The Influence of Residential Building Cluster Orientations on Outdoor Thermal Performance in Hot Arid Regions

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***Abstract*—** This study evaluates the impact of residential building cluster orientations on outdoor thermal performance in New Aswan City, Egypt, using ENVI-met simulations to analyze four configurations: north–south (N–S), east–west (E–W), northwest–southeast (NW–SE), and northeast–southwest (NE–SW). Key metrics—air temperature (T_a) and mean radiant temperature (T_{mrt})—were assessed at pedestrian level (1.5 m) under extreme summer conditions (July 1, peak T_a= 46.11°C). Results demonstrate that the NE–SW orientation outperformed others, reducing T_a by 0.5–1.6°C during peak hours (10:00–14:00) and maintaining lower T_{mrt} (peak: 83°C vs. 83.63°C for E–W) through optimized shading and radiative cooling. In contrast, E–W clusters exhibited the highest thermal stress due to prolonged solar exposure. The findings highlight NE–SW as the optimal orientation for mitigating heat stress in arid regions, providing actionable insights for urban planners to enhance microclimatic stability and reduce cooling energy demands in social housing developments.

Keywords— Cluster orientation; Microclimate; Hot arid regions; ENVI-met.

I. Introduction

The national social housing projects represent one of the most significant governmental initiatives in Egypt over the past decade [1]. These projects aim to provide affordable residential units for low-income citizens, primarily located in newly developed arid regions. However, a critical oversight in their urban planning has been the lack of focus on improving outdoor thermal performance within these housing clusters. Given Egypt's hot climate, optimizing urban design for thermal comfort is essential not only for livability but also for reducing building energy consumption. Urban planning and architectural design significantly influence outdoor thermal comfort in street canyons, which in turn affects energy demand in adjacent buildings. Prior research has demonstrated that shading from buildings and proper street orientation can substantially enhance thermal comfort in outdoor spaces. For instance, Srivanit and Jareemit [2] found that increasing the aspect ratio (building height-to-street width, H/W) extended thermal comfort duration by up to four hours on a hot day in Thailand. Similarly, studies have shown that N–S oriented street canyons maximize outdoor thermal comfort in hot climates, with one study reporting up to 46% of daytime hours falling within comfortable ranges [3-5].

On the building scale, energy efficiency strategies often focus on minimizing heat transfer through the building envelope. Common approaches include enhancing the thermal properties of walls and roofs [6-12], incorporating shading devices [13, 14], and reducing window-to-wall ratios [15-17]. However, fewer studies have examined how outdoor environmental design—such as vegetation, cool pavements [15, 16, 18-20], and street canyon geometry [21-24] can contribute to passive cooling and reduce building energy loads. A notable conflict arises when optimizing for both energy efficiency and outdoor thermal comfort. While N–S orientations improve pedestrian comfort, they may increase cooling energy demands for rectangular buildings due to greater solar exposure. Research indicates that elongated N–S-oriented buildings can experience up to 33% higher solar heat gain compared to square footprints [25, 26]. This trade-off highlights the need for integrated urban and architectural design strategies that balance both objectives. Mahmoud et al. [20] established that optimized shading configurations (50% coverage) in public spaces can yield 35% reductions in cooling loads, validating the energy conservation potential of microclimatic design. Despite existing research, comprehensive guidelines that merge urban planning and architectural design for enhanced thermal performance remain scarce, particularly in rapidly developing regions like Egypt. Without clear design standards, the effectiveness of energy-saving measures and outdoor comfort optimization may be compromised, hindering long-term sustainability goals. This study investigates the relationship between residential cluster planning, architectural design, and outdoor thermal comfort, with the following research questions:

1. How do residential cluster layouts and building designs influence hourly outdoor air temperatures?

2. How can cluster design modifications reduce the T_{mrt} within these developments?

II. METHODOLOGY

This study employs a descriptive-analytical approach, integrating qualitative and quantitative methods to assess the influence of residential building cluster orientations on outdoor thermal performance. The investigation focuses on microclimatic conditions within interstitial spaces between buildings, with the goal of establishing design guidelines for optimizing outdoor thermal comfort in arid regions. To evaluate thermal performance, ENVI-met simulations were conducted, analyzing key parameters such as outdoor T_a and T_{mrt}. These metrics provide critical insights into pedestrian comfort levels and the efficacy of different cluster configurations.

A. Study Area

The research focuses on a social housing project in New Aswan City, situated in southern Egypt (24° 11' N, 32° 40' E) along the west bank of the Nile River [27, 28]. The region experiences extreme summer conditions, with average maximum temperatures reaching 42°C under predominantly clear-sky conditions [29, 30]. Given these climatic challenges, optimizing urban design for thermal comfort is essential. Two distinct residential cluster orientations were selected for comparative analysis (Figure 1). These configurations were examined to determine their impact on microclimatic variables, with the aim of identifying the most effective layout for mitigating heat stress in outdoor spaces.

(a) (b)

Figure 1. The investigated site (a) The location of the investigated cluster in New Aswan; (b) Detailed site.

B. Modeling and Simulation Process

This study examines the impact of residential building cluster orientations on outdoor thermal performance in hot arid regions, with New Aswan City serving as the primary case study. The research employs ENVI-met version 5.1.1, a three-dimensional microclimate simulation tool widely used for analyzing urban thermal environments. Site-specific meteorological data were obtained from the weather station at Aswan University's Faculty of Engineering to ensure accurate boundary conditions for the simulations. The simulation domain was configured with a 50m × 50m grid to comprehensively capture the thermal dynamics of the study area. A high-resolution core domain of 2m × 2m cells was implemented, with both vertical and horizontal grid spacing set at 1m to resolve fine-scale microclimate variations (Table 1). This spatial resolution enables detailed analysis of pedestrian-level thermal comfort parameters, particularly T_a and T_{mrt}. The model accounts for a maximum building height of 18m, representative of the medium-rise residential structures typical in Egypt's social housing developments. This configuration allows the simulation to accurately represent shadow patterns, wind flow interactions, and thermal exchanges within the urban canyon environment while maintaining computational efficiency. The selected parameters optimize the balance between model accuracy and computational feasibility, ensuring reliable assessment of thermal performance metrics on the human scale. This approach provides valuable insights into how building cluster orientations influence microclimate conditions in arid urban environments, with direct implications for thermal comfort-oriented urban design.

Table 1. Input Parameters For ENVI-Met Modeling.

parameter	value
Grid dimension	50 × 50 × 25 Grids dx = 2.00 m, dy = 2.00 m, Base dz = 1.00 m.
Core XY domain size	x = 100, y = 100
Soil profile for all grids	Sandy soil for the neighborhood boundary, Loamy soil and pavement around the buildings, and asphalt for streets.
Floor albedo	Albedo values as follows: sandy soil 0.31, loamy soil 0.1, pavement 0.5, asphalt 0.2
Material emissivity	Emissivity values as follows: sandy soil 0.85, loamy soil 0.9, pavement 0.9, asphalt 0.9
Thickness of wall materials (m)	0.02 Cement plaster, 0.12 Brick wall, and 0.02 Cement plaster
Roof materials	Reinforced concrete thickness = 0.1 m.
Simulation date	1 st of July for 24 hours
Metabolic rate for people (met)	1.4
Clothes (clo)	0.9

C. Proposed Residential Building Cluster Orientations

This study explores four primary orientation strategies for residential building clusters characterized by rectangular central open spaces, specifically examining their north–south (N-S), east–west (E-W), northwest–southeast (NW-SE), and northeast–southwest (NE-SW) alignments. The analysis focuses on the influence of these geometric configurations on the thermal performance of both the central courtyard area and the surrounding built environment. In the N-S elongated cluster, the rectangular open space is aligned along the N-S axis, with the adjacent buildings positioned parallel to this orientation. Under this configuration, the open space receives direct solar radiation along its longitudinal axis during midday, while the building facades are oriented toward the east and west. This results in distinct shading patterns, as E-W facing buildings generate prolonged morning and afternoon shadows across parts of the central courtyard. Moreover, the linear N-S corridor may promote wind channeling along its axis, potentially enhancing natural ventilation under favorable wind conditions. Conversely, the E-W elongated cluster aligns the rectangular courtyard along the E-W axis, producing a different set of microclimatic effects. In this arrangement, the south-facing facades are exposed to prolonged solar radiation, and the central space experiences intense direct sunlight around midday. However, the northern edges of the courtyard benefit from continuous shading by the south-facing buildings throughout much of the day. Additionally, the E-W orientation modifies airflow dynamics compared to the N-S configuration, likely affecting ventilation patterns within the courtyard.

The NW-SE and NE-SW cluster configurations orient the rectangular open space along diagonal axes, introducing unique microclimatic conditions. These orientations reduce solar exposure on south-facing facades relative to the N-S and E-W alignments. The central courtyard benefits from more consistent shading throughout the day, and the diagonal orientation alters the interaction between prevailing winds and the built form, potentially influencing ventilation behavior differently than the N-S or E-W layouts. The rectangular form of the open space generates distinct solar access and shading scenarios depending on orientation. While the N-S configuration benefits from self-shading during peak sun angles, the E-W layout provides steadier shading along the northern edge but allows deeper solar penetration at midday. While the NW-SE and NE-SW cluster configurations provide good shading and ventilation in the central courtyard throughout the day. These variations in solar exposure and shading directly impact outdoor thermal comfort and the thermal performance of adjacent buildings. Figure 2 presents the four orientation scenarios, illustrating their geometric configurations and associated solar exposure patterns. The visual comparison underscores the differences in shadow formation and solar access between the layouts, offering a clear framework for evaluating their relative thermal performance.

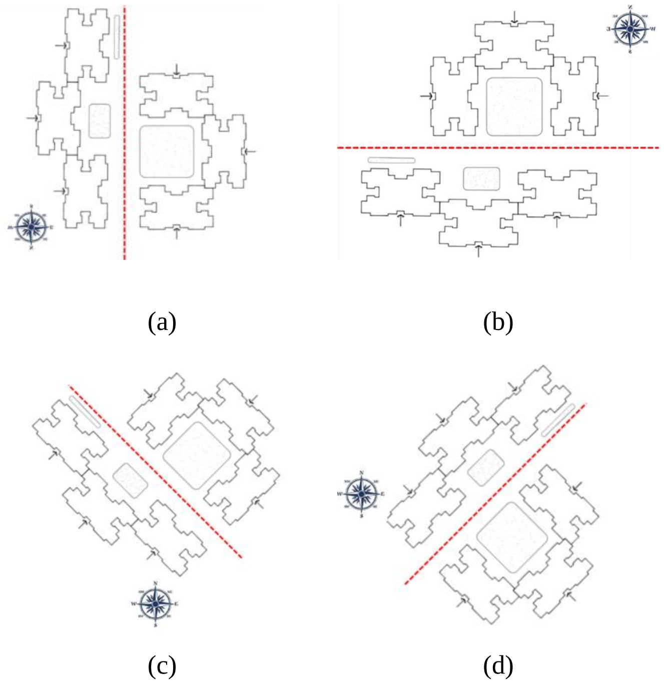


Figure 2. Residential building cluster orientations (a) N-S; (b) E-S; (c) NW-SE; (d) NE-SW

III. RESULTS AND DISCUSSION

This study systematically evaluates the thermal performance of elongated residential building clusters across four principal orientation strategies: north–south (N-S), east–west (E-W), northwest–southeast (NW-SE), and northeast–southwest (NE-SW). A detailed microclimatic analysis was conducted, concentrating on two key indicators of outdoor thermal comfort: Ta and T_{mrt}. These parameters were chosen based on their established importance in accurately assessing pedestrian thermal comfort in urban contexts [31, 32].

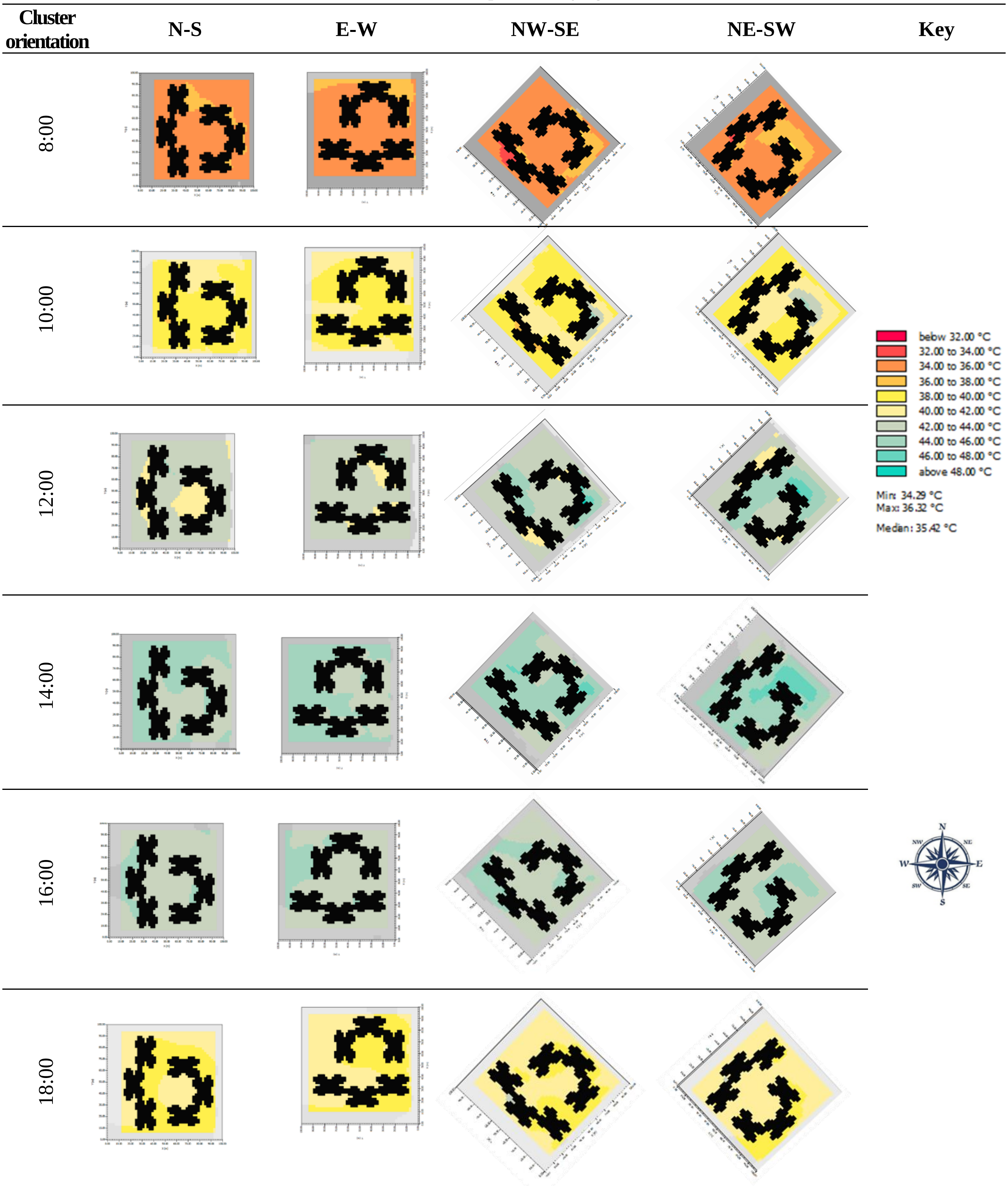
A. The effect of the proposed cases on the air temperature

The comparative evaluation of T_a distributions across cluster orientations—namely (N–S), (E–W), (NW–SE), and (NE–SW)—demonstrates noticeable variations in microclimatic thermal performance, particularly when benchmarked against ambient dry bulb temperatures. Distinct thermal behavior patterns emerge from the analysis. The N–S oriented clusters achieved reductions in T_a ranging from 0.2°C to 0.6°C, while the E–W clusters exhibited slightly broader reductions between 0.2°C and 0.7°C. The NW–SE orientation achieved a wider cooling range of 0.1°C to 1.3°C. However, the NE–SW configuration outperformed all others, with T_a reductions spanning from 0.5°C to 1.6°C during peak daytime periods and displayed a consistently more stable thermal profile.

This trend indicates a significant influence of cluster orientation on outdoor microclimatic conditions, with crossover points identified in (Figure 3) where the thermal advantages of one orientation are overtaken by another. These crossover events highlight the dynamic nature of solar exposure and shading effects throughout the day, depending on orientation. Overall, the NE–SW orientation demonstrated superior thermal performance, attributable to reduced peak ambient temperatures and enhanced diurnal stability. Such performance is crucial in hot arid environments, especially for pedestrian comfort and heat stress mitigation in public and semi-public outdoor spaces. These findings align with established principles of the urban canyon effect, while also offering novel insights tailored to the geometry of social housing clusters in desert regions. Though the temperature reductions may appear moderate in absolute terms, their cumulative impact across large-scale developments can significantly influence outdoor thermal comfort and reduce building cooling demands. (Table 2) summarizes the temporal distribution of T_a at a pedestrian height of 1.5 meters, reported at two-hour intervals throughout daylight hours.

Generally, the obtained results reveal varying air T_a patterns across the four orientation strategies, highlighting the impact of solar exposure and shading on thermal performance. Orientations such as northwest–southeast (NW-SE) and northeast–southwest (NE-SW) exhibit higher morning and midday temperatures, peaking between 10:00 and 14:00. These trends are indicative of increased solar heat gains due to their alignment relative to the sun's trajectory. Conversely, the north–south (N-S) and east–west (E-W) orientations maintain relatively moderate temperature profiles, with less pronounced peaks, reflecting their ability to partially mitigate solar exposure through alignment and potential shading. The midday period (10:00 to 14:00) represents the critical time frame for maximum air temperatures, with NW-SE reaching the highest T_a values at 45.27°C at 14:00. NE-SW closely follows, peaking at 46.11°C at the same time. Comparatively, the N-S orientation peaks at 44.05°C, while E-W records 43.28°C during this time. These findings emphasize the susceptibility of oblique orientations (NW-SE and NE-SW) to increased solar radiation, necessitating targeted interventions such as optimized shading devices or reflective materials to mitigate thermal stress during peak hours. The study underscores the importance of orientation in influencing air temperatures in elongated residential clusters. The N-S and E-W orientations emerge as more thermally favorable options due to their lower exposure to direct solar radiation, especially during critical midday hours. Urban planning strategies should prioritize these orientations while incorporating passive cooling measures, such as vegetation, reflective coatings, and optimized ventilation, to further enhance thermal comfort. These findings provide valuable insights for designing energy-efficient, thermally comfortable urban environments in hot climates, aligning with broader sustainability goals.

Table 2. The Thermal Maps For Daylight Hours In Terms Of T_a.



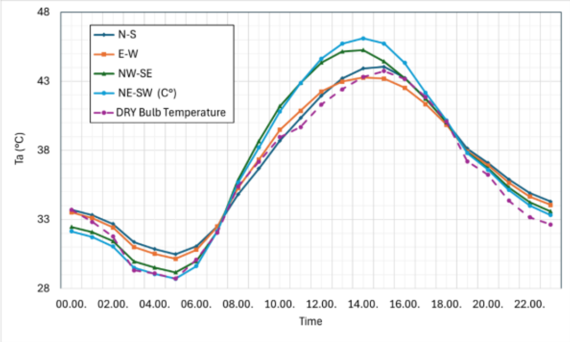
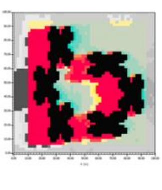
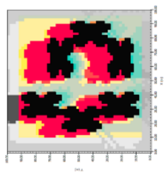
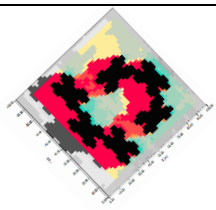
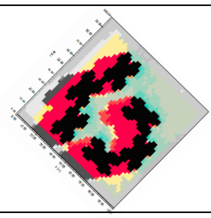
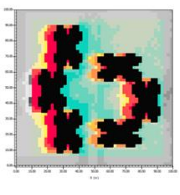
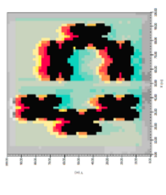
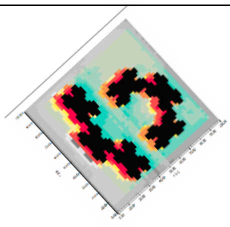
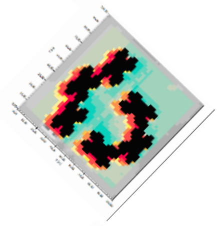
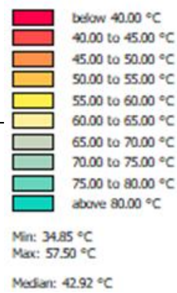
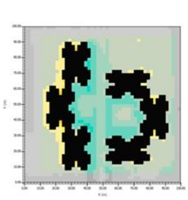
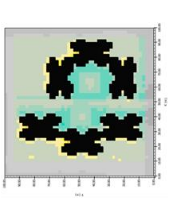
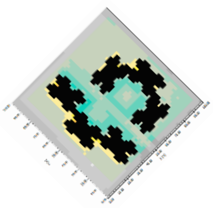
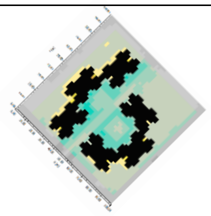
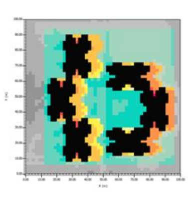
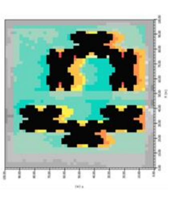
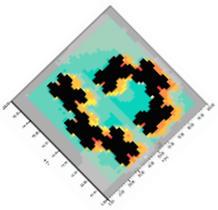
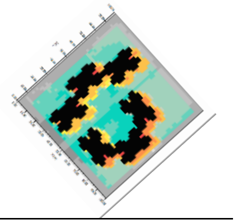
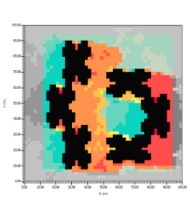
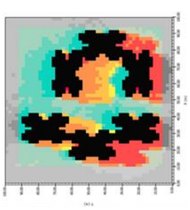
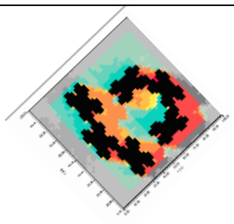
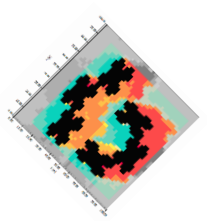
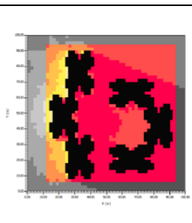
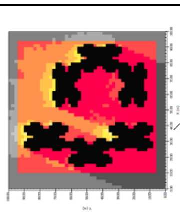
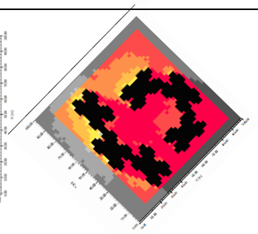
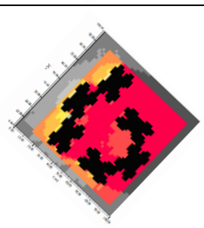


Figure 3. The simulated T_a for the investigated cases.

B. *The effect of proposed cases on the T_{mrt}*

Figure 4 illustrates the thermal performance of four orientation strategies. The N-S and E-W orientations show lower T_{mrt} values during early hours (0–6), rising with solar exposure and peaking in the afternoon. In contrast, NW-SE and NE-SW orientations experience higher T_{mrt} values post-sunrise (7–15), reflecting increased surface exposure to direct solar radiation. Peak T_{mrt} values occur between 10:00 and 14:00, with N-S at 83°C, E-W at 83.63°C, and NW-SE at 80.55°C, while NE-SW exhibits moderate peaks due to reduced solar angles. These results underscore the role of orientation in mitigating radiant heat impacts (Table 3).

Table 3. The Thermal Maps For Daylight Hours In Terms Of T_{mrt}.

Cluster orientation	N-S	E-W	NW-SE	NE-SW	Key
8:00					
10:00					
12:00					
14:00					
16:00					
18:00					

The results emphasize the critical role of orientation in shaping thermal comfort in elongated residential clusters. Orientations that minimize direct solar exposure, particularly the N-S and NE-SW alignments, exhibit relatively favorable thermal profiles, which can significantly enhance outdoor usability and energy efficiency in hot climates. Urban designers should prioritize these orientations to optimize thermal conditions while integrating shading devices and reflective surface treatments for additional mitigation in orientations like E-W and NW-SE. This approach aligns sustainable urban development goals by reducing reliance on mechanical cooling and fostering thermally resilient urban environments.

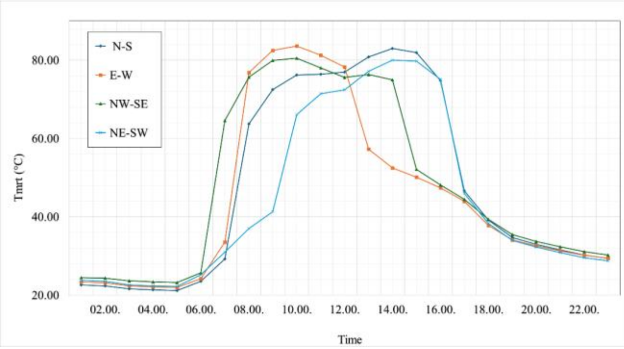


Figure 4. The simulated hours in terms of T_{mrt}.

IV. CONCLUSIONS

This study demonstrates that cluster orientation significantly influences outdoor thermal performance in hot arid climates. The NE–SW configuration emerged as the most effective, reducing peak Ta by up to 1.6°C and maintaining T_{mrt} below critical thresholds (83°C) through strategic self-shading and radiative heat dissipation. In contrast, E–W orientations exacerbated thermal stress (T_{mrt} = 83.63°C) due to unmitigated solar gain on south-facing facades. These results underscore the importance of orientation-specific urban design, particularly for social housing in arid zones, where NE–SW alignments can simultaneously improve pedestrian comfort and reduce building cooling loads. Future research should explore hybrid designs integrating NE–SW orientations with passive cooling strategies (e.g., high-albedo materials, vegetation) to further optimize thermal resilience. Policymakers and planners are urged to adopt these evidence-based guidelines to address urban heat island effects and promote sustainable development in rapidly urbanizing arid regions.

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