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The Role of Green Infrastructure in Enhancing Microclimate Conditions: A Case Study of a Low-Rise Neighborhood in Abu Dhabi

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Abstract: Urban heat islands are characterized by the increased temperature in urban areas compared with the rural surroundings due to human-made interventions that replace natural lands with buildings and roads. This study focuses on the assessment and utilization of using local nature-based solutions such as trees, sensitive landscaping types and design strategies to enhance microclimate in neighborhood streets and the public realm in desert areas, taking Abu Dhabi as a case study. The research utilizes a design-based approach to propose landscaping and layouts of urban street trees in low-rise residential urban areas. In this study, two methods namely an on-site measurement using citizen science, and a numerical simulation model in the ENVI-met software are used. Site-measurements included the tree physical characteristics such as tree height, crown width (crown spread/diameter), and trunk height, and the use of technology (photography and the Fulcrum mobile application, Nikon Forestry pro Laser Rangefinder) and air temperature around trees. ENVI-met included four scenarios: 1—"no-vegetation", 2—"grass-only", 3—"existing conditions" and 4—"proposed landscape design". Grass and three types of local street trees are used in the proposed scenarios including Ghaf, Poinciana, and Temple tree. In addition, a standard of 6 and 8 m spacing between each tree is applied to determine the effect of varying vegetation densities on the outdoor temperature. The combined results using citizen science and the model allowed the identification of particular urban tree species that show substantial cooling effects. This is the case of Poinciana trees, which decreased the air temperature up to 0.9 °C when spaced every six meters in pathways and open unshaded areas amongst alleys, improving the overall thermal conditions in neighborhoods of hot-arid landscapes.

Keywords: urban heat island; nature-based solutions (NbS); urban trees and ENVI-met; microclimate; hot-arid zones; landscape design; citizen science; Abu Dhabi

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1. Introduction

1.1. Background

Rapid urbanization and industrialization have caused the degradation of the urban environment [1]. The atmospheric Urban Heat Islands (UHI) phenomenon is a direct result of inadequate vegetation and landscaping practices such as the usage of materials with low reflectivity to solar radiation in pavements [2–4]. Akbari et al. [5] specified that the UHI is primarily formed due to the dearth of vegetation cover and the low albedo (i.e., reflectivity to solar radiation) of land surfaces and building facades. Other factors contributing to UHI are the pollution and heat emissions resulting from human activities and energy consumption within a city [6].

Buildings, green spaces (areas that include green infrastructure such as trees), and pavements are the three elements that influence the urban temperature on a local scale [7]. There are two kinds of strategies to mitigate urban heat islands used in hot-arid areas (cities such as Cairo, Baghdad, Damascus [8]) that integrate three elements—(i) elevating urban albedo, and (ii) increasing evapotranspiration [9], using nature-based solutions (NbS). Increasing albedo is usually done through cool roofs (e.g., white vinyl roofs, coated roofs, green roofs) and pavement techniques such as open-grid pavements (i.e., a pavement structure that consists of permeable cellular grids) [10]. Evapotranspiration, defined as the combined water loss to the atmosphere by transpiration and evaporation, is the chief mechanism through which trees decrease temperatures of built-up areas [1], highlighting the key and sustainable role of NbS. Evapotranspiration also occurs in impervious urban materials, such as asphalt and concrete, which do not preserve water for evaporation. Instead, these materials emit heat when they are exposed to solar radiation [11]. Hence, high evapotranspiration rates in urban areas are achieved through a combination of reducing the proportion of impervious surfaces and increasing urban landscaping (e.g., shade trees, vegetated walls, and rooftop gardens) [10]. NbS, such as urban trees, reduce temperature through shading which concurrently blocks sun radiation and prevents the warming of the air and ground surface [12–14].

Scientific studies on air temperature and urban landscape provide a crucial understanding of UHI in various urban settings and influence the decision-making process of city planning. These studies found that an urban landscape can lower air temperature by 0.3–1 °C and enhance air quality by decreasing the effects of pollution resulting from human activities [5]. In fact, strategic planning and selection of urban trees may have a large potential for mitigating the impact of UHI. Examples of components in strategic planning of NbS and planning include the importance of incorporating a building science approach (i.e., building facades) with vegetation scenarios [9], the need of spreading plantations and public gardens out across the urban region [15], and using minor green zones with adequate intervals which are desirable for effective cooling of nearby areas [16]. The large diversity of findings in the benefits of urban landscaping require in-depth study for particular climatic zones and urban architecture.

There are numerous studies that are concerned with the effect of vegetation and urban configuration on the built environment. The studies on urban trees in hot arid regions have shown that that the usage of trees in a compact low-density area led to a reduction in air temperature by 2 °C in the city of Baghdad [8], and that trees are effective at lowering air temperature by 0.2–0.4 °C in very high-density built-up areas, but ineffective in low-density built-up areas in Cairo [17]. Benefits of urban trees in these regions have also been proven to expand to other ecosystem services beyond air cooling, such as the improvement of air quality by filtering out dust in Dubai obtained with a landscaping buffer around an urban development [18].

In the United Arab Emirates, The Environment Agency of Abu Dhabi has warned that air temperature in different parts of the UAE is bound to grow considerably, due to the always increasing atmospheric pollution through greenhouse gas emissions. This rise in air temperature directly affects the microclimate of the urban areas, and therefore the built environment and economy by decreasing performance across the UAE [19]. Thus, to mitigate UHI, the Abu Dhabi Department of Municipalities and Transport (DMT) has published a Public Realm Design Manual which contains a list of local climate-sensitive tree species and some guidelines about landscape design [20]. However, the Manual lacks robust scientific foundations on the effects of different native vegetation scenarios on the outdoor ambient temperature.

1.2. Problem Statement

Despite the numerous studies supporting the importance of urban landscaping using NbS [21,22], the literature on landscape and microclimate enhancement do not clearly incorporate in depth-research of urban trees as NbS. The literature has only explored the large-scale effects of vegetation, urban plantations and their impact on energy intake [5]. A clear design approach to demonstrate how a landscape can lessen ambient air temperature is yet to be established. Additionally, there is still a need to specify which type of tree or which design intervention is necessary to improve the urban thermal environment.

Furthermore, there is debate on the differences of air temperature in high-rise built-up areas through various urban design options for the ability to reduce air temperature [23].

The inclusion of vegetation for the understanding of UHI in different urban configurations in hot climates has not been included in the past [24]. Nevertheless, research studies that have considered vegetation have highlighted the need of studying different tree species planted in streets and public open spaces and on the importance of considering tree density and their proximity, surface materials, pavements, streets, and buildings in microclimate calculations [25].

The height and size of trees is an important parameter to consider for understanding the urban microclimate [26]. Larger trees seem to have enhanced microclimatic benefits [27]. However, bigger trees can cause a nuisance in an urban context. According to Francis et al. [28], planting large trees results in an increased probability of causing damage/cracks to sidewalks due to the growth of roots. Moreover, larger trees tend to be more hazardous during a dust or rainstorm, disrupting public areas and/or damaging properties. In addition, studies have found that the reduced sky factor within the canopy of larger trees may restrict the long wave radiation loss during the night, leading to a warmer air temperature [29].

This study contributes to the existing literature by providing design-based empirical evidence about the role of urban trees in enhancing microclimate conditions of low-rise neighborhoods. The innovative contribution of this research lies in its consideration of three aspects of landscape design in low-rise residential neighborhoods. First, the size of trees is considered by selecting small-sized (5–7 m) local trees that provide sufficient shade for pedestrians. Second, this paper considers local landscaping design regulations of vegetation densities represented by six and eight meters spacing between trees. Additionally, third, comparison is made of local available urban species. At the same time, this research provides a clear example of the feasibility and benefits for science and of integrating citizens in the data collection through citizen science. As a consequence of the investigations performed, this research provides unique practical implementation information for landscaping projects. Although this research contemplated particular settings, its findings are applicable to a diversity of nations, particularly those with comparable environmental and social conditions to the UAE.

1.3. Aims

This research utilizes a design-based approach focused on urban trees as NbS to propose landscaping types and layouts in low-rise residential urban areas. The research has three main aims: first, identify among the three locally available trees (Poinciana, Ghaf, and Temple trees) the species that provide the best outdoor air temperature reductions in a low-rise residential neighborhood. Second, identify the vegetation density represented by the minimum distance between trees to achieve the largest outdoor air temperature reductions. ANOVA analysis is carried out to examine the statistical significance between the trees regarding their air temperature reductions. Additionally, third, to prove the feasibility and improve the research by combining empirical data collection using citizen science with desk-based microclimate modeling.

2. Methodology

2.1. Study Sites

A low-density residential neighborhood, Zaafranah, with an area of 0.7 km^2 located in the southeastern part of Abu Dhabi Island, was selected as the case study area (Figure 1). It consists of 160 residential buildings of 3 to 5 stories. Around 97% of these residential buildings are villas, whereas 3% are apartment buildings which also include shops on the ground level. The rest of the neighborhood plots are designated for education, mosques, and health centers. In addition, the neighborhood has open spaces, a children's playground, and a running track. The green area is approximately 25,243 m^2 and accounts for nearly

12.6% of the neighborhood's total area. It is composed of street trees (78.8%), one central park (15.7%), and private gardens (5.5%).

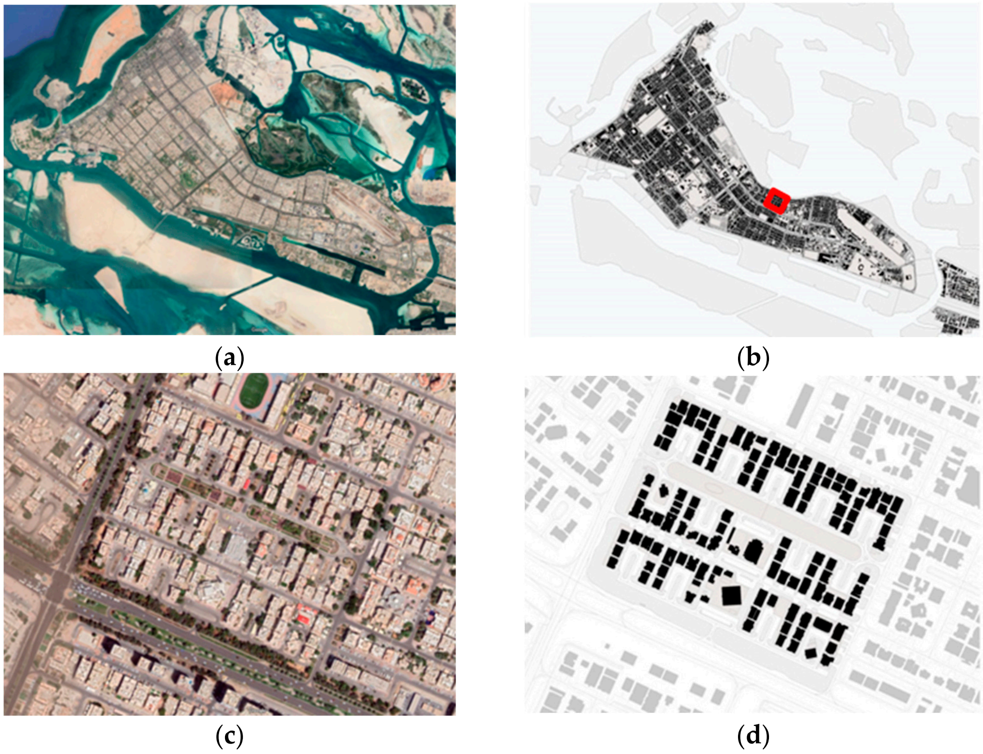


Figure 1. Zaafarana neighborhood in Abu Dhabi island. (**a**) Aerial view of West Island, Abu Dhabi; (**b**) location of the research area within the island; (**c**) aerial view of Zaafarana neighborhood; (**d**) building footprints of Zafaarana neighborhood.

Four sites were selected for analysis within the Zaafarana neighborhood (Figure 2). In order to test trees in diversified surroundings, the site selection criteria were based on location, building configuration, and level of landscaping or vegetation coverage. All sites have a similar block layout except for site 4 and, overall, the proportion of areas allocated for sand and streets are relatively higher than areas occupied by trees and pavements. Here, below is the description of each site:

Site 1 is located on the vegetated edge where an arterial road is located. Vegetation coverage is around 23% mostly located in the western part. A small part of the neighborhood's park falls within the southern area.

Site 2 is well landscaped compared to the other three sites as it contains the maximum existing vegetation (35% of the site area). This relatively high percentage is due to the park being located in the southern area of site 2. Trees are located on the central pedestrian island and four private gardens, and the entrance of the wider alleyways.

Site 3 is poorly landscaped compared to the other three sites, i.e., lack of vegetated area around buildings and pathways, which allows for the comparison of the cooling effects between site 3 and the other study sites as the building's morphology remains constant. Vegetation coverage is 22%, mostly consisting of street trees gathered in the southern part. A mosque is located on the east side of the site.

Site 4 has an existing vegetation ratio of 9%. The landscape mainly consists of a row of large trees (15–20 m) located in the center. Its building typology differs from the other three study sites as it contains a dental center flanked by residential buildings, and parking lots on the northern and southern sides (Figure 2).

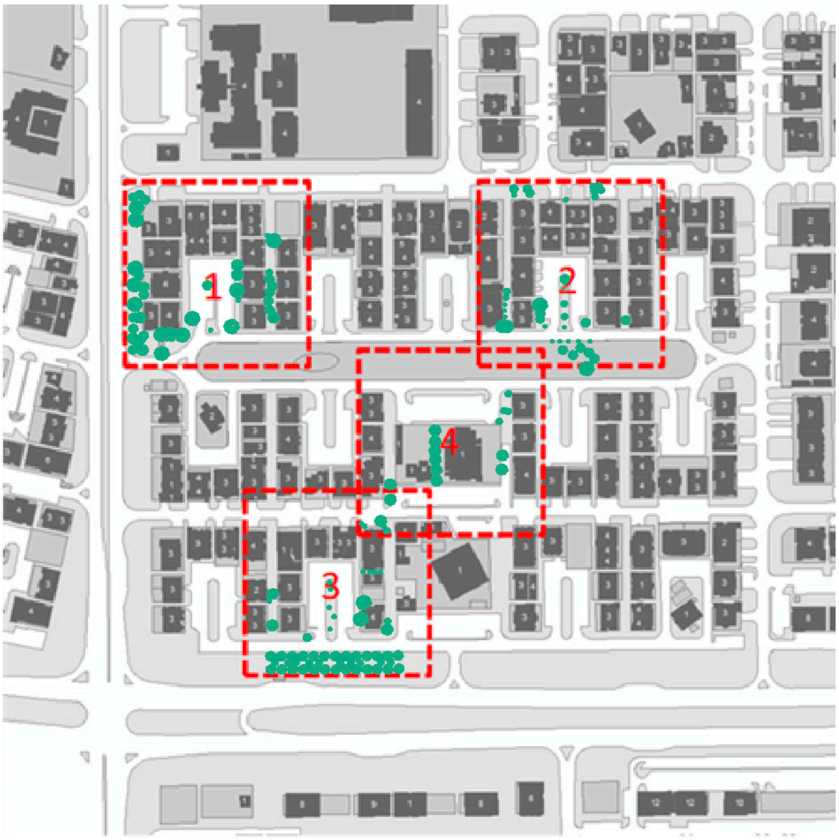
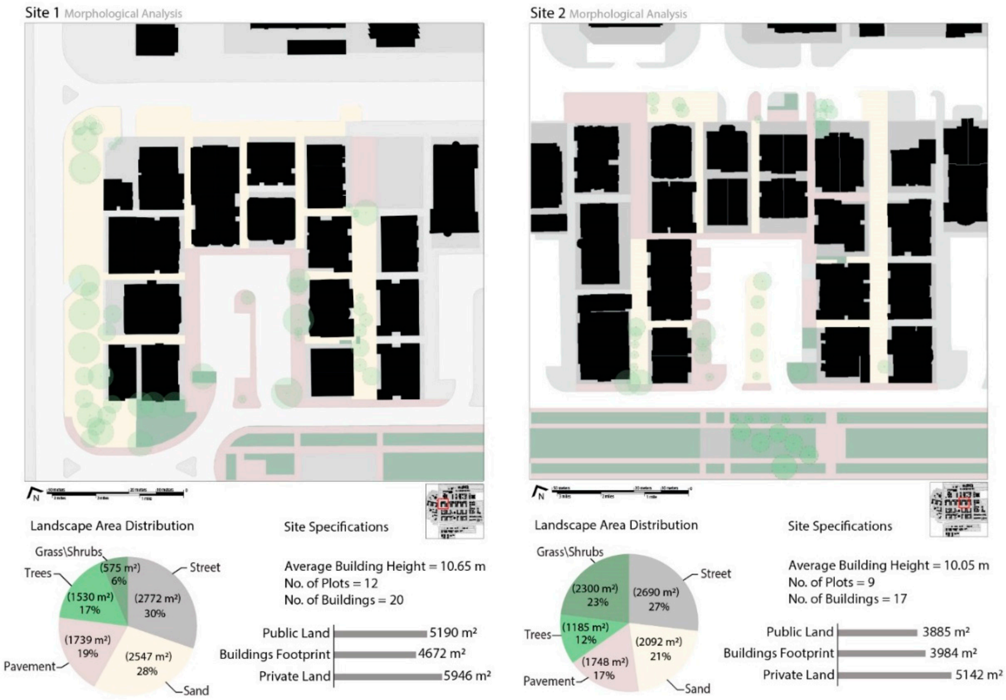


Figure 2. The four study sites in Zaafarana.

A summary of information about the four sites such as landscape coverage, including NbS (trees and grass), and the percentages of surface materials is shown in Figure 3.



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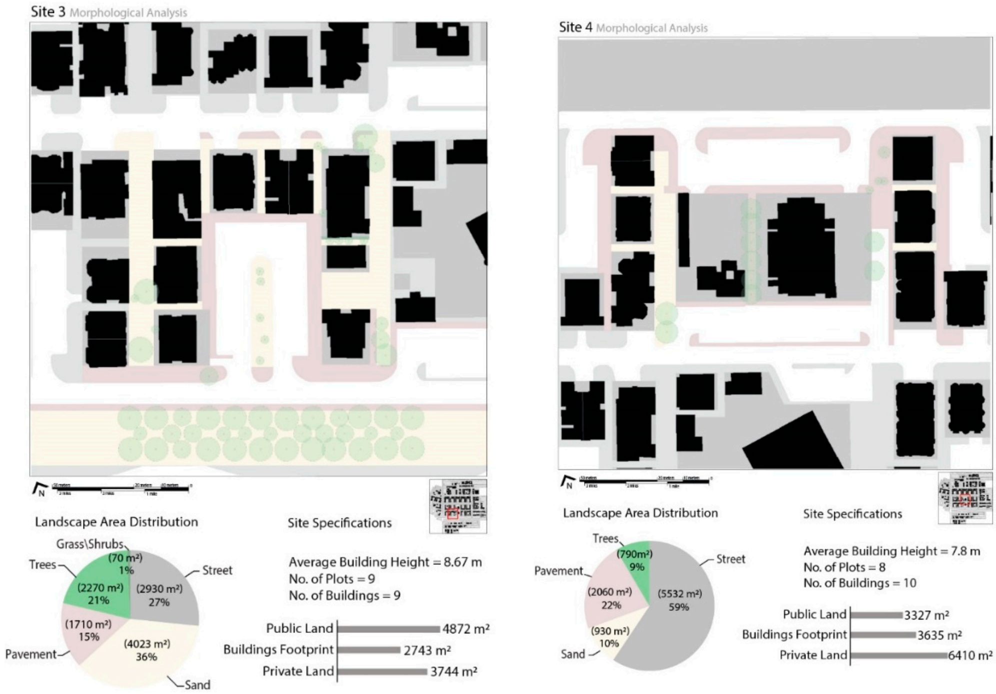


(**c**) (**d**)

Figure 3. Morphological data of the study areas. (**a**) Site 1; (**b**) Site 2; (**c**) Site 3; (**d**) Site 4. Landscape coverage was calculated as the percentage of the green area compared to the total plot area [30]. Public land calculation includes pavements, streets and alleyways. Buildings footprint is the total ground floor areas of the buildings in the site. Private lands are the individual plots (in darker grey) that contain the buildings, in which landscaping interventions are not within the scope of this research.

Two methods were used in this study: (1) on-site measurements of existing trees (location of trees, total height, crown width, and trunk height), air temperature, and mapping surface materials using citizen science and (2) a computer-based simulation using ENVI-met.

2.2. Data Collection

The study trees included the species that are commonly found in locations with hot weather and already available at the study sites. Various locations within the four study sites such as the unshaded open spaces and pathways had the potential for further improvement. Therefore, trees that are suitable for a hot climate region were selected. Ghaf (*Prosopis cineraria*), Poinciana (*Delonix regia*), and Temple trees (*Plumeria obtuse*) were applied and arranged in two proposed layouts for each site (Figure 4). The rationale behind the selection of tree species is based on characteristics like heat tolerance and low to medium irrigation requirements [31]. Their small size of an average of 5–7 m is suitable for the goals of this research. In addition, Abu Dhabi's Department of Municipalities and Transport (DMT) has been using these species majorly on streets and in urban landscaping. The three trees are among the many tree species indicated by DMT which are native or native adaptive. More tree species could not be involved in the analysis due to time constraints and long durations of running simulations.

2.2.1. Field Measurements

Field measurements involving citizen science included: (i) tree data collection of the total height of plants, crown width (crown spread/diameter), and trunk height (vertical distance from the tree base to the lowest branch) using a Nikon Forestry pro Laser Rangefinder, (ii) photo imagery of existing trees with their respective GPS location at each study sites. The data were integrated by using the Fulcrum mobile application, (iii) air temperature measurements across 20 observation points from each study site and (iv) mapping of the existing surface materials in the study sites.

(**a**) (**b**) (**c**)

Figure 4. Locally adaptive trees selected for the research. (**a**) Poinciana; (**b**) Ghaf; (**c**) Temple tree.

The information about existing trees was collected with the Nikon Forestry pro Laser Rangefinder (accuracy of +/−0.3 m). The collected data using this method included—total height of trees, crown width, and trunk height. The total height of the trees was measured as the distance from the base of the plant to the top of the crown. The crown width was calculated by measuring the distance between the two opposite ends of the crown. Finally, the trunk height was measured as the distance from the tree base to the lowest end of the tree crown. For shrubs and hedges, the trunk height was set to zero.

On-site tree data measurements such as crown shape and width, and tree and trunk heights were used to create 3D models of existing and proposed trees. Tree height was assumed to be constant and set at 5–7 m.

On-site tree measurements along with pictures of plants and their location in the study sites were then imported to Fulcrum [32], mobile application—a standalone location-based data collection platform. Fulcrum simplifies the process of collecting and retrieving data by incorporating geotagged pictures automatically in one database while avoiding illegible handwriting often encountered in conventional field data collection.

On-site field measurements of air temperature followed the methodology of spot measurements defined by Ng et al. [33]. The measurements were conducted using Onset HOBO MX 1101 data loggers for comparing real and simulated results.

2.2.2. Desktop Work (ENVI-Met Model)

For each study site, 9 ENVI-met models representing different landscaping scenarios were developed (Tables 1 and 2). The existing scenario is based on the current vegetation conditions in the study sites. "No-vegetation scenario" was prepared by removing all existing vegetation (trees, grass, hedges, shrubs, etc.) from the site while keeping all existing ground and surface materials. Similarly, the "grass-only scenario" was created by replacing soil-covered areas with grass and removing all existing trees. The existing grass areas and other surface materials for this scenario were not changed.

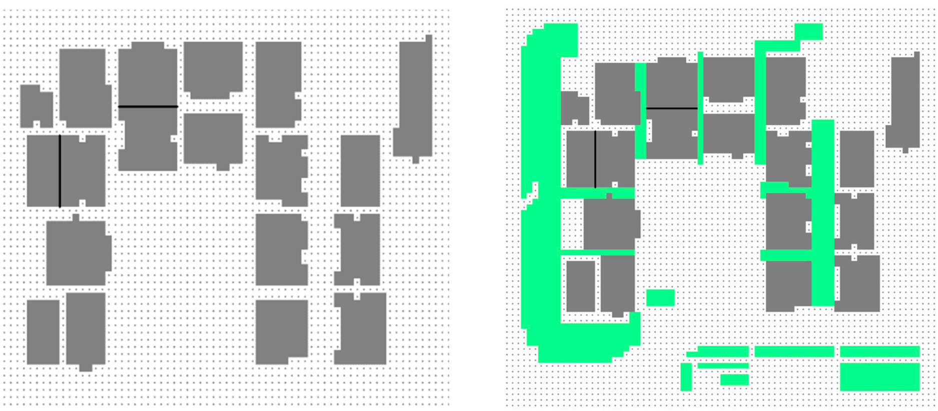
Three locally available trees in the UAE were selected and arranged in two proposed layouts to represent different vegetation densities. The first layout applies 6 m spacing between each tree, and 8 m spacing in the second layout. The proposed landscaping scenarios consist of heat-tolerant trees (Poinciana, Ghaf, and Temple), each with two layouts of different densities (i.e., 6 m and 8 m spacing). Albedo values for the ground and all surfaces (building walls, sand, asphalt, pavement, etc.) were set to the default values in ENVI-met (Table 1). After the simulation of the existing scenario and validation of the model, no-vegetation and grass-only scenarios were applied to all study sites (Figure 5).

Table 1. Input parameters in the ENVI-met simulation.

Input Parameter	Value(s) Used
City location	Abu Dhabi, UAE. Lat: 24.45°; Long: 54.37°
Simulation day	17 June 2019
Simulation duration	24 h
Model resolution	1:2, 180 × 180 × 48 m
Climate type	Hot arid
Wind speed and direction	0.1 m/s at 270°
Relative humidity	63%
Cloud cover	Clear sky
Albedo	grass = 0.2; red tiles = 0.3; light gray pavement concrete = 0.8; sand = 0.4; yellow pavement = 0.5
Building surface	Default settings in ENVI-met
initial soil temperature	28 °C

Table 2. Nine ENVI-met scenarios implemented in each study site.

Scenario	Landscaping Description
Existing	Current vegetation conditions in the study sites consisting of various types of trees and sizes, grass, and shrubs.
No-vegetation	Removing all existing vegetation (trees, grass, hedges, shrubs, etc.) from the site while keeping all existing ground and surface materials.
Grass only	Replacing soil covered areas with grass and removing all existing trees, while keeping the existing grass.
Poinciana 6 m	Poinciana trees (7 m in height) placed 6 m apart
Poinciana 8 m	Poinciana trees (7 m in height) placed 8 m apart
Ghaf 6 m	Ghaf trees (6 m in height) placed 6 m apart
Ghaf 8 m	Ghaf trees (6 m in height) placed 8 m apart
Temple 6 m	Temple trees (5.5 m in height) placed 6 m apart
Temple 8 m	Temple trees (5.5 m in height) placed 8 m apart



(**a**) (**b**)

Figure 5. *Cont.*

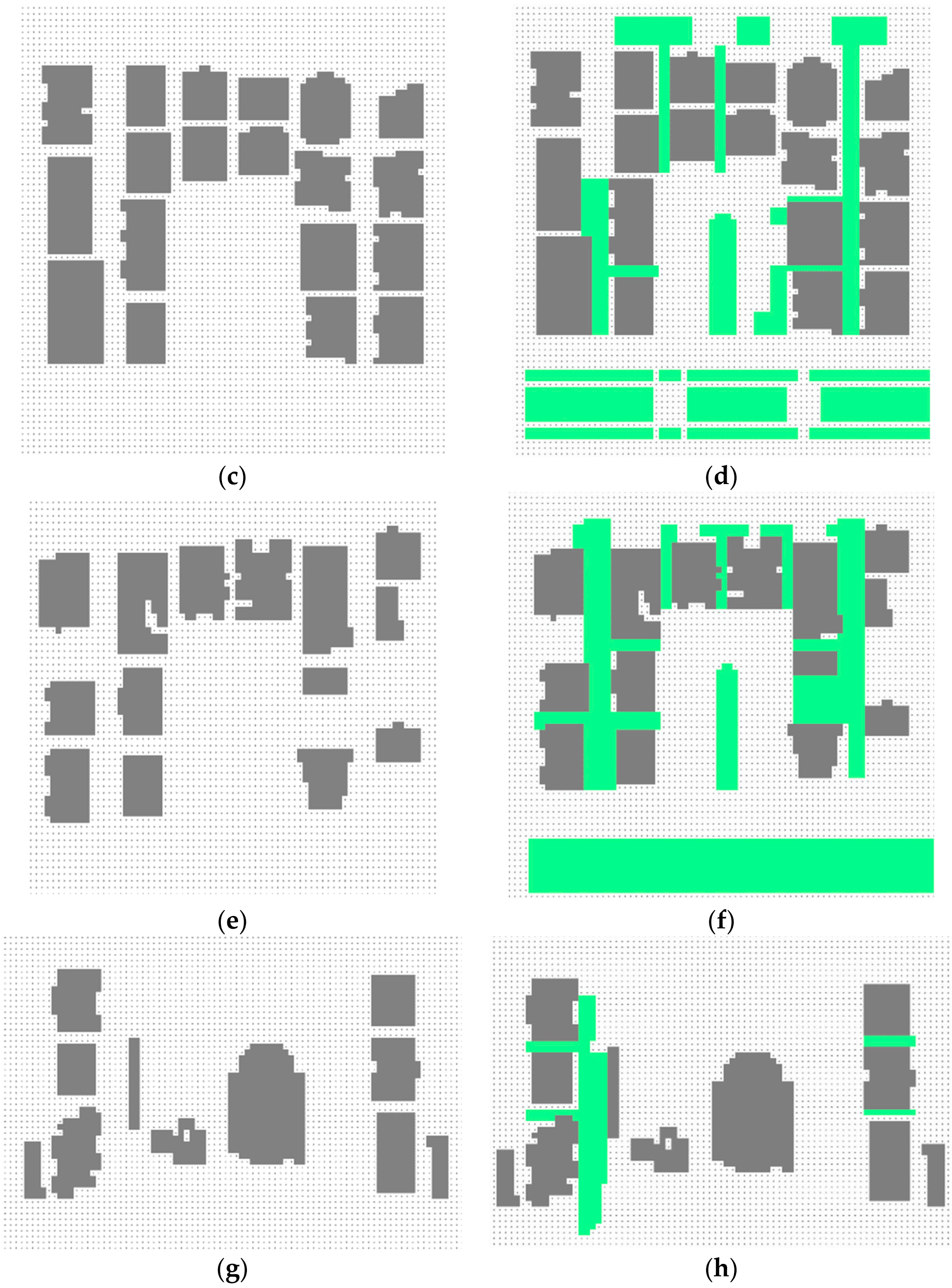


Figure 5. No-vegetation and grass-only scenarios. (**a**) No-vegetation—Site 1; (**b**) grass-only—Site 1; (**c**) no-vegetation—Site 2; (**d**) grass-only—Site 2; (**e**) no-vegetation—Site 3; (**f**) grass-only—Site 3; (**g**) no-vegetation—Site 4; (**h**) grass-only—Site 4.

2.2.3. Proposed Scenarios

The proposed scenarios consider different positions for the urban trees. The first layout consisted of applying 6 m spacing between the trees whereas 8 m spacing was applied in the second layout (Figure 6). According to Dubai Municipality practice, these distances are necessary to achieve efficient irrigation and to allow sufficient space for the growth of tree crowns [34]. The variation of spacing also helps to determine the effect of varying vegetation densities on the outdoor temperature.

Figure 6. Proposed landscaping scenarios for the study sites. (**a**) Trees spaced at 6 m—Site 1; (**b**) trees spaced at 8 m—Site 1; (**c**) trees spaced at 6 m—Site 2; (**d**) trees spaced at 8 m—Site 2; (**e**) trees spaced at 6 m—Site 3; (**f**) trees spaced at 8 m—Site 3; (**g**) trees spaced at 6 m—Site 4; (**h**) trees spaced at 8 m—Site 4.

The rules followed for the proposed layouts are as follows: first, all existing plants in the sites were removed without changing the existing surface materials. Second, all the sand surface located in the public open spaces and pathways was replaced by grass. Third, the proposed trees were placed at 6 m and 8 m as per minimum local regulations to aim for a 30% tree coverage ratio [33]. The arrangement of trees followed the orientation of pedestrian pathways. In order to avoid overlapping of tree crowns, an equal distance between trees was maintained, resulting in a linear pattern of trees. In the proposed landscaping scenarios, careful consideration was taken when placing the proposed trees.

For example, trees were not placed between buildings as the narrow alleyways are used for running underground utility lines. Additionally, a distance of at least 2 m was maintained between the proposed green areas and buildings. This was achieved to facilitate walkability along pedestrian pathways. Moreover, trees were not planted within the private building plots as this research focuses on public lands.

A height of 5 to 7 m was assigned to each type of tree based on its characteristics from the literature and on-site observations (Poinciana = 7 m; Temple tree = 5.5 m, Ghaf = 6 m) [31]. Small trees were chosen to minimize the observed damage to the pavements due to over rooting which occurs in the case of larger trees [28]. Moreover, in order to encourage wind flow and activities under the tree crowns, the trees were modeled with no branches and leaves up to at least 2 m in height [35]. The components that were evaluated in the main model area were trees, ground surfaces, and buildings. Other small structures such as car parking shades and street furniture located in these study areas were not considered due to simulation time constraints.

3. Results

This section begins by analyzing and comparing the existing and no-vegetation scenarios to assess the cooling performance of the existent vegetation in the sites. Then, the results of simulations for the proposed scenarios are shown. The proposed scenarios include arrangements of Poinciana, Ghaf, and Temple trees. The resulting heat maps are illustrated using three heat regions. Finally, a comparison between the existing and the proposed scenarios of the three tree species in each study site is given based on the outcome ratios of the three heat regions. ANOVA analysis was carried out to explore the statistical significance between the trees regarding their temperature reductions (Table 1 Appendix A).

3.1. Existing Scenario and No-Vegetation Scenario

According to the ENVI-met simulation of the existing conditions, the air temperatures in the study areas at 14:00 were between 41.66 °C and 43.60 °C (Table 3). In order to estimate the cooling effects, the existing scenarios were compared with the no-vegetation scenarios for each site. In site 1, the maximum temperature difference between the existing condition and the no-vegetation scenario was 0.33 °C, while it reached 0.44 °C and 0.41 °C for sites 2 and 3, respectively. A maximum temperature difference of 0.46 °C was recorded at site 4. Although grass gives a low surface temperature, the grass-only scenario brings little improvement to the thermal environment.

Table 3. Summary of the air temperature simulation results for the existing and no vegetation scenarios in the study sites.

		Site 1		
Scenario	**Max. Temperature (°C)**	**Min. Temperature (°C)**	**Max. Temp. Difference Compared to Existing (°C)**	**Avg. Temp. Difference Compared to Existing (°C)**
Existing	42.91	41.68	-	-
No vegetation	42.93	41.69	0.33	0.02
		Site 2		
Scenario	**Max. Temperature (°C)**	**Min. Temperature (°C)**	**Max. Temp. Difference Compared to Existing (°C)**	**Avg. Temp. Difference Compared to Existing (°C)**
Existing	42.92	41.66	-	-
No vegetation	43.02	41.66	0.44	0.05
		Site 3		
Scenario	**Max. Temperature (°C)**	**Min. Temperature (°C)**	**Max. Temp. Difference Compared to Existing (°C)**	**Avg. Temp. Difference Compared to Existing (°C)**
Existing	43.60	42.13	-	-
No vegetation	43.65	42.14	0.41	0.03
		Site 4		
Scenario	**Max. Temperature (°C)**	**Min. Temperature (°C)**	**Max. Temp. Difference Compared to Existing (°C)**	**Avg. Temp. Difference Compared to Existing (°C)**
Existing	43.02	41.98	-	-
No vegetation	43.02	42.04	0.46	0.03

The simulation of existing conditions showed that the presence of trees and grass around sites 1, 2 and 3 resulted in a decrease of up to 0.44 °C in air temperature in the surrounding areas. ENVI-met considers the shading caused by buildings in the heat exchange calculations [36]. Consequently, it was observed for all sites that the presence of alleyways lowered air temperature between buildings due to shading. On the other hand, all sites showed high air temperatures in unshaded open spaces and streets surrounding the buildings due to the lack of vegetation and low albedo of ground materials.

3.2. Analysis of Heat Maps Using Three Heat Regions

The simulation in ENVI-met provides results in the form of colored heat maps. The heat regions were classified into three main categories which correspond to a specific temperature range—Magenta–Red–Orange (>42.95–42.50) °C, Green–Yellow (42.50–42.00) °C and Blue (42.00–<41.60) °C. Figure 7 illustrates the proportions of these heat regions in a simplified format in the existing, no-vegetation, and the proposed landscape scenarios. The existing scenario and the no-vegetation scenario consisted of a larger area of the Magenta–Red–Orange region for all sites when compared with the proposed landscape scenarios. For all sites, the Blue region covered a small portion −0% and 5% of the study areas, for existing and no-vegetation scenarios, respectively. Furthermore, the narrow alleyways between buildings were mostly covered by the Blue region for all sites.

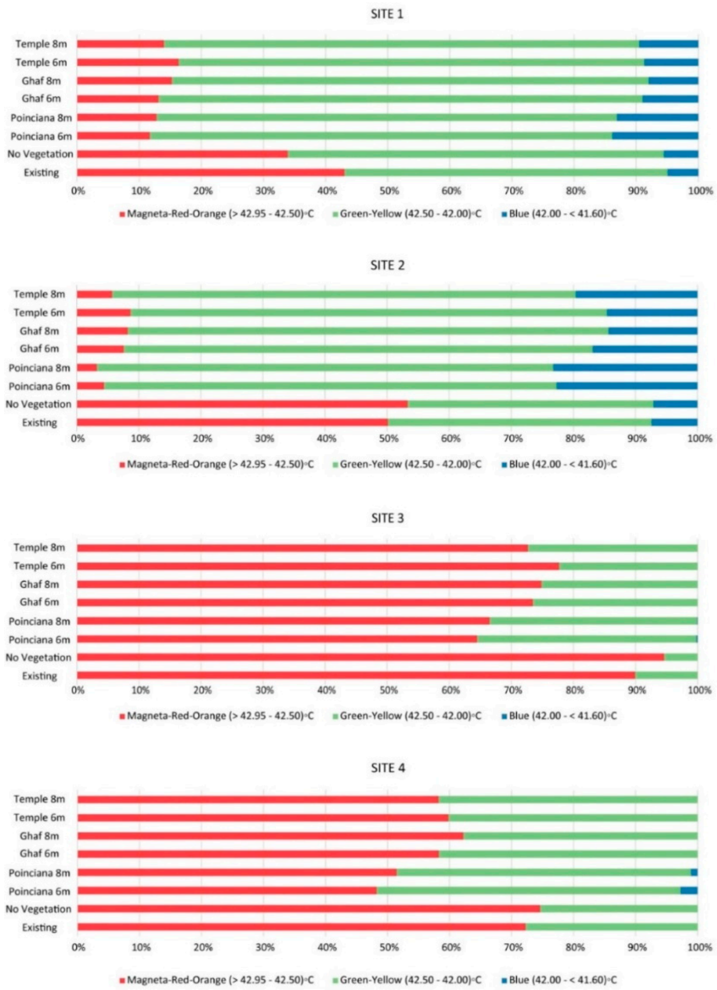


Figure 7. Simplified representation of the heat maps. Ratios of each color region (simplified version of the models) in each one of the four study areas for existing vegetation, no-vegetation, and the presence of Poinciana located every 6 m and 8 m, of Ghaf every 6 m and 8 m, and of Temple every 6 m and 8 m.

3.3. Proposed Scenarios

A total of 24 simulations of proposed landscaping scenarios (six scenarios for each site which are 1—Poinciana 6 m spacing, 2—Poinciana 8 m spacing, 3—Ghaf 6 m spacing, 4—Ghaf 8 m spacing, 5—Temple 6 m spacing, 6—Temple 8 m spacing) were conducted. A summary of the simulation results is presented in Table 4. For all proposed trees in sites 1 and 2 (at 6 and 8 m spacings), the most dominant color was Green–Yellow, where it reached 78% of the total area at both sites. The highest increase in the Blue region occurred at site 2 where it grew by 16%. Under the existing and all proposed landscaping scenarios at sites 3 and 4, there was an absence of the Blue region. However, the Magenta–Red–Orange region was reduced by up to 25% in both sites in the case of Poinciana trees, and around 15% for Ghaf and Temple trees.

Table 4. Summary of 24 simulation results by site (1 to 4) and spacing between trees (6 and 8 m).

Tree Type	Max. Temperature (°C)		Min. Temperature (°C)		Max. Temp. Difference Compared to Existing (°C)		Avg. Temp. Difference Compared to Existing (°C)	
Site 1								
	6 m	8 m	6 m	8 m	6 m	8 m	6 m	8 m
Poinciana	42.85	42.83	41.51	41.54	−0.62	−0.47	−0.21	−0.21
Ghaf	42.95	42.93	41.57	41.56	−0.42	−0.43	−0.18	−0.15
Temple	42.97	42.83	41.57	41.60	−0.45	−0.52	−0.18	−0.23
Site 2								
	6 m	8 m	6 m	8 m	6 m	8 m	6 m	8 m
Poinciana	42.60	42.60	41.54	41.55	−0.69	−0.68	−0.31	−0.31
Ghaf	42.61	42.62	41.60	41.60	−0.55	−0.52	−0.24	−0.20
Temple	42.62	42.61	41.59	41.58	−0.52	−0.58	−0.22	−0.24
Site 3								
	6 m	8 m	6 m	8 m	6 m	8 m	6 m	8 m
Poinciana	43.36	43.34	41.93	41.92	−0.90	−0.87	−0.19	−0.16
Ghaf	43.47	43.33	41.99	42.00	−0.83	−0.80	−0.29	−0.30
Temple	43.42	43.36	41.98	41.97	−0.82	−0.83	−0.19	−0.14
Site 4								
	6 m	8 m	6 m	8 m	6 m	8 m	6 m	8 m
Poinciana	42.89	42.90	41.91	41.92	−0.71	0.70	−0.24	−0.22
Ghaf	42.96	42.92	41.96	41.98	−0.66	0.63	−0.15	−0.11
Temple	42.97	42.95	41.97	41.97	−0.66	−0.68	−0.13	−0.16

3.3.1. Site 1

At site 1, where buildings occupy 34.7% of the total area (highest ratio among all study sites), the existing scenario had an average temperature of 42.29 °C, while the maximum and the minimum temperatures were 42.91 °C and 41.68 °C, respectively. Around 52% of this study area was represented by the Green–yellow region, and 5% by the Blue region. When the vegetation modifications with a tree spacing of 6 m were applied, Poinciana trees reduced the temperatures by up to 0.62 °C, while at 8 m spacing the Ghaf and Temple trees reached a maximum reduction of 0.43 °C and 0.52 °C, respectively (Figure 8). It can be noticed from the figures that the cooling effects of all tree species followed the same pattern around the site, i.e., the air temperature surrounding the trees drops and creates a cool region which varies in intensity depending on the type of tree. Temperature reduction was highest at the vegetated part of the site. Generally, 8 m spacing resulted in a smaller size of Blue and Green–Yellow regions than 6 m spacing for all tree species. However, Poinciana tree included larger amounts of Blue and Green–Yellow cooler regions than Temple and

Ghaf trees. In the best-case scenario (i.e., Poinciana at 6 m), the Magenta–Red–Orange region was reduced by an average of 30% while the Blue region increased by a maximum of 9%.

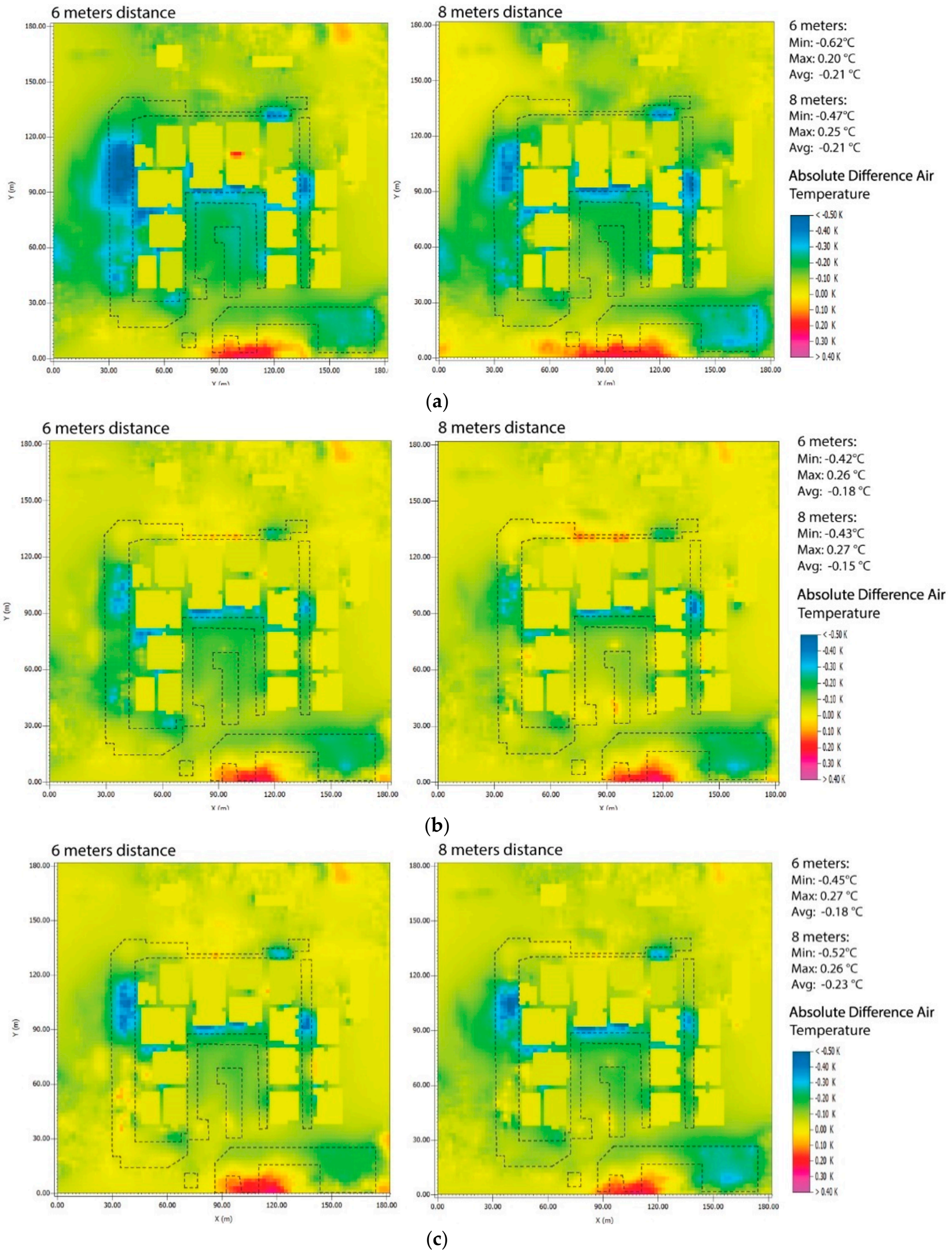


Figure 8. Simulation results of comparing current conditions with 6- and 8- meter spacing layouts for site 1. (**a**) Poinciana: comparing existing conditions of site 1 with the cooling effect of Poinciana trees; (**b**) Ghaf: comparing existing conditions of site 1 with the cooling effect of Ghaf trees; (**c**) Temple tree: comparing existing conditions of site 1 with the cooling effect of Temple trees. Tree location has been outlined with dotted lines.

3.3.2. Site 2

At Site 2, the average temperature, the maximum temperature, and the minimum temperature were found to be 42.29 °C, 42.92 °C, and 41.66 °C, respectively. The Magenta–Red–Orange area covered half of the site, while almost 8% was covered by the Blue region, and 42% by the Green–Yellow region. When the tree spacing was set to 6 m, the cooling effect of Poinciana and Ghaf reached a maximum temperature difference of 0.69 °C and 0.55 °C, respectively. However, Temple trees reached a temperature difference of 0.58 °C at 8 m distancing (Figure 9). The heat maps show that the cooling performance for all trees was dominant in the southern part extending to the center of the site. Those parts include a playground as well as a refuge island (shown in solid lines, Figure 9) where trees are planted in larger quantities compared to other parts of this site. However, it is observed from the maps that a lesser amount of Blue and Green–Yellow regions exist in the case of Temple tree and Ghaf than Poinciana tree. Moreover, due to the replacement of red pavement with grass of lower albedo, higher temperatures appear for all tree species in the upper west alleyway. In the best-case scenario (i.e., Poinciana at 8 m), the hottest areas were drastically diminished and covered only 3% of the site. In contrast, the coolest portions expanded to occupy 23% of the site.

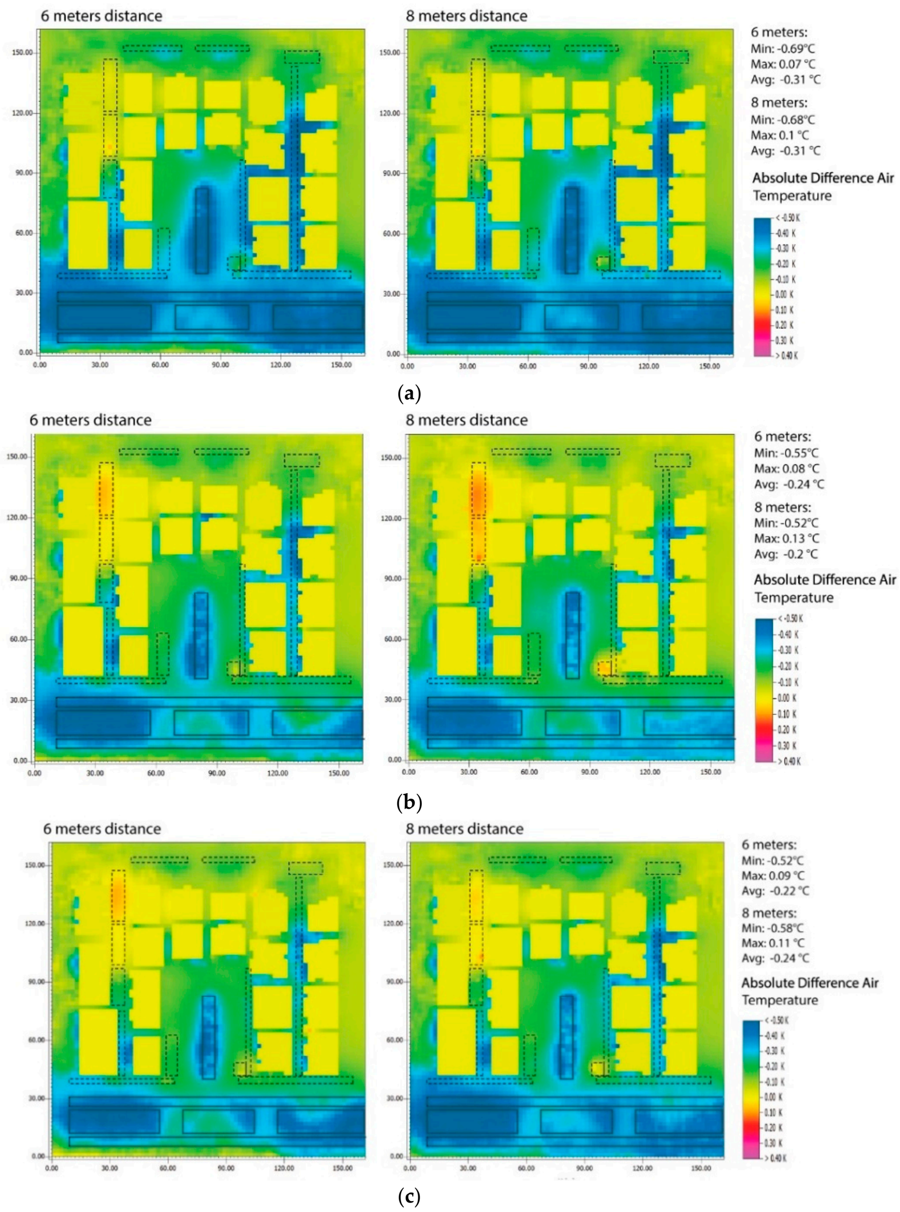


Figure 9. Simulation results of comparing current conditions with 6- and 8- meter spacing layouts for site 2. (**a**) Poinciana: comparing existing conditions of site 2 with the cooling effect of Poinciana trees; (**b**) Ghaf: comparing existing conditions of site 2 with the cooling effect of Ghaf trees; (**c**) Temple tree: comparing existing conditions of site 2 with the cooling effect of Temple trees. Tree location has been outlined with dotted lines.

3.3.3. Site 3

According to the simulations, the existing environmental condition of site 3 was the worst among the study sites, with average, maximum, and minimum temperatures of 42.87 °C, 43.60 °C and 42.13 °C, respectively. Under the existing conditions, the Magenta–Red–Orange region covered 90% of the site which is the highest Magenta–Red–Orange ratio among all sites. In the best-case scenario (i.e., Poinciana at 6 m), the hottest region was decreased by 26% and the air temperature was reduced by 0.9 °C (Figure 10). The heat map that compares proposed scenarios with the existing ones provides interesting insights. Temperature reductions reached their maximum in the unshaded open space in the eastern part of the site, the median pedestrian island, and the western alleyway. However, air temperature increased by almost 0.57 °C in the southern part where large trees were located in the existing scenario. It was also noticed that a lesser amount of Blue and Green–Yellow regions existed in the case of Temple tree and Ghaf than in the Poinciana scenario.

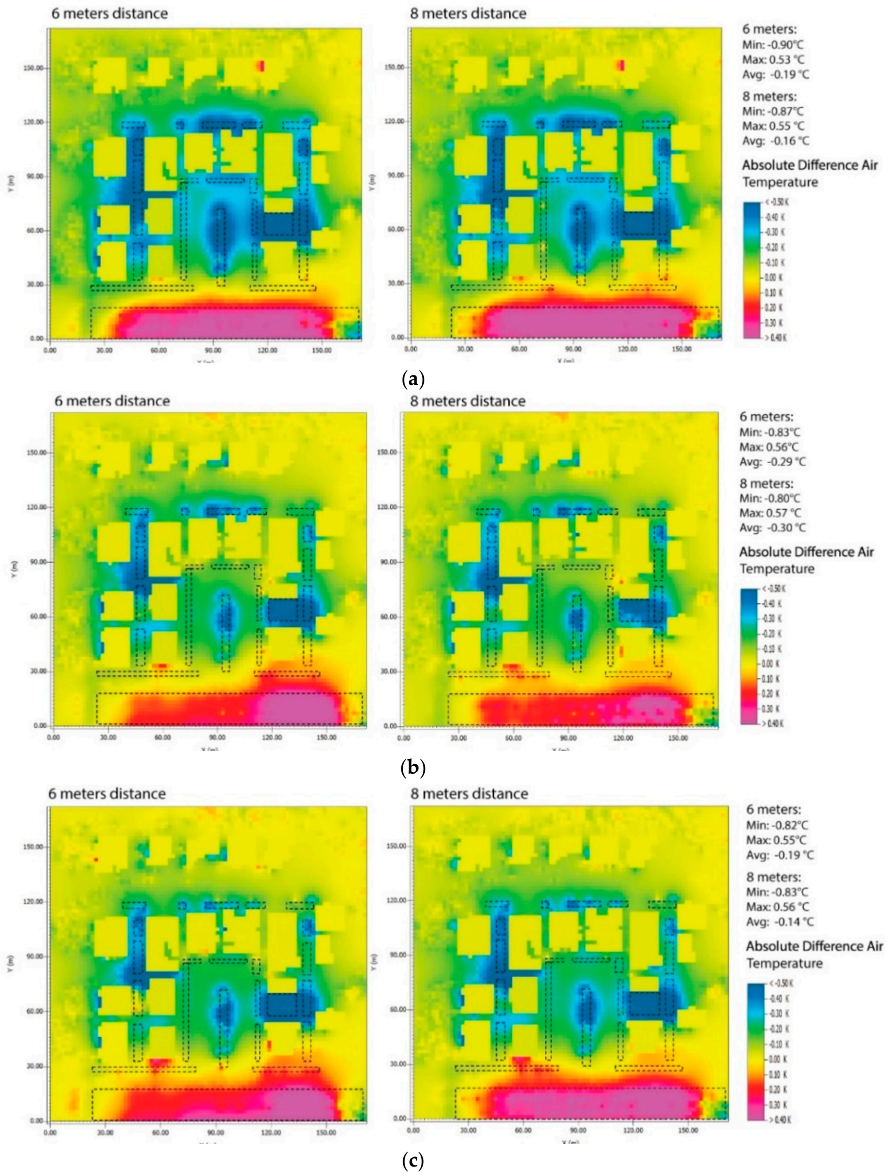


Figure 10. Simulation results of comparing current conditions with 6- and 8- meter spacing layouts for site 3. (**a**) Poinciana: comparing existing conditions of site 3 with the cooling effect of Poinciana trees; (**b**) Ghaf: comparing existing conditions of site 3 with the cooling effect of Ghaf trees; (**c**) Temple tree: comparing existing conditions of site 3 with the cooling effect of Temple trees. Tree location has been outlined with dotted lines.

Due to their similar building layouts, site 2 and site 3 were compared. The existence of few unshaded open spaces between the buildings in site 3 resulted in 0.6 °C higher air temperature than in site 2. Additionally, the percentage of street area is more in site 3 (25.4%, compared to 19.6% in site 2) which indicates relatively more asphalt surfaces. Moreover, more alleyways exist in site 2 as compared to site 3, which largely contributed to enhancing its outdoor air temperature. On the other hand, it was evident that the microclimate performance in sites 1 and 2 was almost identical due to their similar building footprints, street and pavement ratios, and amount of alleyways.

3.3.4. Site 4

In Site 4, the average temperature was 42.5 °C, while the minimum and maximum temperatures were 41.98 °C and 43.02 °C, respectively. The dominant color region was Magenta–Red–Orange expanding over 70% of the site. In the case of 6 m spacing, the cooling effects of Poinciana and Ghaf trees reached a maximum of 0.71 °C and 0.66 °C, respectively. However, at 8 m, the cooling effects of Temple trees reached 0.68 °C (Figure 11). The Magenta–Red–Orange and Green–Yellow regions had an equal distribution occupying between 47% and 63% of the site. The temperature reductions resulting from the trees were evident mostly in the western alleyway. Temperature reductions also occurred where the trees were placed on pathways around the parking areas in the southern and northern parts. However, some increase in temperature was observed in the central and eastern zones where large trees were located in the existing condition.

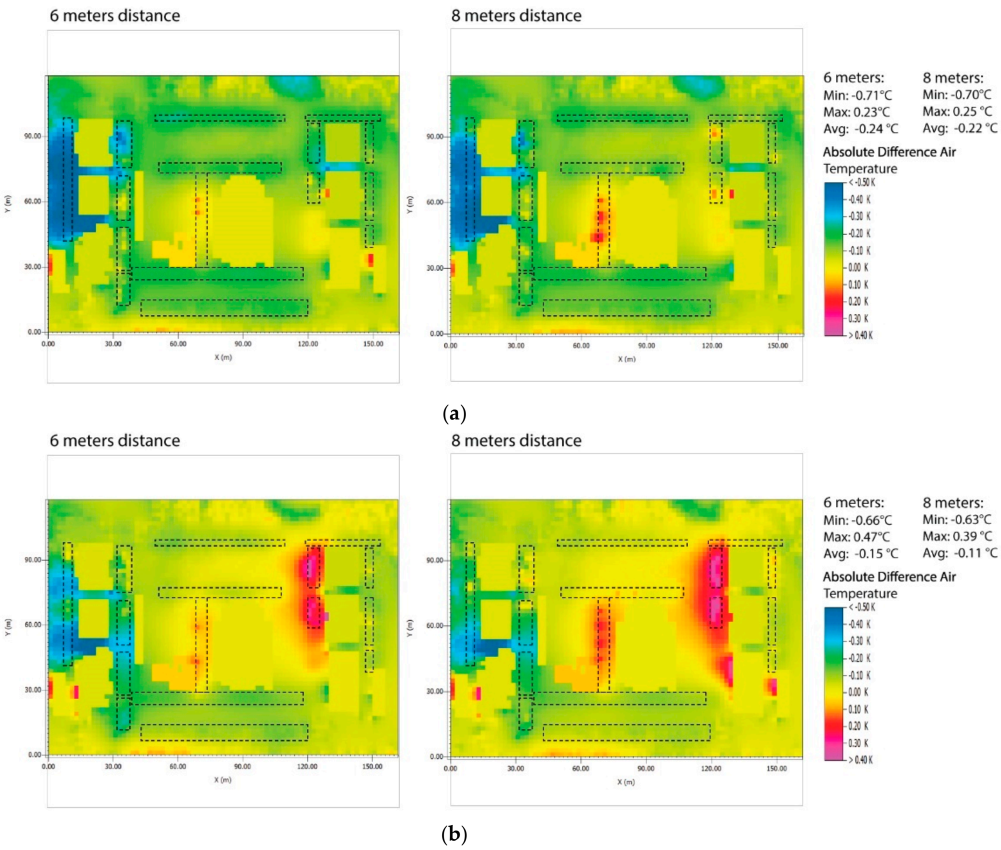
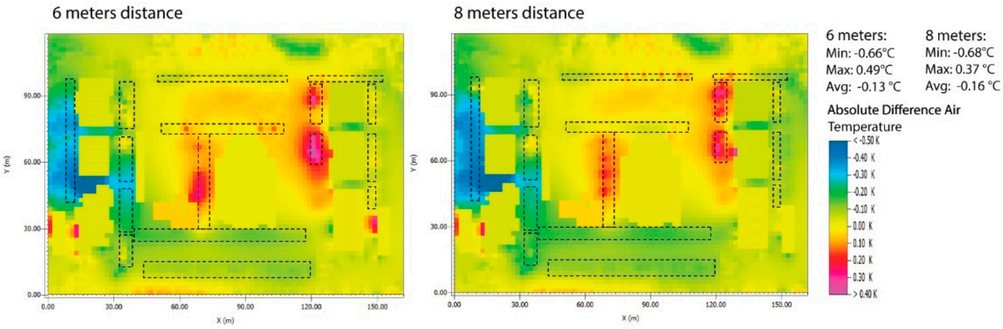


Figure 11. *Cont.*



(c)

Figure 11. Simulation results of comparing current conditions with 6- and 8- meter spacing layouts for site 4. (**a**) Poinciana: comparing existing conditions of site 4 with the cooling effect of Poinciana trees; (**b**) Ghaf: comparing existing conditions of site 4 with the cooling effect of Ghaf trees; (**c**) Temple tree: comparing existing conditions of site 4 with the cooling effect of Temple trees. Tree location has been outlined with dotted lines.

4. Discussion

The data collected with citizen science had a positive impact on the input quality of the simulation models. This was achieved by the citizen science contribution in gathering a larger dataset of air temperature and tree dimensions/locations which allowed the achievement of reliable input data by preserving consistent data values and using them in the models while eliminating the less accurate values. The combination of both on-site measurements using citizen science and model simulation by experts allowed inference of the best landscape arrangements for the improved urban tree cooling effect.

This study highlights that the overall cooling effect of urban trees on the outdoor air temperature is influenced by landscaping design (type of vegetation, spacing, etc.), and urban characteristics (surface materials, alleyways, etc.) [6], which was not defined with previous research, as this was conducted in different climates and urban conditions [17,30,37]. Additionally, the height of the trees used in this study (5–7 m in height) resulted in a lesser cooling effect on the urban microclimate when compared to the past studies [33,38].

The ENVI-met simulations in this study showed a maximum temperature difference of 0.46 °C between the existing and no-vegetation scenarios, in comparison to the results of temperature differences of 0.2–0.4 °C (very high-density built-up areas) [17] to 2 °C (low-density compact areas) [8] in previous studies. The performance in the current study is attributable to the vegetation that lowers air temperature by evapotranspiration as well as intercepting both the sensible heat and the long wave radiation. The grass-only scenario showed minimal cooling effects. Thus, using grass in public spaces should not be regarded as a primary method to enhance outdoor air temperature.

In general, the addition of trees in the model improved the outdoor thermal conditions in each of the four sites. The hottest regions that were visible in the existing scenarios became cooler due to the additional tree landscaping along pedestrian pathways and in unused empty spaces. The air temperatures were reduced by a maximum of 0.9 °C when Poinciana trees were placed 6 m apart in site 3, covering around 80% of public space (Figure 10) and the minimum temperature reduction of 0.42 °C occurred at site 1 when Ghaf trees were placed with 6 m spacing. However, ANOVA analysis indicated that there is no significant statistical difference between the three trees regarding their cooling effects in the public space (Table 1). It is important to notice that the cooling effect of the tree landscaping scenarios was smaller than that reported by Abaas [8], and Ali-Toudert and Mayer [39]. Both studies had reported an air temperature decrease of up to 2 °C in hot–dry regions (Baghdad and Algerian Sahara) but it is expected that this could be explained by the higher cooling effect of evapotranspiration due to the dryer air in those regions [33]. More research into the comparison of these two climatic areas is needed to confirm this finding.

The results obtained from the modified landscaping scenarios in site 2 and 3 (Figures 10 and 11), confirm that trees are more effective in decreasing air temperatures within low-density urban areas (high sky view factor) than in compact urban areas (low sky view factor) as also found in previous studies [40,41]. This explains the higher air temperature reduction of 0.9 °C achieved in this study compared to temperature reductions reported by previous studies carried out in denser urban areas [30,42,43]. However, another study [33], in Hong Kong used larger trees (20 m in height) in the proposed landscape designs, showing an increased cooling effect of trees in high-density urban areas. Similarly, Srivanit and Hokao [38] reported a maximum temperature decrease of 2.27 °C in a university campus of the humid subtropical Saga city, Japan. This value was achieved after creating modified landscaping scenarios using larger trees (15 m in height). This decrease occurred in an unshaded parking lot within the campus. Likewise, the maximum air temperature reduction presented in this paper was found in the unshaded open space in site 3, which has a more well-divided ratio between tree coverage and of sand, street and pavement than the other three sites (Figure 10). Therefore, it could be argued that the cooling effect of trees is most effective in the vulnerable open spaces exposed to sun radiation.

This study demonstrates that the size of the trees had an effect on the cooling effect. During daytime, the cooling effect of the existing tall trees (13 m in height, at site 3, Figure 10), performed better than the smaller trees in the modified landscaping scenarios. Larger trees have the ability to maintain lower leaf temperatures during midday due the to lower volume of leaves exposed to radiation [26]. For smaller trees, higher leaf temperatures occur around midday due to higher sun exposure and therefore radiation [26]. However, during the night, our results show that the denser canopy of tall trees contributed to a higher temperature in the area. Temperature increase of up to 0.5 °C during the night is the result of the reduced sky factor within the denser canopy, which reduces the long wave radiation loss, leading to a warmer air temperature [29]. Therefore, the morphological characteristics of trees, especially height, play a major role in defining the extent to which the microclimate conditions could be enhanced.

Distance between trees had also an important effect on the cooling capacity. It was noted that a layout of trees with six meters spacing performed slightly better than spacing of eight meters in the majority of the proposed landscaping scenarios. The maximum air temperature difference recorded between the two spacings layouts was 0.15 °C. Given the similarity in the cooling performance, applying eight meters spacing (i.e., fewer trees) is considered better from the maintenance and irrigation point of view than the six meters spacing (i.e., more trees).

This research also suggests that the availability of alleyways assisted in reducing air temperature around the buildings (Figures 9–11, refer to Section 3.3.1, Section 3.3.2, Section 3.3.3 of Results). Due to the lower air temperature that already exists in the shaded alleyways, it is better to refrain from planting trees in these areas as this will not achieve an optimized cooling effect. Tree landscaping enhancements are best focused in unshaded open spaces as these areas can become significantly cooler with landscaping efforts.

It should be noted that the analysis in this study can be expanded further to consider a comprehensive comparison of various built environments (e.g., building heights and footprints) and their effect on the temperature reduction across the study areas. In future studies, we will integrate other aspects of microclimate and re-calibrate using solar and wind analyses, as well as using multiple simulations with different ranges of humidity and temperatures of different days to enhance the validity of obtained results (simulation in this study was performed with fixed climatic parameters on one day, i.e., 17 June 2019), and varied grid-sizes (current study was done with 2×2 m grid size).

5. Conclusions

The importance of this research lies in its practical contribution to the sustainable urban planning and landscaping field. Although the DMT (Department of Municipalities and Transport) has indicated which plant species are considered suitable for Abu Dhabi's climate, there is still a need for quantified and evidence-based guidelines regarding the trees' coverage ratio in public spaces, particularly in low-density residential urban neighborhoods. A low-density residential neighborhood was taken as a case study as the current landscaping practices tend to overlook these areas.

This research offers quantified urban tree sustainable landscaping strategies and practical approaches that aim to improve urban microclimate conditions. It also provides additional insights to the existing literature by considering three aspects of landscaping design: (i) size and types of trees, (ii) spacing between trees, and (iii) local landscaping regulations, in the analysis. The small-sized trees (5–7 m) offer adequate shade and they are exempt of some of the disadvantages of larger trees. Poinciana, Ghaf and Temple trees which are suitable for a hot climate region were used in the analysis. Local landscaping regulations of vegetation densities were represented by the minimum required distances between trees (6–8 m). Thus, this research employs NbS that can be applied in real-world landscaping projects.

The results from the ENVI-met model suggest that planting trees in the unshaded open space in the eastern part of area maximizes the cooling effect of trees. A minimum temperature reduction of 0.42 °C can be achieved by planting Ghaf trees six meters apart. Larger trees (15–20 m) are best avoided next to smaller trees (5–7 m height) as the former may inhibit the cooling effect of the former. Moreover, the six meters spacing performed slightly better than the eight meters spacing layout in most of the landscaping scenarios. An overall maximum air temperature difference of 0.15 °C was recorded between the two spacings.

This research provides key information on the key variables that need to be considered for future urban planning and studies that investigate microclimate enhancement in urban public spaces through NbS, particularly in the low-rise residential neighborhoods of hot arid regions. This study highlights the study of landscaping in neighborhoods with different urban morphologies, such as comparing urban and suburban neighborhoods, which is needed to overcome the threats of climate change and support resilient urban societies. The findings encourage using trees in urban areas as a sustainable solution to environmental urban challenges. Improvement of microclimate using well-landscaped urban trees in hot arid regions facilitates lowering fossil fuel burning and electricity needs by encouraging active transportation such as walking and cycling over automobiles in daily commuting and decreasing the utilization of air conditioning systems by cooling buildings with shading and lowering the surrounding air temperature. Overall, well-landscaped trees contribute to mitigating the UHI effect.

We recommend future research in urban microclimate in hot arid regions including factors like Physiological Equivalent Temperature (PET), Mean Radiant Temperature (MRT) and air humidity to comprehensively understand the cooling effect of the three local tree species recommended by this study (Figure 4). Moreover, other locally available trees could be studied and compared for microclimate enhancements. Furthermore, the combined effects of street canyons, trees and hardscape materials in the thermal environment can be explored. In addition, we suggest considering the costs of maintenance and irrigation for a sustainable economic approach.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The HOBO onset data logger has an accuracy of +/−0.2 °C and +/−2% RH from 0° to 50 °C, and although calibration is not needed for accuracy [44], the device was set to start logging 5 min before taking measurements to achieve stabilization. Twenty observation points with different characteristics in the study site were selected for taking temperature measurements on 5 June 2019 between 13:00 and 14:00. These observation points included alleyways, parking lots, open spaces, pavements, and green areas. The logging interval was set to 1 min. Each point was logged three times (total 3 min). Thus, the total time taken for collecting air temperature data for the 20 points in the site was approximately 1 h, minimizing variation in data collection caused by weather changes. The data loggers were positioned at a pedestrian level of 1.5 m using a tripod and protected from direct sun radiation by using a hard cover. Protecting data loggers prevents them from overheating and overestimation of the readings. Finally, each point had three temperature values, which were averaged and assigned to their respective point. Furthermore, these 20 temperature values (real values) were used in the correlation graph with the simulated values of the same points to validate the model. ENVI-met simulates the interaction of atmosphere and trees. Thus, the information gathered from on-site measurements is used in modelling the scenario of the existing trees in ENVI-met. In particular, two user-defined input files are required to build the ENVI-met model. The first input file includes meteorological data and surface properties, i.e., air temperature, air humidity, radiation, soil temperature, etc. required for heat transfer calculations.

The input data for the first input file were obtained by using a fixed meteorological monitoring station in the study area. Twenty-four-h climatic parameters (air temperature and air humidity) were derived for 17 June 2019 [45]. These parameters are user-defined input values that define the varying diurnal atmospheric layer conditions adopted in the simple forcing tool within the ENVI-met simulation. The forcing tool incorporates hourly data for air temperature and relative humidity measured in situ to allow the construction of real and proposed scenarios. The simulation of the existing conditions was run on 17 June 2019 for a duration of 24 h starting from 00:00 to 00:00 of the next day. This is because the overall hours should be above 6 h to curb the effect of initialization [33]. This paper follows a similar approach by Zhao et al. [46], who had carried out simulations on 13 June 2017 at 15:00 to examine how tree arrangements affect the outdoor microclimates and human thermal comfort. However, they had not specified the reason behind selecting this exact date. Other scholars had also selected a one-day simulations in similar research papers [9,33,47]. In this research, 17 June was selected due to its clear sky conditions in the summer month. The second input file required to build an ENVI-met model includes a 3D model of the study area in which the building layouts, surface materials and vegetation are represented. This information is required for calculating the radiation and wind flow in ENVI-met. Thus, existing buildings in the study sites were included in the model using GIS (Geographic Information System) documents available from Abu Dhabi's Department of Municipalities and Transport.

Validation of the ENVI-met model was carried out by comparing simulated temperature values with the empirical values collected on-site in the study area using a correlation graph. The peak air temperature at 14:00 was selected to demonstrate a hot day in the study area at a pedestrian level of 1.5 m. Correlation between the simulation results and the measured air temperature at 20 observation points had an agreement index of 0.867, a Root Mean Square Error (RMSE) of 1.544, and a Pearson correlation coefficient of 0.88. A comparison with Wu et al. [48], Gusson and Duarte [29], and Ng et al. [33], indicated that simulation results showed fairly good agreements with field measurements. However, there is a clear overestimation by ENVI-met for the simulated air temperature which was also reported by previous authors [29,33]. This inaccuracy is related to the limitations of solar radiation input used by the software which tends to be overestimated.

ANOVA analysis was carried out to explore the statistical significance between the trees regarding their temperature reductions. The analysis compared the three trees for 6 m and 8 m spacing scenarios separately. The results of the ANOVA analysis based on air temperature at each of the nine observation points are given in Table 1. The F-scores were then compared with the critical value of 3.40 (extracted from distribution table). The F-value for all scenarios was less than the critical value of 3.40, i.e., showing no statistically significant difference between the three types of trees.

Table 1. ANOVA analysis comparing the three types of trees.

			Site 1 (6 m Spacing)		
	sum of squares	degree of freedom	Mean square	F	Significance level
Between tree species	0.0424	2	0.02118	**1.34**	0.05
Within a type of tree	0.3789	24	0.01579		
Total	0.4213				
			Site 1 (8 m Spacing)		
	sum of squares	degree of freedom	mean square	F	Significance level
Between tree species	0.0361	2	0.01803	**1.19**	0.05
Within a type of tree	0.3626	24	0.01511		
Total	0.3987				
			Site 2 (6 m Spacing)		
	sum of squares	degree of freedom	Mean square	F	Significance level
Between tree species	0.0381	2	0.01907	**0.37**	0.05
Within a type of tree	1.2287	24	0.05119		
Total	1.2668				
			Site 2 (8 m Spacing)		
	sum of squares	degree of freedom	Mean square	F	Significance level
Between tree species	0.0258	2	0.01290	**0.26**	0.05
Within a type of tree	1.2013	24	0.05005		
Total	1.2271				
			Site 3 (6 m Spacing)		
	sum of squares	degree of freedom	Mean square	F	Significance level
Between tree species	0.1002	2	0.05008	**0.94**	0.05
Within a type of tree	1.2751	24	0.05313		
Total	1.3753				
			Site 3 (8 m Spacing)		
	sum of squares	degree of freedom	Mean square	F	Significance level
Between tree species	0.0381	2	0.01905	**0.36**	0.05
Within a type of tree	1.2562	24	0.05234		
Total	1.2943				
			Site 4 (6 m Spacing)		
	sum of squares	degree of freedom	Mean square	F	Significance level
Between tree species	0.0517	2	0.02584	**0.66**	0.05
Within a type of tree	0.9334	24	0.03889		
Total	0.9851				
			Site 4 (8 m Spacing)		
	sum of squares	degree of freedom	Mean square	F	Significance level
Between tree species	0.0242	2	0.01210	**0.34**	0.05
Within a type of tree	0.8644	24	0.03601		
Total	0.8886				

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