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Enhancing Outdoor Thermal Comfort in Residential Areas of Arid Regions: A Case Study from Baghdad

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ABSTRACT

Residential areas significantly contribute to the increase in energy consumption necessary to meet cooling requirements for occupants' comfort. Enhancing human thermal comfort in outdoor environments is a crucial goal in achieving effective designs for open spaces. This study specifically surveys potential measures to enhance pedestrian thermal comfort in hot regions, addressing the issue of modern urban architecture's inability to adequately adapt to human thermal comfort and energy efficiency. It aims to propose different environmental treatments for open spaces between buildings and study their effect on improving pedestrian thermal comfort. For instance, the study employs cool pavements, vegetation, and water bodies. It conducted the evaluation in Baghdad during the hottest days of July, examining thermal comfort metrics using ENVI-met software. The study measures outdoor thermal comfort for six scenarios sequentially using the physiological equivalent temperature (PET). The results demonstrated the importance of environmental treatments for open spaces in residential complexes, and the analysis showed that vegetation has a strong effect on improving outdoor thermal comfort, followed by water bodies and finally paving and coating materials.

1. INTRODUCTION

As of 2021, the global population is 7.8 billion, growing at a rate of 1/11 percent annually, with projections suggesting it will reach 10 billion by 2056. The United Nations estimates that by 2030, 60% of people will reside in urban areas [1]. The increasing population underscores the urgent need to reduce energy consumption, particularly in arid and warm regions where residential cooling demands significantly contribute to energy use. Current urban design practices often fail to adequately address human thermal comfort and energy efficiency [2].

Since the beginning of time, climate change has been a worldwide issue that has impacted every single city on the planet. One of the cities that has experienced a rise in temperature at a rate of 0.7 per decade is Baghdad, which is considered to be one of the hot cities [3].

In recent years, urban planners and designers have faced a number of significant issues, one of the most critical of which is the creation of cities in environments that are hot and dry while also guaranteeing an appropriate level of thermal comfort outside. Creating an environment suitable for pedestrians to use during the daytime hours, when the sun is at its most intense, presents a significant challenge for nations like Iraq. We selected Baghdad as a case study due to its exceptional illustration of a scorching and arid climate. A physiological equivalent temperature, also known as a PET, is an essential component in determining the external thermal comfort of the human body. This is because the PET is accountable for a wide range of radiation types, in addition to environmental elements like humidity and the temperature of the atmosphere [4].

2. LITERATURE REVIEW

2.1 Design requirements in dry climates

Urban architectural factors refer to the design qualities of an urban area. The aspect ratio shows the relationship between building height and identical structure spacing. These elements include the height of buildings. In addition, they take into account the height of structures. Certain designers favor the design of the urban area with a symmetrical aspect ratio of the street, while others design with an asymmetrical aspect ratio of the street. The decision to adhere to the design characteristics of the buildings and the specifications of the urban area when implementing the project is contingent upon the design characteristics of the buildings. A research study concludes that design decisions about roads, walkways, shading systems, materials, landscape design, and building height significantly impact pedestrian thermal safety and, consequently, the climate of metropolitan areas [5].

A study's findings suggest that we might improve the outdoor thermal comfort conditions by adjusting them based on the impact of urban activity, as shown in Figure 1 [6].

A study by Lobaccaro et al. [7] analyzed the thermal stress within typical urban valleys in Bilbao (Spain). The study first analyzed the current situation, then compared the effects of asphalt and red brick as street paving materials, and finally tested the benefits of vegetation elements. The analysis showed that orientation and aspect ratio strongly influence the magnitude and duration of thermal peaks at the pedestrian level, while vegetation elements improve thermal comfort up to two classes of chronophysiological assessment.

The significance of the sky width factor in relation to urban geometry parameters is a topic of extensive discussion due to the unique impact of aspect ratio. The spacing between buildings and the presence of vegetation significantly influence the sky view factor, which in turn influences sky apertures. This factor determines the amount of sunlight that reaches the ground and the roofs of buildings [4].

Figure 1. Illustration of sky view factor: open and closed spaces [8]

The study by Sharmin attempts to show how ENVIMET can benefit from using the right inputs as boundary conditions. While the modeling tool aims to produce excellent results using comprehensive weather information as boundary conditions, this study suggests that it is important to use representative data from the actual site and that hourly inputs of climate variables as boundary information can produce the best results. The results demonstrate the modeling's ability to predict the relative differences in Tmrt conditions between sites, albeit with an overestimation [9].

2.2 Effect of aspect ratio and sky width factor

Shashua-Bar et al. [10] utilize the aspect ratio, also known as the height-width ratio, to represent the geometry of the urban valley in their work. To calculate the aspect ratio, take the average height of neighboring perpendicular structures, such as building facades, and divide it by the average width of the space between them. This calculation provides the aspect ratio, which is crucial for understanding the spatial dynamics of urban environments, as illustrated in Figure 2. Surface grooves with an aspect ratio of H/W = 0.42 experience higher daytime ambient temperatures compared to those with a deeper aspect ratio of H/W = 2.2. Additionally, previous research conducted in Morocco supports the finding that an aspect ratio above 2 leads to increased cooling energy needs due to reduced airflow and higher heat stagnation [11].

2.3 Bodies of water

On sweltering summer days, water bodies emerge as the most effective cooling agents in urban settings [8]. Generally, the presence of water enhances evaporation rates, especially during the daytime, leading to a reduction in air temperatures in areas adjacent to or above these water bodies. In terms of improving thermal comfort in the local climates of residential projects in hot environments, water is often considered more effective than vegetated surfaces [12]. Although it is commonly believed that water bodies are excellent at absorbing radiation, it is important to recognize that their thermal response is somewhat limited due to the high heat capacity of water. Specifically, it requires approximately three times more heat to increase the temperature of a unit volume of water compared to a unit volume of soil. Consequently, planners and architects frequently integrate water features into their designs [8].

2.4 Cold sidewalks

A feasible environmental remedy is the implementation of cold pavements. The surface temperatures of cold materials are lower than those of ordinary materials because cold materials have a lesser capacity to absorb heat than typical materials. There is a correlation between the characteristics of cold materials and their effective performance. These characteristics include heat capacity, solar reflectance, heat transfer rates, surface roughness, and permeability. According to numerous academics, a 10% increase in surface albedo has the potential to decrease surface temperatures by as much as 4 degrees Celsius [13].

2.5 Vegetation and enhanced thermal comfort

Regarding the vegetation cover, the designer must carefully consider its significance in providing suitable shade and the role that afforestation plays in enhancing human thermal comfort. This is because the designer must ensure adequate vegetation cover. The most common and environmentally beneficial option for boosting thermal experience is the planting of trees and plants in locations that are characterized by high temperatures and a lack of precipitation. This method is one of the most common ways to enhance thermal experience. These techniques significantly contribute to the regulation of solar radiation absorption by surfaces, a crucial aspect of the process.

The addition of vegetation is absolutely necessary to improve thermal comfort. Even when the impact of vegetation cover on the temperature of the surrounding environment is practically nonexistent, it nevertheless contributes to the improvement of human thermal comfort. Radiative exchange is typically the most critical aspect when it comes to thermal comfort in hot and arid areas. This is true even though many academics prioritize temperature reduction as a strategy for achieving thermal comfort. Furthermore, vegetation provides direct shade to the individual, which contributes to an increase in outdoor thermal comfort. Roofs accomplish this by lowering the quantity of long-wave radiation they emit and limiting the amount of solar radiation they reflect [10].

Egypt conducted this research, and Cairo found that the clustered shape of the urban area, characterized by the coolness of the green islands and the wind flowing through the main canyons, reasonably mitigates some trends in the urban area. conducted a research study, which confirmed that green roofs did not significantly reduce surface temperatures in metropolitan areas. The study's findings validate this. This is because the cooling effects of green roofs diminish with distance, resulting in a relatively small influence on the overall temperature reduction in metropolitan areas. This phenomenon can be attributed to the fact that the cooling effects of green roofs diminish with distance. Dubai, known for its dry climate, hosted the research study. Additionally, with relation to the amount of flora that is present, trees are the most effective in reducing the temperatures of the surface [11].

3. HUMAN THERMAL COMFORT

Thermal comfort, despite its complexity, can be succinctly defined. The international standard ISO 7730 describes human thermal comfort as "that state of mind that expresses satisfaction with the thermal environment to the individual" [4, 14]. This concept is influenced by six environmental and personal factors which, although independent, collectively enhance human thermal comfort (www.hse.gov.uk).

Environmental factors:
-Air temperature
-Radiation temperature
-Air speed
-Humidity

Personal factors:
-Clothing insulation
-Metabolic heat

We have adapted methodologies originally developed for indoor environments to assess outdoor comfort. We can divide thermal comfort indicators into two main categories: empirical and rational. The empirical category, historically established in a generic manner, depends on individual measurements or simplified relationships that may not necessarily be derived from theoretical foundations. On the other hand, advances in computing technologies have refined rational indicators, making them more sophisticated and reliant on models of human energy balance.

In evaluating heat stress, we utilize indices such as the Heat Stress Index (HSI), Perceived Mean Vote (PMV), and Physiological Equivalent Temperature (PET). These indices are crucial for understanding the impacts of heat stress and enhancing thermal comfort assessments. The PET index, in particular, quantifies thermal comfort in this study [15].

3.1 PET

This parameter helps understand how wind speed and radiation affect heat storage and thermal comfort in urban settings.

Table 1. The classification of PET values in terms of thermal stress and thermal perception [8]

PET	Thermal Perception	Grade of Physiological Stress
4°C	Very cold	Extreme cold stress
8°C	Cold	Strong heat stress
13°C	Cool	Moderate cold stress
18°C	Slightly cool	Slight cold stress
23°C	Comfortable	No thermal stress
29°C	Slightly warm	Strong heat stress
35°C	Warm	Moderate heat stress
41°C	Hot	Strong heat stress
<41°C	Very hot	Extreme heat stress

Recent studies have demonstrated that PET index can effectively assess thermal comfort in outdoor environments, moving beyond traditional indoor thermal indicators. Researchers have explored the implications of this index in tropical countries like Malaysia, which are characterized by hot and humid climates. Their findings suggest that modifying the design of outdoor spaces could significantly enhance comfort levels for inhabitants.

The researchers used the Physiological Equivalent Temperature (PET) index to evaluate the thermal comfort of the environment. Table 1 [16] categorizes PET ranges, highlighting different levels of human thermal sensitivity and physiological stress. This table facilitates an understanding of the specific thermal conditions associated with varying degrees of comfort and discomfort.

3.2 Climate of Iraq

The latitudinal range of 29 to 37 degrees north encompasses Iraq. Baghdad, the capital, is located at coordinates 33°19′N, 44°25′E and forms part of the Middle East and North Africa region. Summers are dry and hot, while winters are cool and wet in the City of Baghdad. In Baghdad, the peak summer temperatures can approach 50°C when the average maximum summer temperature hits 45°C. Additionally, the average temperature remains above 30°C for a duration of 5 months [17].

4. METHODOLOGY

Different scenarios (6) were simulated as follows:

Model (A): Represents the current conditions as a diagram of a current reality.

Model (B): A drawing according to the company’s plan.

Model (C): According to the company’s plan, in addition to two types of trees (Albiza) and the Japanese Sophora tree (Sophora Japonica).

Model (D1): Change the material of the streets (black asphalt) and sidewalks (interlock) to the street with basalt and granite paving stones (Granite, Basalt).

Model (D2): Based on the Model (C), changing the black asphalt material to light gray and changing the color of the pavement to white.

Model (E): Based on Model (D2), reducing the area of the park on the facade of buildings and replacing it with a green space and a fountain with an area of 250 m^2 for each residential building.

4.1 Study area

Figure 2. Location of Baghdad-Iraq map [18]

The study was designed to evaluate the impact of environmental treatments on the sustainability and environmental performance of open spaces within residential complexes. The research was conducted in Baghdad's largest residential city, Bismayah New City, known for its modern and consistent design across various aspects such as building heights, tree species selection, and parking arrangements. The city is divided into eight sectors, each consisting of multiple neighborhoods. Each neighborhood contains several residential units housed in buildings with ten stories. Specifically, our case study focused on Sector B, Area B1. For more details, refer to www.bismayaha.org (see Figure 2 to Figure 8).

Figure 3. Location of the project [19]

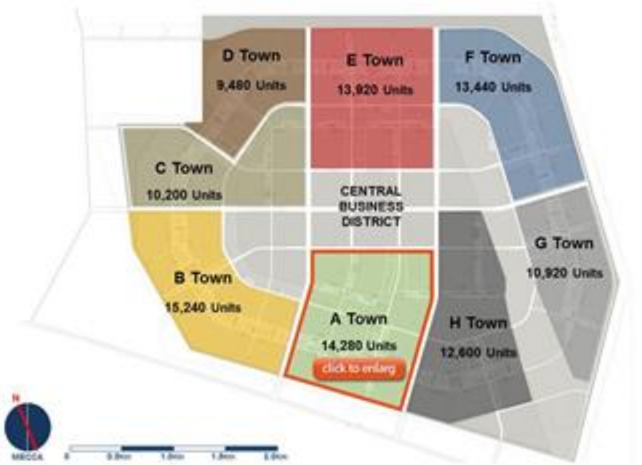


Figure 4. Town plan of the project [20]

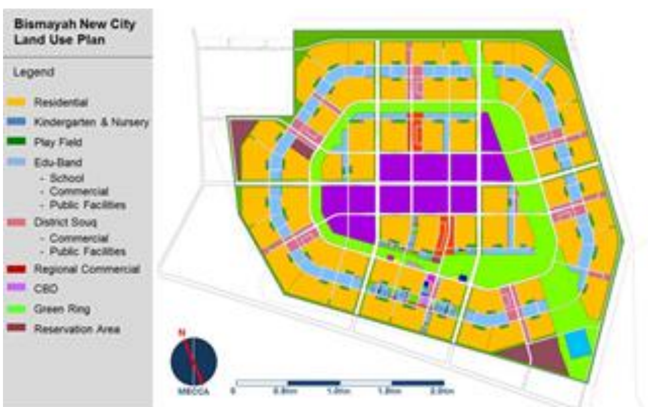


Figure 5. Developed land use plan [20]

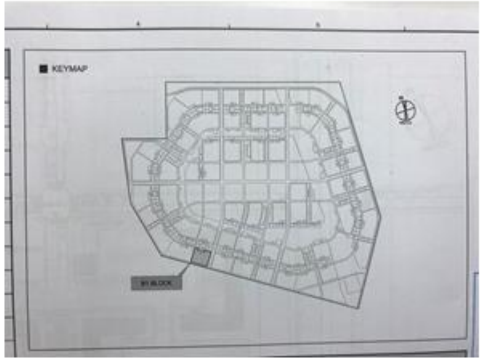


Figure 6. Study area (B1)
[The national center for engineering consultations in Baghdad, Iraq / Photography by the Author]

Figure 7. Study area (B1) [19]

Figure 8. Bismayah complex: Photographed by the Author on 7/21/2023 at 10 am

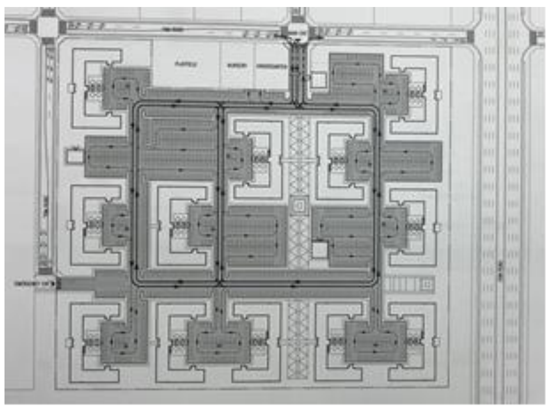


Figure 9. The parking spaces in block B1 in the study area
[The national center for engineering consultations in Baghdad, Iraq / Photography by the Author]

In Bismaya City, each residential apartment is allocated two parking spaces, featuring a central parking lot situated centrally and additional parking spots distributed across each sector. Specifically, the B1 Block provides a total of 1,090 parking spaces, resulting in a parking ratio of 0.76 per apartment in B1. The remaining parking spaces are located in the central parking lot. For further details, refer to Figure 9.

4.2 ENVI-met and Leonardo: Basic aspects of the ecological model

ENVI-met is a sophisticated 3D microclimate model that can accurately calculate and simulate urban climate. It operates at a grid resolution of 0.5 to 10 meters in space and 10 seconds in time. The model computes the temporal variations of the regional climate over a period of 24 to 48 hours by applying the fundamental principles of fluid dynamics and thermodynamics. In addition to wind speed and direction, the software also takes into account air temperature and humidity, turbulence, radiative fluxes, bioclimatology, and gas and particle dispersion. The software uses these key variables for forecasting. Figure 10 [21] illustrates the essential data structure of ENVI-met.

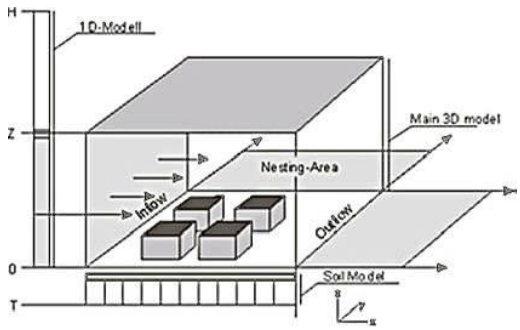


Figure 10. The schematic of the ENVI-met model layout

4.3 Input data for the model

We modeled each scenario using scale dimensions of 90 m × 80 m × 30 m and a resolution of 4 m × 4 m × 3 m per unit, resulting in a total modeled area of 360 m × 320 m × 90 m. Six distinct scenarios were developed for this simulation, which ran continuously for 24 hours. Additionally, we utilized a meteorological data table for the city of Baghdad, as shown in Table 2 and Figure 11.

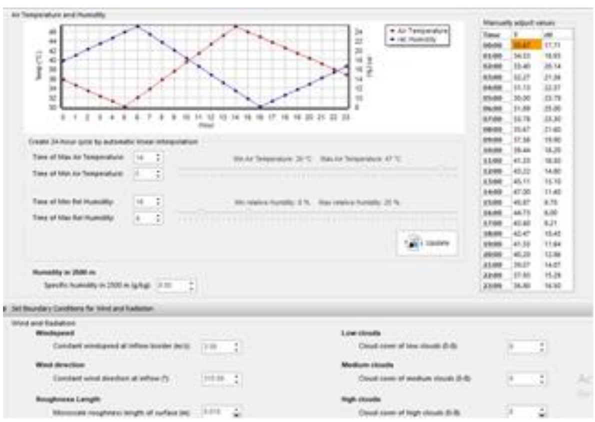


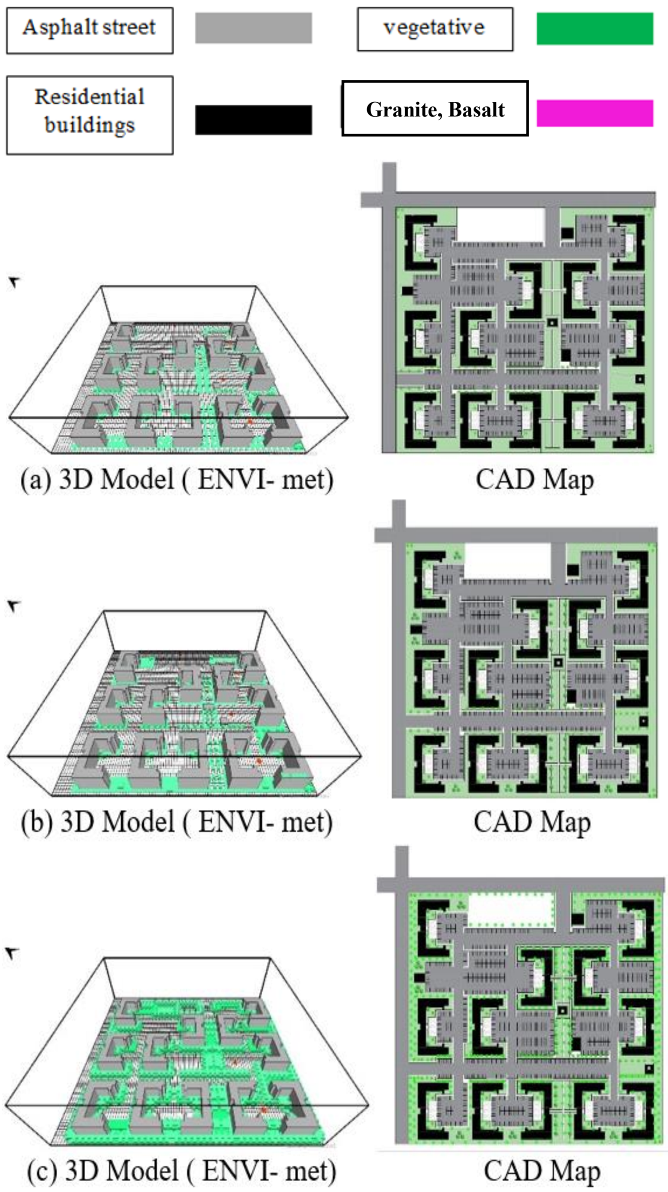
Figure 11. Meteorological data table for the city of Baghdad on July 21, 2023
Source: Author, based on the ENVI-ME and program

Table 2. Temperatures and humidity within 24 hours on July 17, 2023 (Author based on the ENVI-met program)

Temp. (°C)	Relative Humidity (g/kg)	Time (pm)	Temp. (°C)	Relative Humidity (g/kg)	Time (am)
43.22	14.8	12	35.67	17.71	0
45.11	13.1	13	34.53	18.93	1
47	11.4	14	33.4	20.14	2
45.87	9.7	15	32.27	21.36	3
44.73	8	16	31.13	22.57	4
43.6	9.21	17	30	23.79	5
42.47	10.43	18	31.89	25	6
41.33	11.64	19	33.78	23.3	7
40.2	12.86	20	35.67	21.6	8
39.07	14.07	21	37.56	19.9	9
37.93	15.29	22	39	18.2	10
36.8	16.5	23	41.33	16.5	11

4.4 Drawing the study area (block B1)

AutoCAD and (ENVI-met) and applying environmental treatments to achieve the least external thermal comfort and to achieve the research goal (Figure 12).



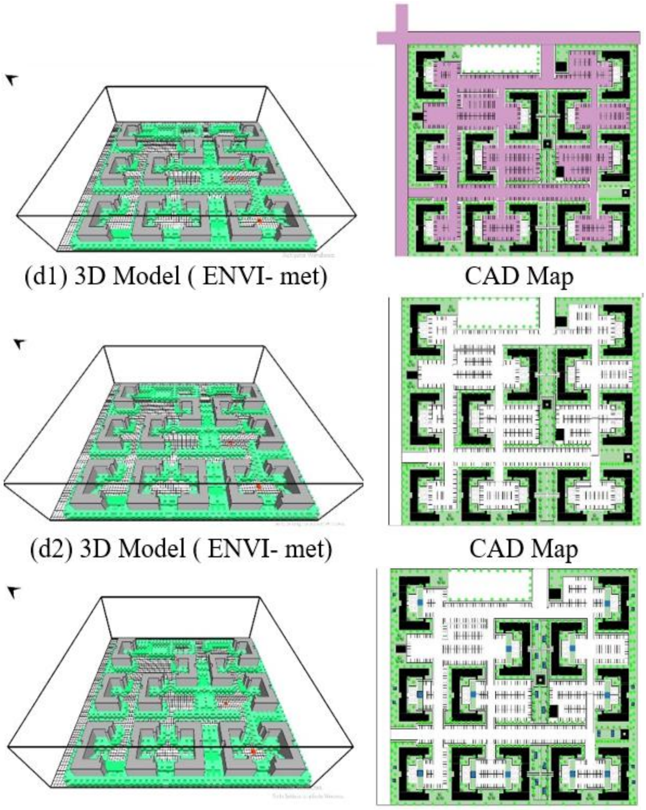
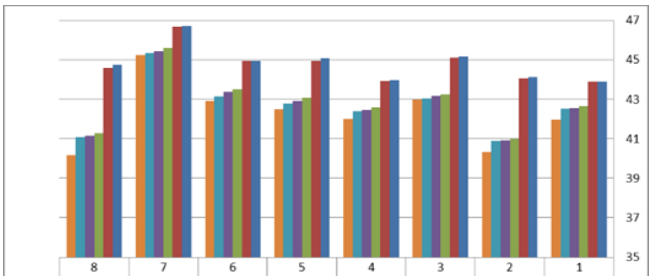


Figure 12. Drawing scenarios using software

5. DISCUSSING

5.1 Air temperature (Ta)

Simulation results show that the air temperatures in general in the region (8 receptors) (Figure 13).



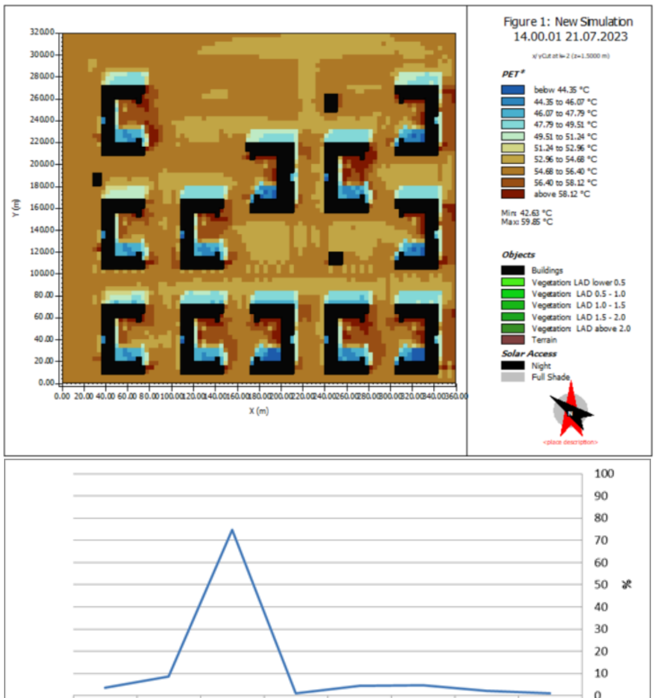
	8	7	6	5	4	3	2	1
A	44.74	46.71	44.95	45.07	43.97	45.16	44.12	43.9
B	44.59	46.68	44.93	44.96	43.94	45.1	44.05	43.9
C	41.28	45.61	43.52	43.08	42.58	43.25	41	42.64
D1	41.14	45.42	43.37	42.93	42.47	43.18	40.91	42.56
D2	41.08	45.34	43.16	42.77	42.4	43.05	40.88	42.52
E	40.18	45.23	42.91	42.49	42.01	42.97	40.33	41.97

Figure 13. Comparison of simulation results for air temperatures for these models at 14:00 pm at an altitude of 1.5 meters at ground level. 8 receptors

5.2 PET

First model:

PET of the first model at 14.00 pm at an altitude of one and a half meters. The lowest temperature is 42.63, and the highest temperature is 59.85. The highest percentage, 74.69%, was at a temperature of 53.6 (Figure 14).

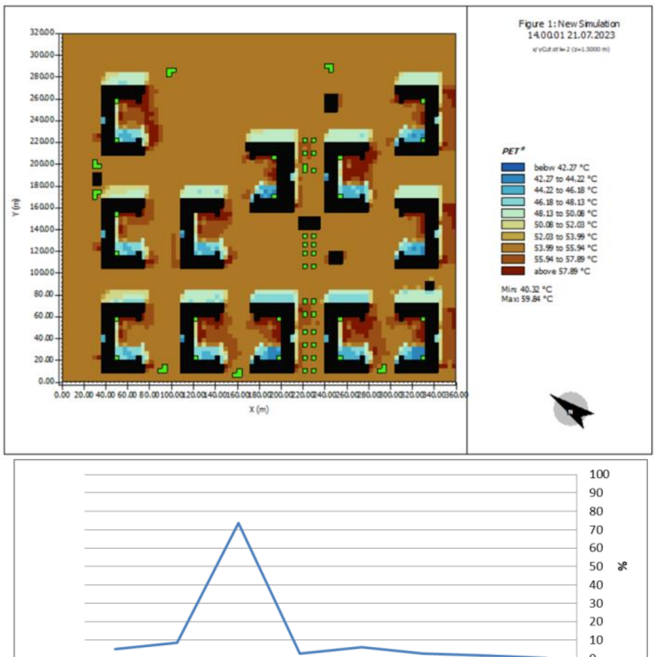


	58	55.8	53.6	51.4	49.2	47	44.8	42.6
%	3.49	8.75	74.69	0.97	4.36	4.62	2.05	1.06

Figure 14. PET of the first model at 14:00 pm

Second model:

PET of the second model at 14.00 pm at an altitude of one and a half meters; the lowest temperature is 40.32s. The highest temperature is 59.84, The highest percentage, 73.44%, occurred at a temperature of 52.8 (Figure 15).



	57.8	55.3	52.8	50.3	47.8	45.3	42.8	40.3
%	4.98	8.66	73.44	2.61	5.97	2.68	1.54	0.08

Figure 15. PET of the second model at 14:00 pm

Third model:

PET of the second model at 14:00 pm at an altitude of one and a half meters. The lowest temperature is 34.23, the highest temperature is 58.47. The highest percentage, 44.73%, was at a temperature of 52.2 (Figure 16).

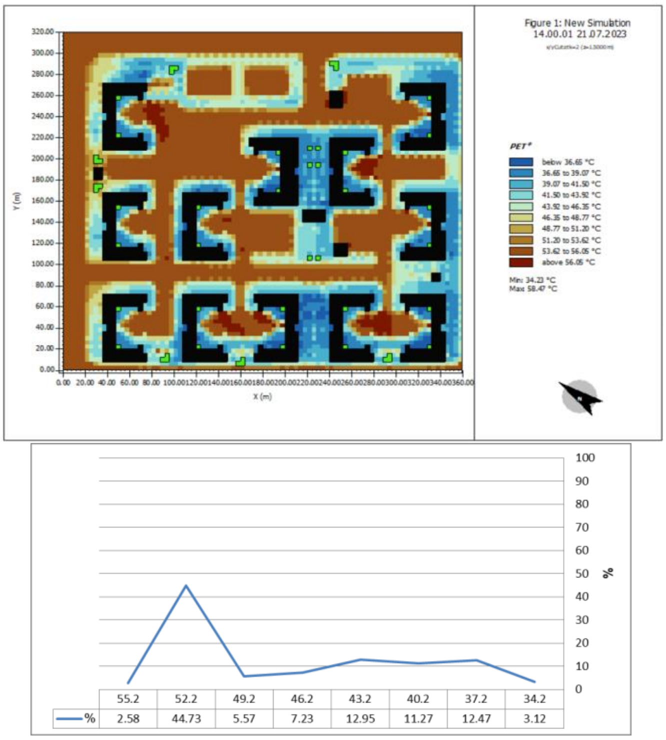


Figure 16. PET of the third model at 14:00 pm

Fourth model:

PET of the Fourth model at 14:00 pm at an altitude of one and a half meters; the lowest temperature is 34.06, The highest temperature is 58.36, The highest percentage, 44.09%, was observed at a temperature of 52 (Figure 17).

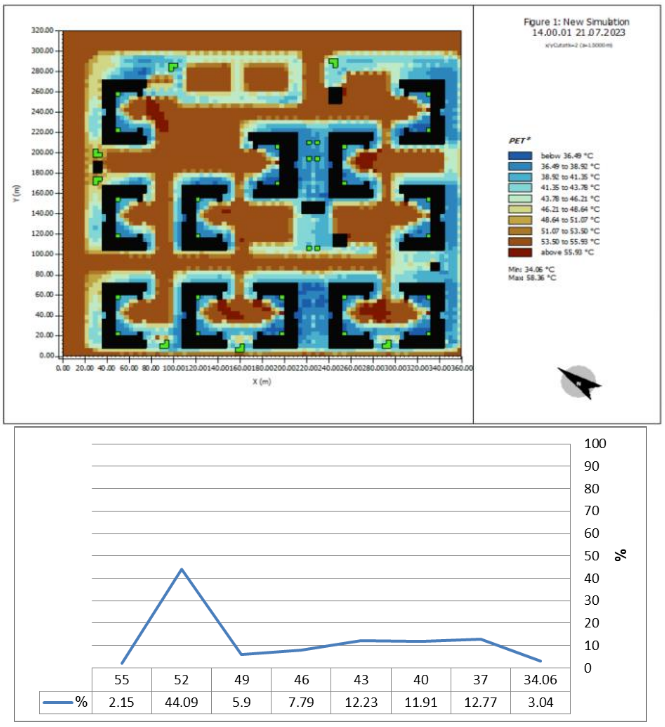


Figure 17. PET of the fourth model at 14:00 pm

Fifth model:

PET of the Fifth model at 14:00 pm at an altitude of one and a half meters; the lowest temperature is 34.17. The highest temperature is 58.63, The highest percentage, 44.22%, was at a temperature of 52.17 (Figure 18).

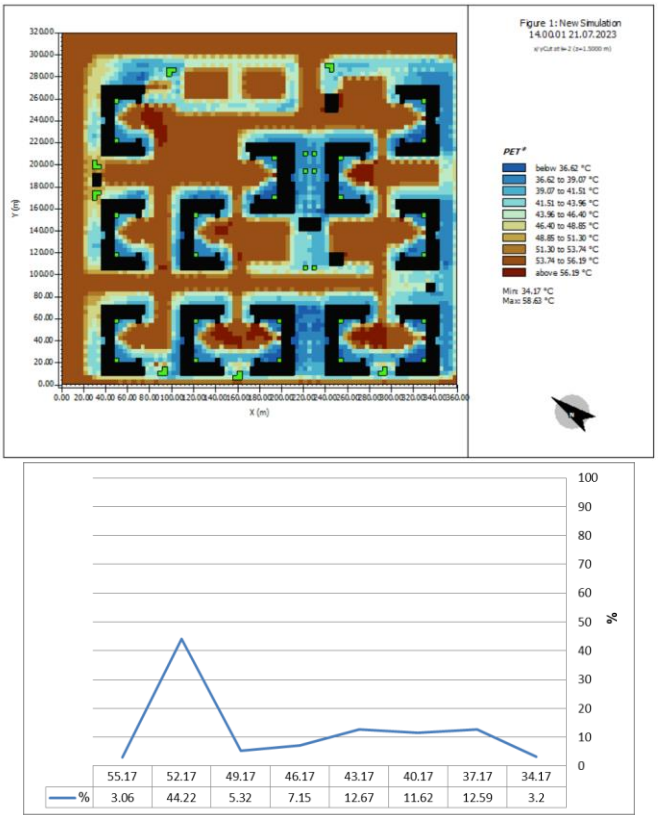


Figure 18. PET of the fifth model at 14:00 pm

Sixth model

PET of the Sixth model at 14:00 pm at an altitude of one and a half meters. The lowest temperature is 33.95, the highest temperature is 58.65. The highest percentage, 40.46%, was recorded at a temperature of 51.9 (Figure 19, Table 3).

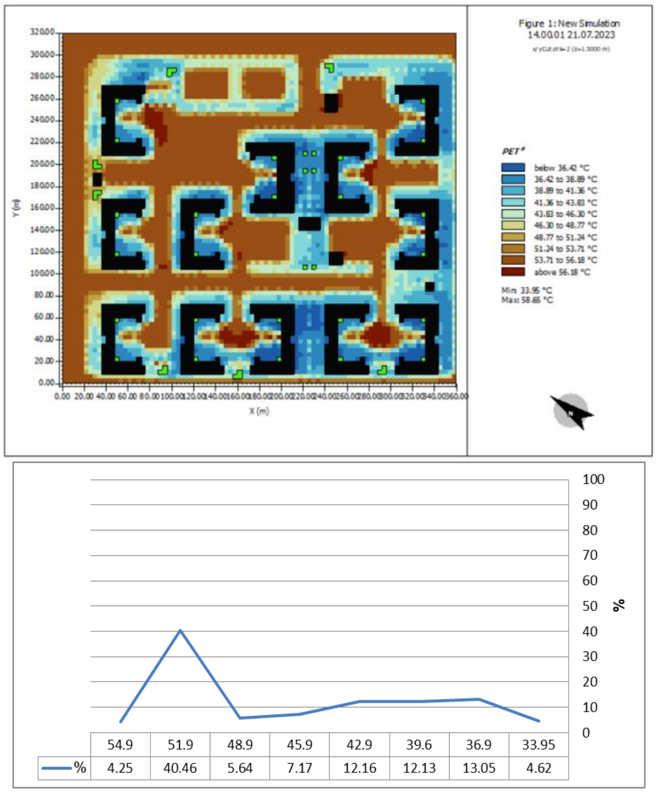


Figure 19. PET of the sixth model at 14:00 pm

Table 3. Simulation results of the PET index for six scenarios at the study site

Scenarios	Time					
	8:00AM		12:00PM		14:00PM	
	MIN	MAX	MIN	MAX	MIN	MAX
A	32.37	57.77	39.16	59.26	42.63	59.85
B	31.85	57.73	37.36	59.26	40.32	59.84
C	28.21	55.45	32.04	58.00	34.23	58.47
D1	28.14	56.93	31.93	58.93	34.06	58.36
D2	28.16	56.00	31.93	58.27	34.17	58.63
E	24.30	55.82	31.07	58.15	33.95	58.65

6. CONCLUSION

This work presents the analysis conducted on a summer day in Baghdad to study the effect of environmental treatments, namely water bodies (fountains), paving materials (materials and colors), and vegetation elements (i.e., grass and trees), on the sustainability of open spaces to improve outdoor thermal comfort.

The results showed a decrease in air temperature by about 4.56 degrees Celsius in open courtyards. We also notice a decrease in the PET by 8.65 degrees Celsius in open courtyards and between buildings.

The first and second models yield results that closely align with the company's design. As for the third model, after adding two types of trees, we notice a significant drop in temperatures. After adding materials to sidewalks and streets in the fourth model, we notice a slight change in temperatures, as the effect of the color of the sidewalks was stronger than the materials on temperatures. In the last model, we observed a significant decrease in temperatures when we added bodies of water in front of every residential building and in the courtyards. The provision of suitable ventilation and the reduction of heat stress during the noontime hours significantly enhanced the thermal comfort of pedestrians. The findings proved that utilizing environmental treatments contributes to proposing an acceptable design to combat climate change in Baghdad, especially during the summer season. It is therefore possible for the findings that were gained from this research to serve as guidance for designers in terms of thermal requirements studies and urban planning in dry regions.

Urban planners and decision makers can apply the study's methodology in the early planning stages to mitigate the risk of human heat stress in open spaces within residential complexes. In fact, by conducting quantitative and qualitative analyses, we can evaluate and prioritize urban interventions in new urban areas and/or compact urban areas to ensure thermal comfort at the pedestrian level. Therefore, the results obtained from this research can serve as a guide for designers regarding thermal requirements studies and urban planning in arid areas.

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