermal performance [22].

2.4. Data collection and model setup.

2.4.1. Location and hypothetical courtyard description.

Based on the Köppen climate classification, Cairo's climate is hot-arid. Using the weather file of the Cairo A.P. monitoring, the average temperature during a typical summer week is 27.5 °C and a relative humidity of 54%. Temperatures can reach even higher during intense heat waves. The average wind speed from mid-July to early March is the slowest at 3.5 m/s, while its highest speed record throughout the rest of the year, at more than (4 m/s). The dominant winds come from the north, the northeast, and the northwest, with average speeds of 3.79, 4.19, and 3.56 m/s, respectively [18].
The hypothetical courtyard is located within the Cairo climate zone at coordinates Lat: 30.12, Long: 30.92, Tz: 2.00, Elev: 151.0 m. The comprehensive simulation workflow is detailed as follows:

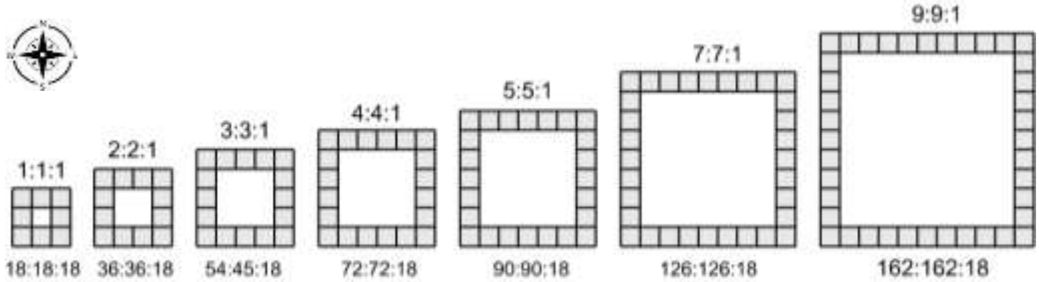


Figure 2: The different proportions and dimensions of the hypothetical courtyard.

A. Building the Model: This involves modeling the courtyards with their various dimensions, surrounding buildings, floors, and surfaces using the Rhino program interface in addition to a tree model that will introduced and discussed subsequently. The different proportions and dimensions of the courtyard are shown in **Figure 2.**

B. Data Entry: This includes inputting a suite of essential data, including the weather data file, orientation, simulation duration, and measurement points represented by the test grid. Data also involves the characteristics of building materials, window-to-wall ratio, ground pavement materials, vegetation cover, and the transmittance of the tree canopy.

C. Simulation process: The simulation was conducted in several stages, beginning with the export of HB-zones to an OPEN STUDIO file, executed via the ENERGY PLUS engine, resulting in outdoor surface temperatures used to assemble an outdoor comfort analysis recipe.

D. Output: The comfort assessment of ENERGY PLUS results includes many measurements, such as Mean Radiant Temperature (MRT), Air Temperature (Ta), Universal Thermal Climate Index (UTCI), and Outdoor Thermal Comfort Percentage (OTCP%). Additionally, the microclimate map can also be generated. **Figure 3** illustrates the simulation workflow, and **table 4.** shows the model input parameters.

Figure 3: An illustrative diagram of the inputs, outputs, and the simulation workflow.

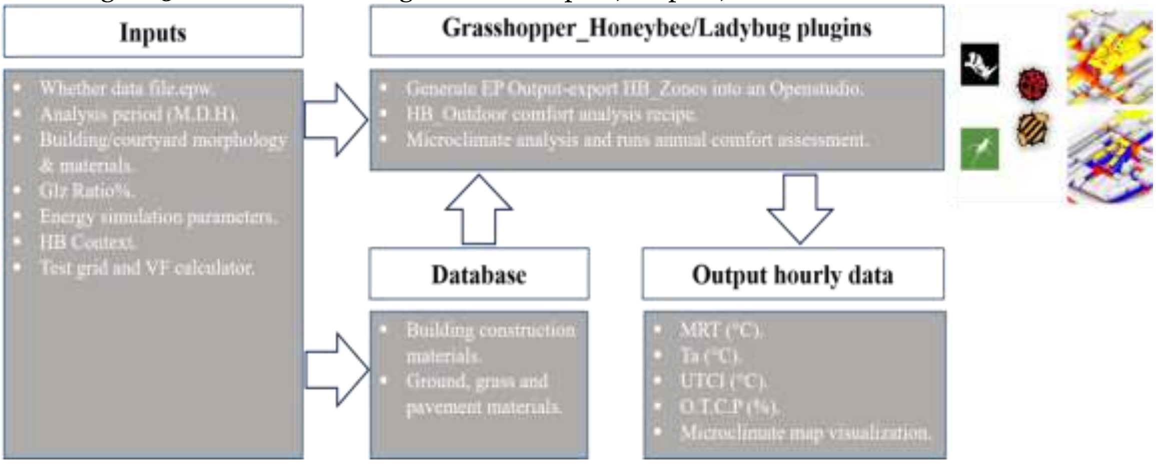


Table 4. Model input parameters.

Input parameters	**Item**	**Value**
Hypothetical courtyard proportions	Length: Width: Height L:W:H	1:1:1, 2:2:1, 3:3:1, and, etc. Incrementally expands
Surrounding buildings height	Fixed (h)	18m/ 6 stories
Model domain	Test grid size (x, y, z)	6m*6m*1.5 m
Duration of the simulation (Typical summer week)	D.M HH:MM	24 Jul – 30 Jul 10:00am – 16:00pm [Daily peak time]
Meteorological data	Cairo.West.AirPort_TMYx	
Orientation	Fixed orientation (N/S-E/W)	
Building program	Midrise Apartment	
Wall and roof materials	Default settings in Rhino GH	
WWR%	15%	
Pavement materials	Concrete	

2.4.2. Tree model description.

The Cassia tree model was built using the Rhino. The tree trunk has a height of 4 meters, and the canopy and foliage have a height of 3 meters. Consequently, the total height of the tree model is 7 meters. The tree canopy diameter was set to 6 meters to align with the cell size of the test grid and to facilitate the tree distribution process during simulation with the incremental increase in the courtyard dimension proportion and the tree coverage ratio.

Regarding the transparency and solar radiation transmission through the tree canopy, the seasonal leaf factor is expressed as 1, indicating complete shading during July (as detailed in **Table 3**). Alternatively, the tree canopy transmittance of 0 can be entered instead in the transparency schedule in the program. **Figure 4** provides the dimensions and inputs for the tree model during the simulation period from July 24 to July 30.

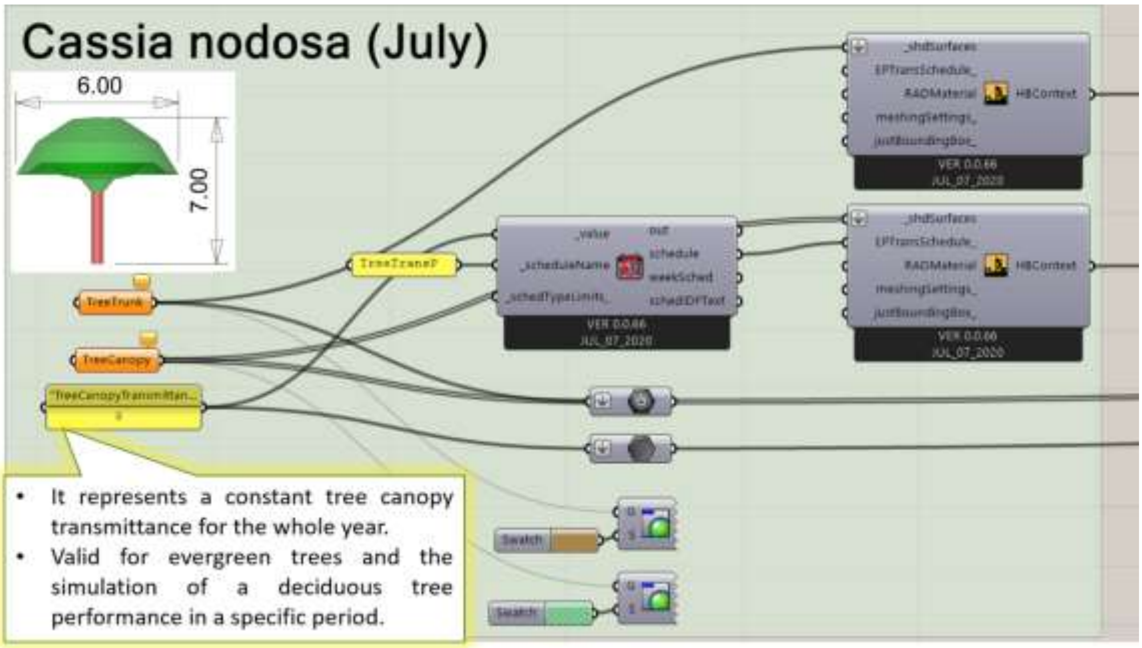


Figure 4: Cassia tree model dimensions and inputs.

3. RESULTS AND DISCUSSION.

3.1. Tree distribution Strategies in the courtyard to enhance thermal comfort.

Based on a previous study on the effect of urban space components on thermal comfort in urban spaces [13], this study addressed the effect of tree distribution strategies on the thermal comfort index (PMV). These strategies are as follows:

1. Grid/chess.
2. Four sides and a middle group.
3. A central mass in the middle of the space.

The study found that the "Grid/Chess" distribution is the worst while the best is "A central mass in the middle of the space," with a slight difference in the (PMV) values between the three cases throughout the day hours.

"**Hotspot track distribution**", as shown in **Figure 5** is a strategy created in this study that considers for the incremental effect of tree shading based on (MRT °C) values on the comfort map. Initially, the hypothetical courtyard was simulated without tree shading. Subsequently, the tree model is distributed across the map, covering 10% of the courtyard area based on (MRT °C) values above the test grid points. The simulation was then repeated for 20% tree coverage using the values obtained from the 10% simulation. This incremental approach was followed for tree coverages of 30%, 40%,50%, and 60%, ultimately reaching 100%.

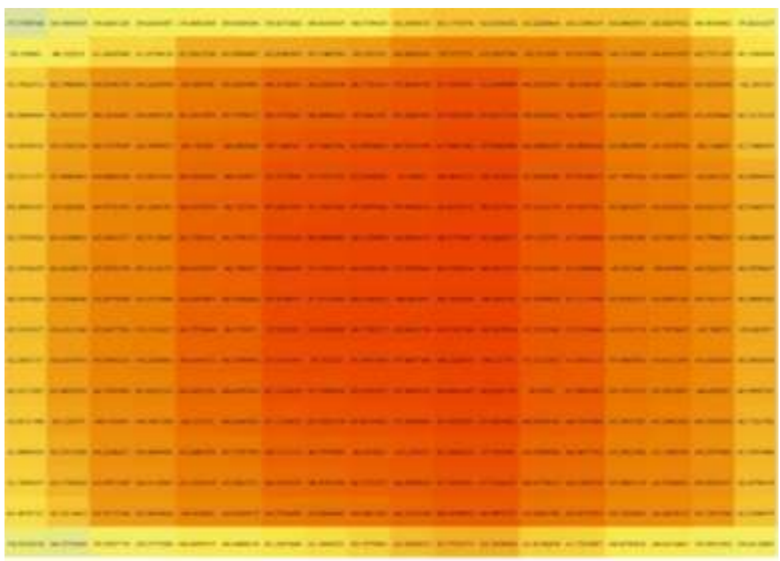
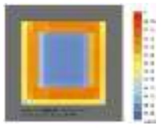
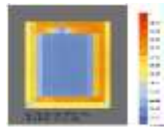
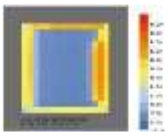
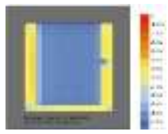
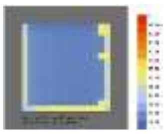
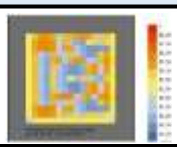
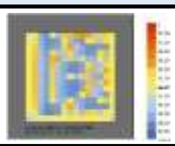
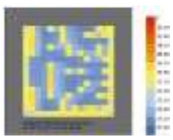
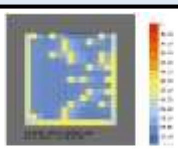
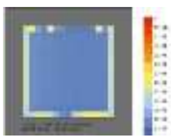
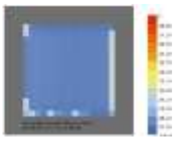


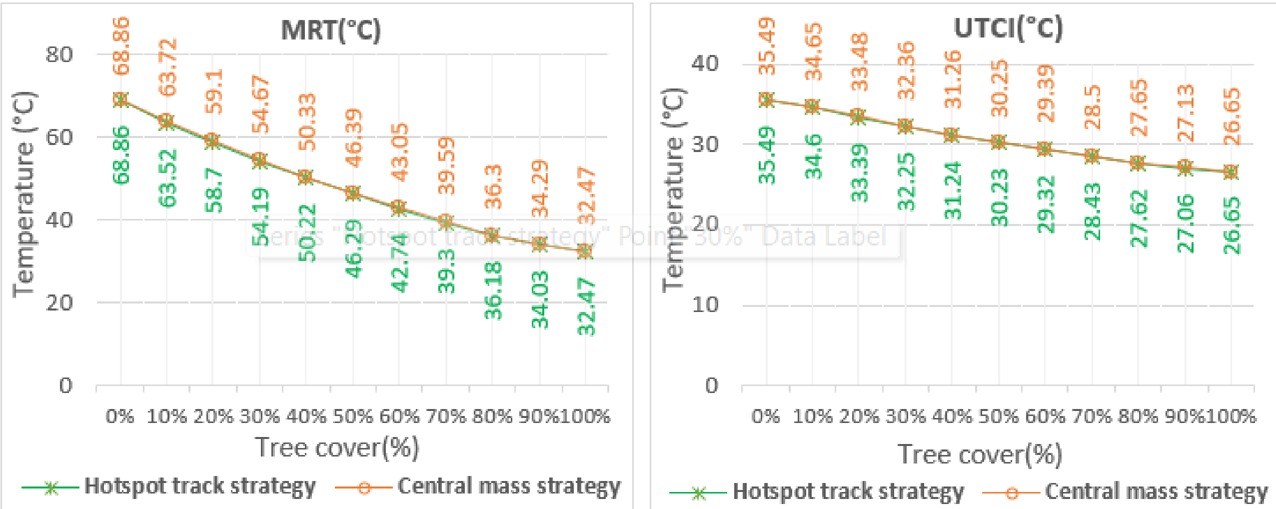
Figure 5: Hotspot track distribution method: incremental tree shading.

To verify and validate the hotspot track and to ensure more accurate results, the strategy was tested and compared with the central mass in the middle of the space strategy, as concluded in the previous research [13].

The results demonstrated that the hotspot track distribution is the most accurate, as evidenced by achieving lower (UTCI) and (MRT) values, with a slight difference in measurements between the two strategies. **Table 6** shows the microclimate map for both strategies during the typical summer week from 24 July to 30 July, from 10:00 to 16:00, for the hypothetical courtyard with proportions (L: W: H) = (5:5:1), where the surrounding buildings maintain a height of 18m. Additionally, **Figure** 7 explains the (MRT) and (UTCI) values extracted for the two strategies, followed by statistical deviation measurement between them.

Table 6: The microclimate map for central mass and hotspot track strategies.

N/S-E/W 5:5:1	**(UTCI) Tree Coverage map (%)**				
	10%	20%	30%	40%	50%
Central mass distribution					
	60%	70%	80%	90%	
					
	10%	20%	30%	40%	50%
Hotspot track distribution					
	60%	70%	80%	90%	
					



Dev.	0	0.003	0.007	0.009	0.002	0.002	0.007	0.007	0.003	0.007	0

Dev.	0	0.001	0.003	0.003	0.001	0.002	0.002	0.002	0.001	0.002	0

Figure 6: The (MRT) and (UTCI) values extracted for the two strategies and the statistical deviation calculation between them.

3.2. The simulation outputs avg. values for outdoor thermal comfort terms.

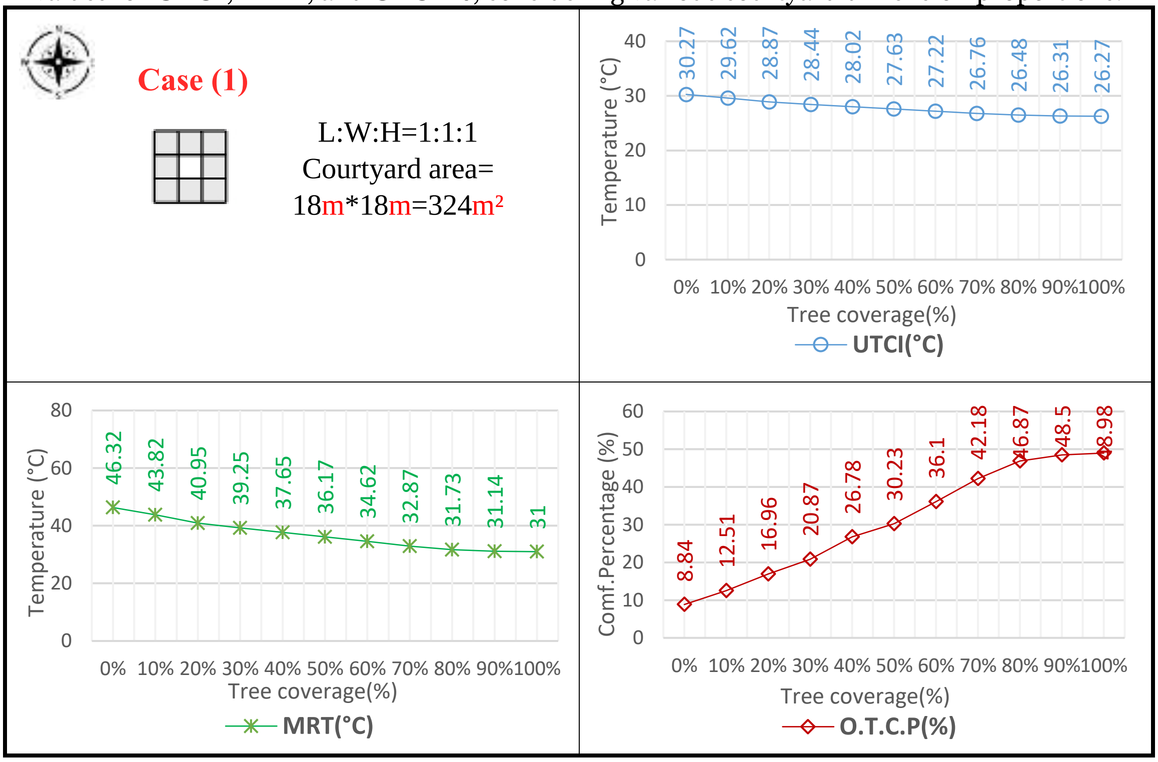
3.2.1. The Impact of Tree Shading on Outdoor Thermal Comfort in Courtyards.

Through simulation results corresponding to various dimensions and proportions of the hypothetical courtyard during a typical summer week from July 24 to July 30, between 10 a.m. and 4 p.m., the impact of tree shading on thermal comfort levels within courtyards with varying proportions and dimensions becomes evident. In all cases, there is a significant reduction in (MRT) values and a corresponding decrease in (UTCI).

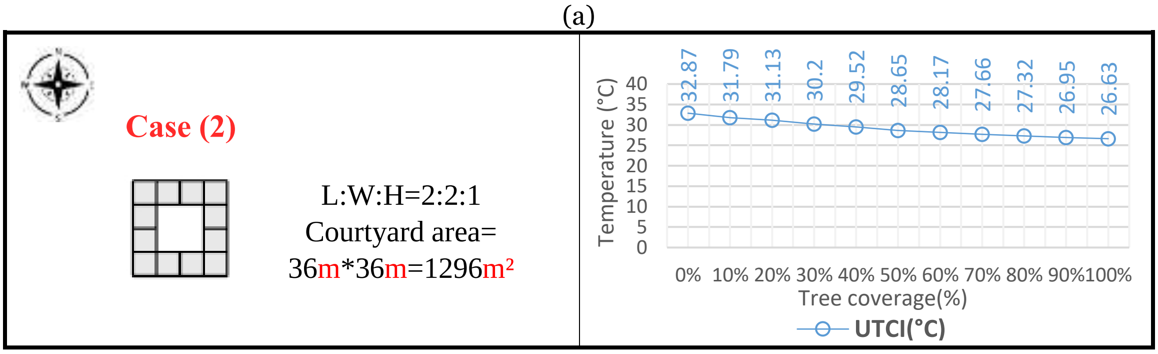
By comparing courtyards under different tree shading conditions—ranging from no tree shading (0%) to maximum tree shading (100%)— The following trends were observed: Courtyard Ratio L:W: H = 1:1:1, where Mean Radiant Temperature (MRT) decreased by 15.32°C and Universal Thermal Climate Index (UTCI) decreased by 4.0°C; Courtyard Ratio L:W: H = 2:2:1, with MRT decreasing by 24.19°C and UTCI decreasing by 6.24°C; Courtyard Ratio L:W: H = 3:3:1, resulting in an MRT decrease of 30.20°C and a UTCI decrease of 7.76°C; Courtyard Ratio L:W: H = 4:4:1, leading to an MRT decrease of 33.97°C and a UTCI decrease of 8.69°C; Courtyard Ratio L:W: H = 5:5:1, causing an MRT decrease of 36.39°C and a UTCI decrease of 9.29°C; and Courtyard Ratio L:W: H = 9:9:1, with an MRT decrease of 41.32°C and a UTCI decrease of 10.51°C.

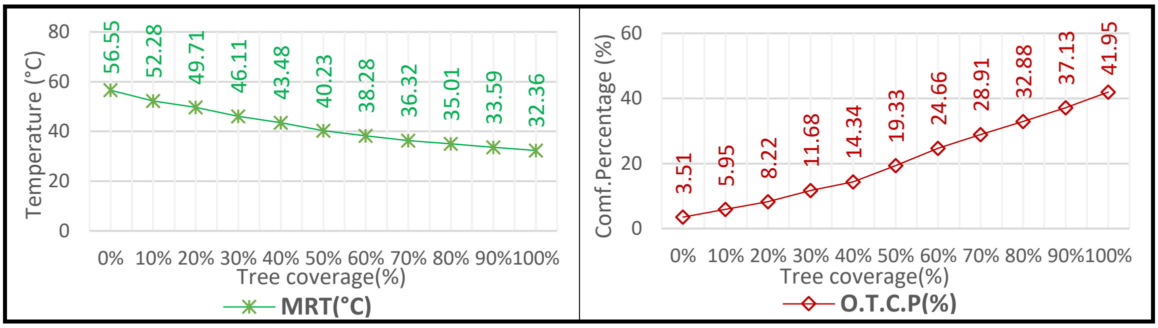
The effectiveness of tree shading in enhancing outdoor thermal comfort becomes particularly obvious as courtyard dimensions proportions increase. Since tree shading mitigates direct solar radiation, it plays a crucial role in creating more comfortable microclimate within courtyards. As a result, the outdoor thermal comfort percentage (OTCP%) increases by approximately 40% for all cases.

Figure 7 shows graphs illustrating the relationship between the tree shading ratio (%) and the corresponding values for **UTCI**, **MRT**, and **OTCP%**, considering various courtyard dimension proportions.

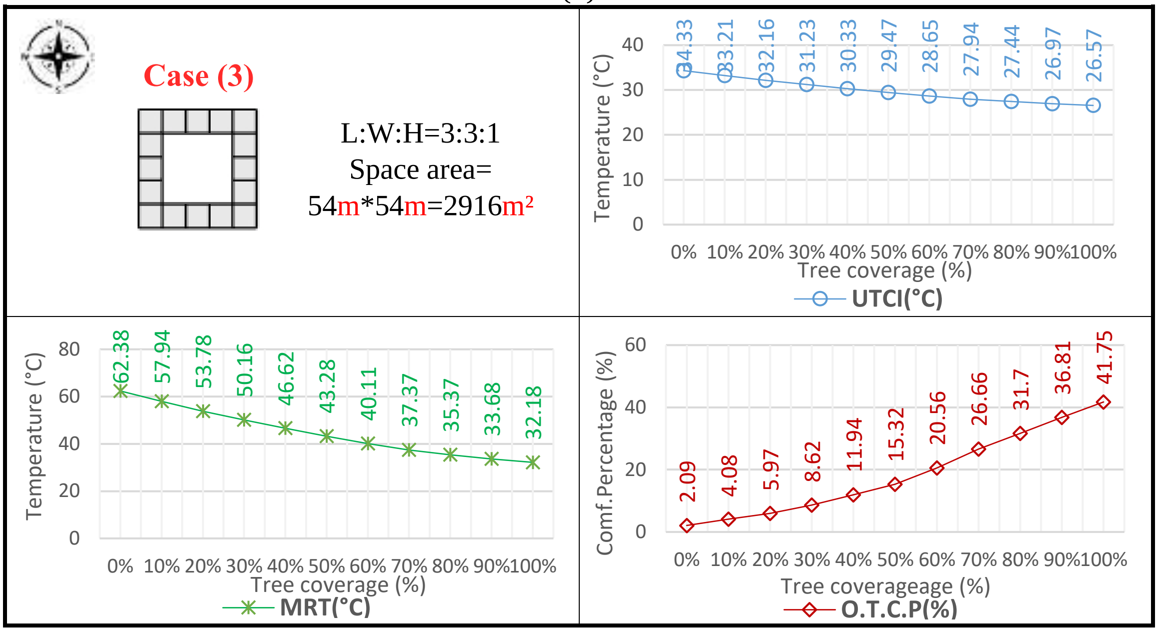


(a)

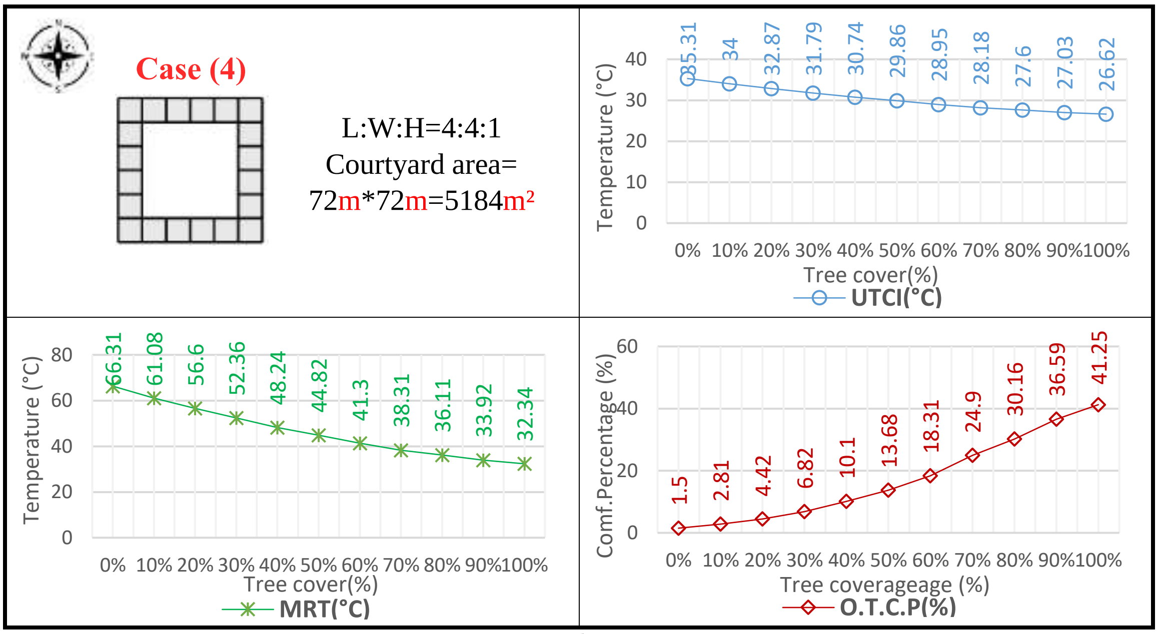



Temperature (°C)
80
60
40
20
0
56.55 52.28 49.71 46.11 43.48 40.23 38.28 36.32 35.01 33.59 32.36
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Tree coverage(%)
MRT(°C)
Comf.Percentage (%)
60
40
20
0
3.51 5.95 8.22 11.68 14.34 19.33 24.66 28.91 32.88 37.13 41.95
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Tree coverage(%)
O.T.C.P(%)

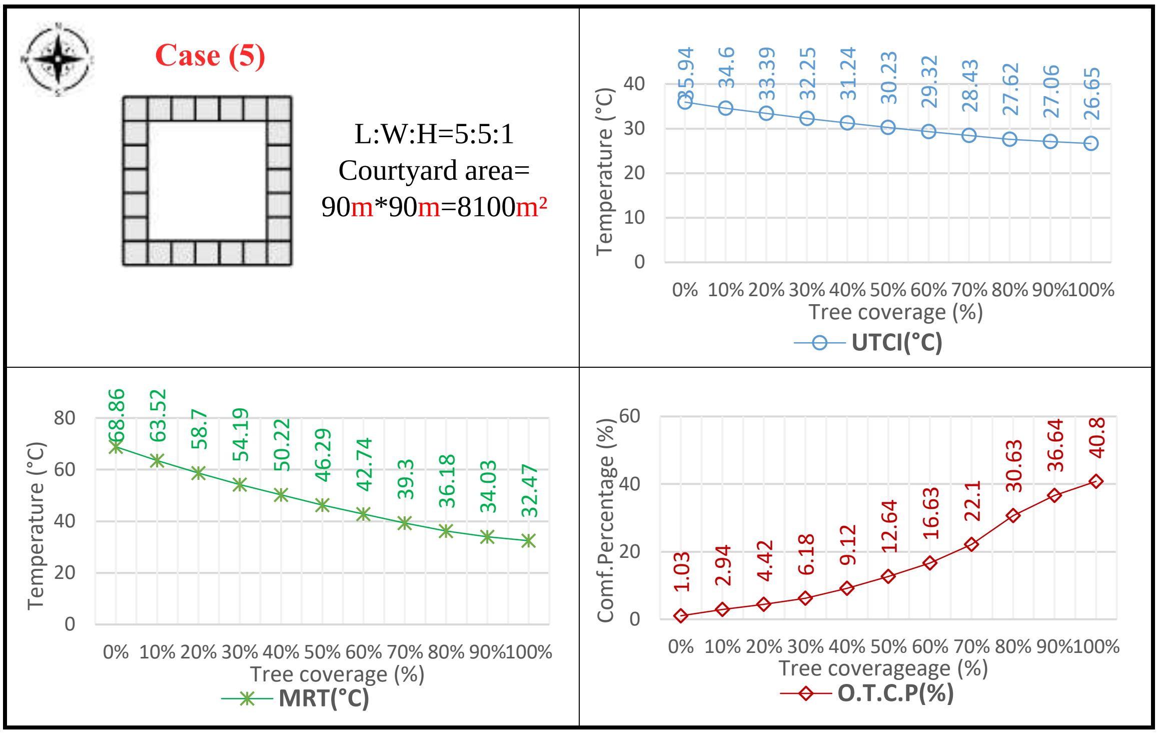
(b)


Case (3)
L:W:H=3:3:1
Space area=
54m*54m=2916m²
Temperature (°C)
40
30
20
10
0
34.33 33.21 32.16 31.23 30.33 29.47 28.65 27.94 27.44 26.97 26.57
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Tree coverage (%)
UTCI(°C)
Temperature (°C)
80
60
40
20
0
62.38 57.94 53.78 50.16 46.62 43.28 40.11 37.37 35.37 33.68 32.18
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Tree coverage (%)
MRT(°C)
Comf.Percentage (%)
60
40
20
0
2.09 4.08 5.97 8.62 11.94 15.32 20.56 26.66 31.7 36.81 41.75
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Tree coverageage (%)
O.T.C.P(%)

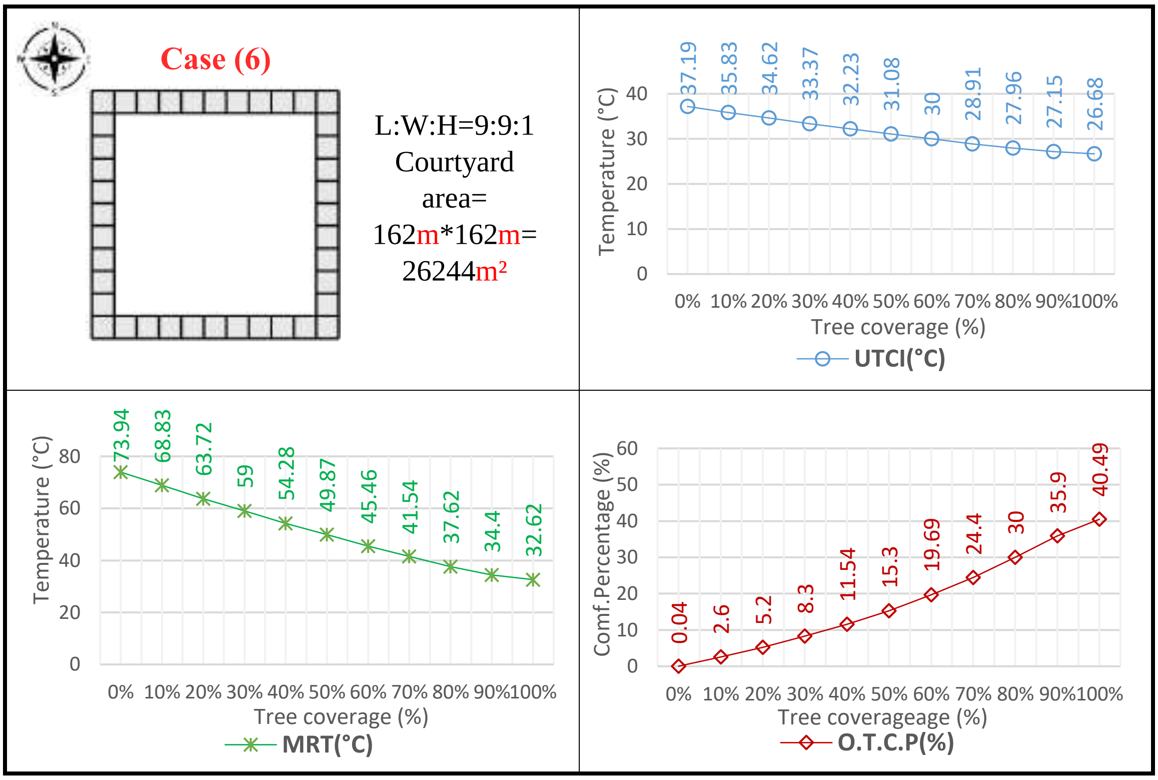
(c)


Case (4)
L:W:H=4:4:1
Courtyard area=
72m*72m=5184m²
Temperature (°C)
40
30
20
10
0
35.31 34 32.87 31.79 30.74 29.86 28.95 28.18 27.6 27.03 26.62
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Tree cover(%)
UTCI(°C)
Temperature (°C)
80
60
40
20
0
66.31 61.08 56.6 52.36 48.24 44.82 41.3 38.31 36.11 33.92 32.34
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Tree cover(%)
MRT(°C)
Comf.Percentage (%)
60
40
20
0
1.5 2.81 4.42 6.82 10.1 13.68 18.31 24.9 30.16 36.59 41.25
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Tree coverageage (%)
O.T.C.P(%)

(d)



(e)



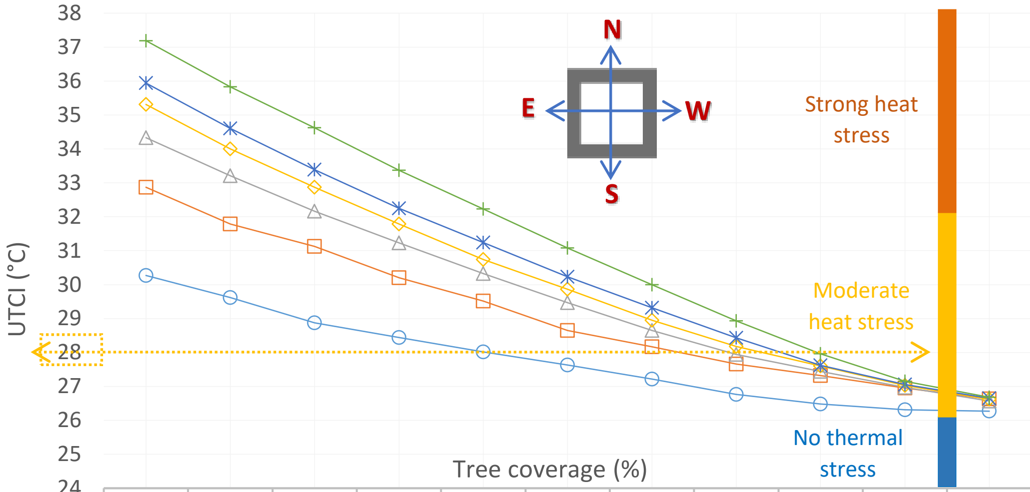
(f)

Figure 7: The relationship between the tree shading ratio (%) and the corresponding values for UTCI, MRT, and OTCP%, considering various courtyard proportions (L:W:H): (a) 1:1:1, (b) 2:2:1, (c) 3:3:1, (d) 4:4:1, (e) 5:5:1, and (f) 9:9:1.

3.2.2. Determine the optimal tree shading ratio that best suits each case.

A combined graphical curve was created for each case, considering the different proportions and dimensions of the courtyards. This curve illustrates the correlation between the tree shading ratio (on the horizontal axis) and the UTCI temperature (on the vertical axis).

The average value of 28 °C determined as a target temperature on the UTCI. Additionally, a horizontal line intersects each curve, indicating the percentage of tree shading required to achieve that specific value. The value of 28°C was selected because it falls near the lower end of the moderate thermal stress range, which extends from 26°C to 32°C. Consequently, it almost touches the boundaries of thermal comfort. Additionally, this choice allows for greater flexibility in applying various tree shading ratio scenarios other than 27°C, as demonstrated in **Figure 8**.

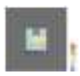
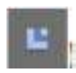
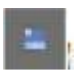
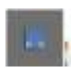


	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
UTCI(°C) 1:1:1	30.27	29.62	28.87	28.44	28.02	27.63	27.22	26.76	26.48	26.31	26.27
UTCI(°C) 2:2:1	32.87	31.79	31.13	30.2	29.52	28.65	28.17	27.66	27.32	26.95	26.63
UTCI(°C) 3:3:1	34.33	33.21	32.16	31.23	30.33	29.47	28.65	27.94	27.44	26.97	26.57
UTCI(°C) 4:4:1	35.31	34	32.87	31.79	30.74	29.86	28.95	28.18	27.6	27.03	26.62
UTCI(°C) 5:5:1	35.94	34.6	33.39	32.25	31.24	30.23	29.32	28.43	27.62	27.06	26.65
UTCI(°C) 9:9:1	37.19	35.83	34.62	33.37	32.23	31.08	30	28.93	27.96	27.15	26.68

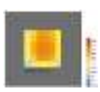
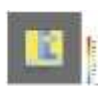
Figure 8: A combined correlation graphical curve for different courtyard proportions.

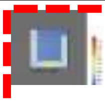
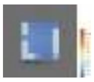
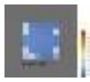
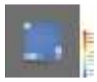
Table 7 presents the microclimate map extracted from simulation results, showcasing the corresponding UTCI values for incremental tree shading ratios. Furthermore, the optimal tree shading ratios and distribution for each courtyard dimension proportion (L:W: H) were determined. Specifically, the optimal tree shading ratios of 1:1:1, 2:2:1, 3:3:1, 4:4:1, 5:5:1, and 9:9:1 are 40%, 60%, 70%, 70%, 80%, and 80%, respectively.

Table 7: The UTCI microclimate map showing the corresponding incremental tree shading ratios for courtyards proportions (L:W: H) of 1:1:1, 2:2:1, 3:3:1, 4:4:1, 5:5:1, and 9:9:1.

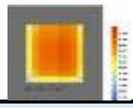
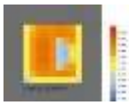
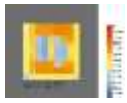
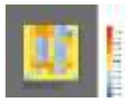
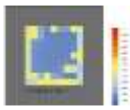
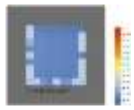
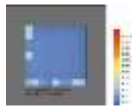
N/S-E/W	**(UTCI) Tree Coverage map (%)**				
	0%	10%	20%	30%	**40%**
L:W:H 1:1:1					
	50%	60%	70%	80%	90%
					

(a)

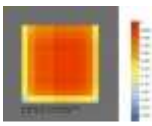
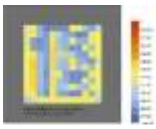
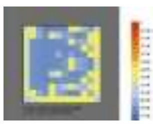
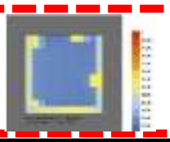
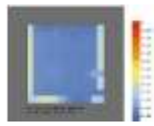
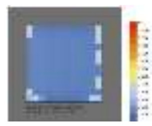
N/S-E/W	**(UTCI) Tree Coverage map (%)**				
	0%	10%	20%	30%	40%
L:W:H 2:2:1					
	50%	**60%**	70%	80%	90%

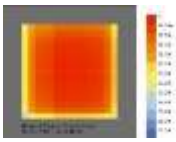
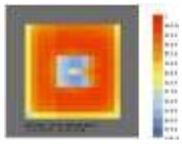
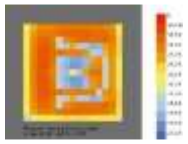
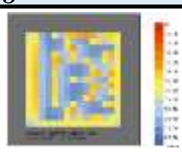
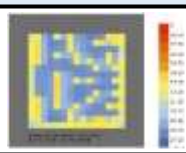
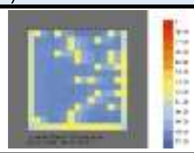
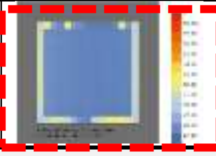
(b)

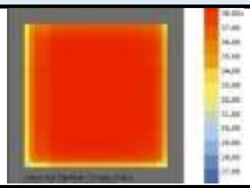
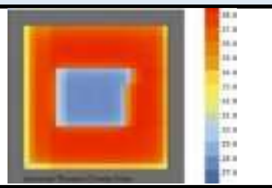
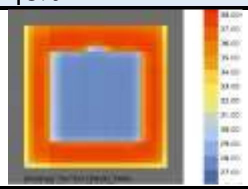
N/S-E/W	(UTCI) Tree Coverage map (%)				
	0%	10%	20%	30%	40%
L:W:H 3:3:1					
	50%	60%	**70%**	80%	90%
					

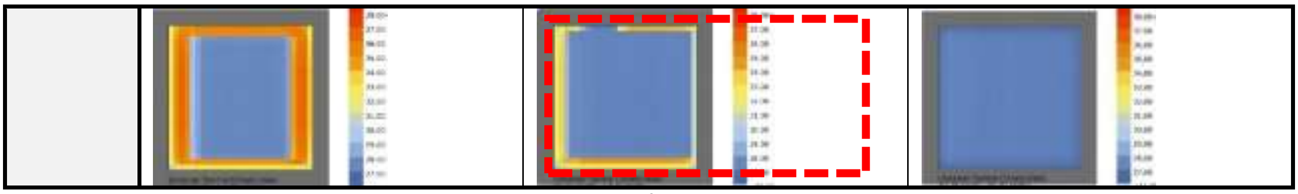
(c)

N/S-E/W	(UTCI) Tree Coverage map (%)				
	0%	10%	20%	30%	40%
L:W:H 4:4:1					
	50%	60%	**70%**	80%	90%
					

(d)

N/S-E/W	(UTCI) Tree Coverage map (%)				
	0%	10%	20%	30%	40%
L:W:H 5:5:1					
	50%	60%	70%	**80%**	90%
					

(e)N/S-E/W	(UTCI) Tree Coverage map (%)		
	0%	20%	40%
L:W:H 9:9:1			
	60%	**80%**	100%



(f)

Based on the graphical curve in **Figure 8**, which illustrates the relationship between various courtyard dimension proportions and the UTCI values, and by referencing **Table 7** for the UTCI microclimate map, we can determine the optimal tree shading ratios corresponding to different courtyard configurations. Applying these ratios allows for calculating the improvement resulting from the differences in MRT and UTCI values for cases with and without trees. The (MRT) reductions for courtyard proportions of 1:1:1, 2:2:1, 3:3:1, 4:4:1, 5:5:1, and 9:9:1 were 8.67°C, 18.27°C, 25.1°C, 28°C, 32.68°C, and 36.32°C, respectively, while the corresponding decreases in (UTCI) values were 2.25°C, 4.7°C, 6.39°C, 7.13°C, 8.32°C, and 9.23°C. Remarkably, the thermal performance across all courtyard scenarios becomes equivalent, as demonstrated in **Figure 9**.

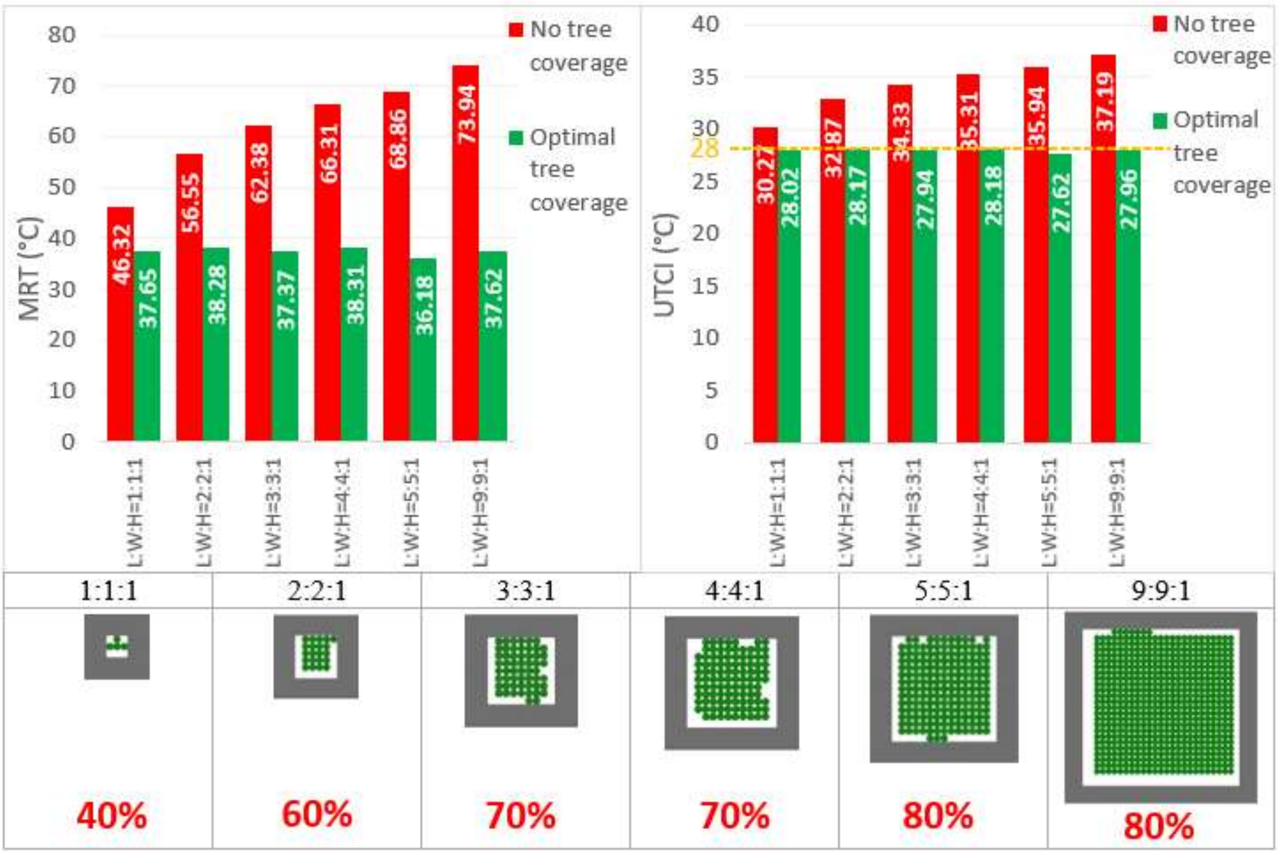


Figure 9: An illustrative chart displays (MRT) and (UTCI) values, comparing scenarios with and without tree shading for different courtyard proportions.

Accordingly, it is possible statistically to conclude a graphical curve for a relationship that combines the proportions of the courtyard dimensions (as represented on the X- axis) and the corresponding optimal tree shading ratio (as represented on the Y- axis).

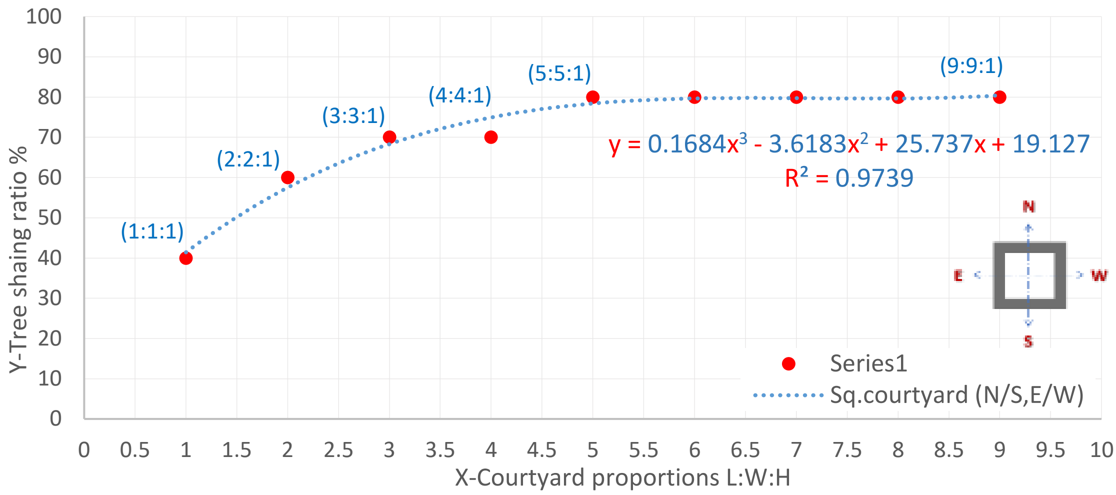


Figure 10: A graphical curve for a relationship between the proportions of the courtyard dimensions (**X-** axis) and the corresponding optimal tree shading ratio (Y-axis).

This curve allows for graphical determination of the relationship or mathematical determination using the polynomial equation of the curve. It is applicable to any square courtyards that have dimensional proportions specified on the horizontal axis, as shown in **Figure 10**.
The equation of the curve is as follows:
$y = 0.1684\, x^3 - 3.6183\, x^2 + 25.737\, x + 19.127.$ [equ.2]

4. CONCLUSION AND FURTHER RESEARCH.

This study has explored the correlation between (North/South-East/West) oriented square hypothetical courtyard dimension proportions and optimal tree shading ratios to improve outdoor thermal comfort. Hence, the findings highlighted the following key points:

a. A slight negligible variation exists between a central mass distribution and hotspot track distribution when comparing (UTCI) and (MRT) results for both strategies.
b. The dimension proportions of courtyards significantly impact the microclimate. By analyzing various courtyards, it has been found that courtyards exhibit variable thermal behavior. Specifically, the (MRT) values corresponding to courtyard proportions of 1:1:1, 2:2:1, 3:3:1, 4:4:1, 5:5:1, and 9:9:1 were 46.32°C, 56.55°C, 62.38°C, 66.31°C, 68.86°C, and 73.94°C, respectively. Similarly, the (UTCI) values were 30.27, 32.87, 34.33, 35.31, 35.94, and 37.19, respectively, with no tree shading for all cases.
c. The optimal tree shading ratio was identified for each courtyard dimension proportion. This ratio ensures a balance between providing shade and enhancing outdoor thermal comfort. The (MRT) reductions for courtyard proportions of 1:1:1, 2:2:1, 3:3:1, 4:4:1, 5:5:1, and 9:9:1 was 8.67°C, 18.27°C, 25.1°C, 28°C, 32.68°C, and 36.32°C, respectively. Similarly, the corresponding decreases in (UTCI) values were 2.25°C, 4.7°C, 6.39°C, 7.13°C, 8.32°C, and 9.23°C. Remarkably, the thermal performance across all courtyard scenarios becomes almost equal.
d. A graphical curve concluded a relationship that combines courtyard dimension proportions and the corresponding optimal tree shading ratio. This curve allows both graphical and mathematical determination of the relationship for any square courtyards with aspect ratios within the limits specified on the horizontal axis of the curve.
e. The study implies that urban planners and architects can benefit from these findings to enhance outdoor thermal comfort by considering the correlation between the courtyard's aspect ratio and the tree shading ratio to promote sustainable design.
f. Future research should focus on studying the thermal performance of courtyards with rectangular aspect ratios and their correlation to optimal tree shading ratios. Likewise, other climatic regions could also be studied, with a specific focus on deciduous Cassia trees during different seasons rather than just summer. Furthermore, investigating the impact of tree shading and other urban elements on indoor thermal comfort and energy consumption is needed.

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