








Article

Outdoor Thermal Comfort Optimization through Vegetation Parameterization: Species and Tree Layout

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Citation: Sayad, B.; Alkama, D.; Rebhi, R.; Menni, Y.; Ahmad, H.; Inc, M.; Sharifpur, M.; Lorenzini, G.; Azab, E.; Elnaggar, A.Y. Outdoor Thermal Comfort Optimization through Vegetation Parameterization: Species and Tree Layout. *Sustainability* **2021**, *13*, 11791. <https://doi.org/10.3390/su132111791>

Academic Editors:
Amir Ebrahimi-Moghadam and
Mohammad Hossein Ahmadi

Received: 17 September 2021
Accepted: 14 October 2021
Published: 25 October 2021

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Abstract: The optimization of outdoor thermal comfort has become the keystone to guarantee the healthy and comfortable use of outdoor spaces. This study aims to optimize the outdoor thermal comfort through vegetation parameterization in a boulevard located in Guelma city, Algeria during summertime. However, two main parameters were investigated, species and tree layout, through a numerical simulation. We first collected microclimate data of a sunny summer day. Second, we used real microclimate data in different simulations using the Envi-met atmospheric model. The findings reveal that *Ficus Nitida* is the most significant species to intercept solar radiation and provide shade over the day in Souidani Boudjemaa Boulevard, with a maximum reduction of $T_a = 0.3$ °C and UTCI = 2.6 °C at 13:00 p.m. Tree layout is a determining parameter in the creation of shaded paths, based on the quality of the shadows cast by the trees, namely, their size. Thereby, planting the washingtonia palm trees along the center of the boulevard is the best option to maximize the shaded area within the boulevard, with maximum reduction of $T_a = 1.8$ °C and UTCI = 3.5 °C at 16:00 p.m.

Keywords: outdoor thermal comfort; vegetation parameterization; tree species; tree layout; summertime; optimization; numerical simulation

1. Introduction

Today, over 55% of the world's population lives in urban areas, a percentage that is expected to increase to 68% by 2050 [1]. In addition to this problematic, current cities are

facing the issue of climate change, such as the Urban Heat Island (UHI) phenomenon [2]. In case of being out of control, extremely hot and overstretched cities with high community residents are going to be born. Outdoor spaces' quality through various functions, such as thermal, hygienic, functionality, aesthetic, and safety functions, is the primary factor influencing the community residents' life quality [3,4]. More attention has recently been paid to outdoor thermal comfort in order to combat the UHI problem and create comfortable outdoor areas [5–7]. Thermal conditions outdoors are likely to experience enormous upheavals in built up areas due to the effect of human-induced climate change, including the increased temperatures and the heat waves in summertime [8–10]. As a result of these facts, a variety of sciences have been gathered in order to enhance the urban microclimate and maximize thermal comfort in outdoor places [11–13]. Hence, a variety of mitigation and adaptation strategies have been created, such as urban vegetation, urban geometry, and high albedo materials [14–16]. Moreover, much interest is associated to nature-based solutions to optimize the thermal comfort levels in urban outdoor spaces [17–19]. The role of vegetation is much more attributable in improving the thermal comfort in outdoor spaces, both as a strategy for adapting to the thermal environment at the pedestrian level and as a strategy for mitigating climate change effects [20–22]. Trees, on the other hand, are the most effective features in terms of microclimatic control and enhancing thermal comfort levels during the hot summer months due to their impact [23,24]. Previous studies have shown that the ratio (number of trees) and the tree layout are two parameters influencing the shading effect outdoors [25,26]. The relationship between the vegetation cover of outdoor spaces and thermal comfort levels finds a very precise modeling in atmospheric simulation models [27,28]. These models have the benefit of being able to replicate smaller spatial scales, as well as recreating the transmission processes of microclimatic factors and their impacts on pedestrians using thermal and climatic indices such as the UTCI, PET (Physiological Equivalent Temperature), SET (Standard Effective Temperature), and PMV (Predicted Mean Vote) indices [29,30]. Other studies have modeled the energy consumption of high-rise office buildings in hot, arid, and cold climate conditions in many buildings [31–35].

Our study aims to optimize the outdoor thermal comfort through vegetation parameterization in a boulevard located in Guelma city, Algeria during summertime. However, two main parameters were investigated, species and tree layout, through a numerical simulation. Microclimatic changes are studied using the output data from the several simulations: air temperature (T_a), relative humidity (RH), mean radiant temperature (T_{mrt}), and wind velocity (V_a). In each situation, the UTCI thermal index (Universal Thermal Climate Index) is utilized to determine the level of climatic comfort.

2. Case Study

This research was conducted in Guelma, a city located 65 km from the Mediterranean Sea in northeastern Algeria (36°27'43 N; 7°25'33 E; 840 ft. elevation), as represented in Figure 1a,b. Its climate is classified as semi-arid, according to Belda et al. [36]. Guelma has a longer and hotter summer than the rest of the country, with frequent heat waves. The warmest days of the year are generally between July and mid-August.

Souidani Boudjemaa Boulevard, in the city's downtown, is the study area. It is a 485-m-long linear outdoor space with two mechanical lanes, two pedestrian pathways on its edges, and a center reservation with Ficus trees on both sides. The southwest aisle is entirely devoid of vegetation, unlike the northeast aisle, which is armed with dense old Ficus trees, Figure 1c.

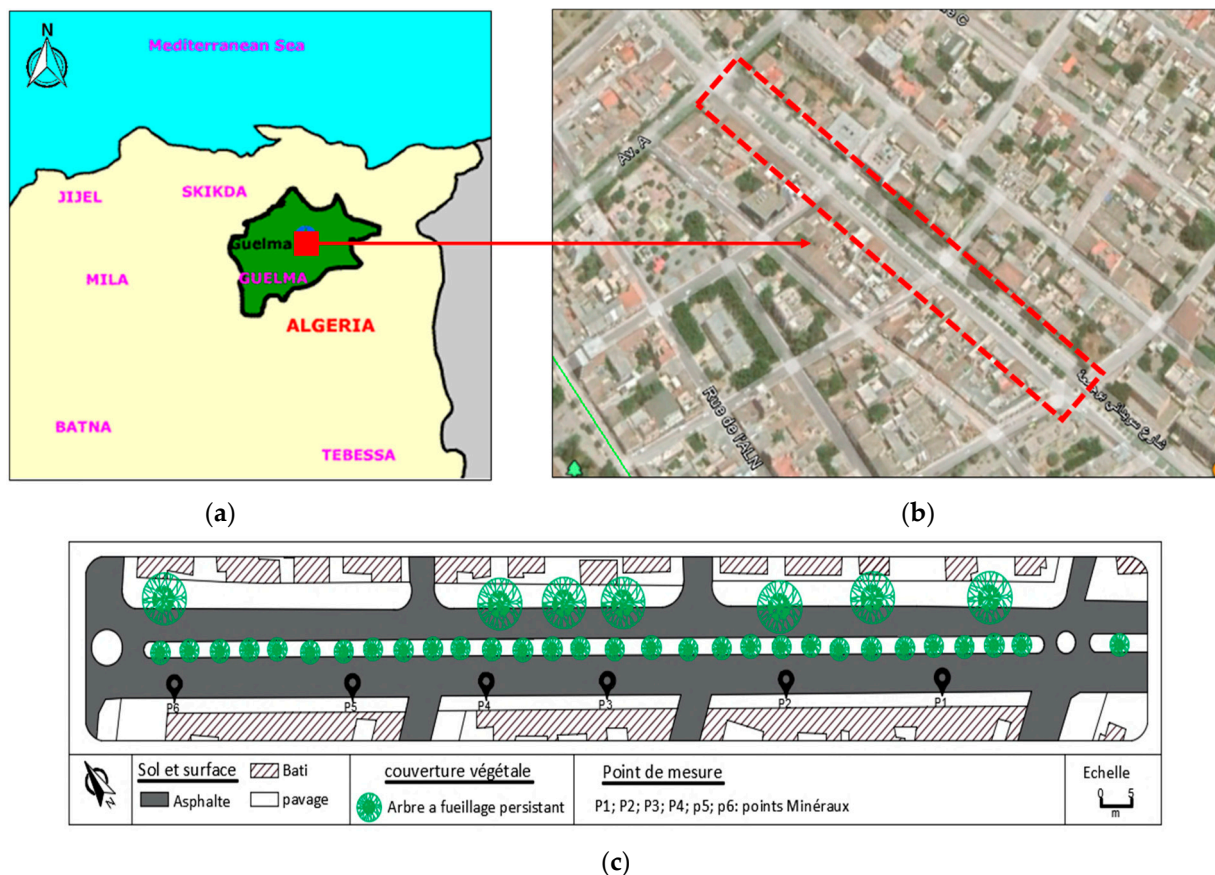


Figure 1. (a) Location of Guelma city; (b) Aerial view of Souidani Boudjemaa Boulevard; (c) Plan view of Souidani Boudjemaa Boulevard showing the measuring points.

3. Methods and Materials

The goal of this study is to improve outdoor thermal comfort in a boulevard in Guelma, Algeria during the summer by using vegetation parameterization. However, a numerical simulation is used to assess two major parameters: species and tree layout. First, microclimate data on a sunny summer day are collected. Second, real microclimate data are used in various simulations using the Envi-met atmospheric model.

3.1. On-Site Measurements

The measurement campaign was carried out within six measuring points devoted of vegetation within Souidani Boudjemaa Boulevard over three successive days, ranging from 20 July until 22 July 2019. As a result, a daily log consisting of six sessions from 9:00 a.m. to 9:00 p.m. of the three parameters, air temperature, relative humidity, and wind Velocity, was obtained.

The measurements were performed using two hand-held instruments, Figure 2. The first (Testo 480-AG 501 1ST, 0563 4800) is a multifunction instrument equipped with intelligent digital probes, independently calibrated. The instrument was used as a thermo-hygrometer and as an anemometer in the following order:

- Measurement of air temperature and relative humidity carried out using a \varnothing 12 mm probe, with a high resolution of 0.01 and an accuracy of $\pm 0.03\%$ RH and ± 0.2 °C (+15 to +30 °C);
- Wind velocity measurement carried out using a \varnothing 16 mm fan-assisted measuring probe (max. 960 mm scale) with an accuracy of ± 0.2 m/s.



Figure 2. Measurement instruments: (a) Testo 480-AG 501 1ST, 0563 4800; (b) HENNA HI 9564.

The second instrument (HENNA HI + 9564) is a thermo-hygrometer, with a resolution of 0.1 °C and 0.1% RH and an optimal precision of ± 0.5 °C and $\pm 3\%$ RH, and its role is to support the measurements temperature and humidity readings by Testo 480.

3.2. Atmospheric Simulation

3.2.1. The Simulation's Boundary Conditions

An atmospheric simulation using the Envi-Met program is described in this study. This program requires input data, such as ratio, species, and tree layout, related to the Souidani Boudjemaa Boulevard's formal and vegetal composition. The Envi-met model's detailed framework and initial parameters are included in Table 1.

Table 1. Detailed framework and initial parameters of the Envi-met model (Envi-met V4.4.4).

Simulation's settings	City	Guelma (36°27'43 N; 7°25'33 E; 840 ft)
	Climate	Semi-arid
	Simulation Date	22 July 2019
	Simulation Time	From 09:00 to 21:00
Configuration's model	UTCI index Calculation	Biomet process
	Results visualization	Leonardo plug-in
	Building	Concrete walls with roof tile
	Soil and surface	[PL] Concrete light [ST] Asphalt road
	Vegetation cover	[BS] Very dense tree, 12 m, Albedo 0.2 [T1] Dense tree, 8 m, Albedo 0.2

The microclimatic parameters resulting from the different simulations, i.e., air temperature (T_a), relative humidity (RH), mean radiant temperature (T_{mrt}), and wind velocity (WV), were used to study microclimatic variations, while the UTCI thermal index was used to measure the level of climatic comfort in each scenario, Figure 3.

3.2.2. Generic Scenarios

The 1st scenario simulates the present outdoor environment, including vegetation cover, in order to assess current thermal comfort level under summer heat stress, Figure 3a;

The 2nd scenario aimed to identify the impact of vegetation cover on outdoor thermal comfort, after which the simulation is run with the vegetation cover removed, Figure 3b;

The 3rd scenario is a simulation of the recent tree layout of Ficus Nitida species, Figure 3c;

The 4th scenario simulates a new tree layout using the existing *Ficus Benjamina* tree species while maintaining the same tree ratio, Figure 3d;

The last scenario (5th situation) simulates a new tree layout for the boulevard, consisting of different kinds of *Ficus Nitida* and *Washingtonia* palm trees, Figure 3e.



Figure 3. Simulated scenarios of Boulevard Souidani Boudjemaa: (a) the current state; (b) the boulevard stripped of vegetation; (c) new tree species; (d) new tree layout; and (e) new tree layout with a new tree species [Envi-met V4.4.4].

4. Findings and Analysis

4.1. Atmospheric Model Validation

In order to validate the Envi-Met model, the simulated values for the air temperature, relative humidity, and wind velocity were correlated with the values recorded in Souidani Boudjemaa Boulevard on 22 July 2019. Hence, the R^2 is the reconciliation coefficient, indicating the degree of correlation. The results are presented in the graphs below, Figure 4a–c.

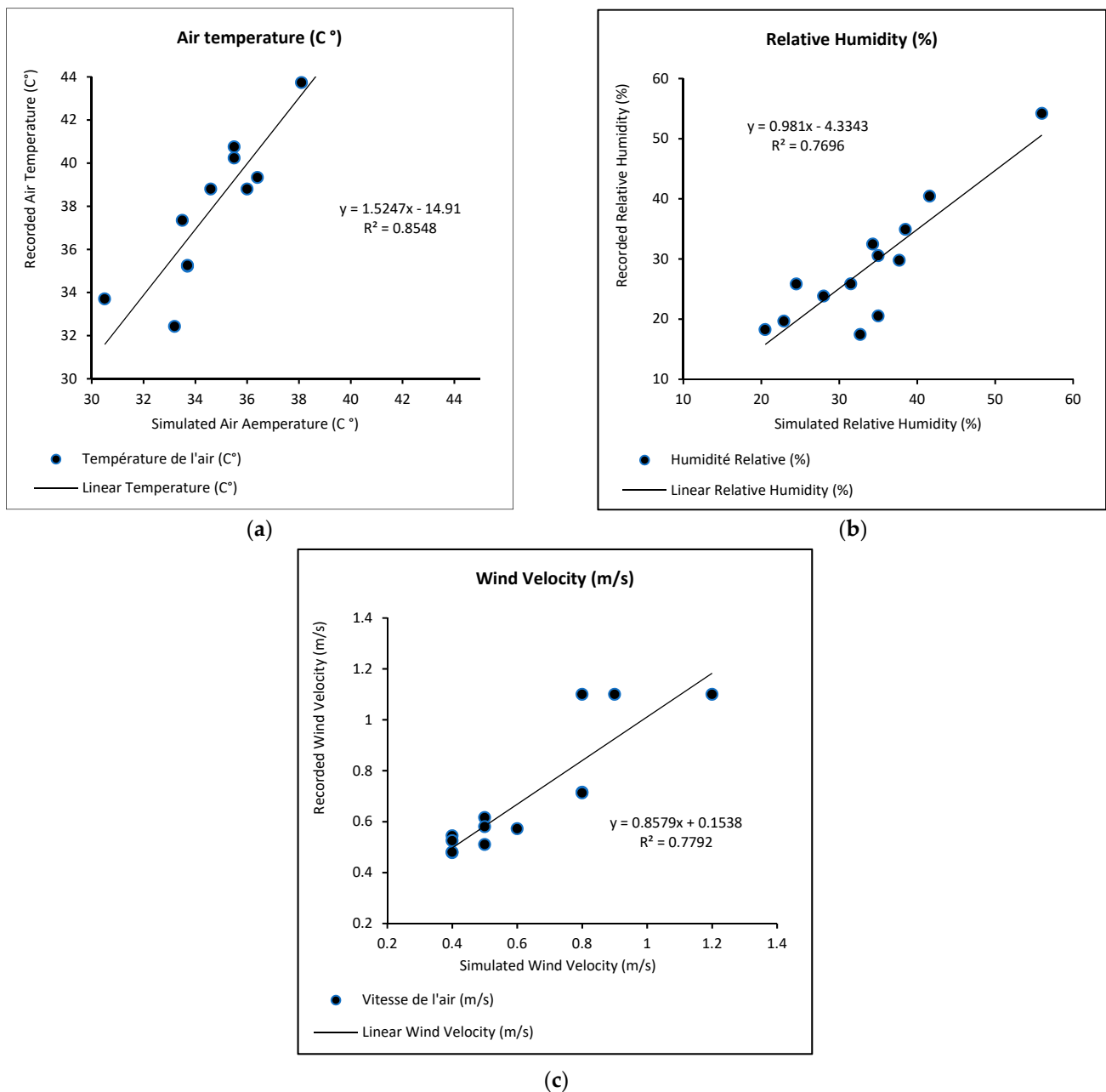


Figure 4. Validation of the Envi-Met simulation model, correlation of simulated and recorded values of: (a) air temperature; (b) relative humidity; and (c) wind velocity of Souidani Boudjemaa Boulevard.

We checked the correlation of the three parameters in two locations within the boulevard from 09:00 a.m. to 21:00 p.m. The reconciliation coefficients of the air temperature, relative humidity, and wind velocity are $R^2 = 0.85$, $R^2 = 0.76$, and $R^2 = 0.77$, respectively. All three indicate that the simulated values are strongly in agreement with the values recorded in downtown Guelma throughout the day of investigation, with a strong correlation of air temperatures.

In general, the model is capable of accurately reproducing the study context's climatic data, allowing for the evaluation of possibilities for enhancing thermal conditions by manipulating the formal and vegetal composition of Souidani Boudjemaa Boulevard. As a result, Envi-atmospheric Met's simulation model is suitable for achieving the study's aims.

4.2. Outdoor Thermal Comfort Optimization

As aforementioned, the study involves the simulation of five different scenarios of Souidani Boudjemaa Boulevard, and the results are shown in the following graphs, Figure 5a–c. For all of the simulated scenarios, the general trend of air temperatures is ascending from 9:00 a.m. to 2:00 p.m. (peak time) and falling for post-peak hours. The relative humidity trend is in reverse order, where the peak time is set at 12:00 p.m. The overall trend of T_{mrt} is similar to that of the UTCI index, which means that the thermal comfort outdoors is initially influenced by the received amount of solar radiation. In addition to wind velocity, evening hours from 8:00 p.m. reveal a certain stability for all of the parameters studied, including the UTCI index.

Scenario (2) revealed that removing the vegetation cover has a detrimental impact on microclimatic conditions. T_{mrt} rose by 2.6 °C, with a maximum rise of 21 °C at 17:00 a.m. The air temperature enhanced by 0.8 °C, with a maximum increase of 1.1 °C at 3:00 p.m. At 12:00 p.m., the relative humidity had dropped to 17.2%. In this situation, the greatest wind velocities were achieved. This indicates that the existing species and tree layout have altered the thermal conditions within the boulevard significantly.

Scenario (3) almost underwent a variation in air temperatures and relative humidity similar to that of Scenario (1), with a slight difference in wind velocities. The low T_{mrt} values suggest that the tree species was able to block shortwave radiation while allowing longwave radiation to pass through its canopy, resulting in a reduction in heat stress and an increase in outdoor thermal comfort.

Changing the tree layout in Scenario (4) involves cast shadows positioned end to end, which maximizes the shaded area, especially during the afternoon period when the sun moves from south to west. This justifies the tangible reduction in the daily values of air temperatures (−0.4 °C at 1:00 p.m. and −0.8 °C at 6:00 p.m.). Such a reduction with the increase in wind velocities is capable of providing a better level of climatic comfort compared to that provided in scenario (1) (the current boulevard), particularly in hot hours ($\Delta UTCI = 1.8$ °C at 3:00 p.m.).

Scenario (5) implies a significant reduction in air temperatures ($\Delta T_{avg} = -1.2$ °C with $\Delta T_{max} = 1.8$ °C at 4:00 p.m.), with relatively low values of T_{mrt} . This is mainly due to the ability of palm trees to block solar radiation and maximize the shaded area, as well as its long trunk facilitating the good circulation of air within the boulevard.

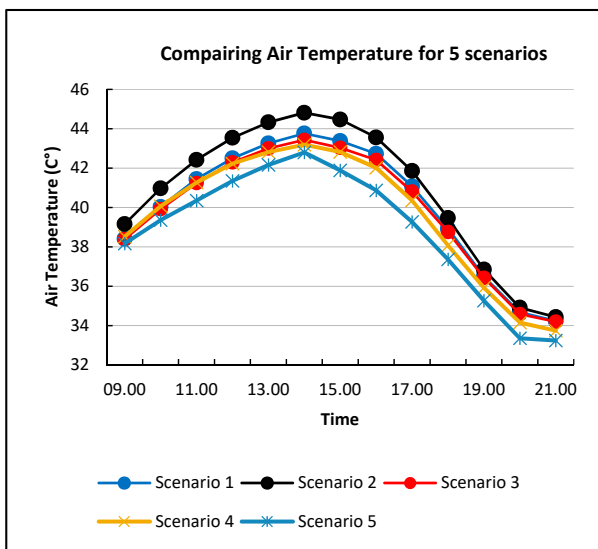
4.3. Effect of Tree Species on Outdoor Thermal Comfort

4.3.1. Ficus Trees

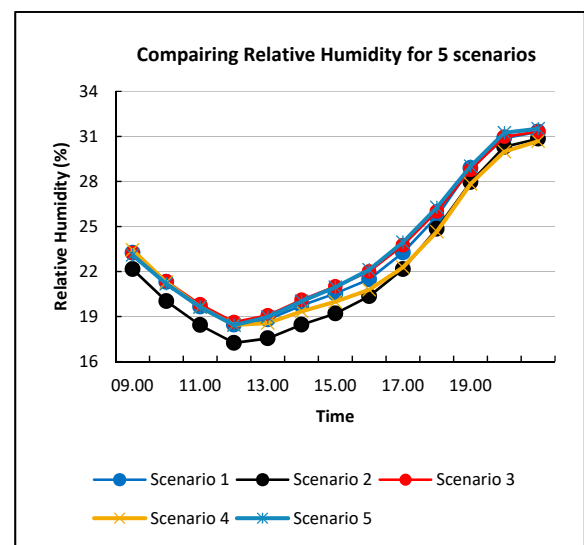
The species *Ficus Nitida*, inherited from the colonial era, has shown a strong ability to offer optimal climatic comfort levels in downtown Guelma, hence the dense and rounded canopy of mature *Ficus* trees constitute strategy of adaptation to the urban thermal environment by shading effect [16].

The *Ficus Benjamina* shares the same qualities of the *Ficus Nitida* with an average size and a smaller shade radius. The *Benjamina* species is established throughout the center of Souidani Boudjemaa Boulevard, characterized by a dense and rounded right canopy, still growing.

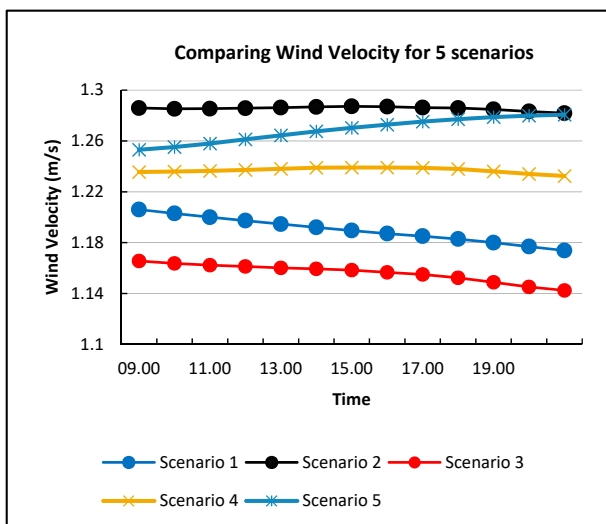
A drop in T_{mrt} was seen when *Ficus Benjamina* tree species were replaced with *Ficus Nitida* trees, along with a small rise in the relative humidity. Both species provide shaded areas throughout the day, however, the difference in radiation at 2:00 p.m. shows that the *retusa* species is the most important in regulating heat exchange during hours of high heat, particularly heat exchange through radiation (Table 2). As a result, the dense and persistent leaf mass of the *Nitida* species successfully blocked shortwave radiation, leaving longwave radiation underneath its rounded and wide canopy over a shadow radius of more than 4 m.



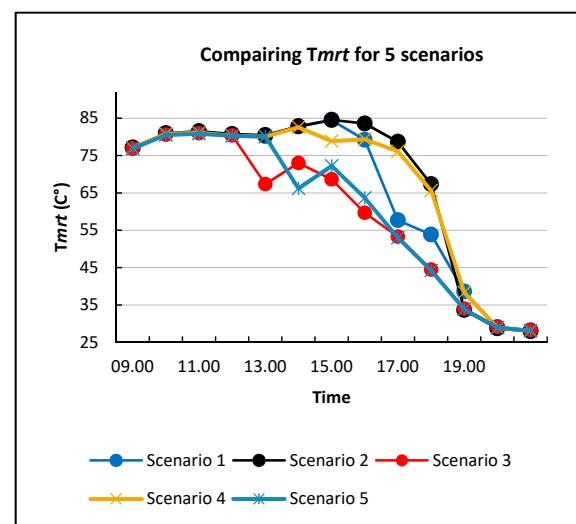
(a)



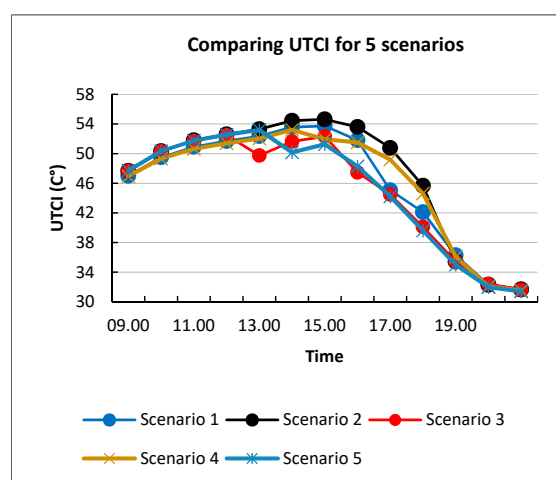
(b)



(c)




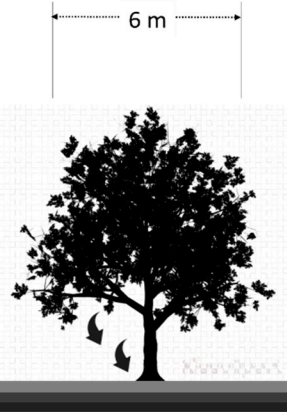
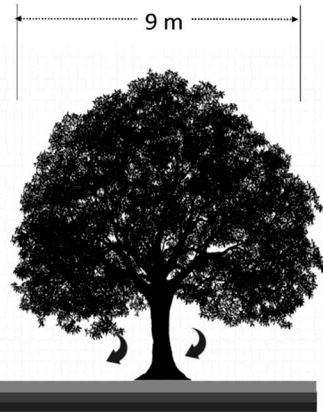
(d)



(e)

Figure 5. Comparing simulation results Souidani Boudjemaa Boulevard: (a) Air temperature; (b) Relative humidity; (c) Wind velocity; (d) Tmrt; (e) UTCI index. (Leonardo-Envi-Met 4).

Table 2. Heat exchanges by radiation of trees in Souidani Boudjemaa Boulevard at 2:00 pm.

Heat Exchanges by Radiation, Reflected and Diffuse, in W/m ²			
Shape and tree canopy			
	Species	Washingtonia palms	Ficus Benjamina
Reflected radiation	281.41	405.29	409.05
Diffuse radiation	77.06	74.51	71.6

Due to its heavy appearance and massive character, the Ficus generates generally low wind speeds, creating an obstacle effect in the urban environment. This effect depends on the mass of the leaves. Indeed, a negligible difference was generated by the species Benjamina compared to Nitida.

4.3.2. Palm Trees

The Washingtonia species is abundantly planted in downtown Guelma, despite the dangers it poses to residential neighborhoods. Various plant compositions have been used in previous research to explore the microclimatic control function of palm plants. Palm trees have the same regulating function as other evergreen trees, however, they are not suited for semi-arid settings, according to the findings [37].

With regard to Souidani Boujemaa Boulevard, the Washingtonia Palms was introduced with its imposing vertical accent as a feature of the landscape throughout the center, with a ratio of 17 palms. Therefore, a significant reduction in air temperatures with relatively low values of T_{mrt} was obtained. This is mainly due to the ability of palm trees to block solar radiation and control solar radiation exchanges.

In short, Washington Palm species affect microclimatic conditions by shading during heat stress and may improve microclimatic conditions by lowering outdoor temperatures. Hence, the diffuse radiation can reach 77.06 W/m².

4.3.3. Effect of Tree Layout on Outdoor Thermal Comfort

Sun position and wind direction are the two factors which indirectly influence the thermal outdoor comfort. However, sun position throughout the day is decisive for the quality of the shadows cast from the trees, although the hydrodynamic barrier effect of trees in outdoor spaces depends on the blow and direction of the prevailing winds.

4.4. Effect of Tree Layout on Outdoor Thermal Comfort

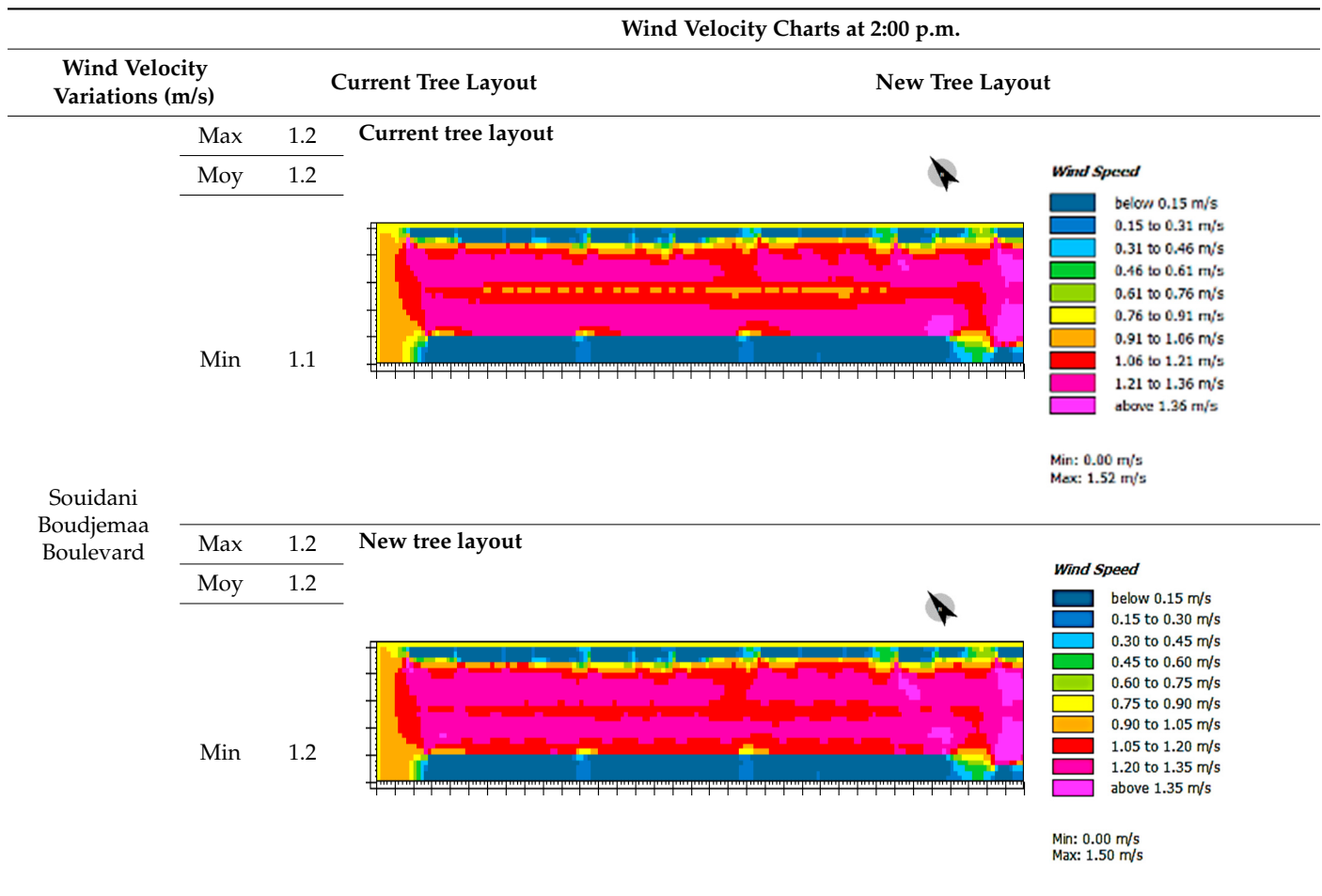
4.4.1. Hydrodynamic Obstruction Effect

Feeling the air flow is important to appreciate the quality of freshness in green outdoor spaces. Considering all the reasons that obstruct the air flow in outdoor spaces, including the massive shape of the trees, the feeling of the draft in summer becomes almost impossible.

Based on this observation, much research has been carried out to make the sensation of air movement possible in urban areas during the summer while studying the physical characteristics of all kinds of obstacles, such as the position, morphology, and size of trees [38,39]. On our part, we have investigated the influence of the tree layout on air flow, which originates from the northwest in Souidani Boujema Boulevard.

The tree layout along Souidani Boudjema Boulevard constitutes a screen against the prevailing wind coming from the northwest, which serves as a windbreak in winter, Table 3.

Table 3. Wind velocity variation according to the tree layout in Souidani Boudjema Boulevard.



In addition, the effects of these shelterbelts on airflow in summer will increase as trees mature. Moving a third of the alignment trees to the southeast side of the boulevard generates both high air speeds along the center and slower speeds at the right aisle of the boulevard. It should be noted that the obstruction effect of trees planted first compared to the buildings of equal or larger size is negligible.

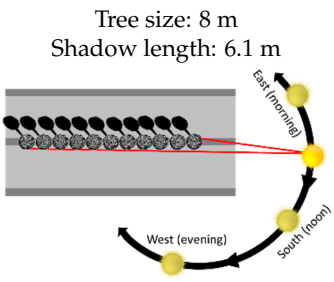
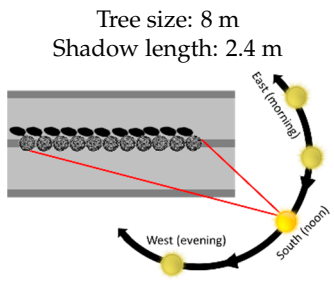
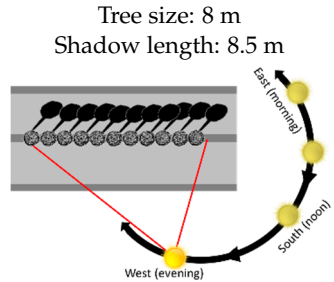
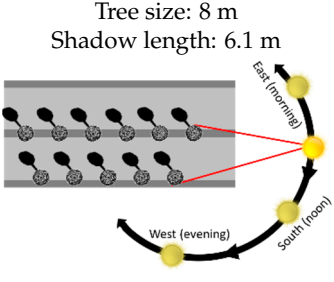
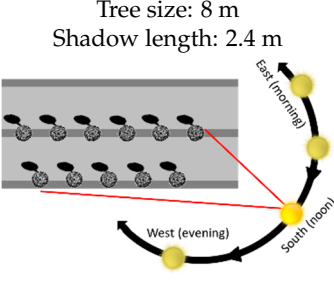
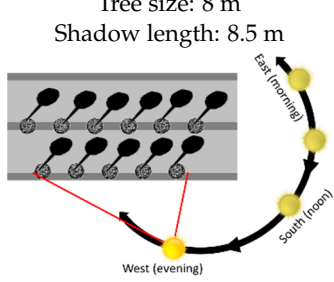
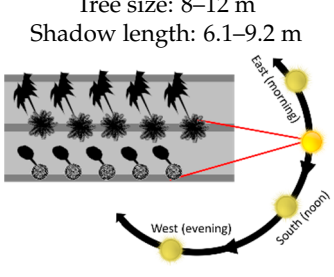
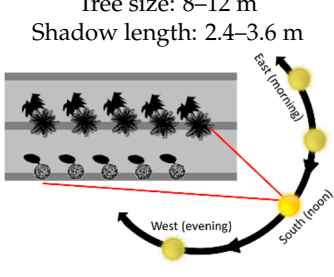
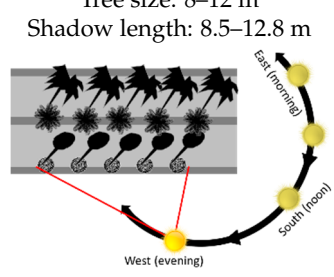
4.4.2. Shading Effect

Previous studies have demonstrated that the quality of the shadows cast by trees is decisive for the thermal comfort of users at the pedestrian level in summer. As the sun's position varies throughout the day, tree arrangements useful in the morning hours may no longer be the evening hours and vice versa.

The effect of the tree layout on outdoor thermal comfort in summer was apprehended by testing the current tree layout and another one with two types of trees at different sizes in Souidani Boudjema Boulevard.

The alignment of trees located along the center of Souidani Boudjemaa Boulevard are on average 8 to 9 m in size and create shadows in the morning from 4 to 9.4 m and from 2.4 to 3.6 between 12:00 p.m. and 14:00 p.m. Shadows from 5.6 to 23.1 m in the afternoon are all projected onto the left lane of the boulevard. The right aisle of the boulevard is entirely devoid of trees, which directly exposes the straight lane to the blazing hot sun from 10:00 a.m. to 2:00 p.m. The new tree layout implies the relocation of a third of the alignment's trees to the southwest side of the boulevard, which involves drop shadows positioned end to end. This helps to create shady paths along the boulevard, especially during the afternoon period when the sun moves from south to west, the length of the shadows depending on the size of the trees (Table 4).

Table 4. Quality of the shadow cast depending on the tree layout in Souidani Boudjemaa Boulevard.

	Time: 10:00 a.m. Sun Rise: 52.27°	Time: 01:00 p.m. Sun Rise: 73.14°	Time: 04:00 p.m. Sun Rise: 43.01°
Current tree layout	Tree size: 8 m Shadow length: 6.1 m 	Tree size: 8 m Shadow length: 2.4 m 	Tree size: 8 m Shadow length: 8.5 m 
New tree layout I	Tree size: 8 m Shadow length: 6.1 m 	Tree size: 8 m Shadow length: 2.4 m 	Tree size: 8 m Shadow length: 8.5 m 
New tree layout II	Tree size: 8–12 m Shadow length: 6.1–9.2 m 	Tree size: 8–12 m Shadow length: 2.4–3.6 m 	Tree size: 8–12 m Shadow length: 8.5–12.8 m 

4.5. Limitations

In the present study, the outdoor of thermal comfort optimization was reached through two plant parameters and three microclimatic parameters to simulate different configurations of natural elements at Souidani Boudjemaa Boulevard, while others could lead to precise results in providing the required comfort in hot summer situations. At this stage, it would be useful to look for optimal comfort levels by calculating the sky view factor, which relates the vegetation to the amount of received solar radiation.

5. Conclusions

This study investigates the outdoor thermal comfort optimization through the parameterization of urban trees in Guelma city, Algeria during the summertime. However, two main parameters were investigated, species and tree layout of Souidani Boudjemaa boulevard, through a numerical simulation. In general, the results indicate that urban trees can improve the thermal comfort levels in summer through shading effect, which is controlled by a set of parameters related to the physical characteristics of trees and their location outdoors. Trees can also cool the ambient environment by the evapotranspiration effect, which depends on the first level of tree foliage, its mass, and its texture. Indeed, the highest relative humidity has been recorded, largely in trees with smooth foliage. The tree species is the first parameter influencing shade quality. Due to its rounded canopy and dense leaf mass, *Ficus Nitida* is the most significant species to intercept solar radiation and provide shade over the day in Souidani Boudjemaa Boulevard. The tree layout is a determining parameter in the creation of shaded paths, based on the quality of the shadows cast by the trees, namely, their size. Thereby, planting the *Washingtonia* palm trees along the center of the boulevard is the best option to maximize the shaded area within the boulevard. The tree layout is also decisive for the air flow in the outdoor spaces, where it is advisable that the trees are not planted against the northwesterly blast of the wind.

Author Contributions: Conceptualization, B.S. and D.A.; methodology, R.R. and H.A.; software, B.S. and M.I.; validation, Y.M. and M.S.; formal analysis, G.L.; investigation, B.S. and R.R.; resources, D.A. and H.A.; data curation, M.I. and Y.M.; Funding, E.A. and A.Y.E.; writing—original draft preparation, M.S. and G.L.; writing—review and editing, E.A., A.Y.E. and Y.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by Taif University Researchers Supporting Project Number (TURSP-2020/32), Taif University, Taif, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data is available in manuscript.

Acknowledgments: We thank Taif University Researchers Supporting Project Number (TURSP-2020/32), Taif University, Taif, Saudi Arabia.

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

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