Assessment of green design strategies to achieve thermal comfort in outdoor spaces: A study in hot and dry climate

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Abstract. Outdoor spaces in cities contribute to improve urban quality. Improving outdoor thermal comfort is important to consider in achieving urban life and functionality. In order, green areas have shown to be effective at reducing the effects of several climatic elements associated with heat stress in urban settings while also giving people a great outdoor setting. The most basic problem is that most recent projects in Constantine cities did not take into account the usage of green design solutions, causing in human outdoor heat discomfort. This study aims to enable designers to ameliorate the conditions in outdoor spaces. The main objective of this paper is to discuss and assess the impact of geometry and shade trees on the external thermal comfort conditions due to the significant effects of thermal comfort on citizens, especially in hot and dry regions. The methodology is based on in-situ measurements and a questionnaire survey during the warm season. A simulation with Envi-met5 software to evaluate different scenarios for five climatic parameters and PMV (predicted mean vote index) are used. The results showed that the presence of trees is an important strategy to modify and regulate the thermal environment in this type of hot and dry climate.

1 Introduction

Outdoor spaces promote urban life quality in cities. The physical environment has an important effect on the use of outdoor spaces.

Thermal comfort has been demonstrated to be the fundamental component of a vital and functional outdoor environment. A good microclimate can improve pedestrian comfort, motivate walking, and contribute to sustainability. The utilization of these areas changes depending on the weather [1]. As a result, reducing pedestrian discomfort outside is one of the primary goals of improving urban space occupation [2]. One of the bases of sustainable urban planning is the investigation of thermal comfort at the level of outdoor areas. Many city features are defined by urban morphology, including its urban quality, density, and open space arrangement, as well as its vegetation, microclimate, and thermal comfort. All of these variables have the aspect of urban space, which is where users create themselves, and so it is an element of value.

The urban street canyon (UC), which is a simplified rectangular vertical profile of infinite length, has been adopted in urban climate research as the basic structural unit [3]. According to Bourbia and Awbi (2004), the geometry of the urban street plays a decisive role in its thermal behaviour [4]. On the other hand, Louafi and Abdou (2013) confirmed that vegetated urban space improves pedestrian's thermal comfort and use of outdoor areas in Mediterranean climate (Constantine) [5]. Some previous studies have pointed out the contribution of such outdoor spaces to the quality of life and wellbeing of their users [6-8]. In order, green areas have shown to be effective at reducing the effects of several climatic elements associated with heat stress in urban settings, while also giving people a great outdoor setting. The most basic problem is that most recent projects in Constantine cities did not take into account the usage of green design solutions, causing human outdoor heat discomfort.

"Green" solutions offer multiple and varied approaches, in this sense, passive technologies such as evaporative cooling, reflective materials, insulation and vegetation. It can be used to minimize the energy gain; recent research has shown that vegetation at the architectural building envelope scale helps control energy consumption, but what about at the urban scale?

Green design strategies enhance the quality of the urban space in the city and the life of its inhabitants. The green design strategies play a vital role with a wide range of benefits provided to humans in their urban spaces such as trees, grass and water features [9].

Base on the above studies, few studies explore thermal comfort using PMV based on in situ measurement and questionnaire surveys within the hot and dry climate. A predicted mean vote (PMV) index with six variables: air temperature, air velocity, relative humidity, mean radiant temperature, garment insulation, and metabolism rate can be used to obtain the thermal comfort requirement. The environmental variables are

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air temperature, wind speed, relative humidity, and radiation temperature. Therefore, the thermal conditions felt by everyone in the same environment can have different sensations. PMV index values range from -3 to +3, which describes the feeling of cold to hot (see Table 1) [10]

This study aims to enable designers to ameliorate the conditions in outdoor spaces; (1) Evaluate the PMV comfort ranges in the city of Ain Smara Constantine, Algeria, based on in situ measurement and questionnaire survey. (2) Analyse the influence of green design on thermal comfort range in outdoor spaces, and (4) compare different scenarios of green design (trees, grass, water), and impact of geometry of the street.

1.1 Design strategies

1.1.1 Vegetation (trees and grass)

Vegetation is a commonly employed green design strategy in various contexts. Integrating vegetation into the built environment offers numerous benefits, including environmental, social, and aesthetic advantages. The use of natural vegetation is one of the green design strategies that is frequently used. Using a landscape element, this research is able to accomplish its two goals (improving the microclimate and a person's outdoor thermal comfort). There are four major main ways to change the urban microclimate through vegetation, particularly by trees:

- modifying the solar radiation intensity
- modifying the reflected radiation from the ground and other surfaces,
- modifying the relative humidity,
- modifying the wind.

The primary influence of vegetation on thermal comfort is its shading effect: trees reduce thermal radiation through reflection and absorption, block most of the incoming shortwave radiation, and reduce longwave radiation by lowering surface temperatures. As a result, the shape, position, and density of leaves are critical tree characteristics [11]. Humidification via the evapotranspiration process, which is the sum of two evaporation processes and one transpiration process, is another principle that affects the microclimate. Previous research has shown that vegetation in arid areas can increase local relative humidity by 3-6% compared to unvegetated areas [12]. Trees are better than other plant components at regulating the urban microclimate and lowering temperatures [13, 14]; they provide thermal comfort by reducing solar radiation through their cooling capacity via evapotranspiration [15]. Trees also provide shade on surfaces, which helps to lower temperatures and improve ventilation [16]. Although different tree species have different transpiration rates, leaf area indices, and crown diameters, their cooling effects vary [17].

1.1.2 Water features

Water considerations are often seen as an important component in green design concepts. Their importance stems from their ability to enhance spatial perception within their location in the spatial organization, as well as their ability to improve the quality of a location and thus their psychological influence on users. Artificial lakes, fountains and water features in outdoor spaces have been used as a bioclimatic technique to improve the microclimate in hot, dry conditions [18, 19]. The presence of water induces evaporation, which causes an increase in latent heat, resulting in improved cooling during the day. These bodies of water can be said to be effective sources of cooling for the areas around them.

When planning and designing water features as part of green design strategies, it's important to consider factors such as water efficiency, maintenance requirements, and the use of eco-friendly materials to ensure their sustainability and minimize any negative environmental impacts.

1.2 Outdoor thermal comfort

The thermal comfort concept is defined as a condition of mind that expresses satisfaction with the thermal condition of the surrounding environment. Controlling the microclimate to provide thermal comfort in hot, arid places is difficult, especially during the summer.

Due to direct exposure to microclimatic variables, the outdoor environment is significantly less predictable and more complex. [20].

Thermal comfort, in general, is focused on balancing heat acceptance and loss from the human body and the environment in order to reduce energy consumption.

From the human body to the environment in order to maintain its core temperature at 37 degrees Celsius. Environmental equilibrium; conduction, convection, radiation, and evaporation all contribute to environmental balance. This situation occurs when an individual is neither too hot nor too cold.

Thermal indices are supplied to architects and urban designers to assist them in making better design decisions. These thermal indices may assess both cold and hot outdoor temperatures. Thermal comfort, which is related to microclimate, is a broad concept that is influenced by a variety of factors, such as air temperature, relative humidity, solar radiation, air speed and clothing insulation. Some indices that fully encompass these factors have been introduced to standardize and simplify the assessment of thermal comfort, such as PET; Tmrt; PMV; SET and UTCI. They include a variety of indices, but one of the most commonly and widely used is the Predicted Mean Vote (PMV) model, which is used in this study. The PMV model was originally developed by Fanger in 1967 for indoor spaces, and it is a seven-point thermal sensation scale that runs from cold to hot, with zero at the midpoint representing the neutral value of human thermal comfort [21]. Jendritzky and Nübler (1981) adjusted the PMV model to account for outdoor climates [22]. The PMV index predicts the mean response of a larger group of people according the ASHRAE thermal sense scale (Table 1.):

Table 1. ASHRAE 7-point thermal sensation scale

+3	*+2*	*+1*	*0*	*-1*	*-2*	*-3*
Hot	*War m*	*Slightl y warm*	*Neutra l*	*Slightly cool*	*Coo l*	*Col d*

2 Materials and Methods

The study included a literature review in addition to research methods: in-situ measurement of microclimate data, and questionnaire survey in warm season, questionnaires to assess the thermal sensation of people in different design of the street. In order to achieve the previously mentioned objective of this study, a simulation is carried out with the software ENVI-met version 5.1. To study and quantify the effect of the application of green strategies on the feeling of thermal comfort in outdoor spaces in a location characterized by a hot and dry climate, and to evaluate different scenarios for five climatic parameters Ta, Rh, Ws, MRT (mean radiant temperature) and PMV (predicted mean vote index) are used.

The objective was to explore the difference between the existing cases and the comparison scenario after the addition of vegetation and water features.

2.1 Study area

The study was conducted in Ain Smara Constantine (Algeria), a city located in the northeast of Algeria at 36.17 North, 7.23 East. The altitude is about 687 m above sea level. This city is characterized by a semi-arid climate (classified as Csa by the Kôppen-Geiger system).

The study site is the city of Ain Smara, about 12 kilometers from the city center of Constantine (Fig. 1.).

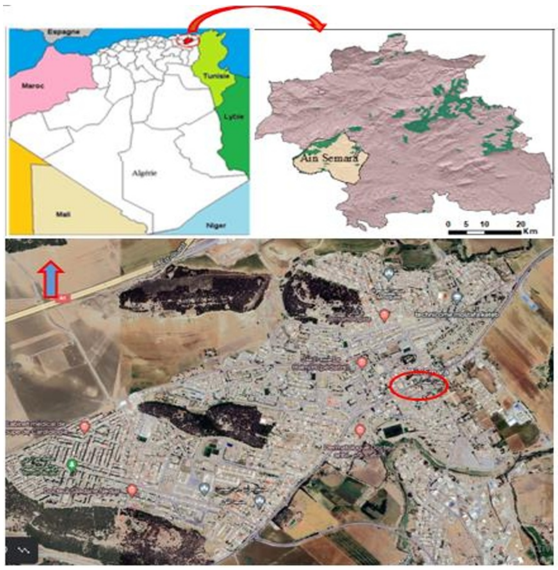

Fig. 1. Location of Ain Smara city (in top) and the site of investigation (in bottom)

The climate is characterized by a continental Mediterranean climate called semi-arid, hot in summer with an average maximum temperature of 37.6°C, cold, and humid in winter accompanied by cold spells and snowfalls with an average minimum temperature of 3.1°C (Fig.2.). The relative humidity varies between 25% in July and 94.5% in February, the duration of sunshine is 334.7 hours as a maximum value during the month of August and the prevailing winds are from the north north-west direction in winter and south south-east in summer with average speeds varying between 2 and 2.9 m/s (Climate Consultant6) [23]. All these factors contribute to the city's harsh climate.

2.2 Field measurements

The city center has a semi dense traditional urban fabric (up to 70%) deprived from vegetation; and a colonial fabric, which was grafted on part of traditional fabric and around this initial core. The presence of the vegetation is not regular there.

The selected site is an urban street with a line of trees, and without vegetation (Fig.2.). The measurements and the survey were carried out under four axes.

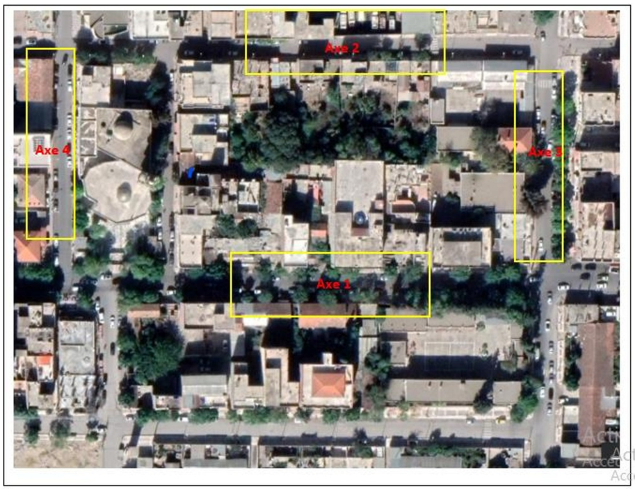

Fig. 2. Site investigation: Axe1 (NE-SW), Axe2 (NE-SW), Axe3 (NW-SE) and Axe4 (NW-SE).

Measurements and surveys were collected from four stations in Axe 1, Axe 2 Axe3 and Axe 4 (NE-SW orientation and NW-SE extended linear buildings), with digital instruments Multifunction instrument (LM800), with an accuracy of ±0.2. Measurement was selected according to variation of presence of trees and aspect of street see (fig.2. and fig.3.).

The measurements located in the built-up environment at a height of approximately 1.5 m and were recorded every two hours at each station from 6:00 to 20:00 each day.

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Fig. 3. Photo showing the site's study axes.

Field comfort surveys of 800 interviews were conducted in four axes with tree shade and isolated one (without tree cover) thought three-week period during the summer period (July 2021). One aim of these surveys was to obtain a better understanding of human thermal comfort response outdoors and to propose an adaptive comfort model for spaces shaded by vegetation in hot-dry summer climates, which will be detailed in a following paper. Qualitative data on respondents' visual and thermal perceptions were collected using a questionnaire (see Table 1) adapted from those used in recent ANSI/ASHRAE indoor studies, with some specific items added [23]. For example, questions inquiring about sun/shade preferences were not part of the ASHRAE questionnaire.

To achieve the mentioned objective, this study was carried out using the Envi-met V5.1 simulation to study and quantify the effect of applying green design on the feeling of thermal comfort in outdoor street with different ratios (W/H). In many research studies, Envi-met has proven its success in performing thermal simulations for outdoor spaces [24-26]. The objective is to study the differences between the case without vegetation or water and the case with vegetation (trees, grass.) and water features. Ta, RH, Wind and PMV are recorded for four cases tested (street without green design, street with row of trees, street with grass and water fountain, street with trees and grass) and these scenarios tested with different ration 0.5, 1 and 2, width of the street is about 14m (fig.4.).

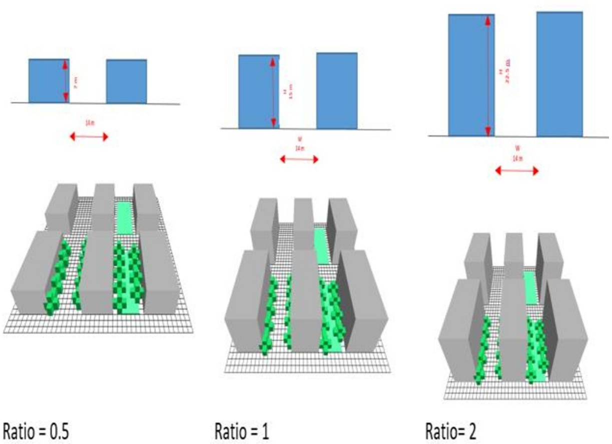


Fig. 4. Model simulated with different scenarios of ratio W/H (0.5-1-2).

3 results and Discussions

3.1 measurement results

The geometry of urban streets is critical in mitigating thermal comfort [3, 27]. In addition, the incorporation of vegetation can reduce and manage the sky view component. Shade trees limit heat gain by directly shading buildings and through evapotranspiration. Planting trees in the environment can help lower temperatures, reduce energy consumption, and improve air quality. The purpose of this research is to verify and explore how green design can play an essential role in the urban microclimate for various forms of urban design. Equations should be centered and numbered with the number on the right.

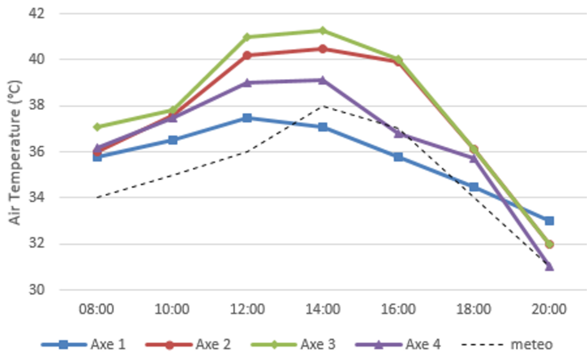


Fig. 5. Average air temperature at the various axes of measurement during July 2021.

Figure 5 shows the evolution of air temperature during a typical summer day at the four measuring stations. It shows that the street without trees is warmer from 10:00 am to 4:00 pm. than the vegetation areas under tree coverage, which is consistent with previous studies of the literature on this subject [1], [2], [6], [12], [16], and [18]. The air temperatures, in all stations, are higher than 32°C during the day. But the temperatures recorded in Axe 2 and Axe 3 remain higher than those in the stations at Axe 1 and Axe 4; with a variation between -0.9°C and -4.52°C at 14:00 and a variation of -3.9°C after midday at 16:00. This result agrees with the results of many studies [11, 20-22].

The graph in Figure 6 shows a negative relationship between relative humidity and air temperature. It should be noted that the vegetated or green stations (axis 1 and axis 3) had higher values of relative humidity than the axis 2 and axis 4 stations. The maximum relative humidity value is recorded at 18:00 (hours) in Axe 1 in the street with tree alignment and with dense foliage, with a variation of 23% compared to Axe 2 without trees and with the same orientation. At the maximum of energy at 12:00 (hours), we see a variation from 3.5% to 10.5% in the stations of axis 1. While one accumulates solar energy, the other records an increase in water content, which is explained by the influence of the latent heat of vegetation evaporation. [7, 27].

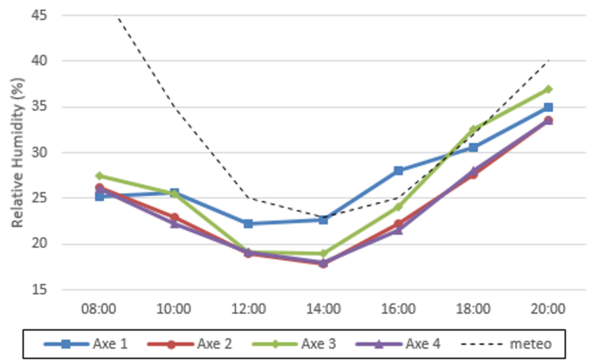


Fig. 6. Average Relative humidity at the various axes of measurement during July 2021.

3.2 Survey results

According to a survey, the majority of people and thermal sensation are influenced by solar radiation (Fig.7). People from different social origins in hot and dry areas use outdoor spaces in diverse ways. The study found that neutral predominates in tree-covered spaces in Axe 1 and Axe 3, which is a positive condition compared to streets without canopy.

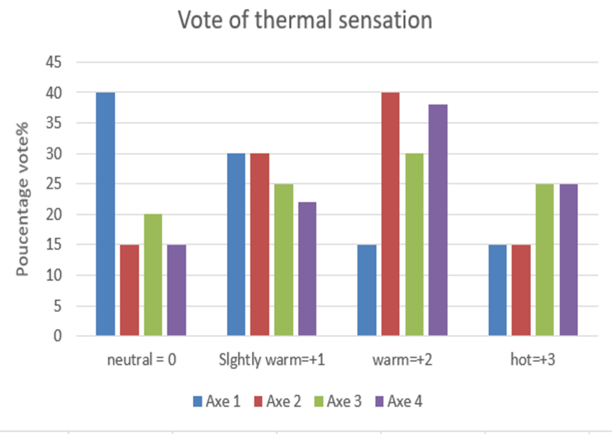


Fig. 7. Percentage Vote of thermal sensation in different axes.

The results also showed significant differences in the evaluation of thermal sensation in the selected area. Figure 8 illustrates the evaluation of space related to thermal sensation from the questionnaire responses in different axes, which were provided to compare the survey results presented below on the users' perspective in different streets (axes).

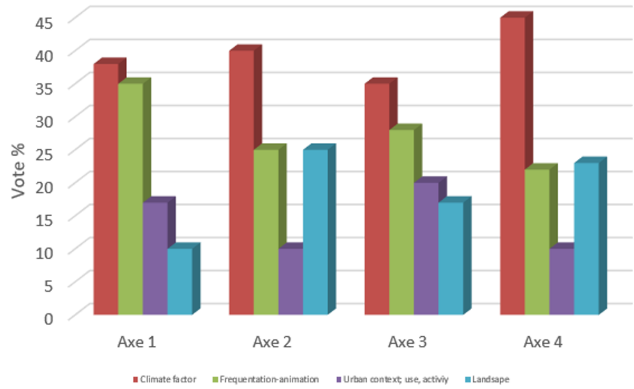


Fig. 8. Percentage Vote of parameter impact comfort.

The microclimate is regarded favorable due to the space's shadow and mild daylight. However, in stations with no tree cover, feelings of discomfort, heat, and brightness are noticeable, and the overall impression of the environment is poor.

Furthermore, research seems that the characteristics most frequently indicated as the cause of in general are intense sunlight, cited by 45% of respondents, and high temperature, cited by 30% (see fig.8.). Other users cited a lack of urban furniture, a lack of trees in the open space, and scorching breeze.

Figure 9 shows people's attitudes toward the sun (solar radiation) at various Axes (with and without tree cover). Solar radiation directly affecting a person.

His/her impression of thermal comfort is significantly influenced. According to the survey data, 75% to 100% of the respondents consider the solar radiation to be neutral in the presence of trees, while 60% to 90% of the respondents consider the solar radiation to be too strong in the absence of trees. Furthermore, this appreciation seems to be tied to the use of space.

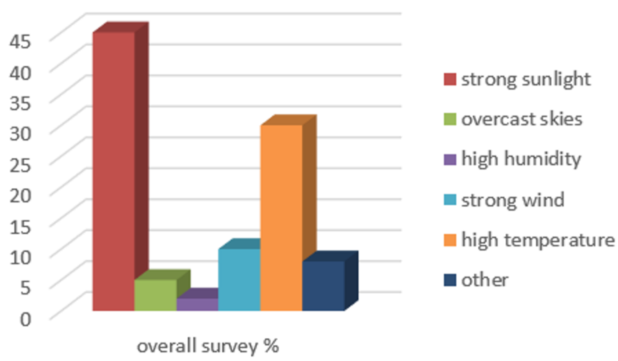


Fig. 9. Principal factors contributing to discomfort.

3.3 Simulation results

The following results were deduced after running the scenarios (Fig. 10.) through the Envi-met program.

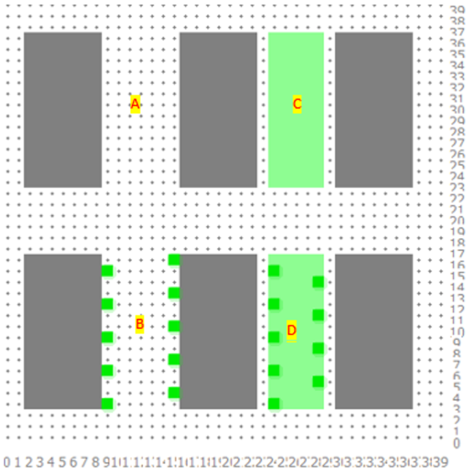


Fig. 10. Simulated area with Envi-met 5.1 with different scenarios: A (without vegetation), B (with row of trees), C (Grass on the floor plus water fountain), and D (grass plus trees)

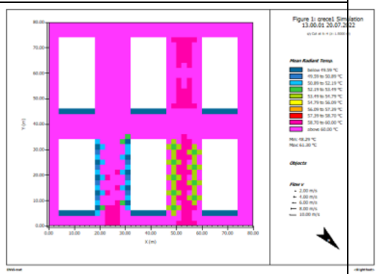
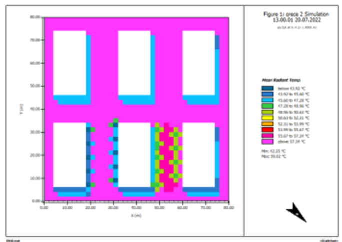
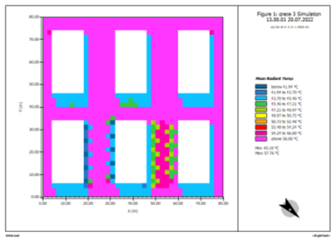
When comparing the fourth cases; without vegetation (Case A) and with vegetation (trees, grass) or water (Case B), (Case C) and (Case D) (Table 2.), The air temperature (Ta) at height 1.8m reach rage between 29°C at 9:00 am and 34 °C at 1:00 pm, in case with vegetation (case B and case D) and can reach 35.4 °C at 1:00pm., in the case without vegetation or water (Case A). Difference of 1.4°C is registered witch can participate in lowering of temperatures. Relative humidity (Rh) reached 48 % at 6:00 in case A without vegetation and 52 % in case D with presence of row of trees and grass with trees participate in humidification of the air environment. Relative humidity increased by about 4 % during the simulated hours, due to the transpiration process. This increase in Rh leads to better human comfort conditions, as the optimal values are 40%–60%. The wind speed (Ws) showed a slight decrease in its values.

Table 2. Simulation values during the simulated hours for Ta, Rh, and Ws.

Simulation parameters	Time	Stations			
		A	B	C	D
Ta (°C)	9:00am.	29.95	29.0	29.3	29.5
	1:00 pm	35.4	34.1	34.3	34.0
	6:00pm.	32.5	30.1	32.3	30.0
Rh (%)	9:00am.	42	60	62	61
	1:00 pm	43	56	58	57
	6:00pm.	48	52	51	52
Ws	9:00am.	1.2	1.1	1.2	1.1
	1:00 pm	0.9	0.7	0.7	0.8
	6:00pm.	1.4	1.2	1.4	1.1

The aspect ratio, which is the most important design factor in providing a thermally comfortable urban environment, is studied in an optimized street configuration with NE-SW orientation and NW-SE extended linear buildings. An increase of 0.5 in the aspect ratio values can reduce the maximum mean radiant temperature (Table 3.) by an average of 2.90°C in the early morning and late afternoon, thus reducing the PMV values. Changing this design parameter from 0.5 to 1 increases the comfort hours by 30.59%. Nevertheless, in this specific dry and hot region, which has a minimum wind speed, it is recommended to increase the H/W ratio to obtain aspect ratios greater than one.

Table 3. Leonardo maps of MRT distribution at human height 1.80m at 1:00pm.

MRT Values	
Case : Ratio= 0.5 Street without trees or green Is two hot Presence of trees can moderate the microclimate Presence of water reduce the incomfort but the shade in the hole strategy	
Case : Ratio= 1 building hight can procure shade	
Case : Ratio= 2 building hight can procure shade	

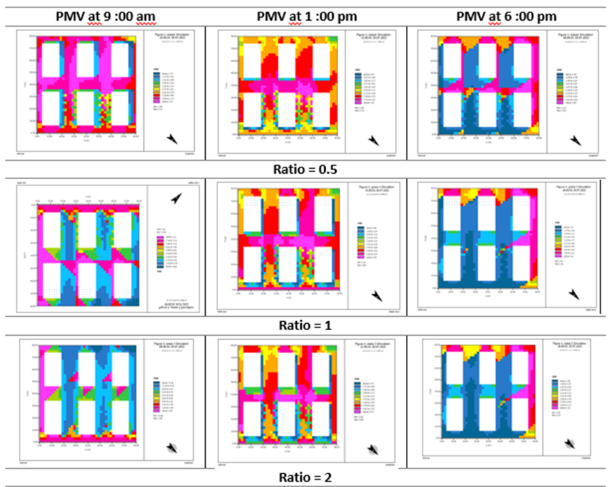


Fig. 11. Leonardo maps of PMV distribution at human height 1.80m during the day and under different ratios aspect.

This increase would move the "comfortable" range and cause the streets to be slightly cold for most of the day. Decreasing the aspect ratio by 0.5 results in a 2.22% loss of thermal comfort. As a result, an aspect ratio of 1 or 2 is considered the ideal choice for buildings located on NE-SW oriented streets. An aspect ratio of 0.5, on the other hand, increases moderate thermal stress between 10 a.m. and 3 p.m. The 0.5 ratio requires special management to ensure thermal comfort and minimize adverse weather effects. (Fig. 11.).

Comparing the green design between vegetation (grass and trees) and the presence of water fountain (Fig.12 and Fig.13) at the height of 1.8m, the air temperature decreased between 0.62°C to 1.56°C, and we notice increased relative humidity due to the transpiration process and the presence of water.

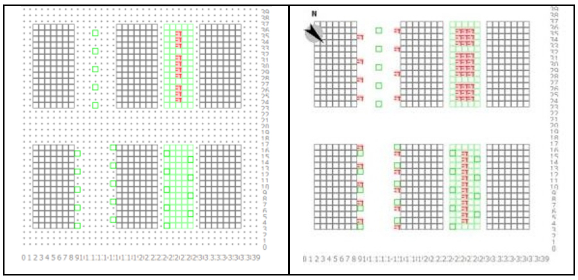


Fig. 12. Green design: trees and grass in green (Left), Green and water fountain in red (Right).

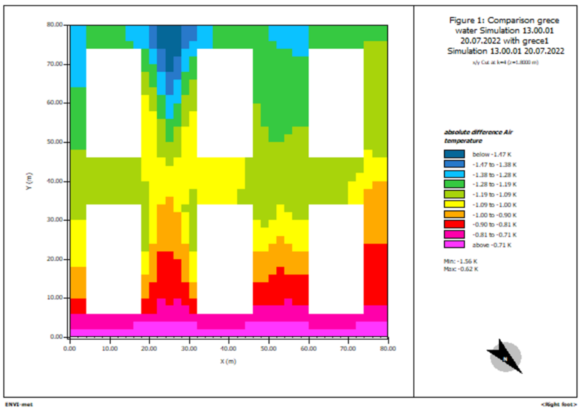


Fig. 13. Absolute difference air temperature (case 1 and presence of water).

When comparing the green design between vegetation (grass and trees) and the presence of water fountain (Fig.14.) at the height of 1.8m, the PMV decreased, and the use of trees and grass on the ground surfaces helped to improve the PMV values, contributing to a great improvement in human thermal comfort. Due to canopy shade, the largest decreases occurred primarily where trees were present. Trees can protect pedestrians from direct sunlight through reflection and absorption; it is well known that trees can remove a significant percentage of incoming shortwave solar energy, resulting in a shading effect. In addition to blocking short-wave radiation, trees can reduce long-wave radiation by lowering the surface temperature. Furthermore, in the case of all plant species, total evapotranspiration plays a significant role in cooling.

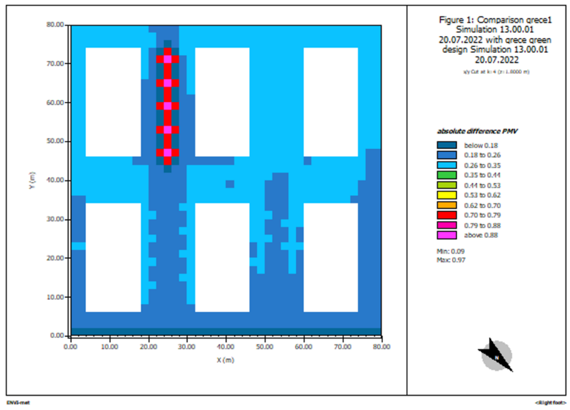


Fig. 14. Comparison of case ratio of 0.5 with green design (trees and water fountain).

4 Conclusion

Green design solutions have been shown to have a significant impact on human thermal comfort due to their potential to improve microclimatic variables. Environmental simulation in hot dry conditions demonstrated this improvement. The results of this study showed that the most influential parameter on the microclimate, especially in the summer heat, is direct solar radiation. This parameter has the greatest impact on air temperature and mean radiant temperature. This was evident in the first scenario, where trees with good positioning and large canopies provided more shade, which is significant.

PMV values in outdoor spaces show an improvement in human thermal comfort. The microclimate is considered favorable due to the shading and mild daylight. However, in stations without tree cover, feelings of discomfort, heat, and brightness are evident, and the overall perception of the environment is unpleasant.

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