

## Research

# Optimizing an efficient urban tree strategy to improve microclimate conditions while considering water scarcity: a case study of Cairo

Ahmed Yasser Abdelmejeed<sup>1,2</sup>  · Dietwald Gruehn<sup>1</sup> 

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## Abstract

This study aims to develop an efficient urban tree strategy (UTS) to enhance the microclimate conditions of cities that suffer from heat stress and strong solar radiation, such as the metropolitan area of Greater Cairo. Cairo recently lost its limited greenery to enhance traffic. The proposed UTS aims to achieve a balance between enhancing microclimate conditions and considering the city's water scarcity. It seeks to consider all strategic factors suitable for local conditions, including the selection of tree species (Step 1), the utilization of new technologies for irrigation (Step 2), and the optimization of the usage of an efficient number of trees (Step 3). When applying the strategy's recommendations to a study area within Cairo's downtown center and when testing different tree coverage percentages within urban canyons of various aspect ratios and orientations using ENVI-met, the microclimate conditions are significantly enhanced in certain streets during summertime compared to wintertime. Applying the UTS not only enhances thermal comfort but also helps to create a better comfort zone during certain hours. In one street, for example, there are average physiological equivalent temperature (PET) reductions of  $-5.18^{\circ}$  and  $-6.36^{\circ}$  at 16:00 and 17:00, respectively, which also changes the thermal comfort zone from extreme heat stress to very heat stress. The results show a strong positive correlation between thermal comfort enhancement and a reduction in the total mean radiant temperature (TMRT), verifying that shading plays a primary role in enhancing the microclimate conditions of urban canyons. Applying the UTS to the study area significantly enhances the microclimate conditions. Furthermore, through the implementation of irrigation technologies that are part of the UTS, water demand is reduced to only 15% when trees with larger canopies are used. Additionally, when the tree coverage percentage reaches 35 to 50% in some streets, it results in a significant enhancement in the PET.

**Keywords** Urban heat island (UHI) · Outdoor thermal comfort · Urban tree effect · Recommended tree species · Urban tree strategy (UTS) · Greenery effect · ENVI-met Greenery simulation · Urban cooling strategies

## Abbreviations

UTS	Urban tree strategy
PET	Physiological equivalent temperature
TMRT	Total mean radiant temperature
WS	Wind speed
LAI	Leaf area index
WP	Water productivity

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✉ Ahmed Yasser Abdelmejeed, [ahmed.abdelmejeed@tu-dortmund.de](mailto:ahmed.abdelmejeed@tu-dortmund.de), <https://sciprofiles.com/profile/2172391>; Dietwald Gruehn, [dietwald.gruehn@tu-dortmund.de](mailto:dietwald.gruehn@tu-dortmund.de), <https://sciprofiles.com/profile/1601806> | <sup>1</sup>Research Group Landscape Ecology and Landscape Planning, Department of Spatial Planning, TU Dortmund University, 44227 Dortmund, Germany. <sup>2</sup>Faculty of Urban and Regional Planning, Cairo University, Cairo 11562, Egypt.



SMS	Soil moisture sensor-based controller
DI	Deficit irrigation
UHI	Urban heat island
EPW	Energy plus weather format
TA	Air temperature
DP	Drip irrigation
H	Specific humidity
LAD	Leaf area density
ET	Evapotranspiration-based controller
RS	Rain sensor controller

## 1 Research background

### 1.1 The climate of Greater Cairo

The metropolitan area of Greater Cairo is located in a hot, arid area, which means that the air temperature is high, there is a large amount of solar radiation, and an urban heat island (UHI) appears. Cairo has a hot and dry climate with limited rainfall and frequently high humidity, influenced by the presence of the Nile River Valley. The mean air temperature in Cairo ranges from 9 to 24.8 °C during winter and 20.1 °C to 34.7 °C during summer, sometimes surpassing 40 °C during heat stress events in summer [1]. During the summer, between June and August, the climate is hot and dry, with a maximum average temperature of 28 °C [2]. The city is exposed to large amounts of solar radiation, which can be converted to energy at solar power stations [3]. The city of Cairo experiences a hot and arid climate, characterized by high levels of solar radiation. This significantly impacts the thermal comfort and health of its inhabitants, as well as the social impacts of occupational heat stress on workers' health, safety, productivity, and social well-being [4]. According to statistics from 2012, the metropolitan area of Cairo has a population of approximately 20.5 million [5]. By 2050, the city is estimated to grow substantially, with an expected increase in population of 11.2 million people [5]. Subsequently, this increase in population will have a direct effect on the demand for residential housing, making the city even denser. Both the air temperature and UHI effect will rise due to the increase in city size and population density, and this will, in turn, lead to a rise in anthropogenic heat [6–8].

### 1.2 UHI effects on greater Cairo

According to an urban study conducted in 2015, higher air temperatures were found in downtown Cairo, while lower air temperatures were found in suburban areas [2]. This illustrates the UHI phenomenon. The UHI phenomenon results in an above-average rise in the surface temperature of urban areas in Cairo, ranging from 0.5 to 3.5 °C. The maximum difference observed was 10 °C compared to the surrounding surfaces [2, 9]. The density of the UHI reached 7.8 °C during summer and 2.1 °C during winter [1]. Remote sensing and land surface temperature (LST) analyses assert that there is a strong presence of the UHI phenomenon in Cairo [1, 2, 9]. It is, therefore, evident that the UHI effect takes place in Cairo and leads to discomfort, particularly during nighttime.

### 1.3 Scarcity of water and greenery in Cairo

Cairo suffers from high levels of heat stress, which directly affects quality of life and human health. Urban cooling strategies, such as increasing the number of trees and the amount of vegetation, should, therefore, be implemented; however, the opposite is occurring: the city is losing its limited greenery and suffering from water scarcity.

Cairo has minimal green areas and open spaces. More than half of the city's population has less than 0.5 m<sup>2</sup> of green space per person, which is a staggering ratio that is considerably below the city's average of 1.7 m<sup>2</sup> [10]. During the last four years, Greater Cairo has lost many of its green areas, and many trees have been removed to widen road lanes in an attempt to improve traffic congestion. This has led to a significant reduction in the amount of greenery in the city, which was already quite low. Figure 1 illustrates an example in which trees and green spaces have been removed to widen roads during the renovation of Al-Hegaz Square in the district of Heliopolis [11].

Water resources in Egypt are limited to the Nile River, rainfall, flash floods, deep groundwater in deserts and the Sinai Peninsula, and the potential desalination of sea as well as brackish water [12, 13]. Egypt receives approximately 98% of its freshwater resources from outside its national borders. The main challenge for water policy and decision makers in the country is the fact that the Nile River supplies over 95% of the country's water needs [12, 14].

Egypt's per capita freshwater availability declined from 1893 m<sup>3</sup> in 1959 to 875–950 m<sup>3</sup> in 2000 and 670 m<sup>3</sup> in 2017. It is estimated to decline even further to 536 m<sup>3</sup> by 2025 [12, 15]. The ever-increasing water demands are dictated by a rapidly growing population, increased urbanization, higher standards of living, and an agricultural policy that focuses on expanding production to feed the growing population. Domestic water use grew from 3.1 BCM in 1990 to 5.23 BCM in 2000 [16]. In addition, in 2011, the Ethiopian government announced the construction of a water dam on the main water source of the Nile River in Ethiopia [14].

## 1.4 Urban cooling strategies

There are two primary methods by which urban cooling strategies can enhance thermal comfort and mitigate the impact of urban heat islands (UHIs). The first approach involves modifying the urban layout of new communities by adjusting the orientation and aspect ratio of urban streets. The second approach entails incorporating an environmental layer into already established urban regions, which includes the addition of vegetation and cooling materials, such as trees, greenery, cool colors, roof gardens, vertical gardens, and bodies of water [6, 17–19]. This research is specifically centered around improving the microclimate conditions of existing areas, with a particular focus on vegetation.

Shady trees as well as other elements of vegetation, such as small trees, bushes, lawns, ground coverage, and climbing plants, help improve urban climate conditions by offering shade and evapotranspiration in urban areas and streets [6, 18, 19]. Vegetation also improves air quality by producing oxygen and removing carbon dioxide from the atmosphere. It also provides health benefits to the population by protecting them from shortwave radiation and reducing heat stress and energy demand for air conditioning [2, 20–22]. Previous study outcomes proved that mature trees with good foliage density absorb at least 60% of solar radiation [23]. The temperature within trees is 5 °C lower than the surrounding temperature, and the temperature above the agricultural land surface is 3 °C lower than the surrounding temperature [17]. Moreover, urban trees reduce the 2 m air temperature by up to 2 °C to 9 °C [24].

## 2 Literature review of cooling performance and irrigation efficiency of trees

Among all the vegetation elements that are used to improve microclimate conditions, planting trees yields the best results in reducing the surface temperature of urban areas. The results of many studies that have investigated the role of vegetation in urban areas, conducted in various cities, demonstrate that the role of urban trees is crucial.

In Port Fillip, a study revealed that the maximum reduction in air temperature occurred when green rooftops were combined with urban trees. The reduction reached 2.4 °C at the pedestrian level of the street [25]. A study conducted in Ho Chi Minh City revealed that the difference in the PET value reached 6 °C in shaded areas and 1 °C in unshaded areas



**Fig. 1** Al-Hegaz Square before and after renovation. Both maps were exported from “Google Earth Pro”. The image on the left was exported in October 2018 and the one on the right in May 2022. No editing applied, and the difference between the colors of both satellite images is due to the conditions of each photo in Google Earth

between the urban tree scenario and the base case scenario. Compared to other scenarios, the urban tree scenario had the best effect on improving the thermal comfort value [26]. In a study conducted in Dubai, the recommended scenario was to only apply trees, given that the results of the urban tree scenario were almost identical to the scenarios involving all other vegetation elements. This means that trees play a major and dominant role in improving the surface temperature of urban areas [27]. In Tehran, a study revealed that the maximum mitigation results occurred in the combined scenario and reached 1.5°C on average, providing similar results to the urban tree scenario [28]. When five greenery planning scenarios were applied on three typical street canyons in Balbo, trees with green surfaces exhibited the best effect, reducing the PET by 2 °C. While the PET increased by 7 °C for low-rise compact urban areas, it increased by 5 °C for medium-rise compact urban areas and 4 °C for high-rise urban areas [29]. A study in the Phoenix Metropolitan area focused on the regional cooling effect of trees in arid environments. The simulation results demonstrated the capacity of urban trees to reduce urban surface and air temperatures by approximately 2 °C to 9 °C and 1 °C to 5 °C, respectively [30]. Another study conducted in the same city used several trees and greenery scenarios for small residential neighborhoods located within the city's downtown center. The study found that the ideal scenario occurred when using a tree shading percentage of 25% in urban canyons [31].

Based on previous case studies that were conducted worldwide, vegetation plays a significant role in urban climate adaptation, with trees being the most effective. A tree-only scenario is equivalent to a scenario that uses all vegetation elements (including trees).

## 2.1 Efficient morphological characteristics of trees

The performance of trees in urban areas includes providing shade and evapotranspiration [6, 18, 19]. Shade is more important than evapotranspiration for trees because it sets them apart from other types of vegetation that do not provide shade [25–29]. Numerous studies have shown that the physical characteristics of tree species, such as their shape, size, density, and leaf features, affect their shading and cooling effects [32–35]. Different tree species have inherent traits that determine their growth, form, physiology, and ability to cool their surroundings [36]. The cooling effects of trees depend on the size and density of their canopy, as well as the properties of their leaves. The tree canopy plays a significant role in creating a microclimatic environment, mainly due to its cooling effect [32, 37].

The characteristics of the vegetation canopy are important in predicting thermal mitigation in urban areas and in helping select the best species for urban greening [37]. The overall shape of the canopy and the arrangement and density of the leaves and branches of trees influence the amount of shade that they provide. Trees that have a wide canopy and a high density of leaves and branches produce more effective shading [36]. Among the parameters of different tree species, the leaf area index (LAI) is considered a central parameter affecting light penetration and below-canopy microclimate [38, 39]. In 2013, urban researchers reported that maximum air temperature reduction occurred under the canopies of trees with a high LAI [32]. The leaf area (based on crown diameter and LAI) is important in relation to all three cooling mechanisms considered (transpiration, reflection of solar radiation, and shading) [36–41]. Species with higher canopy density might be preferred over asphalt surfaces, but low-water-using species with lower canopy density might be chosen over grass surfaces [31]. It can be concluded that the cooling effect of urban trees is species-specific and depends mainly on the tree canopy, although the leaf characteristics, LAI, and local microclimate also play an important role [37].

## 2.2 Trees adapting to local conditions (low water demand and salt and drought tolerance)

The selection process of efficient trees should consider the tree species' ability to grow in the local climate conditions of the city to counteract the UHI effect. There is a need to plant large tree species that can tolerate drought and are able to grow in the arid and dry climate of Cairo. In examining the suitability of trees to adapt to the country's climatic conditions, the average and maximum temperatures of the warmest month should be considered, as well as the ease of tree propagation. Adaptations to drought, high pH, and saline soil are also important [42].

When selecting a tree, the type of tree (evergreen or deciduous) should also be considered, as the cooling effects of trees are twice as high on clear and hot days compared to cloudy and cold days. Additionally, evergreen trees slightly lower the air temperature in winter, and weather conditions do not significantly affect the trees' impact on the microclimate [43]. Evergreen trees will, therefore, not have a significant impact during winter but may cause negative effects by blocking the wind and the desirable warming by the sun. As water demand varies from one tree species to another [44, 45], trees that demand a low to moderate water supply are most suitable for this study. Implementing the strategy citywide will result in significant savings

in water supply due to the small amount of water saved by each tree. Therefore, when choosing the most appropriate tree species, it is crucial to consider water demand as an important factor.

### 2.3 Efficient irrigation technology

Irrigation is the single largest water consumption process in the world [46]. There is a widespread belief among environmental and water policy makers that if irrigators can use water more efficiently, more water could be saved for environmental and urban use [47]. Many emerging irrigation techniques and technologies can enhance irrigation efficiency and reduce water consumption. An example of such a technique is the use of deficit irrigation (DI). This is defined as the application of water below full crop-water requirements and is an important tool in reducing water use during irrigation [46]. A well-designed DI regime can optimize water productivity (WP) over an area when full irrigation is not possible. In many horticultural crops, regular DI has been shown to improve not only WP but also the operator's net income [48]. Another successful technique that has recently become popular is the drip irrigation system (DP), which can also be applied as a part of the DI and is widely believed to conserve water. The DP allows for the precise application of water into the root zones of plants with little loss to run-off or deep percolation. It produces higher evapotranspiration than flood irrigation while also producing higher crop yields. Raising the subsidy on DPs encourages the expansion of drip acreage and total acreage in production [42, 47].

An additional technique to enhance the performance of the DI and DP involves the use of software, which can be programmed and used to compute the exact amount of water, soil parameters, and weather conditions required. Having a day-to-day weather data system is often not available to those who operate irrigation systems and who, therefore, end up using historical data to analyze weather condition requirements. Linking an irrigation system to day-to-day weather forecast websites will ensure that it constantly updates with new weather data and can enhance the daily generation of irrigation [48]. Increasing the scheduling efficiency of an automated irrigation system allows for the conservation of water resources while maintaining landscape quality [49]. To increase water efficiency and savings, it is better to provide software with another source of daily data on weather and site conditions. This could be performed via the automation of landscape irrigation scheduling to improve convenience and minimize irrigation application while maintaining high landscape quality [50]. The different types of irrigation controllers that can help reduce the amount of irrigation include the following:

- Evapotranspiration-based controllers (ETs).
- Soil moisture sensor-based controllers (SMSs).
- Rain sensor controllers (RSs).

### 2.4 Research gaps, objectives, and questions

This research aims to provide a comprehensive green strategy that improves thermal comfort and mitigates the UHI effects in the urban areas of Cairo. It intends to do so by using the most suitable elements of urban greenery. According to the results of other studies, urban trees should serve as the most suitable element. This study seeks to provide an urban tree strategy for the whole metropolitan city of Cairo. The strategy should consider the limited water availability in Egypt, particularly because trees are one of the largest water consumers of greenery elements [44, 45], and large amounts of water will be required to irrigate the large number of trees proposed to be planted all over the city. This aided in generating the research question: "What is the impact of implementing a comprehensive urban tree strategy that considers climate conditions and water scarcity on the city of Cairo?". The strategy should have a significant positive impact that not only motivates its application but also raises awareness regarding the use and application of trees once applied, thereby helping to reduce the current removal of trees from Cairo's urban areas.

## 3 Research methodology

To improve microclimate conditions and consider the scarcity of water, a comprehensive examination should be conducted on all aspects of the strategy. Figure 2 illustrates the three steps involved in the strategy: (1) choosing appropriate tree species, (2) implementing effective irrigation methods, and (3) determining the optimal number of trees to be planted in urban areas.

### 3.1 UTS step 1: efficient tree species

The tree species(s) selected for the UTS should require the consumption of less water to achieve the target of the study, which is primarily because the city is suffering from water scarcity and lacking greenery. To provide and implement a strategy for the metropolitan city of Cairo, millions of trees need to be planted. The selection of tree species should, therefore, be carefully carried out, as the very small effect and consumption of one single tree will have an even larger impact when applied all over the city. All parameters of the tree should be considered when selecting suitable tree species. As in previous studies conducted in different cities, the daily average difference between street air temperatures with and without tree shading varies. While it was 0.1 °C in Indiana, United States, it increased to 0.9 °C in Melbourne, Australia; 1 °C in Munich, Germany; and up to 2.8 °C in southeastern Brazil [51–54]. Microclimatic shading and air-cooling methods vary among tree species [55–57] and depend on the morphological characteristics of the tree, including shape, canopy size, canopy density, and tree leaf features [32, 33, 58]. A comparative study should, therefore, be conducted on the main characteristics and parameters of trees when deciding which tree species should be selected. This study should compare the main elements that can provide better performances with regard to enhancing the microclimate conditions within the limited availability of resources.

#### 3.1.1 Step 1 outcomes: recommended efficient urban tree species

Based on previous studies and recommendations, the ideal tree species should be selected based on the following criteria:

- The size of the tree canopy (bigger canopies are indispensable and should be classified as shading trees).
- Tree density (trees with a higher LAI are preferred).
- Tree type (deciduous trees are preferred).
- The adaptability of the tree to location conditions (trees with high water demand; salt and drought intolerance must be excluded).

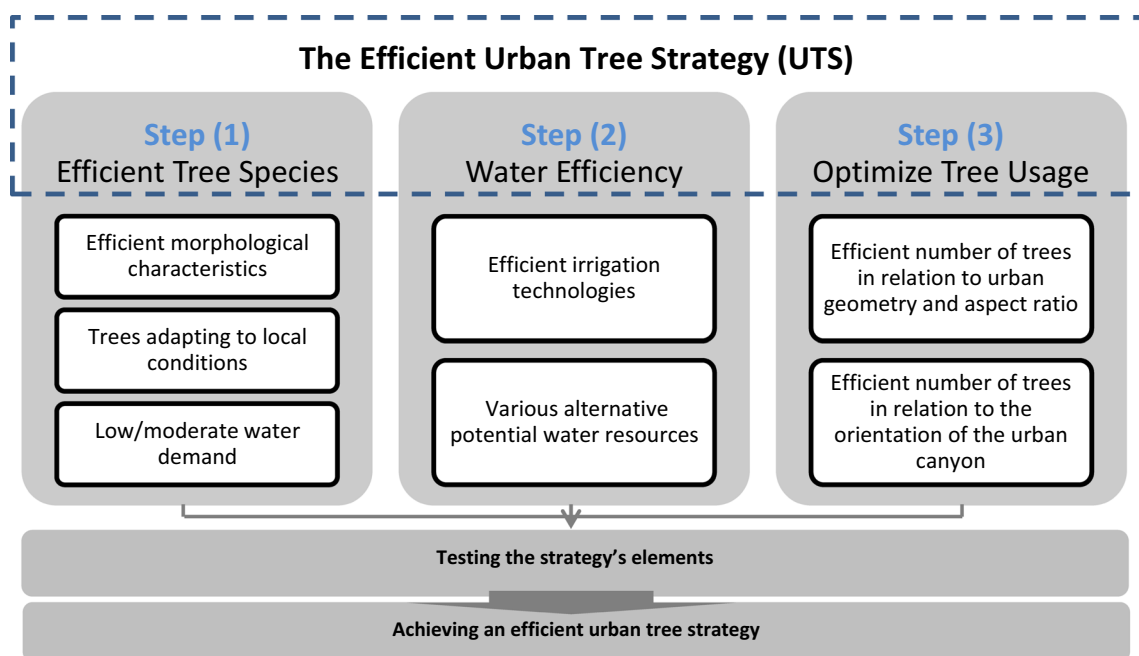


Fig. 2 Research methodology

The selection criteria were applied to 114 trees listed in the planting database for Cairo, titled “Plant Guidebook for Al-Azhar Park and the City of Cairo” [44]. Table 1 shows the 21 trees that were selected from the 114 trees based on the selection criteria of the research study.

As shown in Table 1, there were slight variations in crown size, water demand, LAI, and tolerance to drought and salinity among the chosen trees. While we could have chosen fewer trees, based solely on their characteristics, to include in the table for the intended strategy, we opted to include the aforementioned tree species for two reasons:

- The different tree sizes will be useful when dealing with different street widths, different types of streetscapes, and the available planting areas inside the urban canyons.
- With the 21 shortlisted tree species, a wide range of visual variety and biodiversity can be offered, which is very important for enhancing the city’s image and streetscape.

To maximize the benefits from the selected trees, three main categories should be applied, as shown in Table 1. Category A is for trees with the best properties, category B is for those with good properties, and category C is for those possessing fewer good properties than category B. These three categories should be used as a guide when applying an efficient tree strategy to any urban area in Cairo. However, while category A must be used in all urban areas, categories B and C can sometimes be added to category A to provide more variety and biodiversity to urban areas.

## 3.2 UTS step 2: irrigation technologies

The study seeks to quantify the use of water during irrigation and compare the use of traditional time-based irrigation systems with new technologies such as SMS and RS. SMSs provide significant savings in the amounts of irrigation required, reducing the required amount by 65% compared to homes utilizing traditional irrigation systems [61].

### 3.2.1 Different water resources for irrigation

Reducing water consumption is very important, and finding different water resources is also a significant factor for irrigation. As it is not possible for Egypt to meet the increase in water demand by relying solely on the Nile, it has been developing non-conventional wastewater reuse strategies to meet future demands [42]. Based on the released data from the Holding Company for Water and Wastewater in 2013, Egypt produced approximately 9.6 mcm of treated wastewater per day, which is approximately 3.5 bcm of treated wastewater per year [62]. This amount equates to 6.5% of the total volume of the Nile’s water. These different water resources will support the greening strategy of this study and make its application possible. Assessing the current availability of various water resources and minimizing water consumption make the greening strategy achievable.

### 3.2.2 Water demand for tree irrigation

One of the main objectives of this study is to consider water demand and water efficiency. Calculating water demand is the main factor needed in assessing the UTS. Equation 1 can be used to calculate irrigation water demand for isolated trees, which are widely spaced without other plant material under or around them. Water demand depends on three items: the plant factor, evapotranspiration, and the crown size of the tree, all of which vary among different tree species. The cooling criteria for all trees indicate that having large tree canopies is necessary to increase the percentage of tree coverage. This, in turn, directly leads to an increase in the amount of water needed. To reduce water demand, it is important to minimize both the percentage of tree coverage and the number of trees as much as possible. Therefore, there should be a balance between the required tree coverage percentage and the required water demand to avoid compromising either an improvement in thermal comfort or a decrease in water demand.

Equation 1 can be used to calculate water demand for isolated trees [63]:

$$\text{Gallons} = \text{ETo} \times \text{PF} \times (\text{R} \times \text{R} \times 3.14) \times 0.623 \quad (1)$$

- ETo represents inches of historical average, or real-time evapotranspiration, for the period of interest.
- PF represents the plant factor for the established landscape trees (0.5 for all trees).

**Table 1** The selection of tree species based on the tree efficiency criteria

Category	Scientific name of tree	Common name	Canopy width (m)	Canopy height (m)	LAI [59]	Seasonality	Water demand	Salinity	Drought tolerance
A	<i>Vachellia nilotica</i>	Gum arabic tree	5–10	8–15	3	Evergreen	Low	Tolerant	H. tolerant
A	<i>Prosopis juliflora</i>	Mesquite	Up to 8	10–15		Evergreen	Low	Tolerant	H. tolerant
A	<i>Terminalia catappa</i>	Indian almond	5–10	10–15	3	Deciduous	Moderate	M. tolerant	H. tolerant
B	<i>Albizia lebbek</i>	Lebbek tree	4–8	6–12	3	Deciduous	Moderate	M. tolerant	Tolerant
B	<i>Azadirachta indica</i>	Neem tree	6–10	15–20	3	Deciduous	Moderate	M. tolerant	M. tolerant
B	<i>Bombax ceiba</i>	Cotton tree	6–8	Up to 25	3 [60]	Deciduous	Moderate	M. tolerant	M. tolerant
B	<i>Ceiba speciosa</i>	Silk floss tree	Up to 10	15–20	3	Deciduous	Moderate	M. tolerant	Tolerant
B	<i>Ficus benjamina</i>	Weeping Fig	Up to 15	6–30	3	Evergreen	Moderate	M. tolerant	Tolerant
B	<i>Ficus elastica</i>	India rubber fig	12	9–12	3	Evergreen	Moderate	M. tolerant	Tolerant
B	<i>Ficus infectoria</i>	White fig	8–10	10–12	3	Deciduous	Moderate	M. tolerant	Tolerant
B	<i>Ficus nitida</i>	Indian laurel fig	9	9–18	3	Evergreen	Moderate	M. tolerant	Tolerant
B	<i>Ficus religiosa</i>	Sacred fig	4–8	7–9	3	Semi- Deciduous	Moderate	M. tolerant	Tolerant
B	<i>Ficus sycamorus</i>	Sycamore fig	12–20	15–20	3	Evergreen	Moderate	M. tolerant	Tolerant
B	<i>Jacaranda mimosifolia</i>	Blue jacaranda	7–10	10–15	2.5	Deciduous	Moderate	M. tolerant	Tolerant
B	<i>Peltophorum africanum</i>	African wattle	8–10	10–15	3	Deciduous	Moderate	M. tolerant	Tolerant
B	<i>Tipuana tipu</i>	Yellow jacaranda	6–8	13–15	3	Semi- Deciduous	Moderate	Tolerant	Tolerant
C	<i>Cassia javanica</i>	Pink shower	6–8	10–15	2.5	Deciduous	Moderate	L. tolerant	Tolerant
C	<i>Senna spectabilis</i>	American cassia	10–12	10–15	2.5	Evergreen	Moderate	L. tolerant	Tolerant
C	<i>Delonix regia</i>	Royal poinciana	6–8	10–12	2.5	Deciduous	Moderate	Tolerant	Tolerant
C	<i>Entrobium cyclocarpum</i>	Elephant's ear tree	Up to 9 m	10–12	2 [59]	Deciduous	Moderate	M. tolerant	Tolerant
C	<i>Leucaena leucocephala</i>	Lead tree	4–9	6–15		Evergreen	Moderate	Tolerant	Tolerant



- $R$  denotes the radius of the tree canopy in ft., which can be calculated as follows: canopy diameter in ft.  $\div 2$  (use widest crown spread as the diameter).
- $R \times R \times 3.14$  represents the area of the circle created by the tree's canopy projection over the soil.
- 0.623 is the factor used to convert inches of water into gallons.

### 3.3 UTS step 3: tree amounts and shading percentage

The effect of the tree coverage percentage varies and depends on the street canyon's aspect ratio and orientation [39]. In a study conducted in Athens, the analysis of air temperature patterns for different tree coverage scenarios indicates that the variability in results is mainly due to the effects of tree percentages and the level of aspect ratio [64]. A study carried out in Phoenix showed that an increase in the percentage of tree coverage from 0 to 25% reduces the air temperature by 4.4 °C [31]. A study conducted in Hong Kong, however, recommends 56% tree coverage to achieve the best enhancement of microclimate conditions [65]. Moreover, a study dealing with the effects of tree coverage on deep street canyons within Cairo's downtown center recommends coverage percentages of 22% for northern–western streets and 54% for northern–eastern streets [66]. However, another study conducted in Cairo suggests 50% tree coverage for highly dense urban areas [67]. From all relevant studies within and outside Cairo, it can be concluded that the tree coverage percentage should not be the same for different types of urban canyons with different aspect ratios and street orientations. A detailed study should be conducted to test the ideal tree coverage percentage for each canyon to avoid implementing a tree strategy that will not be efficient given a shortage, or excess, in tree coverage percentages.

### 3.4 Testing the strategy

After studying the three steps, selecting suitable tree species and irrigation technologies, and optimizing tree amounts, the strategy should be tested to examine its efficiency. The outputs of each step should be tested in a study area located in downtown Cairo. This test should validate the strategy's efficiency and measure the impact of applying the strategy to the study area as an example before generalizing the strategy's outputs/recommendations and applying them throughout the entire city of Cairo.

## 4 Method of testing the strategy

As shown in Figure 3, the efficient UTS will be tested using ENVI-met simulations to examine the strategy's impact on the microclimate conditions and ensure that, in alignment with the other studies conducted around the world, the performance of the strategy will also be useful in Cairo.

To test the strategy performance, a comparative study should be carried out between the results of the ENVI-met simulation on the current situation of the study area and the results after the application of the UTS criteria. The results should be statistically analyzed to measure the differences and relationships between the various factors.

### 4.1 The study area

The study area should be located in Cairo's downtown center to observe the effects of the UHI, as they appear most clearly in the central part of the city [2, 9]. The comparative study should be applied using the microclimate simulation tool ENVI-met, which is the most extensively evaluated microclimate model available, with capabilities to accurately simulate an outdoor microclimate for any given location [68]. Using simulation software will also be useful in assessing different scenarios and comparing their results to the results of the current situation.

#### 4.1.1 Study area location and urban characteristics

The study area is situated in the heart of Cairo, specifically in the downtown district or Khedival Cairo. The total area of the site is 150,000 square meters. According to Fig. 4A, it is bordered by 26th of July Street to the north, Kasr AlNil Street to the south, Sherif Basha Street to the west, and Opera Square to the east.

The urban form of the study area follows a grid pattern, oriented in the north direction, as shown in Fig. 4B. The aspect ratios of the urban canyons and spaces vary. Table 2 shows the selected street canyons' aspect ratios and the elements

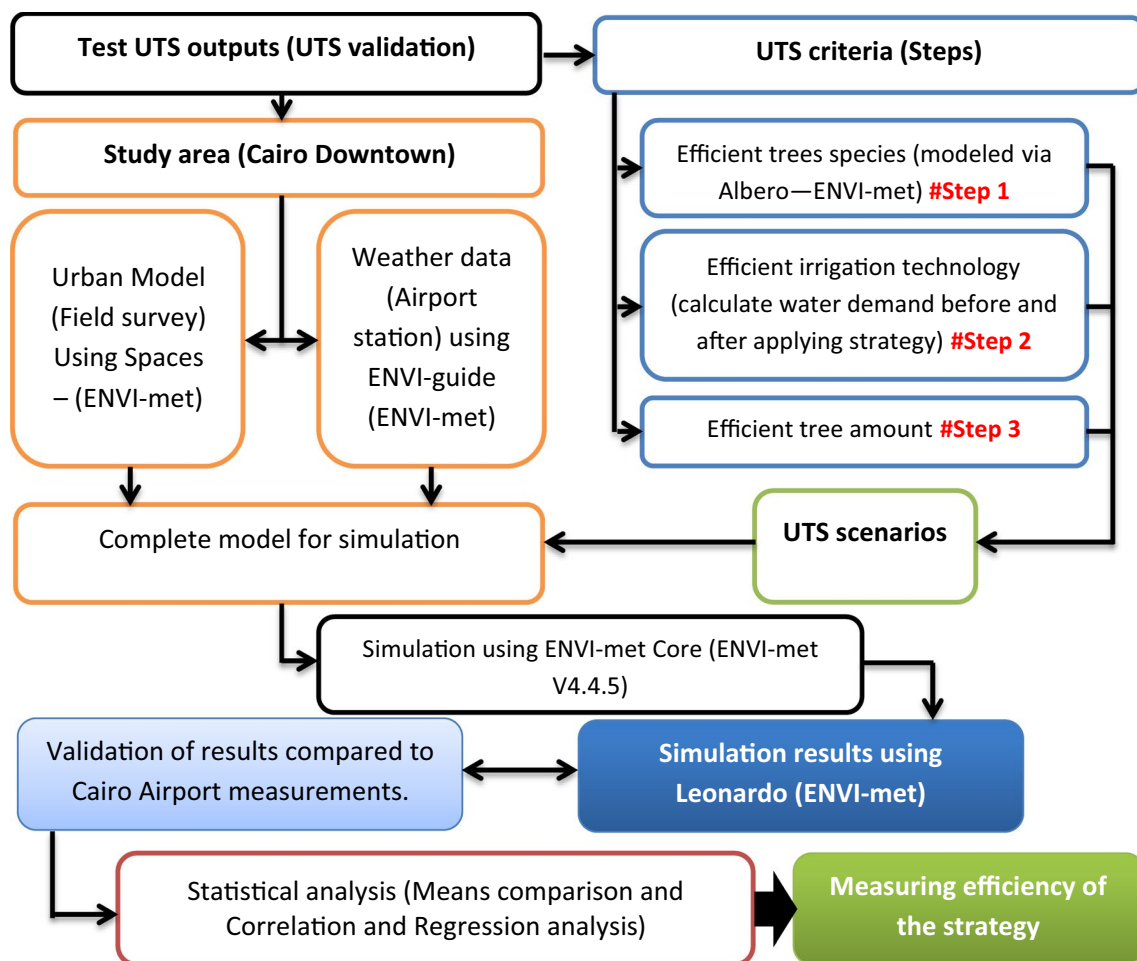


Fig. 3 Method of testing and validating the UTS criteria

of their built environment, such as the building heights, width of roads, tree coverage percentages, and the materials of the street canyon. All urban geometry information is based on the GIS database by the General Organization for Physical Planning (GOPP—Cairo), which was updated through a field survey conducted in September 2021.

#### 4.1.2 Existing trees

As shown in Fig. 4D, some trees already existed within the study area. Fortunately, and as observed during the field survey, these existing trees represent the opposite of what the UTS proposes for selecting tree species; they have very small crown sizes (from 1 to 4 m), are randomly distributed, comprise only one tree species (*Ficus benjamina*—Evergreen), and require manual immersion irrigation. All these differences provide a good opportunity to compare the current situation with the proposed UTS scenarios and, in turn, measure the effectiveness of all criteria and steps of the UTS.

#### 4.2 Different scenarios

Based on the outcomes of the UTS (Step 3), four different scenarios will be applied on selected inner streets of the study area, as illustrated in Fig. 5. Tree coverage percentages should be different for streets with different aspect ratios and orientations [69]. According to two external studies that were conducted and applied in Cairo's downtown center, tree coverage percentages should be between 20 and 50% [66, 67]. Each of the four scenarios will test a different tree coverage percentage. While scenario A will test 0% tree coverage, scenario B will test 20%, scenario C will test 35%, and scenario D will test 50%. All scenarios will be tested during the summer and winter (and, thus, there will be scenarios e, f, g, and h for winter scenarios). For winter scenarios and due to having deciduous trees that lose their leaves during winter, the tree



**Fig. 4** **A** Study area location in Cairo's downtown district (indicated by the pink zone). **B** Selected inner streets for the study (S1, S2, and S3) and buildings heights (m). **C** and **D** Images of the study area's buildings and existing trees from a field survey

percentage in each scenario will not match the same percentage in summer, as clarified in Table 3. As demonstrated in Fig. 5, the results will be compared to the results of the base case scenario during both summer and winter. All information and percentages of the different scenarios are presented in Table 3. For the recommended tree species, three trees from the recommended list will be modeled and used for all scenarios, as shown in Table 3.

### 4.3 Model setup and data input

#### 4.3.1 Model setup, geometry, soil, and materials

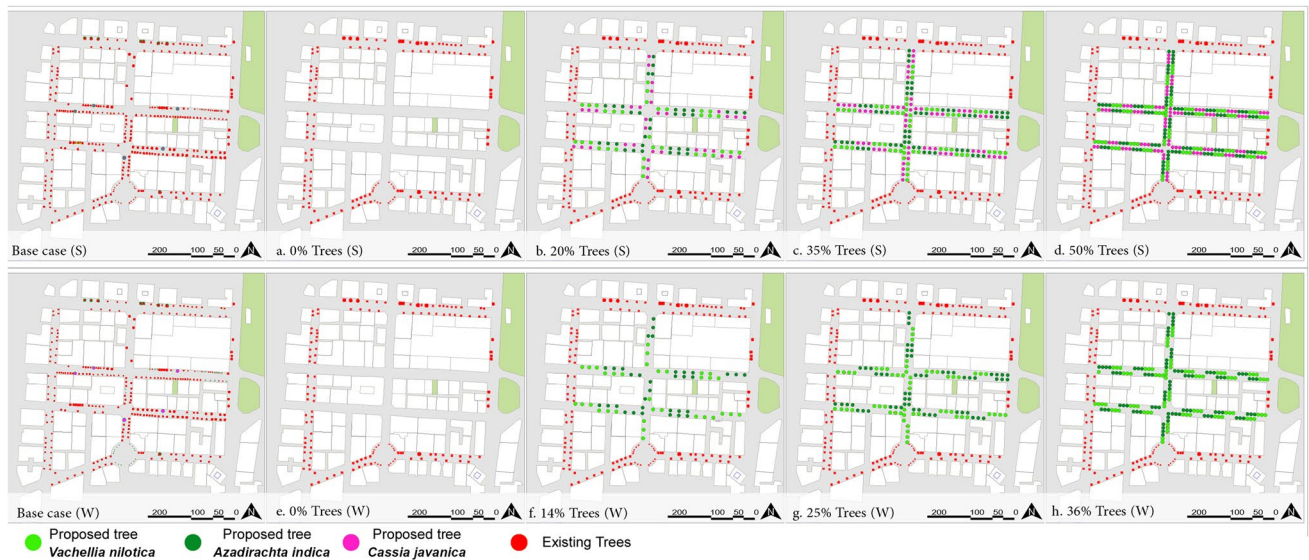
The model geometry and the selected soil and materials represent the current situation of the study area based on the available data and the field survey and do not change for any of the scenarios. To measure the effect of only applying trees, the study area model was built using the model geometry, soil, and materials outlined in Table 4.

#### 4.3.2 Trees and vegetation

This study specifically focuses on the role of urban trees; thus, the modeling of vegetation only focuses on trees. To accurately represent and model different tree scenarios, such as crown size, height, shape, and seasonality, custom tree models need to be developed. These models should meet the criteria and recommendations outlined in Step 1 and

**Table 2** Urban information and field survey outputs for selected streets in the study area

Street name	Abbr	Street orientation	Avg. height	Avg. width	Aspect ratio	Tree coverage % No. of trees	Tree species	Buildings and Streetscape materials
Muhammad Farid	S1	North–South	24 m	20 m	1:1.2	7.3% 33 trees	<i>Ficus benjamina</i>	Buildings: Rendered concrete Sidewalks: Concrete pavers Streets: Asphalt
'Adly	S2	East–West	24 m	24 m	1:1	8.27% 90 trees	<i>Ficus benjamina</i>	
'Abd Al Khaliq Tharwat	S3	East–West	25 m	20 m	1:1.25	11.25% 72 trees	<i>Ficus benjamina</i>	



**Fig. 5** All scenario plans for trees during summer and winter

allow for the measurement of the effects of different tree types in each scenario compared to existing trees in the base case. The ENVI-met application “Albero” is a useful tool for modeling these required tree models and designing their geometries and properties, including crown size, tree height, root size, tree seasonality by month, tree shape, and leaf area density (LAD) of each tree layer [68]. After the trees have been modeled, Albero is able to offer trees with varying crown sizes that can be applied to a specific situation. Albero can also assign an LAD value and determine appropriate heights for the trees. These factors are extremely valuable when integrating small trees into the current conditions of the study area. Additionally, the utilization of tree seasonality aids in elucidating the disparities in performance between deciduous trees during summer and winter. All of these factors will contribute to an efficient and detailed method of measuring tree performance. The distinctions between the different tree scenarios will be evaluated proficiently. While tree modeling and tree variety are based on the existing trees, the proposed trees are based on the efficient UTS, as shown in Table 3 above. Figure 6 shows the differently modeled trees (7 m, 5 m, and 3 m) for the proposed trees scenarios and the current base case scenario.

#### 4.3.3 Meteorological data input

We utilized the recorded data from Cairo Airport on both July 1st, as a representation of summer, and January 1st, as a representation of winter in 2020, [70–72] and employed simple forcing instead of full forcing due to irregular results that did not align with the measured data from Cairo Airport.

#### 4.3.4 Simulation configuration

The simulation setup took two days to prepare: one in the summer on July 1st and one in the winter on January 1st. The simulation started at 1:00 am and lasted for 24 h. We used simple forcing for the measured data from Cairo Airport. Data output was collected every hour and converted using the ENVI-met “Bio-met” program to calculate the PET values for each hour and scenario. The main factor of comparison was the different mean PET values. We compared them across all scenarios to evaluate the impact of each scenario and determine the ideal urban tree model that represents an efficient UTS. We calculated the mean PET values for all cells on each street and compared them to the mean values of the other streets. In addition, we also measured other parameters, such as air temperature (TA), wind speed (WS), humidity (H), and total mean radiant temperature (TMRT). As illustrated in Fig. 7, these parameters were measured at a given point located at the center of each street, away from the shade of tree canopies (R1, R2, and R3). Comparing such detailed results would greatly help in increasing our understanding of the effect of the UTS, after understanding its general effect, by comparing the mean PET values of each street.

**Table 3** Tree data for each scenario

Scenario	Tree species	No. of trees	Avg. crown size	Overall tree coverage (%)
Base case—summer	<i>Ficus benjamina</i>	187	1—4 m	9
	<i>Cassia javanica</i>	5	6.5 m	
	<i>Phoenix dactalfera</i>	3	5 m	
	Total	195		
Base case—winter	<i>Ficus benjamina</i>	187	1—4 m	8.2
	<i>Cassia javanica</i>	5	0*	
	<i>Phoenix dactalfera</i>	3	5 m	
	Total	195		
0% trees—summer—winter	N/A	0	N/A	0
b. 20% trees—summer	<i>Vachellia nilotica</i>	34	7.5 m	20
	<i>Azadirachta indica</i>	34	8 m	
	<i>Cassia javanica</i>	34	7 m	
	Total	102		
f. 20% trees—winter	<i>Vachellia nilotica</i>	34	7.5 m	14
	<i>Azadirachta indica</i>	34	8 m	
	<i>Cassia javanica</i>	34	0*	
	Total	102		
c. 35% trees—summer	<i>Vachellia nilotica</i>	58	7.5 m	35
	<i>Azadirachta indica</i>	60	8 m	
	<i>Cassia javanica</i>	06	7 m	
	Total	178		
g. 35% trees—winter	<i>Vachellia nilotica</i>	58	7.5 m	25
	<i>Azadirachta indica</i>	60	8 m	
	<i>Cassia javanica</i>	06	0*	
	Total	178		
d. 50% trees—summer	<i>Vachellia nilotica</i>	86	7.5 m	50
	<i>Azadirachta indica</i>	85	8 m	
	<i>Cassia javanica</i>	85	7 m	
	Total	256		
h. 50% trees—winter	<i>Vachellia nilotica</i>	86	7.5 m	36
	<i>Azadirachta indica</i>	85	8 m	
	<i>Cassia javanica</i>	85	0*	
	Total	256		

\*Deciduous trees have zero crowns during winter

#### 4.4 Validation of results

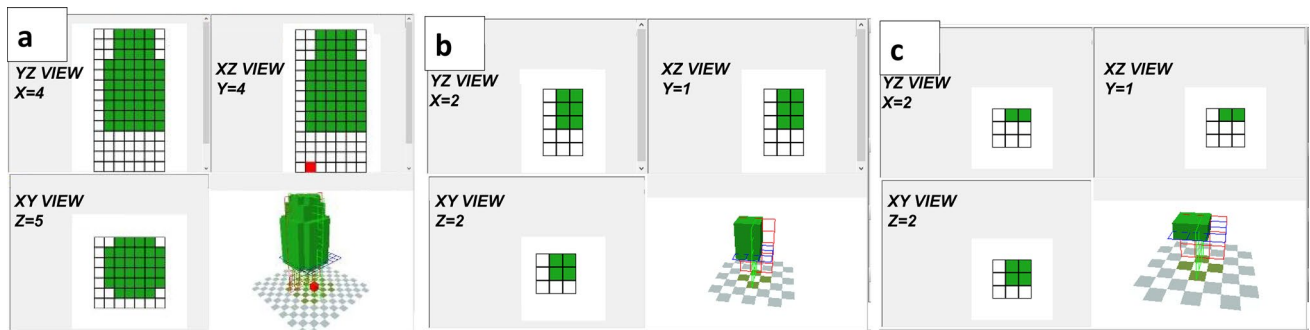
The simulation was performed for all cases based on the model setup and the meteorological data of Cairo's Airport. Before reading and analyzing the outputs and results, it is important to examine the validation results by comparing the values of the results to the measured data. Additionally, the root-mean-square index (RMSE) and the index of agreement (d) are calculated for all results to ensure that the results obtained from the simulation are valid. Air temperature and relative humidity, measured on the 1st of July 2020, are compared to the output results of the simulation to assess whether the results are in line with the measured data, and for better validation, the ENVI-met results are not only compared to airport station measured data but also to data measured in Fatimid Cairo on the same day but in a previous study (1 km away from the study area) conducted in 2013 [73]. As shown in Fig. 8, by applying ENVI-met simple forcing using the measured data, the results for summer air temperature and relative humidity show significant matching, the RMSE for air temperature was 1.45 for the airport data and 2.11 for the site data, with an index of agreement d of 0.94 for the airport data and 0.87 for the site data, and the RH% RMSE was 7.15 for the

**Table 4** Model setup, geometry, soil, and materials

Model information (base case, 0%, 20%, 35%, and 50%) for models in summer and winter	
Model location	30.02 latitude and 31.22 longitude
Area size (Grids)	X = 166, Y = 140, Z = 21
Grid resolution (m)	X = 3, Y = 3, Z = 3
Orientation (from North)	0
Split lower grid box into 5 sub cells	Yes
Telescoping applied	The telescoping factor is 20%, and telescoping should start after 42 m in height
Maximum model height*	88 m
Nesting grids**	Not applied
DEM	Not applied, as the site is flat
Soil	Asphalt for roads, concrete for sidewalks, green turf for green areas, and sand under buildings
Building materials	Default wall—moderate insulation

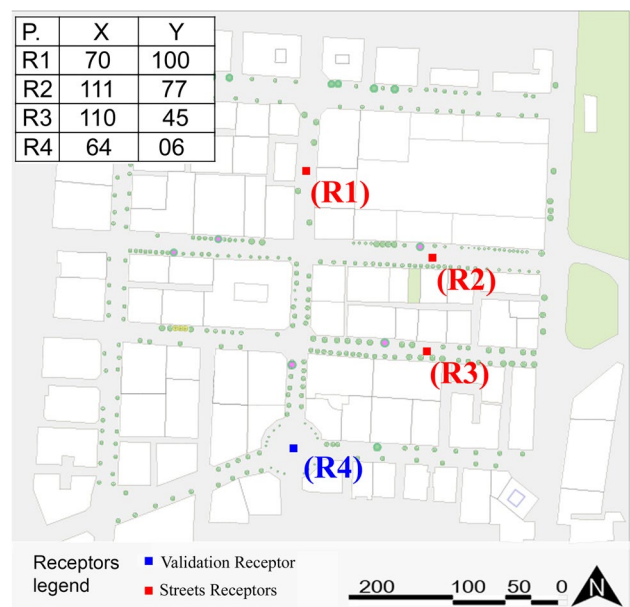
\*The model's height is more than double the height of the tallest building, as recommended by the software [68]

\*\*Nesting grids were not applied; however, 5 cells from the boundary sides of the model were kept empty, as recommended by the software developers [68]



**Fig. 6** Modeled trees using Albero, **a** the 7 m tree, **b** the 5 m tree, and **c** the 3 m tree

**Fig. 7** The location, types, and coordinates of receptors



airport data and 6.91 for the site data, with a  $d$  of 0.89 for the airport data and  $d$  of 0.90 for the site data. Additionally, as depicted in Fig. 8, the ENVI-met results for the same point in the model closely align with the measured data. Similarly, when the validation process is performed during winter, the results closely match the measured data, with an air temperature RMSE of 1.27 and  $d$  of 0.93, and an RH% RMSE of 6.37 and  $d$  of 0.94. Additionally, these results demonstrate that employing a simpler forcing method yields more accurate outcomes compared to the full forcing method, which was applied at the beginning using EPW files of Cairo and showed mismatching results, as shown in Appendix (1). This indicates that all results accurately represent the current situation, with minor discrepancies arising from changes in the surrounding urban context, as the differences in the results are very similar or even better than some ENVI-met simulation studies applied in Cairo [67, 74, 75]. Hence, the simulation output can be utilized to evaluate the impact and influence of various tree scenarios during both summer and winter.

## 5 Results

### 5.1 Comparison of PET (mean values of each street)

To understand the different impacts of each tree scenario in relation to the base case scenario, a comparison of the mean PET values between each street (S1, S2, and S3) and each scenario was performed. The PET value is a good measure to use when comparing the impact of each scenario, as it represents the physiological equivalent temperature felt by people inside the urban canyon. All measured data are selected at a height of 1.5 m, which is the average height of street pedestrians. The PET values are classified under many ranges to represent outdoor thermal comfort. Temperatures of less than 4 °C are considered within a very cold range, between 4 and 18 °C are within a cold range, between 18 and 23° are within a thermal comfort range, between 23 and 41° are within a hot range, and above 41 °C are within a very hot range [76]. Table 5 presents a more detailed PET classification from another study for a subtropical climate (a similar climate zone to Cairo) [77].

#### 5.1.1 Comparison of PET results during summer

By comparing the summer PET values of all the streets, it is clear that the addition of trees to urban canyons has a positive impact on enhancing PET values in general. This impact, however, varies from one street to another and from daytime to nighttime. To further understand this impact, a more detailed comparison is conducted per hour to measure this impact and generate recommendations regarding the application of trees to different urban canyons.

**5.1.1.1 Comparison of mean PET values for S1 scenarios during summer** Applying different percentages of urban trees to S1 slightly enhances its mean PET values. As shown in Fig. 9, the PET values indicate that the base case results during peak hours and during the day are in the hot range. The PET values of the base case scenario are extremely similar to those of the 0% tree coverage scenario. The maximum difference between both scenarios is  $-0.37$  °C, the average difference is  $-0.04$  °C, and most differences are less than  $-0.1$  °C. Therefore, the application of numerous trees with small crowns will not enhance the thermal comfort of this urban canyon, in any way, aligning with the theoretical recommendations of the efficient UTS [32, 78].

Applying 20% tree coverage to S1 slightly increases the PET values, which reach a maximum of  $-0.83$  °C and an average of  $-0.10$  °C during the daytime. Although this scenario yields better results than the one that does not apply any trees, it achieves only a slight enhancement in the PET values during the daytime.

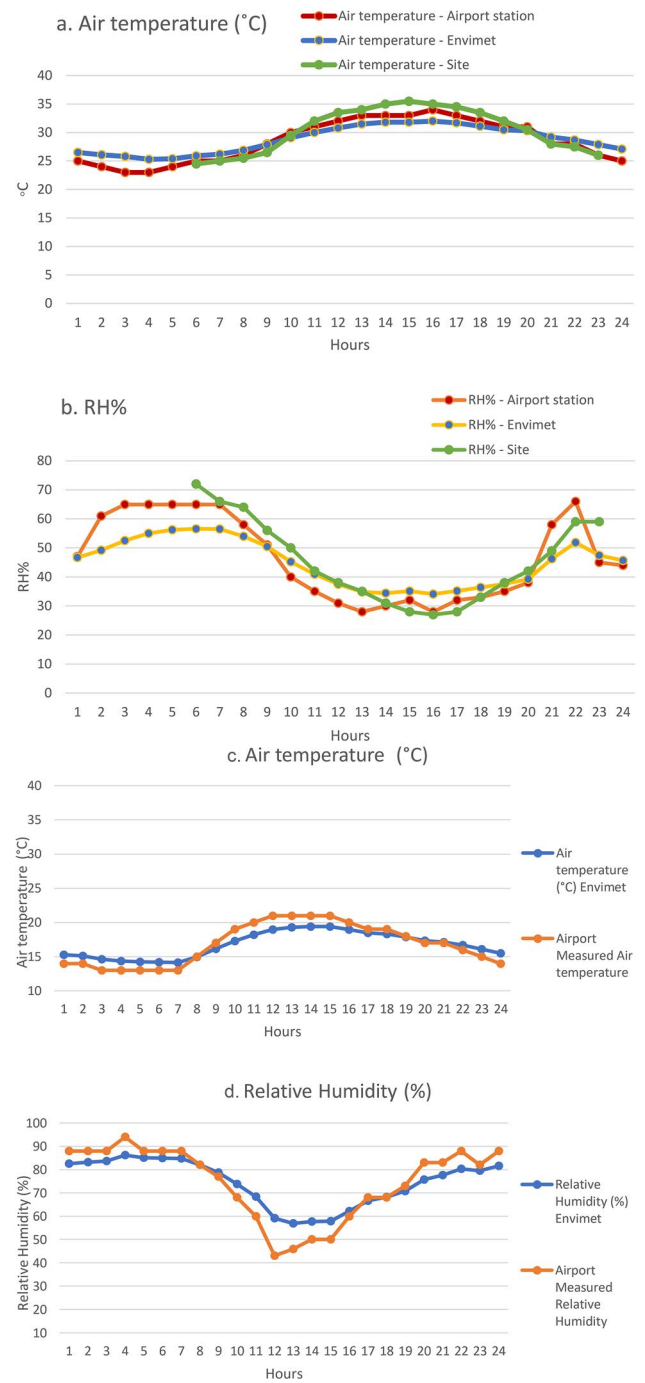
When applying 35% tree coverage to S1, the enhancement in the PET values increases, reaching a maximum of  $-0.69$  °C and an average of  $-0.41$  °C during the daytime. While this scenario also yields better results than the one that does not apply any trees, it achieves only a slight enhancement in the PET values during the daytime as well. The values are higher during nighttime but still fall within the same range.

Applying 50% tree coverage to S1 increases the enhancement in the PET values, reaching a maximum of  $-1.52$  °C and an average of  $-0.79$  °C during daytime. This is very similar to the 35% tree coverage scenario and is still considered only a slight enhancement during the daytime. The PET values are higher during nighttime but fall within the same range.

The overall impact of applying different tree coverage percentages to S1 is not significant at all. Although it slightly enhances thermal comfort, this minor enhancement does not lead to any noticeable improvement, such as changing



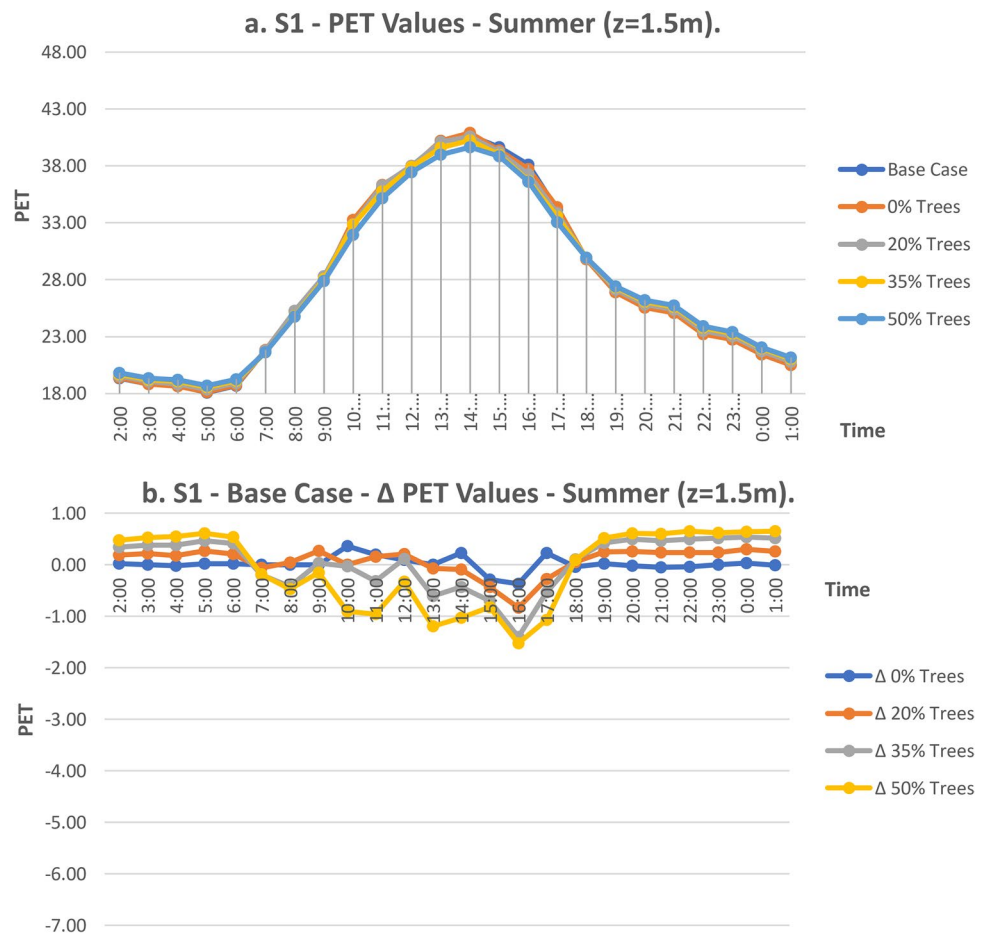
**Fig. 8** Air temperature and RH% validation, summer (a, b) and winter (c, d) (simple forcing)



**Table 5** PET detailed classification for a subtropical climate

Range*	13–18	18.1–23	23.1–29	29.1–35	35.1–41	41.1 ≤
Thermal perception	Slightly Cool	Comfortable	Slightly Warm	Warm	Hot	Very Hot
Grade of physiological stress	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

**Fig. 9** **a** S1: mean PET values for S1 scenarios, **b** S1—base case  $\Delta$ PET—summer (01-07-20)



the thermal range. The PET values were higher during nighttime across all scenarios (20%, 35%, and 50%); however, the increase was very minor and still fell within the same thermal range.

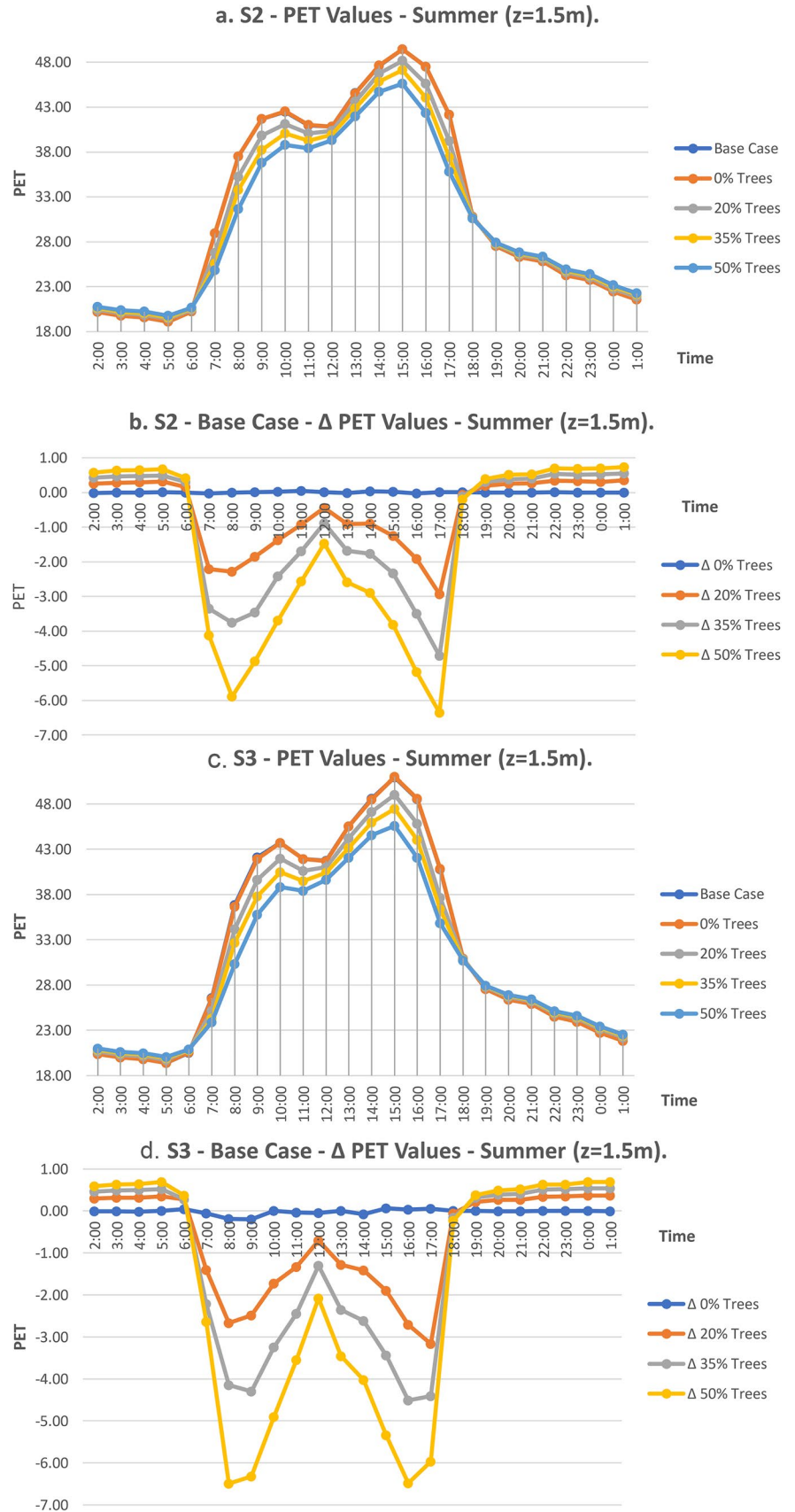
Applying different percentages of urban trees to S2 and S3 significantly enhances their mean PET values. As shown in Fig. 10, the PET values indicate that the base case results during peak hours and daytime are in the extreme heat stress zone. The PET values of the base case are extremely similar to those of the 0% tree coverage scenario. The maximum difference between both scenarios is 0.04 °C, the average difference is 0.02 °C, and most differences are less than 0.01 °C. This means that the application of many trees with very small crowns to both these urban streets (S2 and S3) will not enhance their thermal comfort, in any way, aligning with theoretical recommendations of the efficient UTS [32, 78].

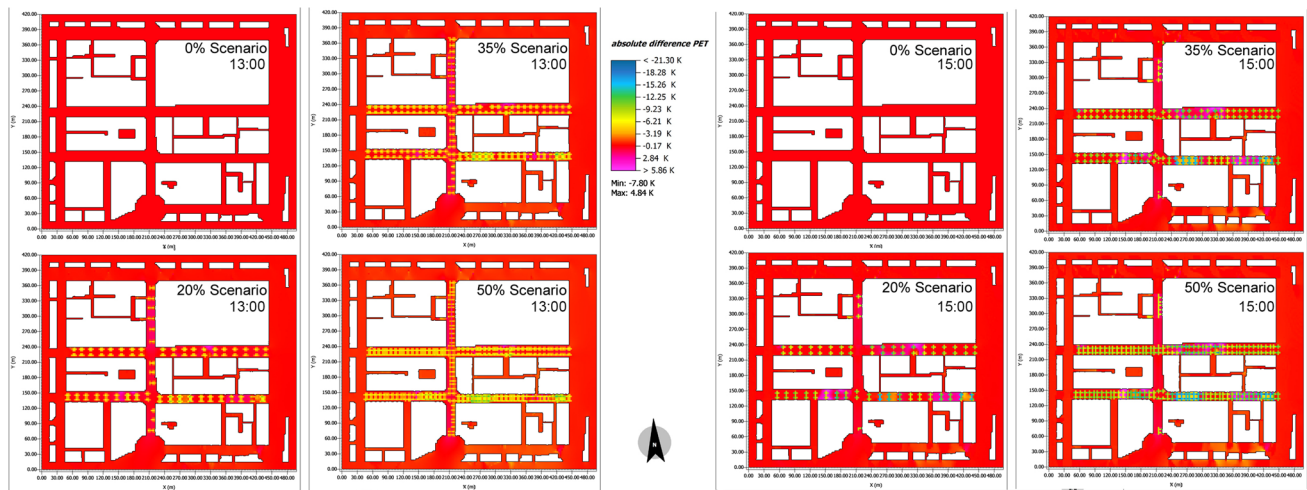
When applying 20% tree coverage, the enhancement in the PET values noticeably increases, reaching a maximum of – 3 °C in S2 and – 3.16 °C in S3 during the daytime. The average increase during the daytime is – 1.55 °C in S2 and – 1.89 °C in S3, which is higher than the results of the scenario that uses 0% tree coverage, which is considered a good enhancement. The PET values are higher during the nighttime and lie within a smaller range, reaching a maximum of – 0.35 °C in both streets. When applying 35% tree coverage, the enhancement in the PET values increases and reaches a maximum of – 4.71 °C in S2 and – 4.51 °C in S3 during the daytime. The average increase during the daytime is – 2.69 °C in S2 and – 3.18 °C in S3, which is considered a very good enhancement. The PET values are slightly higher during the nighttime and reach a maximum of – 0.55 °C in both streets.

When applying 50% tree coverage, the enhancement in the PET value significantly increases and reaches a maximum of – 6.36 °C in S2 and 6.49 °C in S3 during the daytime. The average increase during the daytime is – 3.95 °C in S2 and – 4.66 °C in S3, which is considered a significant enhancement, as the average enhancement during peak hours is – 3.56 °C in S2 and – 4.41 °C in S3. The PET values are higher during the nighttime and reach a maximum of – 0.7 °C in both streets.

The overall impact of applying different tree coverage percentages is clearly significant and strongly enhances thermal comfort, helping change the thermal comfort zone in S2 at 11:00, 12:00, 16:00, and 17:00 and in S3 at 11:00, 12:00, and 17:00. PET reduction helps change the thermal comfort zone from extreme heat stress to strong heat stress. Figure 11 illustrate the effects of trees at 13:00 and 15:00.

**Fig. 10** **a** S2: mean PET values for S2 scenarios, **b** S2—base case  $\Delta$ PET, **c** S3: mean PET values for S3 scenarios, **d** S3—base case  $\Delta$ PET—summer (01-07-20)





**Fig. 11** PET reduction values for each scenario compared to the base case (on the right at 13:00, and on the left at 15:00 on 01-07-20)  $Z=1.5$  m

### 5.1.2 Comparison of PET values during winter

By comparing the PET values of all the streets during winter, it is clear that the addition of trees to the urban canyons does not have an impact on enhancing their PET reduction values. Such an impact is usually not recognized due to the cold microclimate conditions of winter, as all the simulation scenarios were carried out on the 1st of January, which is considered the middle of winter. In general, the absence of trees in urban canyons will not have a negative impact on human thermal comfort. The application of different tree species (whether evergreen or deciduous) will not change the microclimate conditions that occur during winter.

**5.1.2.1 Comparison of PET values for S1 (winter scenarios)** As shown in Fig. 12A, the maximum reduction in the PET reached  $0.58 \text{ }^{\circ}\text{C}$  and  $0.55 \text{ }^{\circ}\text{C}$  at 11 am and 12 pm only and in the 50% tree coverage scenario. This reduction equates to only 9% of the reduction value for the same tree scenario in the summer. During some hours, the addition of trees increases the PET. For example, the maximum reduction in the PET is  $0.43 \text{ }^{\circ}\text{C}$  at 10 am in the 20% tree coverage scenario. The average reduction in the PET during peak hours is  $0.02 \text{ }^{\circ}\text{C}$  in the 20% tree coverage scenario,  $0.045 \text{ }^{\circ}\text{C}$  in the 35% scenario, and  $0.07 \text{ }^{\circ}\text{C}$  in the 50% scenario.

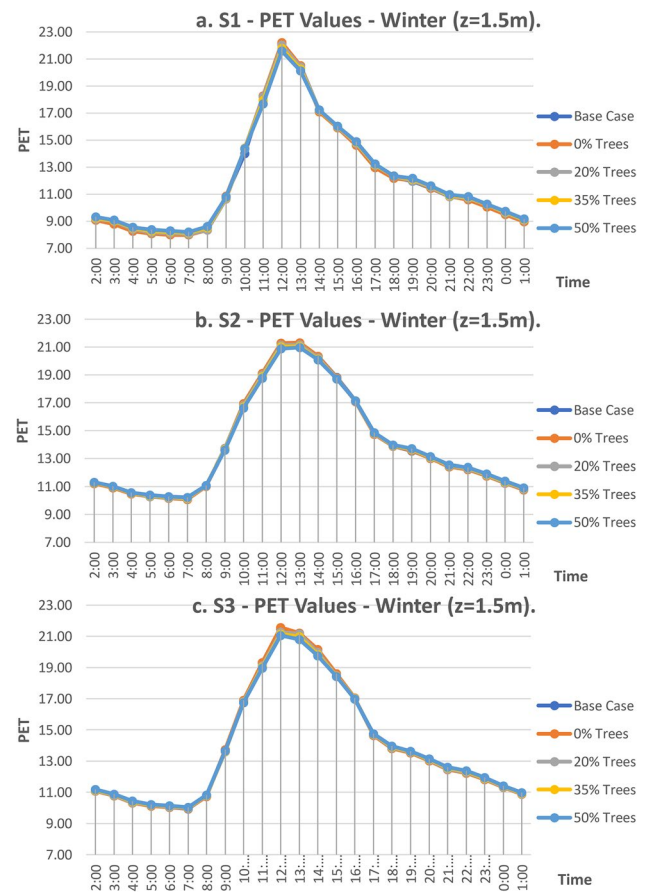
**5.1.2.2 Comparison of PET values for S2 and S3 (winter scenarios)** As shown in Fig. 12B and C, the maximum reduction in the PET for S2 ranged between  $0.32$  and  $0.42 \text{ }^{\circ}\text{C}$  between 10 am and 1 pm in the 50% tree coverage scenario. This reduction equates to only 6.8% of the reduction value for the same tree scenario for S2 in the summer. For S3, the maximum reductions in PET are  $0.58 \text{ }^{\circ}\text{C}$  and  $0.55 \text{ }^{\circ}\text{C}$  at 11 am and 2 pm, respectively, in the 50% tree coverage scenario.

This reduction equates to only 6.5% of the reduction value for the same tree scenario for S3 in the summer. The average reduction in the PET for S2 during peak hours is  $0.07 \text{ }^{\circ}\text{C}$  in the 20% tree coverage scenario,  $0.13 \text{ }^{\circ}\text{C}$  in the 35% scenario, and  $0.19 \text{ }^{\circ}\text{C}$  in the 50% scenario. For S3, the average reduction in the PET value during peak hours is  $0.10 \text{ }^{\circ}\text{C}$  for the 20% tree coverage scenario,  $0.15 \text{ }^{\circ}\text{C}$  for the 35% scenario, and  $0.21 \text{ }^{\circ}\text{C}$  for the 50% scenario.

## 5.2 Comparing PET parameter results for all receptors

To understand the main factors contributing to the enhancement in the microclimate conditions in S2 and S3, a detailed investigation should be conducted by studying all thermal comfort parameters of both streets. All parameters should be measured at the same point, located in the middle of each street (indicated as R2 and R3 in Fig. 7). Measuring and comparing all parameters, including air temperature (TA), wind speed (WS), TMRT, and specific humidity (H), will help to clarify which parameter is enhanced by the addition of trees, consequently leading to an enhancement in the PET. Figure 13 demonstrates that when comparing the results of each factor for both R2 and R3, significant changes are found to

**Fig. 12** Mean PET values—winter (01-01-21) Z=1.5 m. (A: S1, B: S2, C: S3)



occur in WS and TMRT upon the addition of trees. Changes in these two specific factors explain why the shading provided by trees reduces the TMRT and their physical blocking of the wind reduces wind speed. No major changes take place, however, in the air temperature and humidity of both streets before and after the addition of trees.

### 5.2.1 The impact of adding trees on air temperature and humidity

The addition of trees leads to a very slight enhancement in air temperature, which reaches a maximum of  $-0.124\text{ }^{\circ}\text{C}$  at 17:00 in R3 and  $-0.113\text{ }^{\circ}\text{C}$  at 16:00 in R2. This slight enhancement is not considered to be the reason behind the observed significant enhancements in the PET values. Similarly, the results for specific humidity showed very minor enhancements when trees were added to both streets, in which humidity was reduced by a maximum of 0.09% at 10:00, 11:00, and 12:00 in R2 and reached a maximum reduction of 0.17% during the same hours in R3.

### 5.2.2 The impact of adding trees on wind speed

As shown in Fig. 13, the addition of trees to all streets leads to significant changes in wind speed. The wind speed is reduced due to the vertical blocking of the trees planted on both sides of the street. This impact, however, varies from one street to another, as the wind speed is different within each street due to the different orientations of the streets. While S1 is oriented toward the north, S2 and S3 are oriented toward the east. Figure 14.a illustrates a comparison between wind speed figures for the base case scenario at the receptor points of each street (R1, R2, and R3). As shown in the figure, the wind speed is significantly different and high in S1 given that its northern orientation matches Cairo's main wind direction. The wind speed in S1 ranges between a maximum of 3.25 m/s and a minimum of 2.86 m/s, which lies within the comfort limit of 1 m/s to 5 m/s [79]. In S2 and S3, which have an eastern orientation that goes against

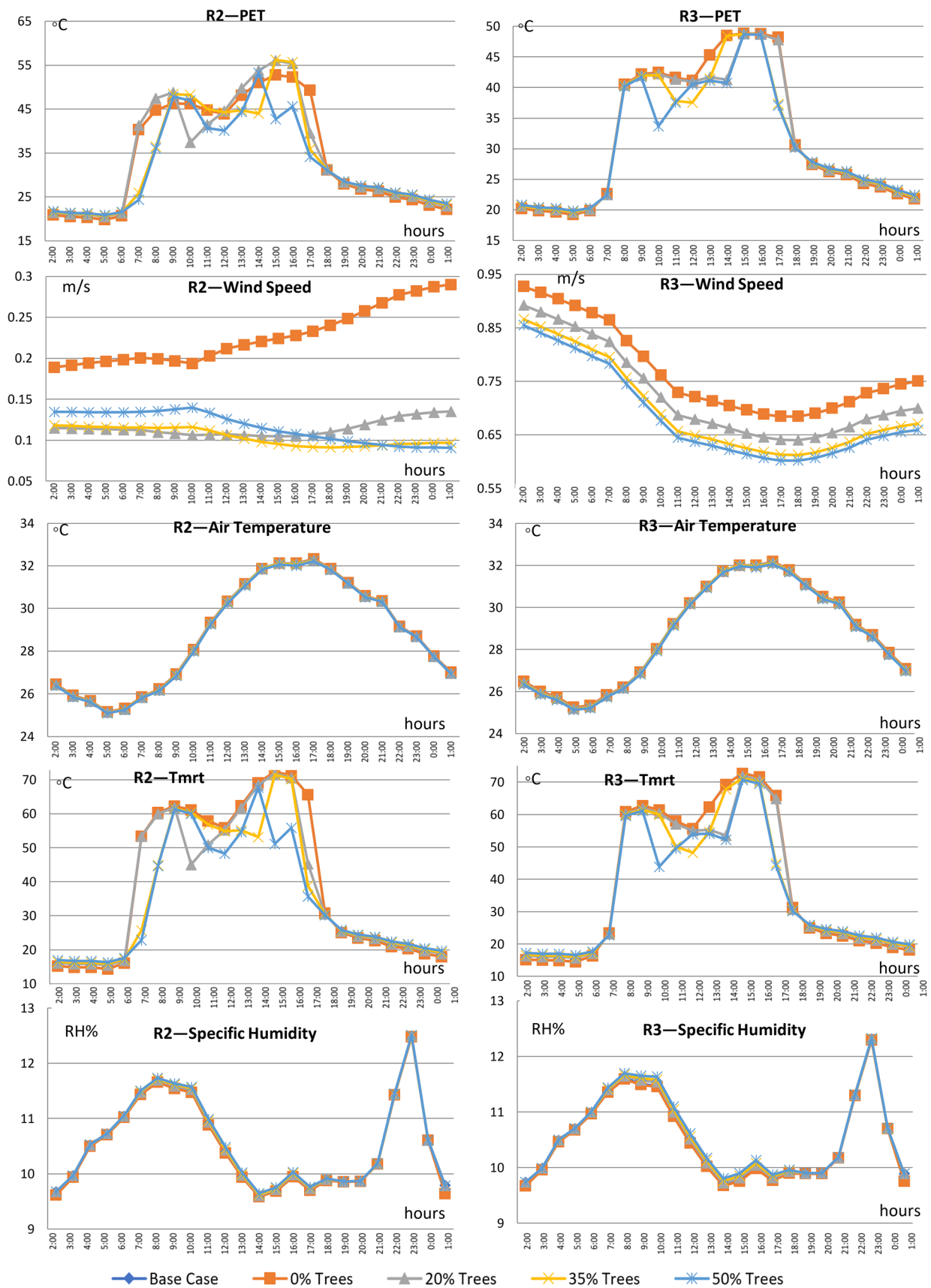
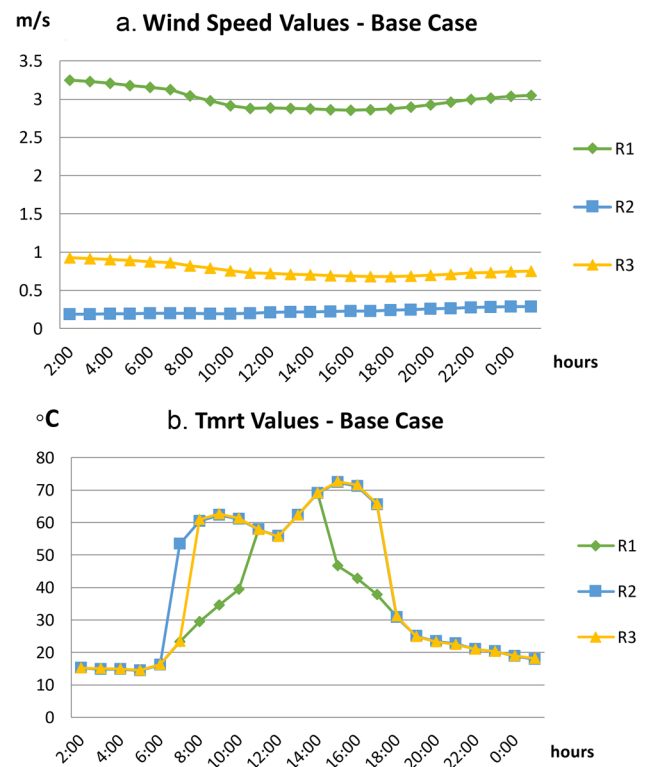


Fig. 13 Comparison between PET, WS, TA, TMRT, and H for R2 and R3

**Fig. 14** **a** Wind speed values, **b** Tmrt values for the base case for R1, R2, and R3



Cairo's wind direction, wind speed values are between 0.29 m/s and 0.19 m/s in R2 and 0.74 m/s and 0.92 m/s in R3. These are considered very minor values in comparison to those of S1. Although the addition of trees reduces wind speed in all streets, the large difference in wind speed between S1 and the other two streets indicates that their impact varies from one street to the other. In S1, the addition of trees reduces the wind speed in R1 by  $-1.7$  m/s to  $-1.8$  m/s during the day, which is more than double the maximum wind speed figures of the other streets. In S2 and S3, the addition of trees reduces the wind speed by  $-0.05$  m/s to  $-0.2$  m/s in R2 and  $-0.07$  m/s to  $-0.09$  m/s in R3.

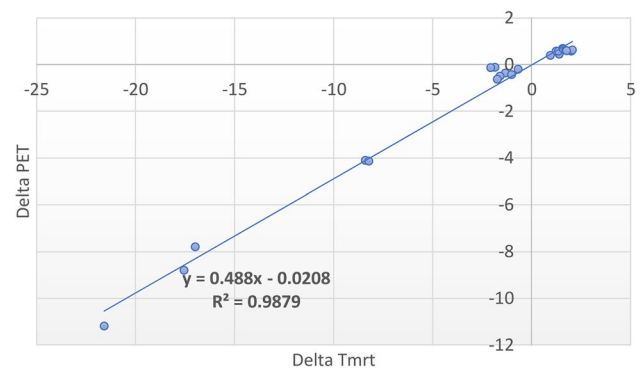
The impact of adding trees on the wind speed of both S2 and S3 cannot, therefore, be considered the main factor affecting their PET, as the wind speed of both streets is already extremely low. A reduction in wind speed will, thus, not impact their PET values. This is due to other factors that significantly enhance the PET values in both streets, as shown in Fig. 10. In contrast, the wind speed reduction in S1 is quite significant, being reduced to almost half of its original figure. According to Fig. 9, the enhancement in the PET in S1 is very limited. It can, therefore, be claimed that the addition of trees to S1 does not enhance the PET and significantly reduces wind speed.

### 5.2.3 The impact of adding trees on TMRT

Figure 13 shows how the addition of trees clearly changes the TMRT figures for R2 and R3. The changes in the TMRT charts are significant in comparison to the other measured parameters outlined in Fig. 13. This means that the addition of trees to urban areas, with the additional shading they provide, significantly reduces the total radiant temperature (including solar radiation) of the urban canyon at the pedestrian level. After the addition of trees to S2, the maximum reductions in TMRT at R2 reached  $-21.3$  °C,  $-15.4$  °C, and  $-29.9$  °C at 15:00, 16:00, and 17:00, respectively. After the addition of trees to S3, the maximum reductions in TMRT at R3 reached  $-17.0$  °C and  $-21.6$  °C at 17:00 and 14:00, respectively. As illustrated in Fig. 13, the PET and TMRT charts look very similar, and their reduction values are almost the same for both streets. This means that the significant enhancement in the PET is directly related to the major reduction in TMRT. In S1, the TMRT reduction is minor, and the PET enhancement is not significant, further demonstrating the relationship between PET and TMRT.

Figure 14b shows the TMRT values of all the streets for the base case scenario. As displayed, during the daytime (i.e., during solar radiation), the TMRT values are much lower in S1 than in S2 and S3 due to the different street orientations. The addition of trees helps protect the street canyon at the pedestrian level from such high levels of radiation. Accordingly,

**Fig. 15** Correlation between  $\Delta$ PET and  $\Delta$ TMRT



**Table 6** Water demand increase/decrease in relation to the base case scenario

Scenario	Tree coverage %	Number of trees	Water demand increase (+)/decrease (-)	Water demand decreased based on irrigation and planting technologies criteria – 65%
Base case	9	195	0	0
0%	0	0	– 9%	– 9%
20%	20	102	+ 11%	+ 3.85%
35%	35	174	+ 26%	+ 9.1%
50%	50	256	+ 41%	+ 14.35%

and because the TMRT values in S2 and S3 are much higher, adding trees significantly reduces the TMRT, which leads to significant enhancements in the PET for both streets. In contrast, and because TMRT values are lower in S1 (given its northern orientation), the added trees are not able to further enhance the TMRT as the urban canyon is already protected from solar radiation and shaded by buildings; thus, the enhancements in the PET values are minor.

### 5.3 Correlation between PET and TMRT

It is clear that there is a strong relationship between TMRT reduction and PET enhancement within urban canyons and at the pedestrian level. To demonstrate this relationship, an SPSS statistical analysis is conducted to examine the correlation between the reduction in TMRT and the enhancement in PET. The correlation study is applied to the results of the 50% tree coverage scenario in R3. Before calculating the correlation between both mentioned variables, the Kolmogorov–Smirnov (K–S) test is applied to all input data to check if the data are normally distributed. This (K–S) is because the test results guide the selection of the method for calculating the correlation. After applying Spearman correlation, since the data were not normally distributed in the K–S test, and as shown in Fig. 15, the results of this correlation study reveal a strong positive correlation, and the degree of association (correlation coefficient) is  $r = 0.898$ , indicating a strong relationship between  $\Delta$ TMRT and  $\Delta$ PET. When testing the regression, the  $R^2$  value is 0.9879, and the significant F value is  $< 0.001$ , indicating that the results of the study are reliable and statistically significant, and the co-efficiency value is  $Y = 0.488x - 0.0208$ . This statistically demonstrates the strong relationship between  $\Delta$ TMRT and  $\Delta$ PET and proves the direct relationship between shading and PET enhancement. It is also a clear indication to focus on increasing overall shading (through various elements, including buildings, trees, and shading structures) to further enhance the PET.

### 5.4 Comparison of water demand

As shown in Table 3, different scenarios require different numbers of trees and tree coverage percentages. Although the 20% and 35% tree coverage scenarios require a smaller number of trees in comparison to the existing trees in the base case, both scenarios require larger amounts of water for irrigation, as they have high coverage percentages, as calculated in Eq. 1. The only advantage in these scenarios is that the required amount of maintenance is less given the fewer number of trees. Table 6 illustrates the percentages of irrigation required for each scenario in comparison to the base case scenario. The green-highlighted column in Table 6 shows the increased or decreased percentage of water demand for each scenario compared to the base case (the current situation). This percentage is calculated based on the increase



**Table 7** UTS recommendation for each step. Tree species, coverage percentages, and the calculated water demand for each street in comparison to the base case

Street	(Step 1) recommendations Proposed Trees species	(Step 3) recommendations		(Step 2) recommendations	
		Recommended tree coverage percentage (%)	Number of trees	Increase (+)/decrease (-) in water demand (%)	65% Water demand decreasing (%)
S1	- <i>Vachellia nilotica</i> or similar from Category (A)	0	0 added (33 small trees removed)	- 7.3	- 7.3
S2	- <i>Azadirachta indica</i> or similar from Category (B)	35	60 added (90 small trees removed)	+ 26.73	+ 9.36
S3	- <i>Cassia javanica</i> or similar from Category (C)	50	86 added (72 small trees removed)	+ 38.75	+ 13.56
Total			146 added (195 small trees removed)	+ 58.18	+ 15.62

and decrease in the canopy percentage, which is the primary factor controlling the water demand. The recommended urban tree model should consider using the lowest percentage of tree coverage possible to avoid an increase in water demand without compromising enhancements in thermal comfort. In addition, the irrigation and planting technologies recommended in Step (2) should be applied to reduce the water demand.

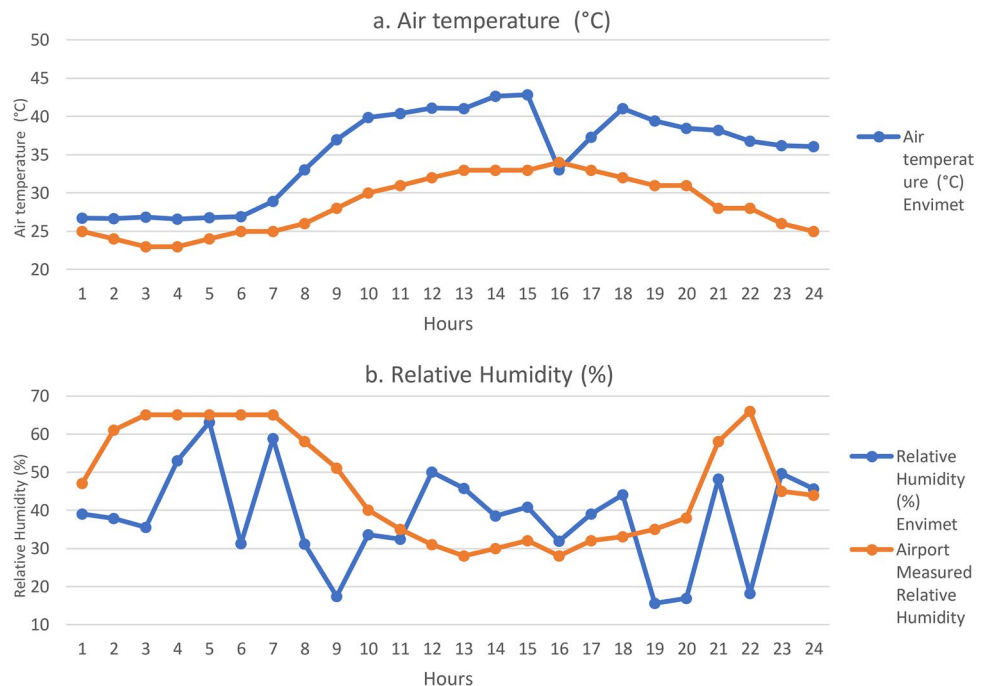
## 6 Discussion

The results of this study indicate that the application of trees has a positive impact on various types of street canyons in the study area. Enhancements from the addition of trees are greater when the street orientation, aspect ratio of the street, and season change. The results also show that it is not just about adding trees to the urban canyon; tree species and their properties should also be carefully considered, as such factors can lead to significant variations in performance.

The application of trees to S1 (northern/southern orientation and an aspect ratio of 1:1.2) shows slight improvements in the microclimate conditions during the summer and winter. Although the addition of trees to S2 and S3 (east/west orientation, aspect ratios of 1:1 and 1:1.25) leads to significant enhancements in microclimate conditions, such enhancements only occur during the summertime. During the wintertime, the application of different tree coverage percentages exhibits no impact, and the maximum enhancement in their microclimate conditions then only equates to 9% of their mean enhancement values during the summertime. The type of tree that is applied, whether evergreen or deciduous, would not change the impact during winter. The enhancements that occur during the summer in S1 are very minor, and increasing the tree coverage percentage of this street would not lead to any significant enhancements. It would also result in the loss of various resources (water, trees, and maintenance). In addition, it significantly reduces the wind speed and slightly increases the relative humidity due to evapotranspiration. For S2 and S3, using trees and increasing tree percentages significantly enhances the microclimate conditions. During some hours, they not only help to enhance the PET values but also change the thermal comfort zone. During winter for S2 and S3, the results show no enhancements across all scenarios, which is in line with recommendations from reference [43] regarding the use of trees during winter.

The overall results of this study align with the results of other studies. The maximum PET reduction of 6.5°C is quite similar to the PET reduction values between 1 and 6°C for case studies conducted in Ho Chi Minh and Spain [26, 29]. The slight enhancements in air temperature are also similar to case studies conducted in Dubai, Tehran, and Phoenix [27, 28, 31]. Additionally, the overall results and improvements in the PET values are similar to those of the two prior case studies conducted in downtown Cairo (although this study presents more promising microclimate enhancements during some hours) [66, 67]. The minor differences between the enhancement values of the different case studies are due to the different street orientations

**Fig. 16** Result validation (using full forcing)



and aspect ratios within each study. Moreover, the results demonstrate the strong relationship between shading and microclimate enhancement, as shown by the strong correlation between TMRT reduction values and PET enhancement values.

## 7 Conclusion

According to the results of all scenarios, the recommended tree coverage percentage to be applied should not be the same for all streets; it should vary. Additionally, the tree model should be independently designed for each street such that matches its geometry, orientation, and other conditions, which aligns with findings of previous studies [66, 67, 69]. The recommended tree model should consider tree seasonality and tree variety for biodiversity, as well as contribute to a visually appealing image for the city. Nothing, however, would be required to enhance the microclimate condition, as all winter results show that applying different tree coverage percentages to different street canyons would not have a significant impact on thermal comfort. For water demand, it is recommended that the use of trees be reduced. The ideal way to reduce water demand is to minimize the use of trees without compromising enhancements in the microclimate conditions, in addition to applying irrigation technologies.

### 7.1 Recommended tree percentages and tree species for each street

The recommended tree coverage percentages for all three streets that enhance microclimate conditions while also considering water demand are 0% for S1, 35% for S2, and 50% for S3. As trees did not provide any significant enhancement in S1, the enhancement by the 35% tree coverage was very similar to the enhancement by the 50% tree coverage in S2. In S3, the enhancement by the 50% tree coverage was higher than the enhancement by the 35% tree coverage, which is due to the wider aspect ratio in S3. The recommended ratio of deciduous trees relies on the suggested motivation of the design itself and not on the requirements of thermal comfort and UHI. Based on the abovementioned tree coverage percentages, Table 6 demonstrates the total number of trees and the total tree coverage percentages recommended for each street. The table also states the selected seasonal tree species ratio for each street and calculates water demand, comparing it to the current condition of the case study.

According to the recommended model, and as shown in Table 7, although the total number of trees is lower than the existing number of trees (146 large trees are added instead of the 195 small existing trees that are removed), the total water demand increases by 58.18% in comparison to the current situation. This is because water demand depends on the crown size of the trees and not their numbers, as shown in Eq. 1. Based on the recommendations of the efficient UTS, irrigation methods and technologies should help absorb this increase in water demand. Applying such methods and technologies to the current situation should reduce at least 65% of the total water consumption [61]. Their application would also help reduce water demand for irrigation, reducing the increase in water demand from +65.48% in both S2 and S3 to +22.92%, in addition to saving 7.3% in S1, while increasing the tree coverage percentage and reaching significant PET enhancements with very limited water demand increase.

Although the results of this study can be applied and generalized to the city of Cairo, the recommended tree coverage percentage cannot be generalized, as different urban canyons, with varied aspect ratios and/or orientations, lead to completely different results. The methodology used to determine the tree percentages in this research can be generalized and applied in the same way (with the same inputs, scenarios, and analyses) in any location in Cairo. A limitation of this study is that it was only applied to one existing area in downtown Cairo, which was adequate to measure the efficiency of the study; however, application in diverse situations would provide more comprehensive results and a stronger assessment of the strategy's effectiveness. Additionally, the lack of current information regarding the required level of irrigation for trees prevented a full comparison and assessment of irrigation consumption, as the trees were irrigated manually. In addition, the field survey was somewhat challenging due to security restrictions.

Urban shading is a critical factor that should be prioritized, as it consistently influences the effects of urban trees and impacts the application of the strategy. Therefore, the UTS should be carefully considered in relation to urban shading when implementing the strategy in various locations throughout the city.

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**Data availability** The data that support the findings of this study (all ENVI-met files) are available upon request.

## Declarations

**Competing interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix 1

Validating the results of the model using the full forcing ENVI-met method, the resulting values in R4 (using the full forcing method) do not match the measured values. As shown in Fig. 16, air temperature was always higher with ENVI-met in comparison to the measured air temperature. The difference in temperatures was obvious and significant, reaching 8 °C in 5 h and more than 10 °C in 10 h. The results for air temperatures with ENVI-met were, therefore, completely different than the air temperatures that were measured in reality. Regarding the relative humidity figures, the simulation results demonstrate completely different figures than the measured results, showing a difference of – 40% in five hours less than the measured results. During some hours, the difference was approximately + 10% in 3 h. This means that the results of relative humidity do not represent the relative humidity of the study area. The differences in these two sets of figures show that the simulation results are not only valid but also that the irregularity of the results itself indicates the same. By conducting a results analysis on the air temperature charts, one finds that a great decrease in air temperature occurs from 43 °C at 15:00 to 33 °C at 16:00, which then increases again to 41 °C at 18:00. These significant increases and decreases are inexplicable and do not reflect real-world conditions. Upon analyzing the relative humidity charts, it becomes evident that the figures lack any discernible pattern, fluctuating consistently every hour. For example, at 5:00am, it is 60%, which decreases to 30% at 6:00am, and then increases to 55% at 7:00 am. This does not reflect real-world conditions. These results are, therefore, not valid and do not represent the real-world meteorological conditions of the study area. A step back should, thus, be taken to revise the simulation setup, with which new validation results can be achieved.

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