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Designing Climate-Adaptive Buildings: Impact of Courtyard Geometry on Microclimates in Hot, Dry Environments

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Abstract

Designing climate-adaptive buildings is crucial for mitigating the adverse effects of climate change by enhancing energy efficiency and reducing greenhouse gas emissions. Additionally, such designs improve thermal comfort and resilience in urban environments, particularly in regions with extreme climates, thereby promoting sustainable living conditions. This study aims to mitigate climate change through strategic urban and building design, focusing on the impact of building geometry and courtyard configurations on enhancing microclimates and thermal comfort in the UAE's hot arid climate. Utilizing ENVI-met software for qualitative analysis, the research examines design modifications in a school building's layout and courtyards. The analysis and findings reveal that strategic alterations can reduce outdoor air temperatures by up to 1.45°C and average building temperatures by approximately 1.89°C. Additionally, these modifications significantly improve thermal comfort perceptions on the PMV scale. The findings underscore the potential of architectural design to contribute to climate change mitigation efforts, highlighting the importance of thoughtful building and courtyard designs in promoting sustainable architecture and urban planning. This study offers novel insights into the role of design in enhancing thermal environments, providing a practical approach for developing climate-adaptive buildings in hot, dry environments.

Keywords: Microclimates and Climate; Courtyards; Building Geometry; Energy Efficiency; Thermal Comfort; UAE.

1. Introduction

This paper delves into the critical role of architectural design, particularly courtyard geometry, in enhancing microclimates within public buildings in hot, dry environments, a key factor in mitigating climate change effects. Highlighting the urgency for climate-responsive design, it draws on significant research [1, 2] to underscore the necessity of integrating sustainable practices in architecture to improve thermal comfort and energy efficiency [3]. The studies, informed by Dervishi & Baçi [4], Sanaieian et al. [5], and Johansson [6], explored how urban form and courtyard designs impact microclimatic conditions, emphasizing the benefits of incorporating green spaces and water features as elucidated by Gupta [7]. Conducted in the UAE's challenging climate, this research employs ENVI-met software to simulate how strategic design modifications can create diverse microclimates, drawing on methodologies from Nawawi & Shamsudin, [8] and recent findings by Hachem-Vermette [9] and Singh et al. [10] on natural ventilation and Zhao et al. [11] Investigating the effect of solar heat gain control. This study aims to advance sustainable urban design by offering a nuanced understanding of architectural design's role in climate adaptability.

1.1. Impact of Architecture Responsive Design on Microclimate

Climate-responsive architecture plays a pivotal role in mitigating the effects of climate change, blending innovative and traditional building geometries to create sustainable and adaptable environments. The design and configuration of

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architecture significantly influence microclimate conditions, affecting thermal performance and comfort in buildings [12]. This is particularly evident in the creation of microclimates through specific building configurations such as courtyards, which have been shown to positively impact thermal performance [13, 14].

The study of urban microclimates has become increasingly important, focusing on the interplay between natural and anthropogenic factors and their effects on urban living, including human well-being and the energy performance of buildings [15]. The Urban Heat Island (UHI) effect, significantly influenced by urban structures, highlights the critical role of spatial variables in design choices [16, 17]. Furthermore, urban density and building height are identified as key factors in determining UHI intensity, suggesting that optimized urban geometry could alleviate this effect [18, 19]. The role of vegetation, water ponds, and green walls in modifying urban microclimates is also noteworthy, especially in humid tropical climates [20, 21]. Courtyards serve as effective microclimate modifiers, with their orientation and proportions playing a significant role in enhancing thermal comfort [22].

Innovative studies like that of Kim, et al. [23] have introduced flexible, biomimetic responsive building façades using hybrid actuators and fabric membranes, demonstrating the potential of biomimicry in architecture. This complements the insights from Salameh & Touqan [1] who emphasize the value of heritage architecture in hot arid climates as a source of inspiration for contemporary sustainable design. Similarly, the integration of bioclimatic principles with architectural geometry is highlighted by Xhexhi [24], advocating for a reduction in mechanical system reliance.

The necessity of evolving architectural practices to address climate change challenges is discussed by Ingaramo & Negrello [25], who stress the importance of incorporating nature-based solutions and responsive geometries in urban design. This collective body of research underscores the critical role of building geometry in climate-responsive architecture, advocating for an integrated approach that blends innovative solutions with traditional wisdom to create sustainable, resilient environments capable of enhancing human and environmental well-being in the face of changing climates.

1.2. Buildings' Courtyards and Forms Effects on Microclimates

Courtyards play a pivotal role as passive design strategies, contributing to improved microclimates and climate change mitigation [1, 26-34]. Rajapaksha et al. [35] emphasize how limited sun exposure and courtyard design influence passive cooling. Wen et al. [36] note the stack effect's role in ventilation, influenced by outdoor and indoor temperature differences. Courtyard forms vary based on site constraints, topography, and orientation [37, 38], with geometry impacting shading and air circulation [39]. Vegetation, alongside geometry, enhances courtyard performance [40-42]. Traditional courtyards with optimal thermal performance have specific area ratios [43], while square courtyards are recommended for energy savings [44]. Higher courtyard walls and plants improve thermal performance [45]. The stack effect aids ventilation in hot arid areas [46].

To assess thermal comfort, ASHRAE standards, particularly the Predicted Mean Vote (PMV), are widely used [47, 48]. Courtyard geometry significantly influences overall building microclimate [49], making it a crucial factor in architectural design [50]. Overall, the interplay of courtyard design, vegetation, and building materials is pivotal in optimizing microclimates and fostering sustainable architectural solutions.

1.3. Significance of the Study in Relation to Previous Studies

This study addresses several significant gaps identified in previous research on courtyard design and its impact on microclimates and thermal comfort.

Akubue & Adesina [51] explored the microclimatic performance of individual courtyards in their study "The Effect of Courtyard Geometry on Airflow Regimes for Ventilation in Tropical Nigerian Environment." However, their research did not extend to overall geometric forms. This study fills this gap by examining various courtyard geometries and integrating multiple approaches to enhance thermal comfort, providing a comprehensive analysis of how different geometric configurations affect microclimates.

Tabadkani et al. [52] focused on small-scale courtyards (15-60 m²) and their microclimatic performance, without exploring larger courtyards. This research addresses this limitation by examining large courtyards up to 800m², offering insights into the performance of bigger courtyard spaces and their impact on thermal comfort and energy efficiency.

Soflaei et al. [53] investigated the microclimatic performance of housing courtyards but did not consider large-scale courtyards for public buildings. This study fills this gap by focusing on courtyards in public buildings, specifically schools, providing a broader perspective on how courtyard designs can improve thermal conditions in educational environments.

Mousighichi [54] examined the microclimatic performance of traditional courtyards but did not explore modern existing courtyards. This research addresses this by examining modern courtyards in schools, offering contemporary insights into courtyard design and its effects on thermal comfort in current architectural contexts.

Al-Khatatbeh and Ma'bdeh [55] focused on changing building materials to improve lighting and thermal performance in their study "Improving Visual Comfort and Energy Efficiency in Existing Classrooms Using Passive Daylighting Techniques." This study instead examines the geometry of courtyards as passive design solutions for schools, expanding the scope of passive techniques beyond material changes.

Gil-Baez et al. [56] adopted passive refurbishment solutions like insulation, shading, and glazing to improve school building envelopes. This research fills this gap by examining the geometry of courtyards as passive design solutions, exploring a different aspect of passive improvements.

Heracleous & Michael [57] aimed to decrease unwanted energy gains and raise cooling needs, focusing on solar shading devices. This study looks at the geometry of courtyards as passive design solutions, offering an alternative approach to managing energy performance.

Salameh et al. [58] sought to improve student satisfaction and academic performance through courtyard design. This research examines the geometry of courtyards as passive design solutions for schools, further analyzing their impact on thermal performance and overall comfort.

Kolozali & Kolozali [50] along with Soflaei et al. [22] emphasized the critical role of greenery in courtyards for enhancing thermal performance and aesthetic value. While they highlighted the benefits of greenery in creating cooler microclimates, reducing air temperatures, and providing relaxation spaces, this research examines the geometry of courtyards as passive design solutions, demonstrating how courtyard configurations can enhance thermal performance without solely relying on greenery.

In summary, this study fills substantial gaps identified in previous research by expanding the scope of courtyard geometry analysis, considering larger courtyard sizes, focusing on public buildings, and exploring modern courtyard designs (Table 1). It also extends the understanding of passive design solutions for schools beyond material and retrofit solutions, integrating the role of courtyard configurations in enhancing thermal performance. This paper addresses a crucial gap in the current understanding of how courtyard geometry affects microclimates within public buildings in hot, dry climates. While previous research has established the significance of climate-responsive architecture design and the benefits of incorporating green spaces, there is a distinct lack of detailed studies focusing specifically on the impact of courtyard design on enhancing thermal comfort and energy efficiency. Moreover, the existing body of work is limited, often only reflecting the direct effect of the new microclimates on the buildings without delving into the variations in microclimates in relation to the original local climate. This research aims to fill this gap by conducting a focused investigation using advanced simulation tools to quantify the effects of architectural modifications on microclimates. By exploring the integration of courtyard geometry with building geometry, this study contributes valuable, data-driven insights towards the development of sustainable urban design and architecture in challenging climates, highlighting the nuanced role of courtyard configurations in modifying local microclimates, thus improving building performance.

Table 1. State-of-the-art review for previous studies

Previous Studies	Aim of the Previous Study	Identified Gap	Present Study Domain to Fill the Gap
The Effect of Courtyard Geometry on Airflow Regimes for Ventilation in Tropical Nigerian Environment [51]	Explores individual courtyards' microclimatic performance but does not extend to overall geometric forms	Limited research on overall geometric forms	Examines various courtyard geometries by integrating multiple approaches to enhance thermal comfort
Courtyard Design Impact on Indoor Thermal Comfort and Utility Costs for Residential Households: Comparative Analysis and Deep Learning Predictive Model [52]	Explores small-scale courtyards (15-60m²) and their microclimatic performance but does not explore large-scale courtyards	Limited size of courtyards	Examines large courtyards up to 800m²
A Simulation-Based Model for Courtyard Housing Design Based on Adaptive Thermal Comfort [53]	Explores housing courtyards' microclimatic performance but does not explore large-scale courtyards for public buildings	Limited to housing courtyards	Examines courtyards in public buildings, specifically schools
Comparison of Courtyards in Traditional Iranian Houses in Different Climates of Iran [54]	Explores traditional courtyards' microclimatic performance but does not explore modern existing courtyards	Limited to traditional courtyards	Examines modern courtyards in schools
Improving Visual Comfort and Energy Efficiency in Existing Classrooms Using Passive Daylighting Techniques [55]	Adopted changing the building materials for school buildings to improve lighting and thermal performance	Limited to building school's materials	Examines the geometry of the courtyards as passive design solutions for schools
Passive Actions in the Building Envelope to Enhance Sustainability of Schools in a Mediterranean [56]	Adopted passive refurbishment solutions to improve the envelope of school buildings (insulation, shading, and glazing)	Limited to insulation, shading, and glazing effects on school thermal performance	Examines the geometry of the courtyards as passive design solutions for schools
Climate Change Resilience of School Premises in Cyprus: An Examination of Retrofit Approaches and Their Implications on Thermal and Energy Performance [57]	Aimed to decrease unwanted energy gains and raise cooling needs, focusing on solar shading devices	Limited to decreasing unwanted energy gains and raising cooling needs	Examines the geometry of the courtyards as passive design solutions for schools
Enhancing Student Satisfaction and Academic Performance through School Courtyard Design: A Quantitative Analysis [58]	Sought to improve student satisfaction and academic performance through school courtyard design	Limited to examining student satisfaction based on courtyard thermal performance	Examines the geometry of the courtyards as passive design solutions for schools
The Role of Greenery in Enhancing Thermal Performance and Aesthetic Value in Courtyards [50]	Emphasize the critical role of greenery in courtyards for enhancing thermal performance and aesthetic value. They note its benefits in creating cooler microclimates, reducing air temperatures, and providing relaxation spaces.	Limited to the role of greenery in courtyards	Examines the geometry of the courtyards as passive design solutions, including how courtyard configurations can enhance thermal performance without solely relying on greenery

Following the comprehensive analysis of previous research and the identified gaps, it is crucial to justify the choice of the studied problem within the context of this study. The significance of examining courtyard geometry and its impact on microclimates in hot, dry climates cannot be overstated. Given the increasing challenges posed by climate change, especially in arid regions, there is a pressing need to develop sustainable urban designs that enhance thermal comfort and energy efficiency.

Previous studies have established the benefits of climate-responsive architecture and green spaces, but have not adequately addressed how specific architectural elements, like courtyards, can be optimized to improve microclimates in public buildings such as schools. This research aims to fill that gap by providing a detailed investigation into how courtyard configurations can be leveraged to modify local microclimates, thus enhancing building performance. By using advanced simulation tools and integrating various architectural modifications, this study offers valuable insights that can inform future urban design and architectural practices, ultimately contributing to more resilient and sustainable built environments.

The choice of this problem is justified by the need for data-driven solutions to improve thermal conditions in educational facilities, which are critical for both student well-being and energy conservation. The focus on courtyard geometry in modern public buildings, as opposed to traditional or residential contexts, highlights the study's relevance and potential impact in addressing contemporary architectural and environmental challenges.

2. Material and Methods

The study adopted a qualitative approach to examine the accurate microclimates associated with five evolving geometric shapes of a school building. These shapes were chosen as case studies, all situated on the same plot of land. The research aimed to compare these microclimates with the standard weather file for the corresponding area, assessing their distinct effects in generating microclimates that deviate from the country's standard climatic data. The evaluation primarily focused on key factors such as average outdoor air temperature, wind speed, and outdoor thermal comfort in the UAE, characterized by a hot arid climate. ENVI-met software was utilized for this analysis (Figure 1). The intention behind this assessment was to advocate for the utilization of constructive urban microclimates when studying the thermal conditions of buildings and urban fabrics.

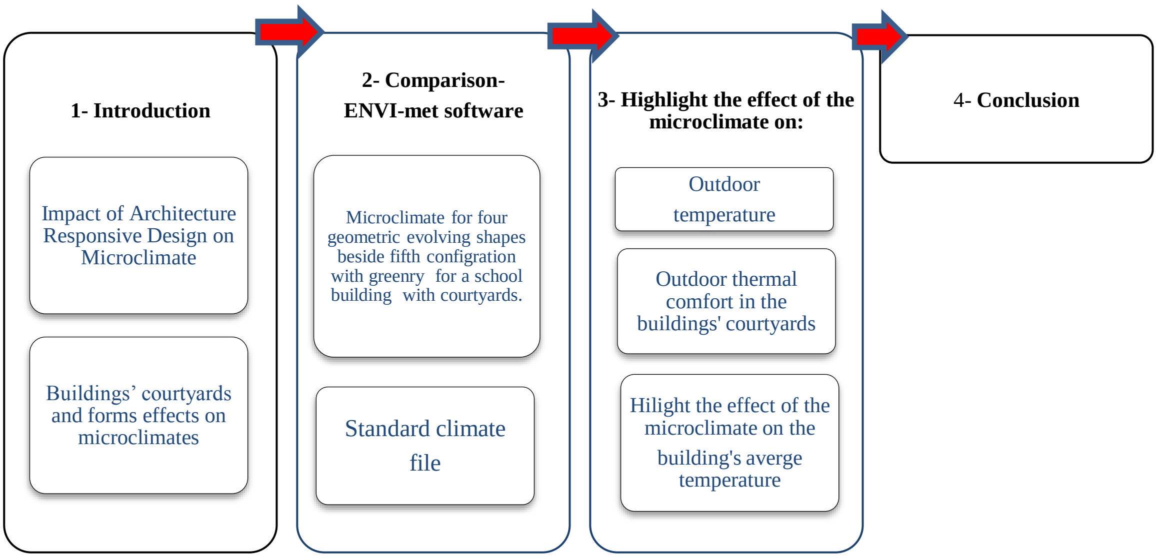
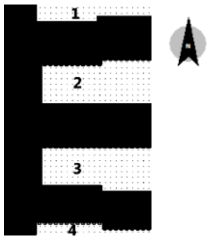


Figure 1. Framework of the research methodology

2.1. Case study characteristics

This study utilized a fundamental design approach, focusing on the most recent school in the UAE as the primary case study. The designated case study, named "Upa with fingers" (Upa-fin), adheres to a specific template. The school encompasses various facilities, including 38 classrooms, multipurpose rooms, six laboratories, activity areas, indoor and outdoor play spaces, an administration section, among others. The foundational design of the school incorporates two equal semi-closed courtyards arranged with reflective symmetry. The total plot area spans approximately 10,206 square meters, with the courtyards covering around 2,682 square meters. The built-up area is approximately 6,750 square meters. The ratio of courtyard area to plot area is 26%, while the ratio of courtyard area to built-up area is approximately 40% (see Table 2).

Table 2. The characteristics for basic Upa-fin

	School name	No. of outdoor space	Type of outdoor space	Area of outdoor space
 	Plot Area (m^2) (27×3) × (42×3)= 10206 m^2	Court 1	Recessed space	((21×3) × (3×3))-((10×3) × (1×3))= 477 m^2q
		Court 2	Semi-closed court	((20×3) × (8×3))-((11×3) × (1×3))= 1341 m^2
		Court 3	Semi-closed court	((20×3) × (8×3))-((11×3) × (1×3))= 1341 m^2
		Court 4	Recessed space	((21×3) × (2×3))-((9×3) × (1×3))=297 m^2

2.2. Research Software

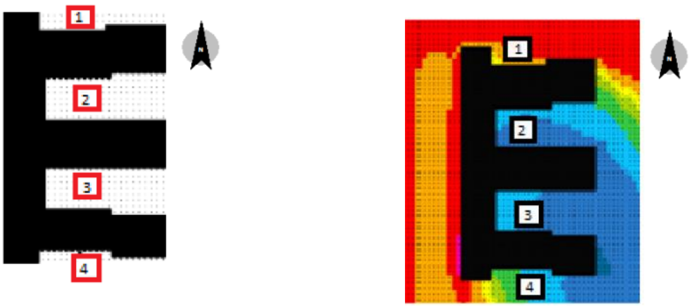
The study employed the ENVI-met software to simulate buildings, analyze urban microclimates, and assess external thermal conditions. ENVI-met is a pioneering three-dimensional micrometeorological simulation system based on mathematical equations, widely recognized for its capability to model thermal conditions in building arrangement designs [59, 60]. Notably, this software is advanced in modelling real microclimates for urban tissue configurations [21, 48, 61]. ENVI-met provides high-resolution simulations for accurate microclimate situations, incorporating fluid, atmospheric, and physical climatic values, along with enforced real climate settings such as wind and air temperature [62]. Furthermore, it can simulate outdoor humidity, air temperature, the impact of plants, and water features [63]. The investigations conducted by the ENVI-met software for the simulated buildings, based on design configurations, included:

- Microclimate - Outside air temperature.
- Thermal comfort PMV (Predicted Mean Vote).
- Building’s average temperature.

2.2.1. Software Validation

In this study, the primary case study school, referred to as "Upa-fin," was chosen for the validation of the simulation software by comparing the average simulated air temperature data with the measured values. Field measurements and simulations were conducted at four points in the courtyards and around the school. The average air temperature was calculated on September 21st for a 12-hour period from 8 am to 8 pm, while the simulation covered a 24-hour duration for more precise results. Simultaneously, Extech 45170 meters were used for field measurements, displaying readings for air temperature in the range of 0 to 50°C and wind speed between 0.4 to 20.0 m/s. The meter is designed with an accuracy of about ± 1.2°C [64]. The meter was fixed at a height of 1.8 meters to collect air temperature readings for the specified 12-hour timeframe.

Following the collection of average air temperature data from the selected points in both the field measurements and the simulation (see Figure 2), a comparison was carried out, and the results are presented in Table 3. Figure 3 illustrates the relationship between the simulated and measured air temperature data, revealing an R^2 value of approximately 0.89. Despite the differences in the average data, this correlation can be reasonably justified, primarily due to the accuracy range of the meter (Extech), which was around ± 1.2°C for the field measurements [64].



a- The selected four points in the school building for the average air temperature for the field measurements.

b- The selected four points in the school for the average air temperature in the simulation by ENVI-met.

Figure 2. The selected four points in the school building for the average air temperature for the field measurements and the simulation

Table 3 The simulated air temperature by ENVI-met and the Measured air temperature by Field measurement

Date	1 (°C)	2 (°C)	3 (°C)	4 (°C)	Average Measured Temperature °C	Date	1 (°C)	2 (°C)	3 (°C)	4 (°C)	Average simulated Temperature °C
8:00 AM	27.9	28.1	28.2	27.7	28.0	8:00 AM	28.6	28.2	28.0	28.0	28.2
9:00 AM	31.2	30.6	30.5	30.5	30.7	9:00 AM	32.6	31.9	31.6	32.6	32.2
10:00 AM	32.3	32.1	32	32.3	32.2	10:00 AM	31.9	32.2	32.5	32.1	32.2
11:00 AM	34.7	34.1	33.8	34.7	34.3	11:00 AM	33.2	33.8	33.1	33.8	33.5
12:00 PM	36.6	35.9	35.5	36.8	36.2	12:00 PM	37.6	36.7	36.8	37.2	37.1
1:00 PM	38	37.2	36.8	38.3	37.6	1:00 PM	36.9	36.6	37.0	37.4	37.0
2:00 PM	38.4	38.4	37.2	39.2	38.3	2:00 PM	38.4	37.8	38.2	38.3	38.2
3:00 PM	38	37.7	37.2	38.7	37.9	3:00 PM	36.3	36.5	36.4	36.8	36.5
4:00 PM	37.1	36.8	36.3	37.5	36.9	4:00 PM	34.4	34.6	34.8	34.7	34.6
5:00 PM	35.3	35.5	35.2	35.9	35.5	5:00 PM	34.0	33.0	33.4	34.7	33.8
6:00 PM	34.1	34.2	34.1	34.3	34.2	6:00 PM	34.1	34.1	34.1	34.1	34.1
7:00 PM	32.9	33.1	33.1	33	33.0	7:00 PM	33.5	33.1	33.0	33.0	33.2
8:00 PM	32.2	32.4	32.4	32.3	32.3	8:00 PM	32.4	32.4	32.3	32.3	32.4

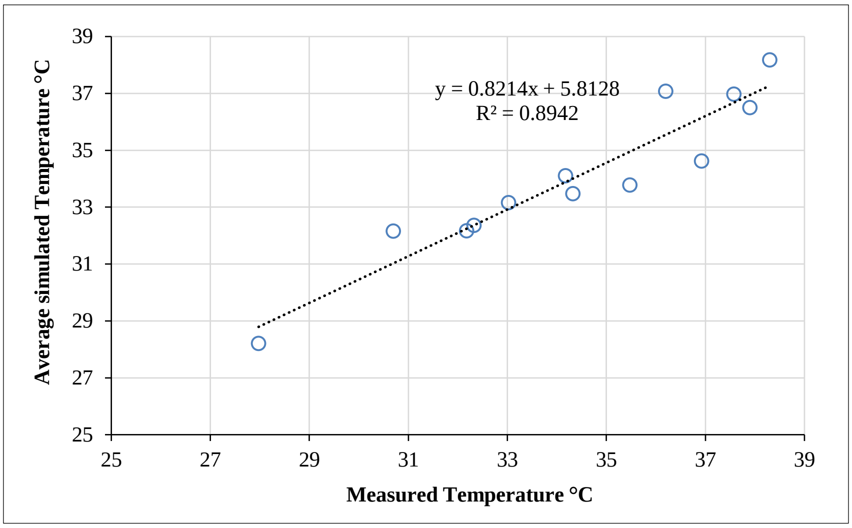


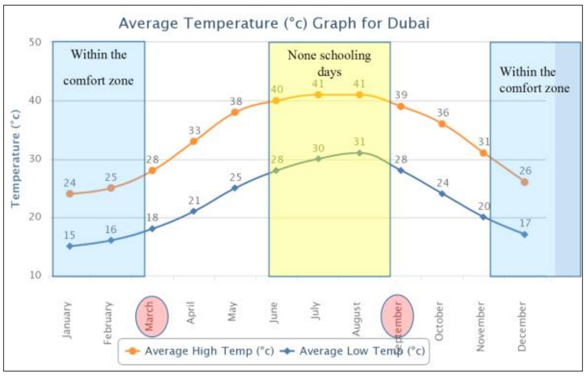
Figure 3. Scatterplot for the average measured and average simulated data

Numerous studies have affirmed the effectiveness of ENVI-met software in simulating microclimate data with high resolution. For instance, Wang et al. [65] conducted a comparison between the predicted data generated by ENVI-met software simulation and field measurements of air temperature to validate the simulated predictions. Their findings highlighted distinct ranges of correlation between the measured data and the simulated data. Additionally, various other studies have corroborated the accuracy of ENVI-met software simulation output by comparing it with actual readings from field measurements. Researchers have attested to the software's capability to generate precise data through the simulation of microclimates for building geometry and urban tissue, as observed in studies by [61, 66-68].

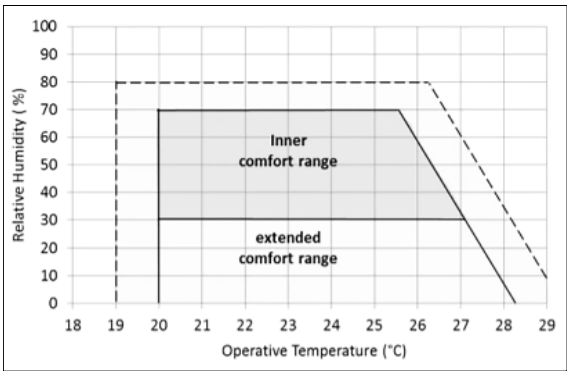
2.3. Case Studies Simulation Dates and Climate

This research was centered around comparing the standard climate with various microclimates resulting from different configurations of modifications to the courtyard design in a school case study situated in the hot climate of the UAE. The UAE experiences a hot arid climate with minimal rainfall, a predominant northwest wind direction, and an average maximum air temperature of 41°C in August, and an average minimum air temperature of 24°C in January [69].

The assessment of thermal performance and thermal comfort in this study was conducted on September 21st (representing maximum average temperature) and March 21st (representing minimum average temperature), as both periods surpass the comfort zone of 27˚C. According to Khalfan and Sharples [70], the comfort zone lies between 20-27˚C, based on Schnieders' thermal comfort diagram (see Figure 4). The primary challenge in hot arid areas like the UAE is to reduce energy consumption for cooling purposes [71].



a) Selected dates for simulation [69]



b) the comfort zone [70]

Figure 4. Simulation dated and the comfort zone

2.4. Simulation Analysis Criteria and Models

In this study, the simulation was carried out using the ENVI-met software, focusing on the area of the case study, which includes the school building and its proposed configurations. The plot area for the case study measures 81 m × 126 m thus the simulation area was built up to 180 m × 180 m. As part of the simulation process, 3D models representing the school buildings were generated within the ENVI-met boundary. The software was supplied with data detailing the roughness type of the site, as well as information on wind direction and speed, as emphasized by Jin et al. [72] Hourly temperature and humidity data were also input into the software. According to Huttner [59] ENVI-met allows the imposition of real climate boundary conditions, such as air temperature and humidity, to create a microclimate based on authentic inputs, thereby enhancing the accuracy of results.

Certain parameters were standardized in the ConfgWizard during the simulation process across all cases. These parameters pertained to building location, materials, glassing ratio in the walls, the size of the main model, and the size of the cell [73]. This standardization aimed to generate results that could elucidate the effects of different courtyard configurations in relation to the investigation matrix (see Table 4).

The research simulation conducted using the ENVI-met software focuses on a comprehensive analysis of microclimate variations within public buildings in Dubai, UAE, characterized by its hot and arid climate. The study meticulously simulates the impact of architectural designs, particularly courtyard geometries, on enhancing thermal comfort and energy efficiency under specific climate conditions.

For the simulations, the forced climate data includes a ground wind speed of 3.5 m/s with a dominant direction of 315° from the north. The investigation spans two critical dates, September 21st and March 21st, showcasing a detailed hourly breakdown of average air temperature (T) and relative humidity (RH). On September 21st, temperatures range from 35.75°C at midnight, gradually increasing to a peak of 41.00°C at noon, before decreasing again to 36.19°C by 23:00, with relative humidity percentages adjusting correspondingly. On March 21st, the temperature starts at 21.00°C at midnight, reaching a high of 29.00°C by 14:00, and then it diminishes back to 21.80°C by 23:00, with relative humidity adjustments reflective of the cooler temperatures.

The simulation model's building characteristics define the school building as two floors high, with each floor measuring 4 meters, adopting concrete slab hollow block and concrete walls as primary materials for all simulation scenarios. Building openings are standardized at 20% of the exterior walls, aligning with Al-Sallal [74] optimal ratio for window to external wall surfaces in classrooms.

Key model parameters include a main model area of 180×180 meters with a height of 40 meters, and a grid configuration of 60×60×20 cells, resulting in a total area coverage of 180 square meters. The chosen cell sizes are dx=3 m, dy=3 m, and dz=2 m, selected after multiple trials to ensure optimal simulation performance. The simulation spans 24 hours starting from 00:00 P.M. on the 20th, concluding the results for the 21st of September and March, with a roughness length (z0) of 0.01 and output intervals for main files set at 60 minutes.

This detailed simulation framework aims to provide a nuanced understanding of how specific architectural configurations, particularly in relation to courtyard designs and building geometry, can significantly influence the microclimate and, by extension, the thermal comfort and energy usage within public buildings in hot, arid climates like that of UAE. The simulation results, encompassing outdoor temperature, average building temperature, and the Predicted Mean Vote (PMV), were considered dependent variables for each configuration. These variables were analyzed in relation to independent factors to emphasize the impact of each configuration layout on the related microclimate. The interrelation of these factors is expected to influence the air temperature, thus the thermal comfort experienced by the users, as highlighted by Shrestha and Rijal [75].

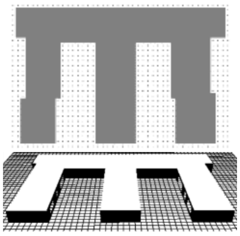
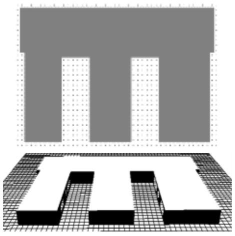
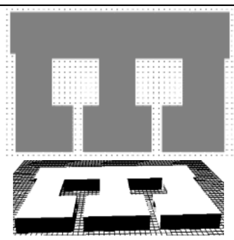
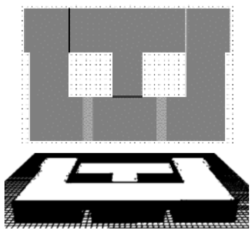
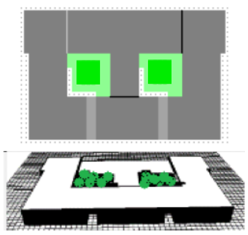
Table 4. Basic settings for the simulated models

Location and climate					
• The location	Dubai – UAE.				
• The climate	Hot and arid				
Forced in climate data					
Wind speed on the ground	3.5 m/s				
Dominant Wind direction	315° from the north				
• Average air temperature (T) and relative humidity (RH) 21st September			• Average air temperature (T) and relative humidity (RH) 21st March		
Time	**T °C**	**RH (%)**	**Time**	**T °C**	**RH (%)**
00:00	35.75	64.25	00:00	21.00	76.67
01:00	35.31	66.94	01:00	20.20	77.33
02:00	34.88	69.63	02:00	19.40	78.00
03:00	34.44	72.31	03:00	18.60	78.67
04:00	34.00	75.00	04:00	17.80	79.33
05:00	34.88	69.63	05:00	17.00	80.00
06:00	35.75	64.25	06:00	18.33	78.89
07:00	36.63	58.88	07:00	19.67	77.78
08:00	37.50	53.5	08:00	21.00	76.67
09:00	38.38	48.13	09:00	22.33	75.56
10:00	39.25	42.75	10:00	23.67	74.44
11:00	40.13	37.38	11:00	25.00	73.33
12:00	41.00	32.00	12:00	26.33	72.22
13:00	40.56	34.69	13:00	27.67	71.11
14:00	40.13	37.38	14:00	29.00	70.00
15:00	39.69	40.06	15:00	28.20	70.67
16:00	39.25	42.75	16:00	27.40	71.33
17:00	38.81	45.44	17:00	26.60	72.00
18:00	38.38	48.13	18:00	25.80	72.67
19:00	37.94	50.81	19:00	25.00	73.33
20:00	37.50	53.50	20:00	24.20	74.00
21:00	37.06	56.19	21:00	23.40	74.67
22:00	36.63	58.88	22:00	22.60	75.33
23:00	36.19	61.56	23:00	21.80	76.00
Buildings characteristics					
The building height	The school building assumed to be 2 floors high, where each floor equals 4 m.				
The building materials	The materials were fixed as concrete slab hollow block and concrete walls hollow block, as default for all the models in all simulation scenarios.				
The buildings openings	The openings set as 20% of the exterior walls as fixed parameters the ratio for window/external walls of the classrooms				
The simulation model characteristics					
Main model area	180×180 m^2 with height 40m				
Grid number for the cells	x-Grids= 60, y-Grids=60, z-Grids=20. Total area = 180				
The cell size	dx=3 m, dy=3 m, dz=2 m, this size was chosen after several attempts for best performance				
The simulation time	24 hours starting on 00:00 P.M. on the 20th of September to conclude the simulation results for 21st of September, same for 21st of March				
Roughness Length z0	0.01				
Output interval main files	60 min				

This research investigates the alterations and enhancements in microclimates resulting from various design configurations of a school building situated in the UAE's hot, arid climate. The study specifically analyzes five different configurations, including the original case study setup and four additional developed designs, to assess their impact on the local microclimate. These configurations, as presented in Table 5 and elaborated further in the subsequent sections, aim to explore how changes in the school building's design can influence the surrounding microclimatic conditions. Th configurations are as below:

1. First configuration: The basic case for the school building with the following characteristics:
   - Courtyard area to Building Ratio (CA/BA) is approximately 40%.
   - Rectangular courtyard.
   - Two floors with a height of 8 meters.
2. Second configuration: CA/BA ratio reduced to 20%, proposed based on recommendations from Soflaeiet al. [43] who identified a good thermal performance in traditional courtyards with CA/BA ratios ranging between 18-44%. Tablada [76] also suggested a CA/BA ratio >25% for better thermal performance.
3. Third configuration: New courtyard shape designed as a square to enhance thermal performance, inspired by Yaşa & Ok [77], who asserted that in hot areas, a square courtyard is expected to increase shaded areas, reducing the energy required for cooling in summer.
4. Fourth configuration: Additional floor added to increase building height, designed based on Tablada's [76] recommendation for buildings with wide courtyards and direct street access. For such buildings, Tablada suggested a maximum height of up to 14m (3-4 floors) to achieve better thermal conditions in the courtyard and interior spaces. The UPA-fin was investigated with a new height of 12m (three floors).
5. Fifth configuration: Addition of a mixture of trees and grass, with approximately 30% trees in the middle, 56% grass, and the remaining 14% as concrete tile. This configuration was inspired by findings from various studies, including Lee et al. [61]. The selected cases were defined based on an extensive review of relevant literature and insights from previous studies.

Table 5. The five configurations of the building with courtyard modifications beside fifth configuration includes greenery

C1-First configuration	C2-Second configuration	C3-Third configuration	C4-Forth configuration	C5-Fifth configuration
				
1- First configuration is the Basic case for the school building: • Courtyard area to Building Area Ratio (CA/BA) is around 40%; • Rectangular courtyard; • Two floors 8 m height.	2-Second configuration with: • Courtyard area to Building Area Ratio (CA/BA) is around 20%; • Rectangular courtyard; • two floors 8 m height.	3-Third configuration with: • Courtyard area to Building Area Ratio (CA/BA) is around 20%; • Square courtyard; • Two floors 8 m height.	4- Forth configuration with: • Courtyard area to Building Area Ratio (CA/BA) ratio is around 20%; • Square courtyard; • Three floors 12m height.	5- Fifth configuration: • Courtyard area to Building Area Ratio (CA/BA) ratio is around 20%, • Square courtyard; • Three floors 12m height; • Adding a mixture of trees and grass.

3. Results

Microclimate variations in this study were influenced by modifications to the school building's courtyard characteristics, which underwent five configurations and were tested using ENVI-met software. These configurations included the basic courtyard design and subsequent modifications based on the Courtyard Area to Building Area (CA/BA) ratio, courtyard outline, and courtyard height. To conduct an analysis of building energy performance and emphasize energy consumption savings, two types of climate data were presented on the simulation date.

1- The first type comprises general climate data sourced from the standard ASHRAE weather data for Dubai/UAE provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). This data was collected from local weather stations based on synoptic observations over several years. However, it is important to note that this data, primarily gathered in the countryside or at airport weather stations, may differ from the air temperature in densely populated urban areas [78].

2- The second type involves new, specific microclimate data calculated by ENVI-met. To assign microclimate data for the best models in the five configurations, six points (receptors) were located in critical positions around the school buildings and inside the courtyards, as illustrated in Figure 5. This methodology, employed by Sharmin & Steemers [78], involved locating points to design new microclimates for buildings in their research using ENVI-met software. A weighted average calculation based on the walls' area and the nearest receptors was utilized to calculate and design the microclimate of the school buildings at each stage, highlighting the maximum and minimum new temperatures for the new microclimates on both simulation dates.

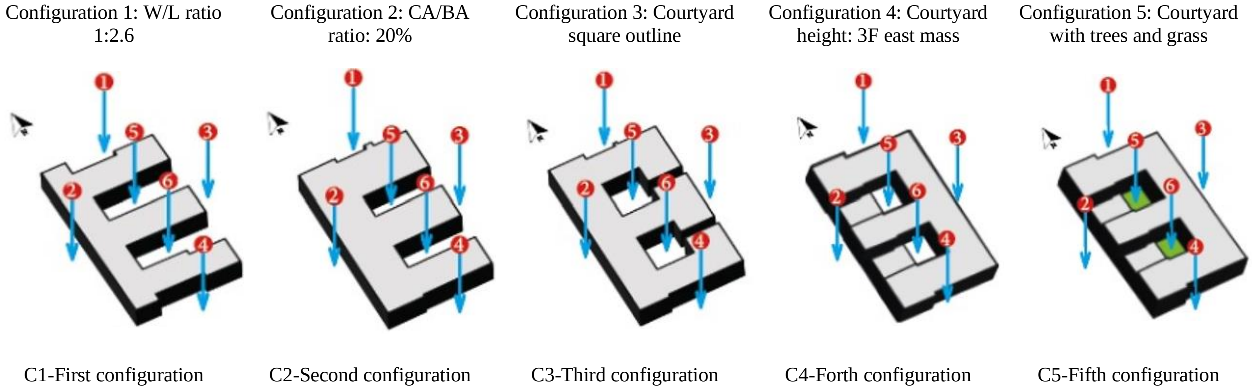


Figure 5. The receptor points for the UPA-fin schools used to calculate the microclimate for each case in the five Configurations in ENVI-met software

3.1. Positive Variation in the Air Temperature Between the Configurations' Microclimates and the Standard Climate

The difference in air temperature between the standard climate and specific microclimates is clear with improvement based on the context of changes in building courtyard design. As the implementation of new configurations has resulted in a reduction in the extent of microclimates. These adjustments underscore the crucial role of building courtyard design in influencing local environments. It was observed that there was a decrease of approximately 0.74-1.45 °C on September 21st and about 0.5-1.4 °C on March 21st in the average outdoor air temperature within the microclimates of the school buildings. This reduction is attributed to the new configurations related to courtyard design compared to the standard climate, as depicted in Figure 6 and Figure 7-a. Furthermore, the decrease was approximately 0.5-1.4 °C lower on March 21st, as illustrated in Figure 6 and Figure 7-b

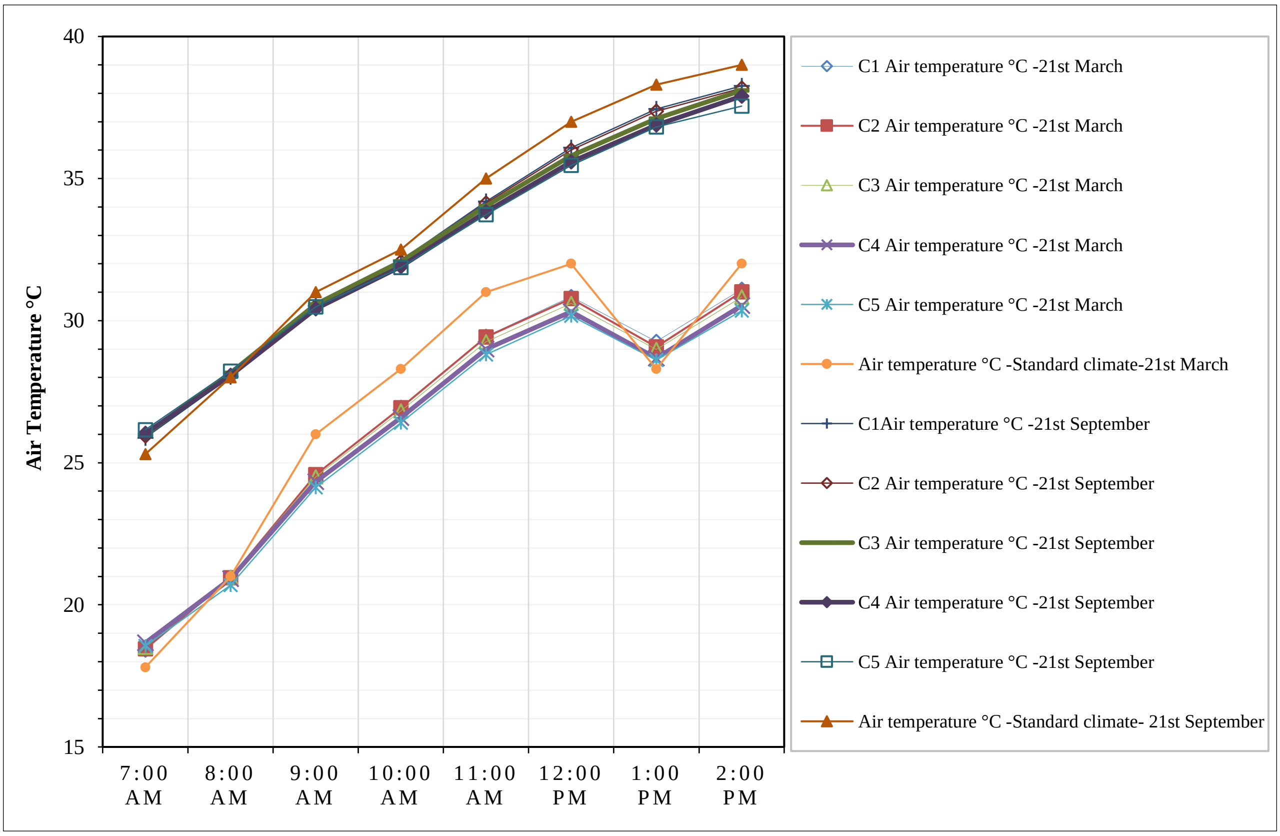
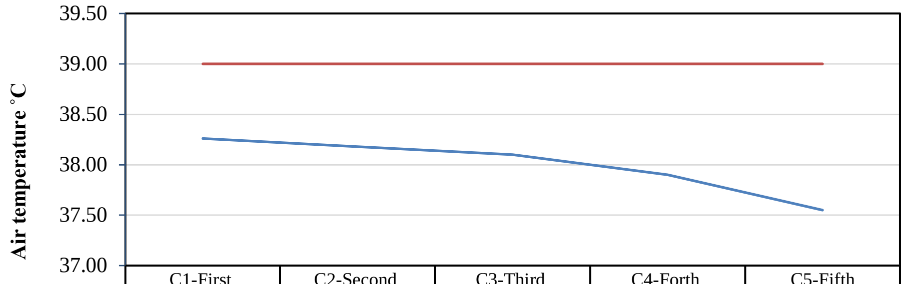
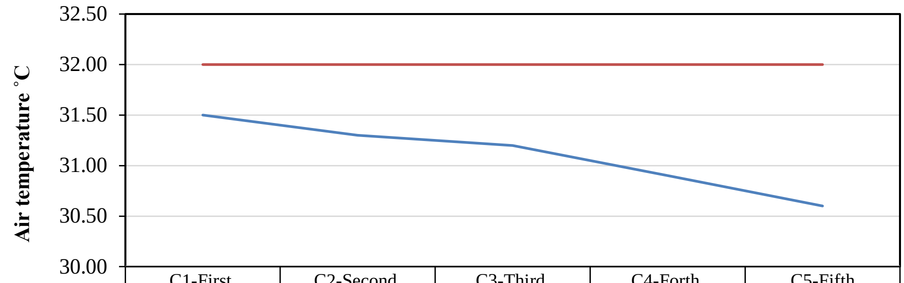


Figure 6. Average air temperature from the receptor points for five configurations for the school and the average air temperature from the standard climate on the 21st September and 21st March



	C1-First configuration	C2-Second configuration	C3-Third configuration	C4-Forth configuration	C5-Fifth configuration
Configrations' microclimates- Max average air temperature	38.26	38.18	38.10	37.90	37.55
Standard climate- Max air temperature	39.00	39.00	39.00	39.00	39.00
Difference between max average air temperature for the configrations' microclimates and the standard climate (39˚C)	0.74	0.82	0.90	1.10	1.45

a) Difference between max average air temperature for the configurations' microclimates and the standard climate (39˚C) on 21st of September.



	C1-First configuration	C2-Second configuration	C3-Third configuration	C4-Forth configuration	C5-Fifth configuration
Configrations' microclimates- Max average air temperature	31.5	31.3	31.2	30.9	30.6
Standard climate- Max air temperature	32	32	32	32	32
Difference between max average air temperature for the configrations' microclimates and the standard climate (32˚C)	0.5	0.7	0.8	1.1	1.4

b) Difference between max average air temperature for the configurations' microclimates and the standard climate (32˚C) on 21st of March

Figure 7. Difference between max average air temperature for the configurations' microclimates and the standard climate

3.2. The Effect of the Configurations' Microclimates on the Thermal Comfort

The observed variation in microclimates compared to the standard climate, as depicted in the previous figures (6-7), highlighted a reduction in the maximum average air temperature within the microclimates of the configurations compared to the standard climate. Subsequent investigations were conducted to assess the impact of these microclimate changes on thermal comfort. The assessment of outdoor thermal comfort primarily relies on microclimate indicators, with air temperature being a key factor. The evaluation of outdoor thermal comfort was measured using the Predicted Mean Vote (PMV) within the school courtyard. PMV is a metric reflecting an individual's satisfaction with the thermal microclimate, considering various interactive, biological, and psychological factors. It represents a stable condition for heat balance in the human body [79].

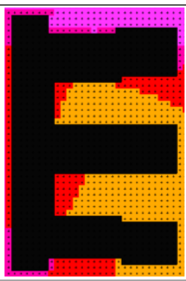
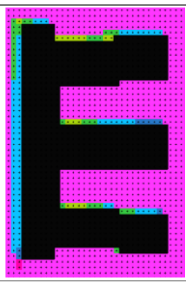
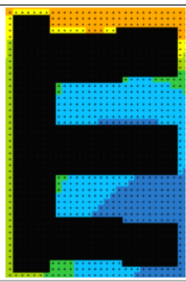
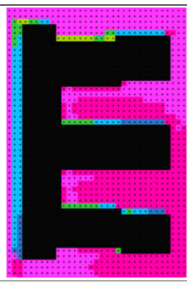
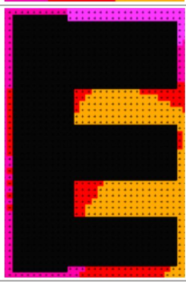
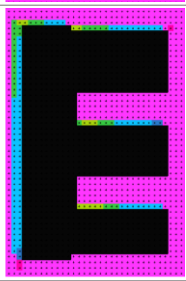
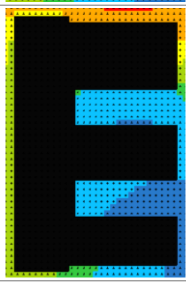
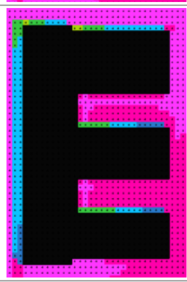
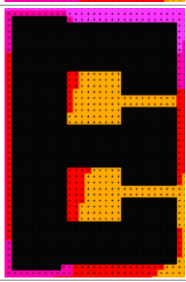
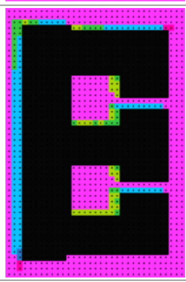
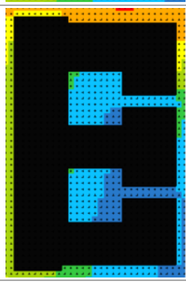
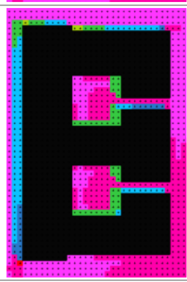
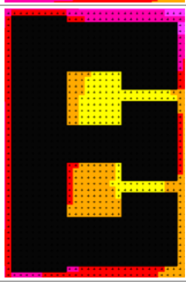
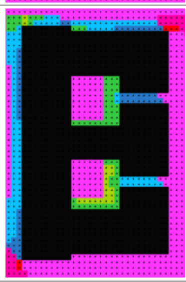
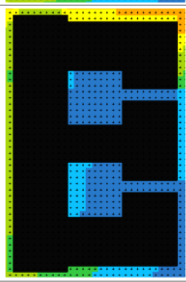
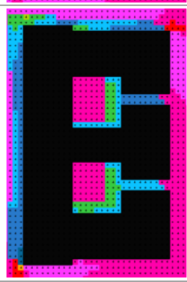
ENVI-met software was employed to evaluate outdoor thermal conditions in the courtyards. The software extended the ASHRAE scale of PMV, originally following Fanger's experimental scale, from seven points (-3 to +3) to a nine-point scale for thermal comfort in outdoor areas ranging from -4 (very cold) to +4 (very hot) [80, 81]. The Biomet wizard in ENVI-met software calculates thermal comfort in outdoor spaces like courtyards. It incorporates input data related to outdoor conditions such as air temperature, horizontal wind speed, and relative humidity. Additionally, personal human parameters, including metabolic rate, clothing insulation, and average age and weight of students, were defined and input into the software for accurate thermal comfort assessment [82].

The assessment of thermal comfort (PMV) was conducted based on the predicted microclimates of the five configurations of the school case study at 10:00 AM during the students' break time, considering that the basic case study was a school building. On September 21st, at 10:00 AM, the air temperature distribution results, as presented in Table 6a, indicated that most courtyard microclimates for C1 and C2 exhibited high air temperatures ranging between 39.1°C and 39.7°C, with slight improvement in C3. In C4, the microclimate air temperature was reduced in some areas to 38.8°C, and the most significant reduction occurred in C5, where the air temperature ranged between 38.5°C and 38.8°C. A similar trend was observed on March 21st, with some areas in C3 experiencing reduced air temperatures from 27.2°C to 26.6°C compared to C1 and C2. Additionally, a notable improvement in air temperature was recorded in C4 and mostly in C5, with some areas showing temperatures below 26.3°C (Table 6b).

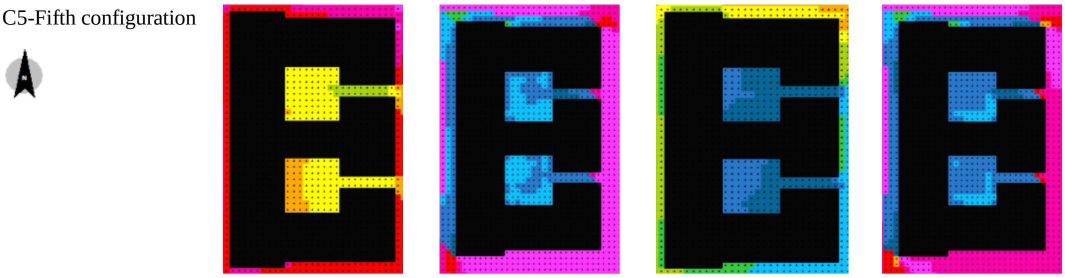
The alterations in microclimates had an impact on the PMV outcomes. In configurations C1 and C2, most courtyard areas were characterized by discomfort, with a PMV around 4. This discomfort was ascribed to the low height of surrounding structures, open courtyards with limited shaded areas in the initial two configurations, resulting in extended exposure to direct solar radiation and elevated air temperatures. Conversely, a notable enhancement in PMV readings for school courtyard spaces was observed with the increase in building height to three floors in C4 and the addition of vegetation in C5 after altering the height to a three-floor east mass. Refer to Table 6 for air temperature distribution and PMV values in the courtyards of the five configurations at 10:00 AM during the students' break time on both September 21st and March 21st. The simulation results demonstrated that thermal comfort, indicated by PMV, varied for each configuration's microclimate, depending on the alterations in the building's courtyard design on both simulation dates, showcasing distinct changes from C1 to C5.

Significant enhancement in PMV readings for school courtyards was observed with the introduction of a three-floor height in C4 and the incorporation of vegetation in C5. In the C5 configuration, the highest PMV reading was 3.15, covering 15% of courtyard areas, in contrast to C1, where the upper reading was approximately 4.35, covering 48% of courtyard areas. Increasing the height of the surrounding structures in C5 led to a reduction in the sky view factor (SVF), blocking some solar radiation and improving thermal comfort, with a reduction of about 1.2 on the PMV scale compared to C1, as depicted in Figures 8-a and 8-b. A similar trend was observed on March 21st, with notable PMV improvements in C5 configuration due to the addition of vegetation. In C5, the upper PMV reading was around 1.9, covering 2% of courtyard areas, whereas in C1, the upper reading was approximately 3, covering 48% of courtyard areas. This represented a reduction of about 1.1 on the PMV scale from C1 to C5 configuration, as illustrated in Figures 8-c and 8-d.

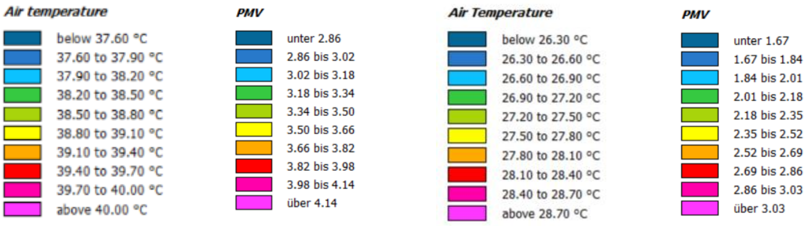
Table 6. Average air temperature distribution and PMV at 10:00 AM during the students' break time on both September 21st and March 21st

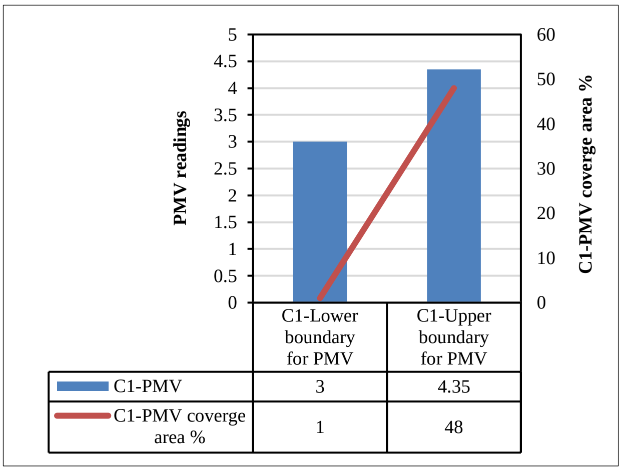
	a- 21st September		b- 21st March	
	Air temperature	**PMV**	**Air temperature**	**PMV**
C1-First configuration				
C2-Second configuration				
C3-Third configuration				
C4-Forth configuration				

C5-Fifth configuration

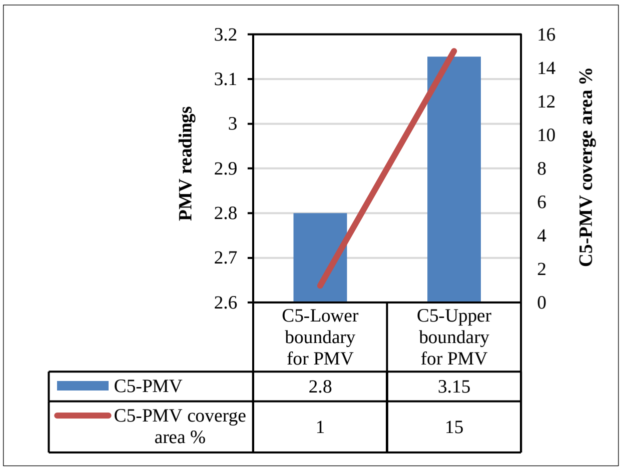


Map Key

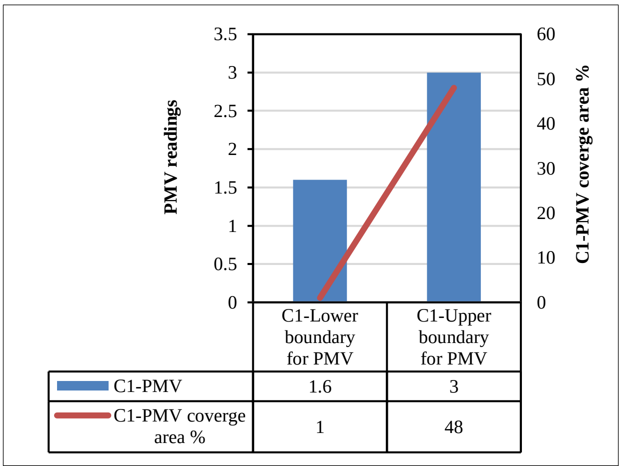




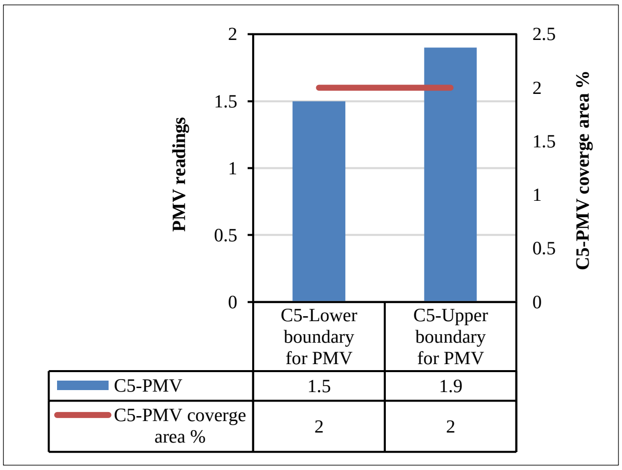
a. Upper and lower boundaries for the PMV in the courtyards of C1 configuration at 10:00 AM at the break time for the students on the 21st of September.



b. Upper and lower boundaries for the PMV in the courtyards of C5 configuration at 10:00 AM at the break time for the students on the 21st of September.



c. Upper and lower boundaries for the PMV in the courtyards of C1 configuration at 10:00 AM at the break time for the students on the 21st of March.



d. Upper and lower boundaries for the PMV in the courtyards of C5 configuration at 10:00 AM at the break time for the students on the 21st of March.

Figure 8. Upper and lower boundaries for the PMV in the courtyards C1 and C5 configurations at 10:00 AM at the break time for the students on the 21st of September and the 21st of March

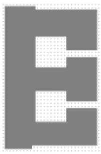
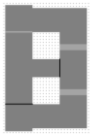
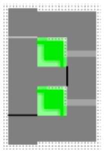
3.3. Effect of the Variation between Climate and Microclimates on Buildings' Average Temperatures (T_{in})

The alterations in microclimates had a noticeable impact on the average temperature of the buildings (T_{in}) in different configurations. As evident in table 7, the average building temperature changed from 28.06 °C in C1 configuration to 26.17 °C in C5 configuration, representing a reduction of approximately 1.89 °C on September 21st. Similarly, on March 21st, the average building temperature shifted from 23.80 °C in C1 configuration to 22.12 °C in C5 configuration, with a reduction of around 1.68 °C.

These findings underscore that modifications in school courtyard design configurations can lead to improvements in courtyard air temperature, a decrease in the average building temperature, and concurrent enhancements in PMV in outdoor courtyard spaces, as observed in the optimal configuration, C5.

By strategically refining courtyard layouts and architectural features, it is feasible to adjust outdoor air temperatures within microclimates. This adjustment not only improves thermal comfort but also promotes the development of more sustainable and pleasant living spaces, adept at adapting to changing climate conditions.

Table 7. The best five cases of the five Configurations of stage two for school UPA-fin to the north

Configurations	Investigation field	Top view for best case	The built-up area - m^2	Number of floors	Total built up area - m^2	Average Tin °C on 21st of September	Average Tin °C on 21^{st} of March
Configuration 1	Shape factor: W/L ratio 1:2.6		6750	2	13500	28.06	23.80
Configuration 2	CA/BA ratio :20%		8046	2	16092	27.88	23.62
Configuration 3	Courtyard outline: square		8091	2	16182	27.47	23.30
Configuration 4	Courtyard walls height: 3F east mass		8415	3	22824	26.88	22.76
Configuration 5	Courtyard with vegetation Trees and grass		8415	3	22824	26.17	22.12

4. Discussion

The present study provides a significant contribution to the current research community by offering a detailed and comprehensive analysis of courtyard configurations in hot arid climates. The study's focus on different configurations (C1 to C5) and their impact on microclimates and thermal comfort in school buildings in the UAE highlights the practical applications and benefits of strategic courtyard design configurations as the following:

1. ***C1 - Basic Configuration*:**

   ○ *Details*: Courtyard area to Building Area Ratio (CA/BA) of 40%, rectangular courtyard, two floors (8 m height).

   Findings: The basic configuration exhibited higher air temperatures, contributing to discomfort. The average outdoor air temperature in the courtyard was high, with minimal impact on reducing the heat island effect. The PMV reading was around 4, covering 48% of courtyard areas, indicating significant discomfort due to low height and lack of shading, resulting in extended exposure to solar radiation. The average building temperature was 28.06°C on September 21st and 23.80°C on March 21st. This configuration demonstrated poor thermal regulation, highlighting the need for design improvements.

2. ***C2 - Reduced Courtyard Area:***

   ○ *Details*: CA/BA ratio of 20%, rectangular courtyard, two floors (8 m height).

   Findings: Reducing the courtyard area resulted in a minor improvement in thermal conditions but was not significant compared to the baseline configuration, as the air temperatures remained high, similar to C1, due to limited changes in geometry and height. The PMV readings remained high, indicating minimal improvements in thermal comfort. The design changes were insufficient to significantly enhance shading and ventilation. There was a slight reduction in the average building temperature, but it was not significant enough to improve overall thermal comfort.

3. ***C3 - Square Courtyard:***

   ○ *Details*: CA/BA ratio of 20%, square courtyard, two floors (8 m height).

   Findings: Changing the shape to a square courtyard provided better shading and air circulation. Thus, marginal improvement in air temperature was noted, with readings ranging from 39.1°C to 39.7°C on September 21st and 27.2°C to 26.6°C on March 21st. The square shape provided some benefits but did not significantly affect thermal comfort. The PMV readings showed slight improvement, but discomfort remained. The changes in courtyard shape did not provide sufficient shading or cooling. The average building temperature showed a marginal improvement, indicating that changes in shape alone were not effective in significantly reducing indoor temperatures.

4. ***C4 - Increased Building Height:***

   ○ *Details*: CA/BA ratio of 20%, square courtyard, three floors (12 m height).

   Findings: A noticeable reduction in air temperature to 38.8°C on September 21st, showcasing the impact of increased building height in reducing solar radiation exposure. Temperatures on March 21st dropped to 26.3°C in some areas. PMV improved to around 3.5, showing better thermal comfort due to the increased height reducing the sky view factor (SVF) and blocking more solar radiation. The average building temperature reduced to 27.00°C on September 21st, indicating better thermal regulation. This configuration demonstrated the positive impact of increased height on both outdoor and indoor temperatures.

5. ***C5 - Vegetation Addition:***

   ○ *Details*: CA/BA ratio of 20%, square courtyard, three floors (12 m height), with added trees and grass.

   Findings: The most significant improvement was observed, with air temperatures ranging from 38.5°C to 38.8°C on September 21st and below 26.3°C on March 21st. Vegetation effectively enhanced shading and cooling. PMV readings showed significant improvement, with a reading around 3.15, covering 15% of courtyard areas on September 21st, and around 1.9, covering 2% of courtyard areas on March 21st. The addition of vegetation and increased height provided substantial shading and cooling, reducing PMV by about 1.2 points from C1 to C5 on September 21st, and by 1.1 points on March 21st. The average building temperature reduced to 26.17°C on September 21st and 22.12°C on March 21st. This configuration offered the best thermal regulation, highlighting the efficacy of combining increased height and vegetation in reducing indoor temperatures by approximately 1.89°C on September 21st and 1.68°C on March 21st.

4.1. Advancements of this Research in Courtyard Design for Climate Adaptation

The present study advances the field by offering specific, actionable insights for enhancing thermal comfort and reducing energy consumption in hot arid climates through strategic courtyard design. It builds on and extends the findings of previous research by providing more precise and targeted data. The detailed analysis of various configurations, including the impact of increased building height and added vegetation, highlights the critical role of courtyard geometry in climate-adaptive architecture. The findings underscore the superiority of the present study in providing practical recommendations for sustainable urban planning and architecture in challenging climates. The following outlines how the present study compares to and advances previous research in the field:

- Zhu et al. [83] emphasized that courtyards with north-south orientation (within 45° deviation) and high aspect ratios (greater than 2) provide excellent shading in hot climates, while square courtyards with high openness are optimal for cold climates. They also highlighted the importance of integrated design strategies involving geometry, orientation, openings, wall materials, and landscape elements. The present study corroborates these findings on the importance of orientation and geometry but provides more precise and targeted data specific to hot arid climates, demonstrating the effectiveness of particular design strategies in reducing temperatures and improving thermal comfort.

- Diz-Mellado et al. [84] found that courtyard geometry significantly impacts cooling energy demand, with reductions of 8–18% depending on the configuration. They also noted that the floor level and orientation of adjacent rooms can influence energy demand by 15% and 22%, respectively. While Diz-Mellado et al. focused on energy demand, the present study offers a more detailed analysis of temperature reduction and thermal comfort improvements, providing specific configurations that can reduce outdoor air temperatures by up to 1.45°C and improve PMV readings significantly.

- Bassal et al. [85] highlighted that Mediterranean courtyard houses demonstrate high adaptability, sustainability, and functionality, with courtyard morphology providing bioclimatic benefits and meeting physical and sociocultural requirements. The present study extends these bioclimatic benefits to a hot arid climate context, providing actionable design recommendations that enhance thermal comfort and reduce building temperatures more effectively.

- Sahnoune & Benhassin [86] recommended north-east and south-east orientations and H/W ratios less than 0.8 for better winter conditions in semi-arid climates. Focusing on summer conditions in hot arid climates, the present study complements their winter analysis by demonstrating significant improvements in thermal comfort through increased building height and the addition of vegetation in courtyards.

- Akubue & Adesina [51] identified optimal H/W ratios for enhancing natural ventilation in tropical climates. Both studies underline the importance of geometry for natural ventilation. However, the present study goes further by analyzing overall thermal comfort and energy efficiency, providing a more comprehensive understanding of courtyard design impacts.
- Wu et al. [87] developed a new TMRT model that is faster and more accurate than existing models, with significant implications for climate-resilient courtyard design. The present study's use of ENVI-met for detailed simulations complements Wu et al.'s model development, both aiming to improve courtyard design for climate resilience. The present study provides detailed guidance on specific courtyard configurations to enhance thermal comfort.
- Diz-Mellado et al. [88] found that courtyards with an AR > 3 achieve thermal comfort 90–100% of the time during the warm season. The present study supports these conclusions on thermal comfort in courtyards but offers more specific guidance on configurations that reduce outdoor air temperatures and improve PMV readings, demonstrating superior practical applications for energy efficiency.

4.2. Contribution to Current Research

1. ***Enhanced Understanding of Courtyard Configurations:***
    - The study provides detailed insights into how different courtyard configurations affect microclimates and thermal comfort in hot arid climates. By analyzing configurations C1 to C5, the research demonstrates the specific impacts of courtyard shape, size, building height, and vegetation on environmental conditions.
2. ***Practical Applications for Sustainable Design:***
    - The findings offer practical guidelines for architects and urban planners on optimizing courtyard designs to improve thermal comfort and reduce energy consumption. The study emphasizes the importance of strategic design modifications, such as increasing building height and adding vegetation, to achieve significant improvements in microclimates.
3. ***Targeted Data for Hot Arid Climates:***
    - Unlike many studies that provide broad recommendations for various climates, this research focuses on the hot arid climate of the UAE. The precise data and targeted recommendations make it highly relevant for regions with similar climatic conditions, addressing a crucial gap in the literature.
4. ***Quantitative Analysis Using Advanced Tools:***
    - Utilizing ENVI-met software for detailed simulations, the study provides robust quantitative analysis of the effects of courtyard design modifications. The use of advanced simulation tools ensures the reliability and accuracy of the findings, contributing valuable empirical data to the field.
5. ***Improved Thermal Comfort Metrics:***
    - By focusing on PMV readings and actual temperature reductions, the study offers a comprehensive evaluation of thermal comfort improvements. This approach provides a more nuanced understanding of how design changes can enhance occupant comfort, which is essential for designing livable and sustainable urban environments.
6. ***Guidance for Future Research:***
    - The detailed configuration analysis and the empirical findings serve as a foundation for future research. Other researchers can build on this work to explore additional variables, such as different vegetation types, building materials, and further height variations, to continue improving courtyard design strategies.

Thus, the present study makes a substantial contribution to the current research community by filling critical gaps in the understanding of courtyard design in hot arid climates. Through detailed analysis of specific configurations and their impacts, the research provides valuable insights and practical recommendations that enhance the field of sustainable architecture and urban planning. The findings underscore the importance of thoughtful courtyard design in promoting thermal comfort and energy efficiency, offering a clear pathway for future studies and real-world applications

5. Conclusion

In this research the courtyard design and layout for each design configuration (C1 to C5) played a pivotal role in shaping microclimates, impacting variables like outdoor air temperature, and buildings average temperature in a confined area. This dynamic interaction emphasizes the significance of architectural choices in design of courtyards and buildings geometry on the related microclimates. Based on that, the thermal conditions in each configuration of the case study - in the hot conditions of UAE - varied according to the changes in the microclimates including reducing the outdoor air temperature, better PMV, lower building’s average temperature from C1 to C5. The reduction in the indoor temperature was because of the developments on the courtyard, and because of the new microclimates which was created according to the courtyard design at that stage, which is expected to reduce the energy consumption for the building.

Based on that, there was a reduction about o.74-1.45 ˚C on 21st of September and about 0.5-1.4 ˚C on 21st of March in the average outdoor air-temperature in the microclimates of the school buildings – based on the new configurations related to the courtyard design- compared to the standard climate.

A clear improvement was achieved in the readings of the PMV for the courtyards of school buildings when the height increased to 3Floors in C4 and when vegetation was added in C5. When changing the height to 3 floors in the east mass in C5. As in C5 configuration the upper reading of the PMV was 3.15 that covered 15% of the courtyards areas compared to C1 that has upper reading around 4.35 that covers 48% of the courtyards areas, increasing the height of the masses around the courtyards can decrease the SVF (sky view factor), thus blocking some of the solar radiation and improving thermal comfort with a reduction of about 1.2 on the PMV scale from C1 to C5 configuration. A similar situation happened on 21st March as the significant improvements for the PMV sensation was in C5 configuration by adding vegetation. Based on that, the upper reading of PMV for C5 was around 1.9 that covers 2% of the courtyard's areas, compared to C1 that has upper reading around 3 that covers 48% of the courtyard's areas, with a reduction of about 1.1 on the PMV scale from C1 to C5 configuration.

The changes in the microclimates affected the average buildings temperature (T_{in}) in the configurations, as it was clear that the average building's temperature was changes from 28.06 ˚C in C1 configuration to 26.17 ˚C in C5 configuration with reduction around 1.89 ˚C on 21st of September. Same on 21st of March as it was clear that the average building's temperature was changes from 23.80 ˚C in C1 configuration to 22.12 ˚C in C5 configuration with reduction around 1.68 ˚C. Thus it was clear that the changes in the buildings microclimates according to the changes in the school courtyard design configuration can improve the courtyards air temperature , reduce the average building's temperature, and at the same time it can improve the PMV in the outdoor spaces of the courtyard as that was met in the best configuration C5 .

Ultimately, through the strategic design of courtyards and architectural elements, it becomes possible to enhance outdoor air temperature regulation within microclimates. This optimization contributes to the creation of more pleasant and sustainable living environments, effectively adjusting to evolving climate conditions. The intricate connection between architecture and microclimatic factors is exemplified by the manner in which factors like geometry, vegetation, and the positioning of building masses around courtyards collectively shape their influence on the surrounding climate.

6. Declarations

6.1. Author Contributions

Conceptualization, S.M. and T.B.; methodology, S.M. and T.B.; software, S.M.; validation, S.M. and T.B.; formal analysis, S.M.; investigation, S.M. and T.B.; resources, S.M.; data curation, T.B.; writing—original draft preparation, S.M. and T.B.; writing—review and editing, S.M. and T.B.; visualization, S.M.; supervision, T.B.; project administration, S.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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