Acta Sci. Pol., Administratio Locorum 24(2) 2025, 299–310.
https://czasopisma.uwm.edu.pl/index.php/aspal plISSN 1644-0749 eISSN 2450-0771 DOI: 10.31648/aspal.11080

ORIGINAL PAPER
Received: 02.02.2025 Accepted: 14.03.2025

ANALYSIS OF THERMAL COMFORT IN RESIDENTIAL ENVIRONMENTS OF HOT-ARID CLIMATES: A CASE STUDY OF BAGHDAD

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ABSTRACT

Motives: Thermal comfort improvement strategies are among the most challenging aspects of planning and design in hot-arid cities. In recent years, Baghdad has witnessed the development of 46 residential investment complexes, highlighting the need to investigate their thermal comfort. Therefore, the research was conducted to address the lack of knowledge and local studies in Iraq regarding the integrated approach (shading and environmentally efficient materials) in residential complexes.
Aims: The current study aimed to examine the effect of shading and the use of environmentally efficient materials to improve thermal comfort levels in the Budour Baghdad residential complex, and selected development scenarios under typical summer day conditions. A quantitative approach was adopted. The study demonstrated that the integrated scenario C enabled to achieve a considerable improvement in PMV and PET values, leading to a significant reduction in heat stress areas.
Results: The research findings provide valuable insights for the development of planning and design guidelines for sustainable residential complexes that can be efficiently adapted to the local environment.

Keywords: thermal comfort, ENVI-met software, "predicted mean vote" (PMV), "physiological equivalent temperature" (PET), Baghdad

INTRODUCTION

Improving thermal comfort in residential environments is a critical challenge in hot-arid regions where extreme climatic conditions significantly affect the quality of life. Consequently, the aim of the current research is to examine the effect of shading and the use of the environmentally efficient materials to enhance thermal comfort levels.

The research problem is the lack of knowledge and local studies in Iraq regarding the integrated approach (shading and environmentally efficient materials) in residential complexes. The research adopted the quantitative approach, focusing on data gathering and analysis. Digital maps in AutoCAD format were obtained for the selected project, while the information on plants, soils, and surface materials was gathered through field surveys and site visits. The weather data provided by the Iraq Meteorological Organization and Seismology. The simulation results were analyzed using ENVI-Met 5.7.1 program to assess PMV, and PET in the selected case study. Figure 1 shows the simulation stages in the research

The research organized into several sections. The first section provide a review on the environmental modelling in ENVI-MET. The second section provides

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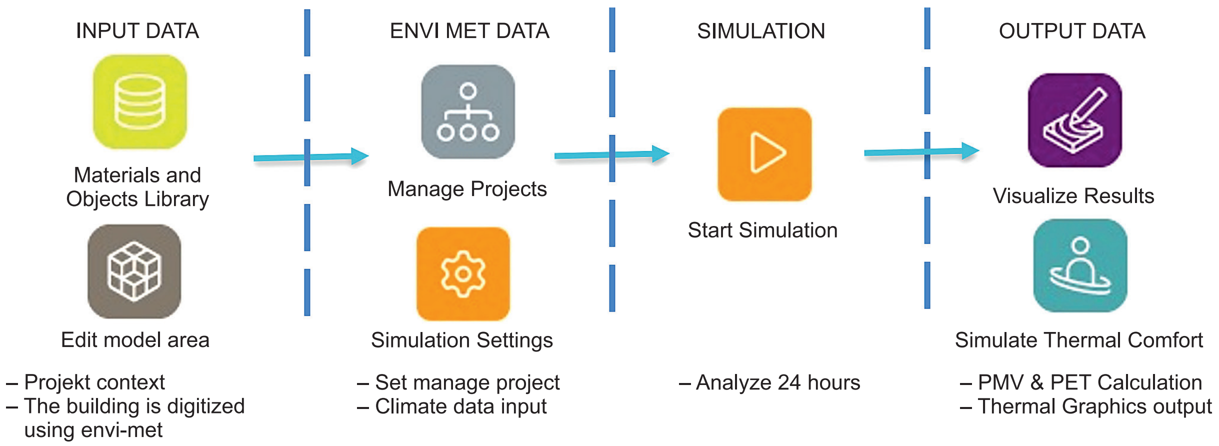

Fig. 1. Simulation stages in the research
Source: own elaboration.

a review of the relevant literature. The third section presents the simulation results, followed by thorough analysis of the findings. Finally the fourth section discusses the conclusions and recommendation.

ENVIRONMENTAL MODELING IN ENVI-MET

Studying environmental factors at the urban level is a complex process that requires field measurements, experimental analyses, and other time-consuming and labor-intensive methods (Al-Khafaji & Kamoona, 2015; Wang et al., 2019). Scenario analyses using environmental modeling provide an ideal approach to evaluate and compare the effectiveness of modification strategies. Therefore, microclimate models simulation used physically-based like "ENVI-met" have a significant role in assessing the potential and limitations of climate adaptation strategies for existing and new city developments (Eingrüber et al., 2023; Hassan & Al-Kindy, 2023; Shaheen & Khalaf, 2009). The core of environmental modeling lies in systems thinking which an important key to understanding environmental indicators is. Technological and methodological developments with in this field have made it possible to implement such models in the planning and designing of cities and neighborhoods from an environmental aspects (Ozkeresteci et al., 2003; Shaheen, 2016), the "ENVI-met" program defined as "a holistic three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions not only limited to, but very often used to simulate urban environments and to assess the effects of green architecture visions", which was developed in 1993 by Michael Bruse and his team (Ayyad & Sharples, 2019; Salem, 2008).

The software is dedicate to simulate the local climate environment in an urban area. It has the following key functions: (1) computational simulation of the thermal stress interactions between building facades, vegetation, surface materials and air (Wang et al., 2019), (2) a compact 3D climate model that calculates and simulats urban climate at a typical grid resolution of 0.5 to 10 meters within 10 seconds over a daily cycle (24 to 48 hours) using the core principles of hydrodynamics and heat dynamics. The primary factors of the program include wind speed and direction, air temperature humidity, etc. (Ozkeresteci et al., 2003).

As demonstrated by Salvati and Kolokotroni (2019), ENVI-met assist as an accurate tool for climate change analysis when applied correctly and with appropr settings, that include faultless local data with regard to size constraints (Salvati & Kolokotroni, 2019).

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LITERATURE REVIEW

Thermal comfort contributes urban design studies, as it represents the state of wellbeing with the thermal conditions when an individual is in thermal balance (i.e., the body doesn't store heat). It is affected by many factors like activity level, clothing and personal preferences (Hassan & Al-kindy, 2023; Teshnehdel et al., 2020), thermal comfort defined as the state of contentment with the surrounding thermal conditions, that is examined through self-assessment. This state is influenced by the climatic region, as individuals living in hot climates tend to be more resistant to high temperatures but are vulnerable to cold temperatures. Thermal comfort is also considered as an important measurement to evaluate the quality of the urban climate (Al-Kindy, 2012; Kusumastuty et al., 2018), Table 1 shows the thermal comfort classification.

Table 1. Thermal comfort classification

PMV	PET	Thermal Sensation	Level of Heat Stress
-3	<4	Very cold	Extreme cold stress
-2.5	4-8	Cold	Strong cold stress
-1.5	8-13	Cool	Moderate cold stress
-0.5	13-18	Slightly cool	Slight cold stress
0	18-23	Neutral	No thermal stress
+ 0.5	23-29	Slightly warm	Slight heat stress
+ 1.5	29-35	Warm	Moderate heat stress
+ 2.5	35-41	Hot	Strong heat stress
+ 3.5	>41	Very hot	Extreme heat stress

Source: own elaboration based on (Mohamed & Shawesh, 2021, p. 17).

Various studies have been carried out using climate simulation with the "ENVI-met" program in the climate of Iraq, such as the studies (Ridha, 2024; Ridha et al., 2023) which focused on the challenges of designing in hot-arid climate conditions such as Baghdad with an emphasis on achieving external thermal comfort. They also evaluate the relationship between the design of residential buildings and their effectiveness in improving thermal performance. The study by (Kareem & Mohammed, 2024) focused on improving living conditions and the surrounding environment through studied a residential complexes in Baghdad. It assumed the use of solar panels and afforestation, along with an analysis of thermal factors such as PET and SVF using the ENVI-met program. The study by (Karaaslan et al., 2024) aimed to measure the effect of green spaces on the microclimate on the campus of Nawroz University located in northern Iraq, by utilizing climate simulation by the "ENVI-Met" program and analyzing indicators such as PET and Tmrt.

The study by (Ibraheem & Abaas, 2023) addresses the assessment of thermal comfort in urban areas in Baghdad, Utilizing a comprehensive climate model that integrates environmental and structural factors to enhance local climate conditions. This is achieved through the use of a microclimate simulation model (MicroClimate Model), along the same lines the study by (Musa & Hussein, 2023) investigates the influence of (UHI) "the urban heat island" on outdoor thermal comfort in residential complexes. The study analyze the "Durrat Karbala" in southern Iraq residential complex, aiming to provide solutions to reduce the negative consequences of UHI on the resident's thermal comfort, spatially through vegetation.

The study by Abrahem et al. (2020) explored the impact of buildings facades materials on outdoor thermal comfort in residential complexes located in hot semi-arid areas. While the study (Alobaydi et al., 2016) focused on the effects of the urban form on the urban heat island (UHI) in Baghdad.

Literature review focused on environmental simulation using the "ENVI-met" program to enhance the urban environment, primarily by embracing shading or utilizing efficient materials of Iraq hot arid climate. Alternatively, it also expose the research problem the lack of knowledge and local studies in Iraq regarding the integrated approach (shading and environmentally efficient materials) in residential investment complexes.

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CASE STUDY

Detailed overview

Budour Baghdad Residential Complex was elected. Located in Baghdad (Fig. 2), it occupied a strategically location near Baghdad international Airport, a distance of no more than 5 km. Additionally, its location along the expressway affords access to the heart of the capital. The complex at present under construction, with part of the residential units have been delivered to the beneficiaries in stages.

The project consists of 7210 residential units, each with two floors, covering a range of size from 160 m^2 to 800 m^2, classified into 10 categories. The project is basically divided into five main areas:
1. The Hills, which includes (1113) housing units.
2. The Boulevard, which includes (2074) housing units.
3. The Gardens, which includes (2180) housing units.
4. The Waterfront, which includes (1843) housing units.
5. The Downtown, which includes educational and commercial services and other services.

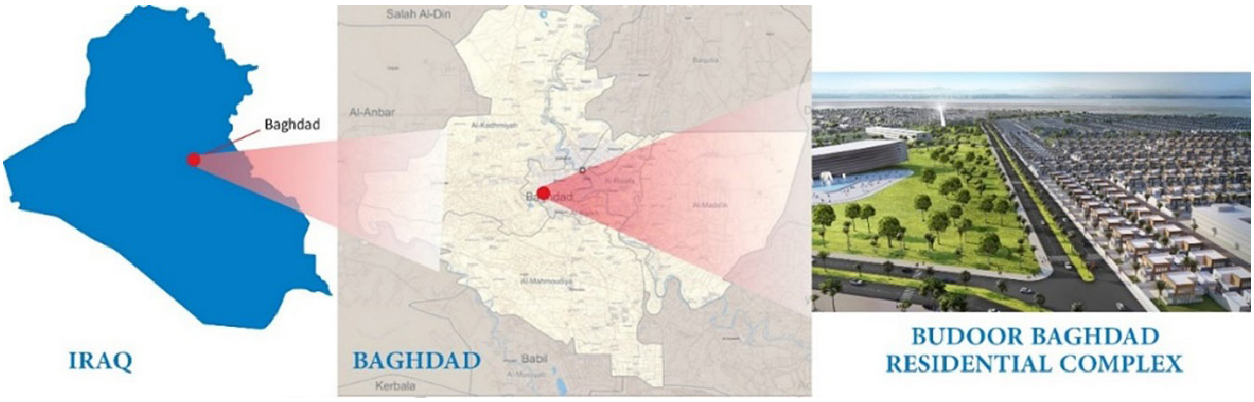

Fig. 2. Location of Budour Baghdad Residential Complex
Source: own elaboration.

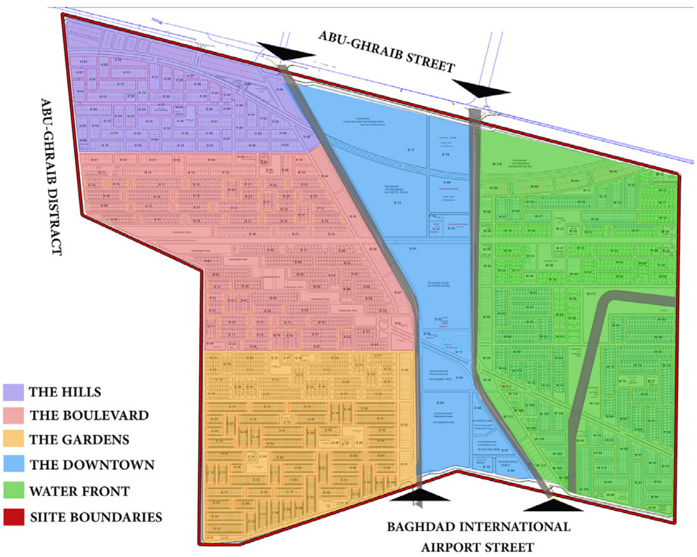

Fig. 3. Budour Baghdad Residential Complex site
Source: own elaboration.

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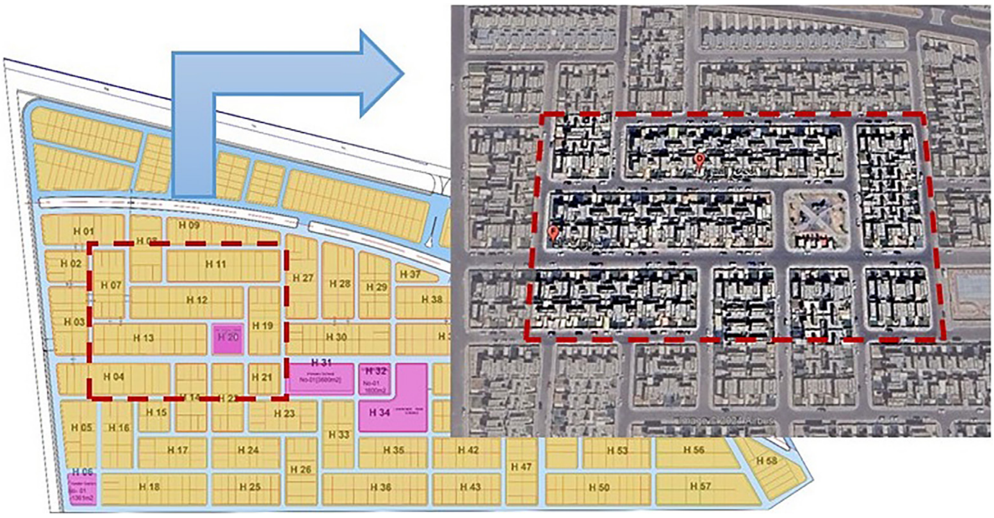

BODOUR BAGHDAD COMPOUND – THE HILLS

Fig. 4. A sample from the Hills area
Source: own elaboration.

Basic Simulation Settings

A sample from the Hills area of the Budour Baghdad Residential Complex, which is the part of the project that has been completed and occupied Figures 3 and 4.

The input data for the simulation can be summarized as follows (Table 2).

Table 2. Data of the simulation input in ENVI-met

Model location	Baghdad city location (Lati.33◦34′N, long. 44◦40′E)
Boundary model	X-Grids = 142, Y-Grids = 110, ZGrids = 25
Grids	dx = 2, dy = 2, dz = 2
Model rotation out of grid north	0
Simulation date	13th August 2023
simulation starting time	00:00 AM
Simulation duration	24 hours
The temperature of the atmosphere (°C)	Min = 30 at 6:00 a.m. Max = 50 at 18:00 p.m.
Relative humidity in 2m %	Min = 6 at 2:00 a.m. Max = 26 at 12:00 p.m.
Wind speed	3.9
Wind direction	315 (0=from North …180=from South)

Source: own elaboration.

Simulation Scenarios

Simulation of the existing situation of the selected sample from the Budour Baghdad residential complex and the proposed development scenarios were conducted as follows shown in (Fig. 5):

1. The existing situation for the selected sample: This model represent the existing situation, with residential units constructed of bricks, concrete pavements floors and asphalt for the streets and grass for the internal gardens.
2. Scenario A for the selected sample: This scenario relied on changing the finishing materials for the residential units to greening, while the sidewalks were replaced basalt bricks instead of asphalt.
3. Scenario B for the selected sample: This scenario involved adding shading by planting Sophora Japonica trees. It was assumed one tree for the residential units with one facade, while the corner residential units have (2–3) trees for each house depending to the area of the garden.
4. Scenario C for the selected sample: This integrated scenario merging scenario A and scenario B. The finishing materials for the residential units

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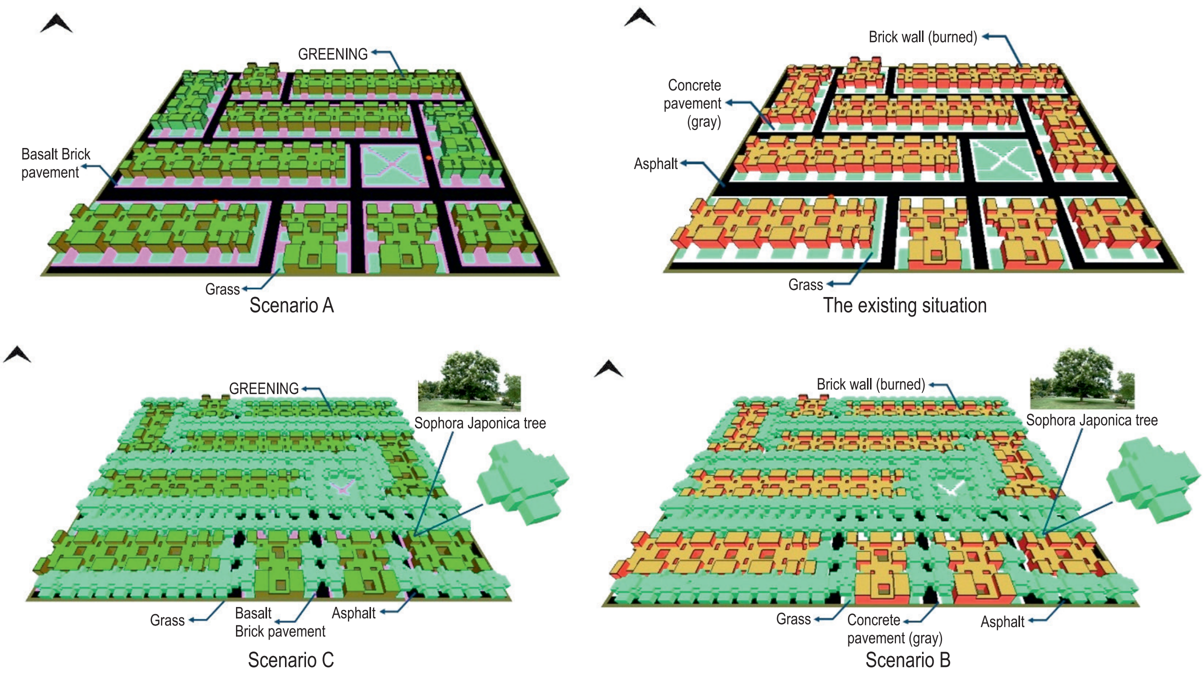

Fig. 5. Budour Baghdad Residential Complex simulation scenarios
Source: own elaboration.

were changed to green spaces, with basalt bricks used for sidewalk instead of asphalt. Shading was added through planting Sophora Japonica trees.

RESULTS

The simulation results of the existing situation and the proposed development scenarios were evaluate and compare the thermal comfort indicators (PMV, PET) and the results are as follows shown in Fig 6.

The results, shown in Fig. 6 for the existing with the proposed development scenarios at 12:00 noon, measured 1.8 m above the ground level. It showed in (Table 3).

The results indicate differences in both the maximum and minimum PMV values, between the existing with the proposed development scenarios. Scenario A exhibited the lowest in the maximum PMV value, while scenario C was the lowest in the minimum PMV value. In addition, the simulation results can also be summarized as in Fig. 7, which compare the percentages of the site area in terms of PMV values.

Table 3. The results of PMV values simulation

Difference	Min PMV	Difference	Max PMV	Simulation
–	4.51	–	6.95	The existing
-1.45	3.06	-0.29	6.66	Scenario A
-0.92	3.59	-0.2	6.75	Scenario B
-1,56	2.95	-0.24	6.71	Scenario C

Source: own elaboration.

The results were classified into two main classifications for this research:
1. PMV: X < 5.5
2. PMV: X > 5.5

In the existing simulation, 89% of the site area was at PMV: X > 5.5. In scenario A, this percentage decreased to 81%, scenario B to 70%, and in scenario C,

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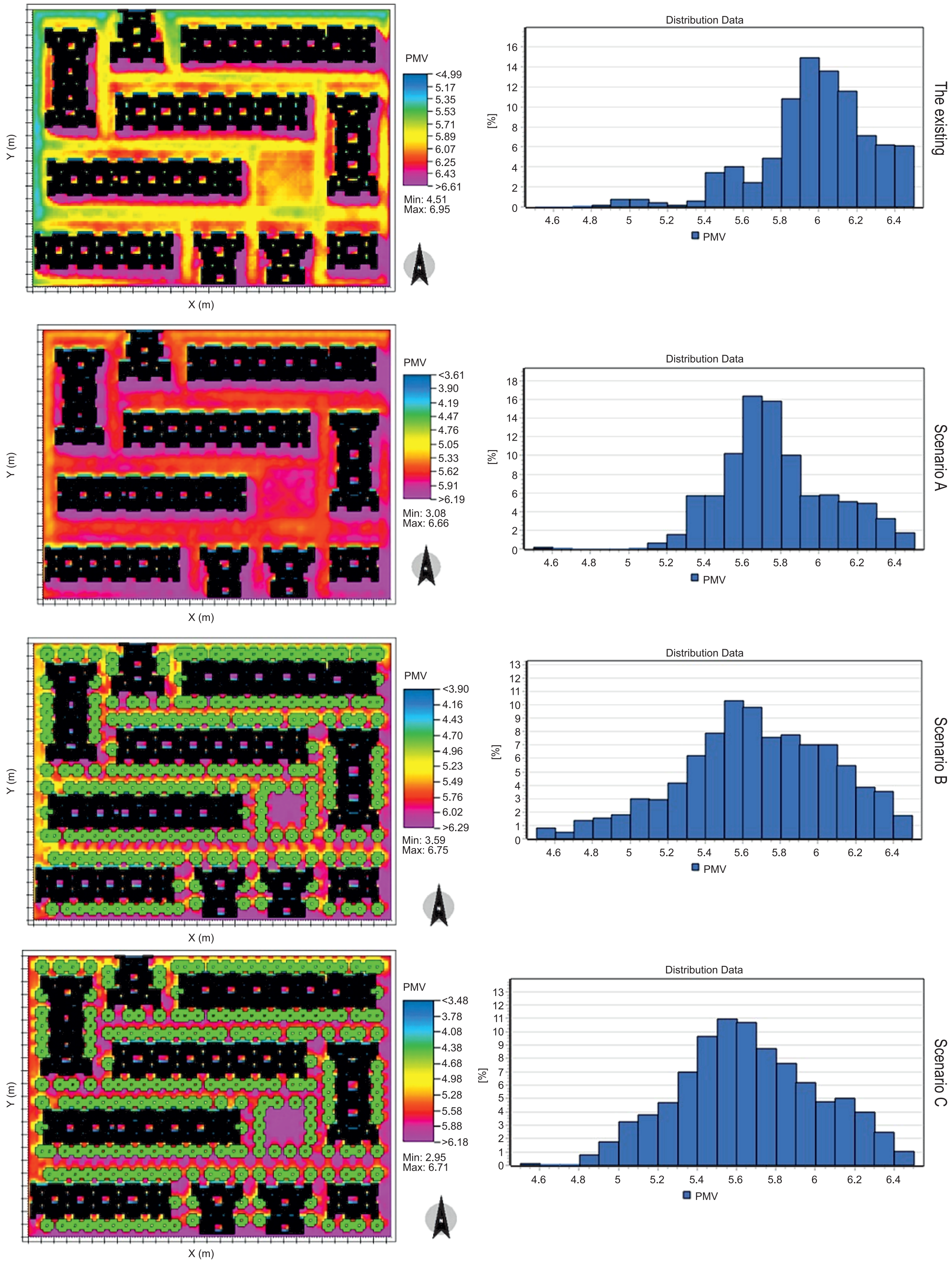

Fig. 6. "The Predicted mean vote" (PMV) results in the simulation
Source: own elaboration.

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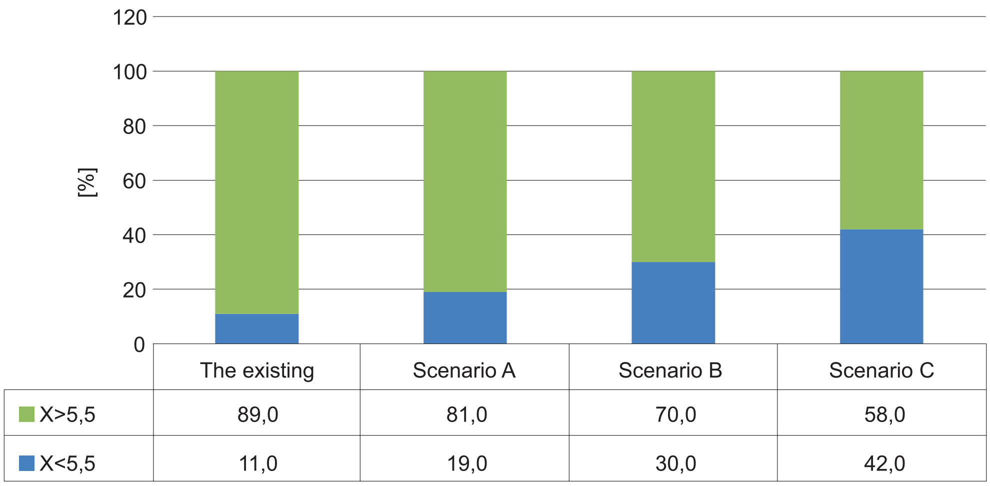

Fig. 7. The percentage of PMV values in the site
Source: own elaboration.

it was the lowest at 58%. These findings underscore that the integrated scenario, that combined shading through afforestation with the use environmentally efficient materials, was most efficient in reducing the PMV value.

The results, shown in Fig. 8 for the existing with the proposed development scenarios at 12:00 noon, measured 1.8 m above the ground level. It showed in (Table 4).

The results indicate differences in both the maximum and minimum PET values, between the existing with the proposed development scenarios. Scenario A and C exhibited the lowest in the maximum PET value, while scenario C was the lowest PET minimum value. In addition, the simulation results can also be summarized as in Fig. 9, which compare the percentages of the site area in terms of PET values.

Table 4. The results of PET values simulation

Difference	Min PET	Difference	Max PET	Simulation
–	46.89 C^{o}	–	59.23 C^{o}	The existing
-6.44 C^{o}	40.45 C^{o}	-0.05 C^{o}	59.18 C^{o}	Scenario A
-4.74 C^{o}	42.15 C^{o}	+0.33 C^{o}	59.56 Co	Scenario B
-7.04 C^{o}	39.85 C^{o}	-0.05 C^{o}	59.18 C^{o}	Scenario C

Source: own elaboration.

The results were classified into two main classifications for this research:
1. PET: X < 55
2. PET: X > 55

In the existing simulation, 69% of the site area was at PET: X > 55. In scenario A, this percentage decreased to 44.5%, scenario B to 42%, and in scenario C, it was the lowest at 41%. These findings underscore that the integrated scenario, that combined shading through afforestation with the use environmentally efficient materials, was most efficient in reducing the PET value.

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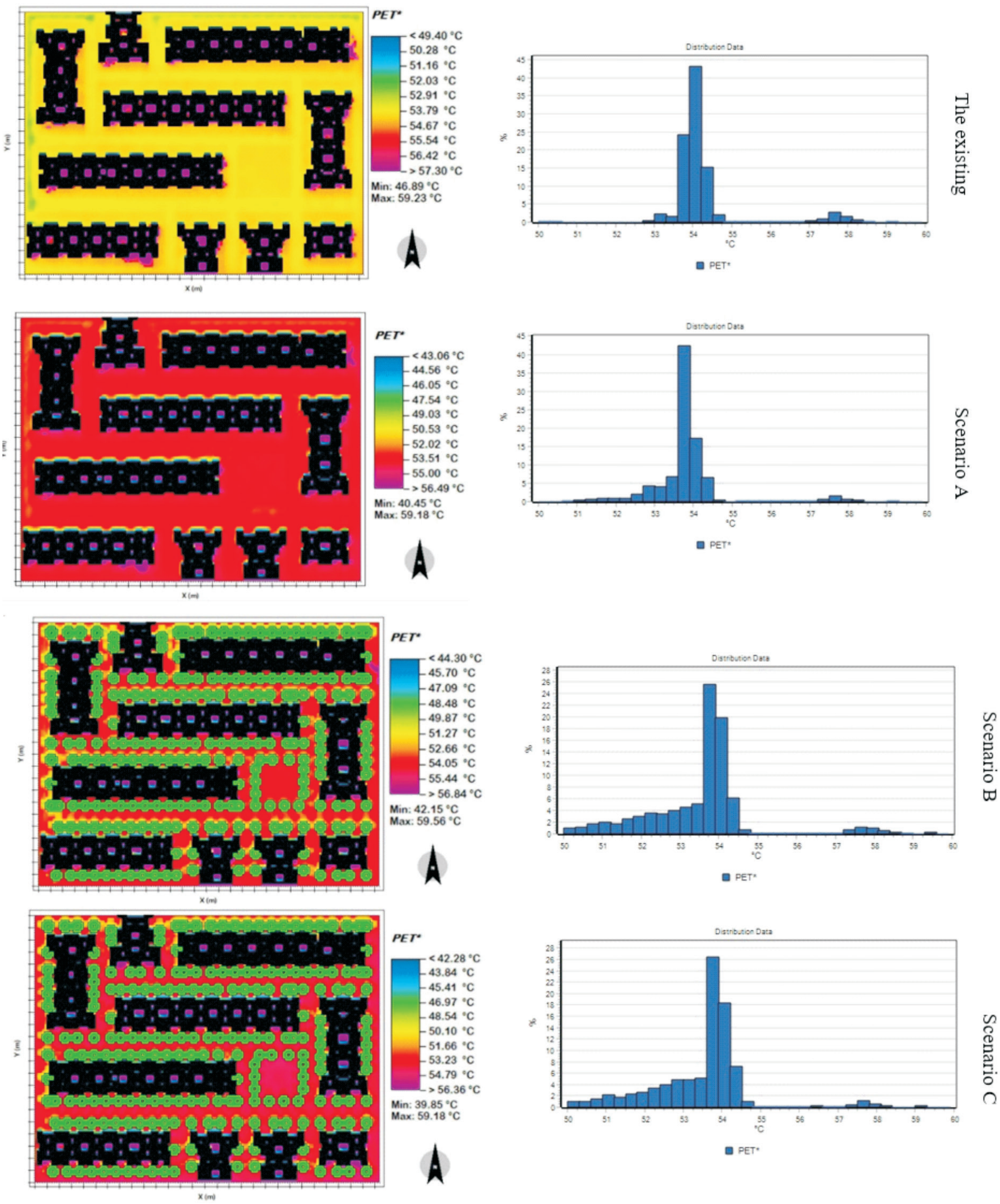

Fig. 8. "Physiological Equivalent Temperature" (PET) results in the simulation
Source: own elaboration.

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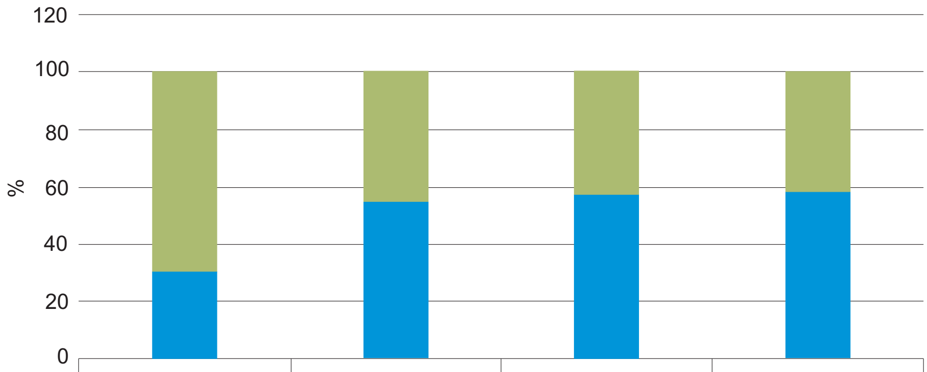

	The existing	Scenario A	Scenario B	Scenario C
X>55	69,0	44,5	42,0	41,0
X<55	31,0	55,5	58,0	59,0

Fig. 9. The percentage of PET values in the site
Source: own elaboration.

CONCLUSIONS

The aim of the study is to assess and enhance thermal comfort in residential complexes within Baghdad's hot-arid climate by analyzing PMV and PET values. It evaluates and compares selected scenarios (A, B, C) with the existing. The findings indicate that the integrating scenarios (C) is the most effective in improving thermal comfort under the daytime conditions of a typical summer day, significantly reducing thermal stress area. This underscores the critical role of integrated passive strategies in enhancing thermal comfort in residential environment. The climatic comfort evaluation indicators used in the study provide valuable tools for urban planners and designers, providing a sold foundations for developing local policies that capable to create more livable and healthier urban environments.

LIMITATION AND RECOMMENDATION

The research analyzes thermal comfort improvement strategies in residential investment complexes. In hot-arid cities Baghdad as a case study of. PMV & PET are two fundamental parameters were evaluated. Although different data input were incorporated, but there are some limitations relates to both the program and simulated scenarios. One of the limitation that the measurement tool relied on computer program. Further studies, using field measurement or remote sensing technique are recommended to expand knowledge.

AUTHOR CONTRIBUTION

The author/authors has/have approved the final version of the article. The authors have contributed to this work as follows: Donia Naseer Tareq developed the concept and designed the study, collected the data, analyzed, interpreted the data, and drafted the article, Sajeda Kadhum Al-kindy revised the article critically for important intellectual content (style: Supplementary information).

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