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# A methodological approach to evaluate the passive cooling effect of Oasis palm groves

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ABSTRACT

With climate change and the recurring heat waves in arid lands, human well-being and activities in oasis settlements can be critical subjects for the ongoing years. This paper introduces a methodological approach to investigate the potential passive cooling effect inside the oasis palm groves, their spatial characteristics, and microclimatic thresholds. Based on the Physiological Equivalent Temperature (PET) index, the paper evaluates oasis palm groves' ability to ensure a neutral human outdoor thermal comfort zone. The research aims to determine guidance of an optimal and nearly optimal thermal comfort threshold based on a series of parametric scenarios of oasis configurations. The study provides a cross of 12 ideal oasis scenarios. The paper evaluates the oasis cooling effect and thermal comfort and recommends aligning urban planning with thermal thresholds. Results reveal that PET neutral zone can be assured into ranges of 29°C to 37°C, 19°C to 20°C, 55% to 58%, and 1m/s to 2m/s of mean radiant temperature, air temperature, relative humidity and air velocity, respectively. The results refer policymakers and urban planners to invest in the passive cooling effect of the oasis palm grove in future urban design strategies to maintain the maximum neutral comfort hours during heat waves.

## 1. Introduction

The relationship between vegetation and human has been the subject of numerous studies throughout different contexts. A study by (Givoni, 1991) analyzed the impact of vegetated areas, such as public parks and private planting around individual housing, examining their influence on the quality of the built environment. Other studies have also explored the role of trees, planted areas, and parks in contributing to the sustainability of cities (Bernatzky, 2012; Chiesura, 2004; Rowntree, 1986). Numerous other research projects have investigated the effect of trees and vegetation within the urban environment on human thermal well-being, air quality, and urban heat island (UHI) effects in various contexts (Lin et al., 2023; Matallah et al., 2020; Vailshery et al., 2013; Rakoto et al., 2021; Cárdenas-Jirón et al., 2023). In their research, Dimoudi and Nikolopoulou (2003) (Dimoudi and Nikolopoulou, 2003) found that green plantations can greatly improve the microclimate of urban environments and effectively mitigate the urban heat island effects leading to a reduction in summer air temperatures. Moreover, their study revealed that the benefits are not confined solely to the vegetated areas but extend to the surrounding park perimeter. These studies and others have concluded several positive aspects and significant contributions of the vegetated areas upon human well-being, specifically on outdoor thermal comfort at various levels. Regardless of size, any green space, whether trees, plants, or grass, plays a crucial role in the urban climate (Akbari, 2009; Shiflett et al., 2017; Zhou et al., 2019; Xhexhi, 2023). Therefore, their benefits and effects have attracted the attention of many researchers, who have categorized them into five points: (a) surface temperature modification, (b) air moisture control, (c) air purification from pollutants, (d) noise control, and (e) regulation of carbon emissions (De Abreu-Harbich et al., 2015; Lehmann et al., 2014; Picot,

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2004; Shashua-Bar et al., 2009). In the last decade, several researchers oriented their studies to investigate the impact of vegetation on outdoor thermal comfort in arid and semi-arid climates (Battista et al., 2023; Darbani et al., 2023; de Wolf, 2023; Geng et al., 2023). From a technical standpoint, the vegetation's climatic functions in urban environments have been rigorously studied. Andrade and Viera (2007) (Andrade and Vieira, 2007) classified the effects of green spaces into three scales of climate impact: microclimate, local climate and meso-climate. Subsequently, other classifications followed the specific climate impact scales. In desert areas, the oasis effect refers to the phenomenon of a potential cooling effect created by vegetation (Potchter et al., 2008; Oke and Cleugh, 1987). The most common vegetated area in the desert is the palm grove which covers the large arid lands and identifies a source of resilience, livability and human settlements.

The palm grove is a meticulously planned agricultural complex crafted by human hands and organized into a regular grid. This grid pattern may vary from region to region based on specific vegetative cover types and includes the dwellings of local farmers (Ahriz et al., 2019). Mainly consisting of palm trees (*Phoenix Dactylifera L.*), the palm grove has a noticeable impact on the local climate of an oasis-arid area. It can protect from variant winds and sun rays and enhance the microclimate by reducing the ambient temperature, increasing humidity and creating a breeze (AHRIZ et al., 2017). Regarding the air temperature and hygrometric balance, many grown trees can produce significant water levels through evapotranspiration (Rchid, 2012), which increases humidity and lowers temperature (Potchter et al., 2008; Potchter et al., 2012). The amount of water generated through this process depends on the types of trees and the air temperature. Generally, plants and trees in arid lands, especially palm trees, have low water loss rates as they conserve water for themselves. Therefore, inside the palm groves, high humidity is not solely a result of date palm trees but also the presence of other species, cultivated crops, and moist soil.

On the other hand, when considering built-up areas, the impact of palm trees on the air temperature and humidity is insignificant because a single palm tree cannot humidify a house's courtyard. Nevertheless, during stagnant summer days characterized by limited air movement, the built-up areas heat up faster than the adjacent palm groves. This temperature differential creates a localized low-pressure area that induces cool airflow from the palm trees, known as the oasis breeze (Hao et al., 2016).

Considering a comprehensive analysis of these insights, many studies have investigated the microclimate of vegetated areas compared to bare surroundings, providing interesting findings. Geiger (1965) observed that at noon, temperatures inside a forest were up to 5°C cooler, and in an irrigated cereal field, temperatures were up to 3°C cooler than the surroundings nearby bare. Similarly, Taha et al. (1991) discovered a daytime oasis effect within an orchard, with temperatures inside the canopy dropping by 4.5-6°C during the day while nighttime temperatures were 1-2°C higher. Another study conducted by Jonsson (2004) in the subtropical city of Gaborone, Botswana, during the spring season. The research resulted that during the day, small areas with highly vegetated areas acted as a cooling oasis in the city through evaporation. In comparison with the countryside, irrigated areas within the city were cooler by approximately 2°C, while sparsely vegetated areas were hotter by the same margin. However, none of the previous studies considered the impact of the oasis effect on human outdoor thermal comfort.

The estimation of costs associated with global warming is critical. It reveals that between 1960 and 1990, over 600 million people were pushed outside the human climate niche Lenton et al. (2023). The imminent future poses an alarming threat to arid lands, as they face unprecedented heat for the next years and the risk of banishment of one-third of their population due to the relentless surge in global warming, which could reach a level of 2.7°C by the end century (Lenton et al., 2023).

A literature review aimed to define the oasis cooling effect under climate conditions with associated disruptions in the built environment throughout the arid regions. The publications included scientific journal articles, reports, and books. The study opted for large databases and high-quality web sources with complete bibliographic data. The initial Scopus and Web of Science research resulted in publications relevant to the oasis effect across the built environment.

In this context, very limited research has been conducted on the oasis effect within desert areas (BWh), leading to different findings. The study by Potchter et al. (2008) (Potchter et al., 2008) in Arava Valley, southern Israel, indicated that during the summer, desert trees create an oasis effect at night but can cause a warming effect during the day. In their second study, Potchter et al. (2012) (Potchter et al., 2012) focused on winter. They found that nighttime warming is a central feature of the desert oasis phenomenon, with a less dominant cooling effect limited to midday. Both studies suggest that investing in palm tree plantations has the potential to influence local climate conditions positively. In a different context, Xue et al. (2019) (Xue et al., 2019) studied the Qira oasis in a hyper-arid zone in China, indicated by site measurements that oasis vegetation significantly influences the local atmospheric environment, indicating the importance of conserving and restoring the oasis vegetation to maintain the microclimate and sustainability of desert oasis environment. Another study conducted by Hao et al. (2016) (Hao et al., 2016) used remote sensing tools to investigate the Tarim Basin oases in China over a time series from 1961 to 2014. Their findings demonstrated a significant cold oasis island effect, especially in summer. Moreover, Boudjellal and Bourbia (2017) (Boudjellal and Bourbia, 2018) resulted that in the Ouargla region of southern Algeria, where a traditional oasis palm grove characterized by high density showed a low value of Land Surface Temperature (LST), and generated a strong oasis cold island. On the other hand, none of the previous studies have addressed the relationship between the oasis cooling effect and its impact on human well-being.

Furthermore, Georgescu et al. (2011) (Georgescu et al., 2011) evaluated the climatic summertime of the diurnal cycle of the oasis effect in Phoenix metropolitan urban area, USA, based on the Weather Research and Forecasting System (WRF). Between June and July, the study showed that the oasis effect's sensitivity to land use and land cover change (LULCC) was small on the regional scale. In another context, a study by Ahriz et al. (2019) (Ahriz et al., 2019) in Algeria focused on developing a mathematical prediction method for the oasis effect generated by palm groves. Their results revealed that temperatures within oasis palm groves can be reduced by about 2°C in nighttime and up to 5°C in daytime compared to neighboring desert areas. Understanding the impact of the oasis effect upon human outdoor thermal comfort can have crucial implications on arid urban planning and oasis agricultural development of one of the world's largest territories, specifically in North Africa, which remains sparsely populated (Santoro, 2023). The North African oasis territories occupy large areas despite their low population density, mostly concentrated in urban areas (Table 1).

This paper aims to investigate the potential passive cooling effect of an oasis palm grove impact on the outdoor thermal comfort in the Tolga oasis settlement in southern Algeria. Consequently, the research places significant methodological emphasis on identifying novel and precise spatial aspects and microclimatic ranges pertinent to agricultural and forestry development, particularly concerning their design and integration within the built-up areas in arid environments. The primary objective is to promote human well-being through these endeavors while contributing to a comprehensive analysis of Saharan climate adaptation, especially in North African oasis territories (Fig. 1).

The study is based on numerical modeling of several scenarios under three seasons. Hence, two questions arise strongly:

a) What are the limits of an oasis palm grove's potential passive cooling effect?
b) What are the favorable spatial characteristics and the microclimatic thresholds of an oasis palm grove for neutral thermal comfort?

**Table 1**
North Africa Oasis territories

| No | Territory | City, Oasis settlement | Country | Climate zone (koppen-Geiger) | Population |
|---|---|---|---|---|---|
| 1 | Ziban | Biskra, Tolga, Sidi Okba, El Kantara | Algeria | BWh | 592 951 |
| 2 | Souf | El Oued | Algeria | BWh | 191 517 |
| 3 | Oued Righ | Touggourt, Djamaa, Meghaier | Algeria | BWh | 178 310 |
| 4 | Ouargla | Ouargla | Algeria | BWk | 280 902 |
| 5 | Mzab | Ghardaia | Algeria | BWh | 280 902 |
| 6 | Laghouat | Laghouat | Algeria | BWk | 127 165 |
| 7 | Gourara | Timimoun, Tinerkouk | Algeria | BWh | 48 832 |
| 8 | Tidikelt | In Salah | Algeria | BWh | 6 433 |
| 9 | Touat | Adrar, Zaouiet Kounta, Tamantit | Algeria | BWh | 108 538 |
| 10 | Saoura | Bechar, Beni Abbes, Tindouf | Algeria | BWk | 246 594 |
| 11 | Figuig | Bni Tadjite, Bouanane, Ain Chair | Morocco | BSk | 27 699 |
| 12 | Ouarzazete | Ouarzazete, Tafilelt | Morocco | BWh | 207 337 |
| 13 | Chebbi | M'hamid El Ghizlane, | Morocco | Csa | 11 667 |
| 14 | Adrar of Ifoghas | Kidal, Abeibara, Boughessa, Tessalit | Mali | BWh | 84 000 |
| 15 | Agadez | Agadez | Niger | BWh | 134 995 |
| 16 | Borkou | Faya-Largeau, Omoul, Am-chaloba | Tchad | BWh | 241 000 |
| 17 | Jerid | Tozeur | Tunisia | BWh | 107 912 |
| 18 | Kebili | Douz | Tunisia | BWh | 39 270 |
| 19 | Fezzan | Sebha, El Fejeij, Gaberoun, Ghadduwah | Libya | BWh | 345 353 |
| 20 | Ghat | Ghat | Libya | BWh | 22 000 |
| 21 | El Kufrah | Al Jawf | Libya | BWh | 17 320 |
| 22 | Siwa | Siwa | Egypt | BWh | 42 740 |
| 23 | Fayoum | Madinet El-Fayoum, Nazla | Egypt | BWh | 357 674 |
| 24 | Al-Farafra | Al-Farafra | Egypt | BWh | 10 152 |
| 25 | Ad-Dakhla | | Egypt | BWh | 106 277 |

To answer the questions above, this paper supplies experimental insights into the impact of the oasis effect on human thermal comfort in arid areas. The current research presents a new theme and robust methodological approach that couples the oasis cooling effect and outdoor thermal perception experienced within typical human settlements located in arid environments, which is rarely addressed together in previous studies.

The paper's originality is the determination of the spatial and microclimatic thresholds that can assure a neutral thermal zone inside an oasis settlement passively under extreme weather conditions. 12 oasis agricultural scenarios, including the reference model, were carried out during three seasons. Furthermore, to enhance the quality of livability within these areas, which has been significantly impacted by the architectural anarchy and inadequate urban planning strategies, thorough consideration is necessary regarding the adaptation between the oasis agricultural zones and built-up areas (Fig. 2). Integrating agricultural oasis into well-organized urban environments can greatly improve the outdoor thermal conditions within these specific areas.

A comprehensive technical report was developed. Field

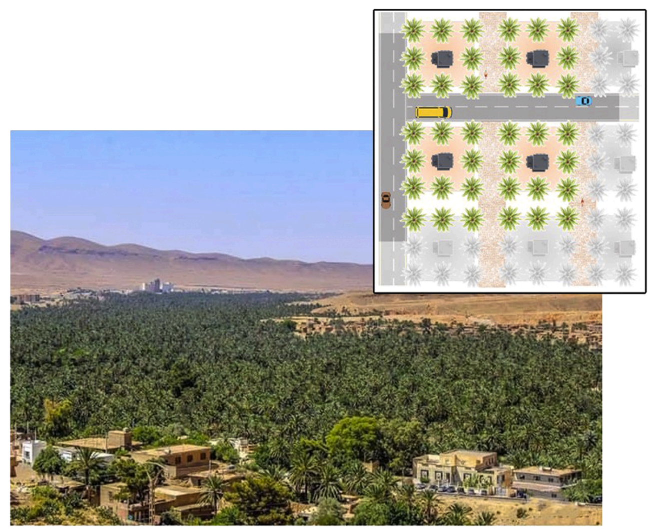


**Fig. 2.** Actual oasis settlement versus the future sustainable urban planning vision

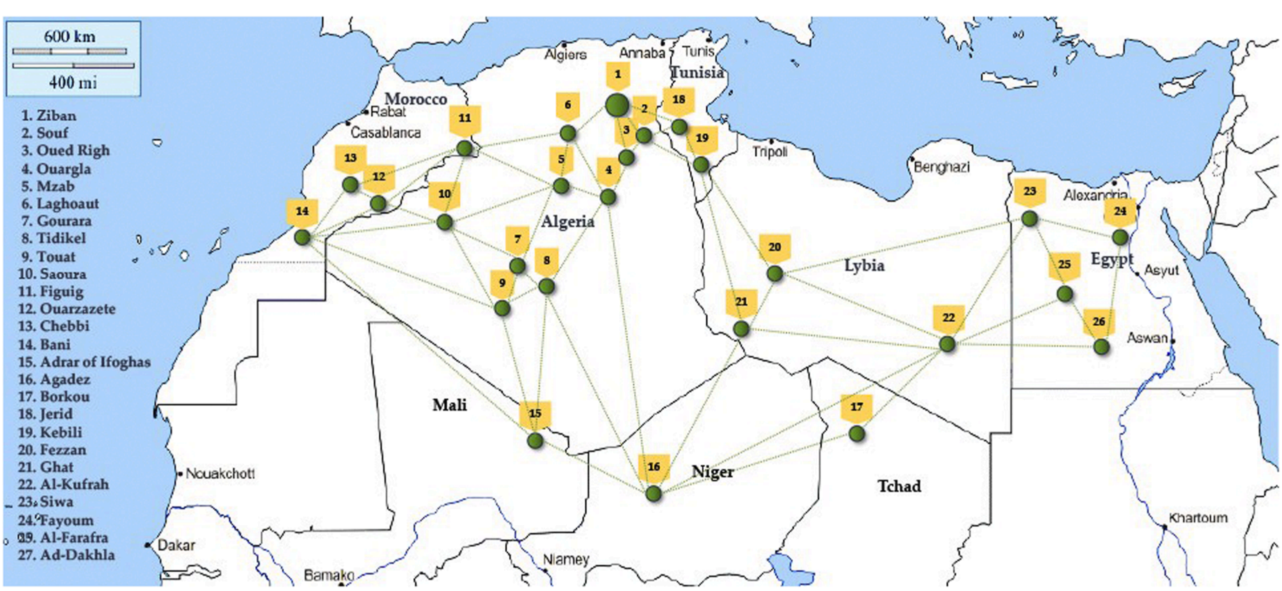



**Fig. 1.** Geographic locations of the oasis territories in North Africa

measurements and simulation datasets were performed. To our knowledge, this is the first paper that supplies pertinent information on the oasis cooling effect thresholds with their effects on outdoor thermal comfort in arid climates. The paper lies in identifying the key spatial characteristics and microclimatic thresholds that can passively maintain a comfortable thermal zone inside an oasis settlement for extended and successive heat waves.

Finally, the paper strongly recommends future urban planning strategies among the oasis territories that can be applied within the worldwide arid lands.

## 2. Methodology

Fig. 3 presents the research methodology, including its followed study conceptual framework. The methodology aims to define the significant thresholds for an oasis cooling effect in hot and dry climates. Our quantitative research methodology relies on continuous field measurements, numerical modeling, and running simulations. The research methodology is based on four significant steps, each detailed in the following section.

The research was conducted on a representative agricultural oasis settlement in Tolga Oasis Territory, Algeria, characterized by a dry and hot climate (BWh). The focus of the urban climate design in such cooling-dominated regions was primarily on cooling strategies across urban fabrics during the harsh period. Passive oasis cooling effect to mitigate is considered a potential strategy for the built environment adaptation under extreme weather conditions.

### 2.1. Study area

Oasis settlements are strongly attached to contextual aspects of the nearly surrounding environment that are essential to their sustainability over time. So far, these lands have become more vulnerable, undergoing many factors such as demography, urban growth, climate change and other environmental factors.

There are numerous criteria to define the different oasis settlements in North Africa based on geographical characteristics, water mobilization systems, built environment forms, and agricultural landscapes.

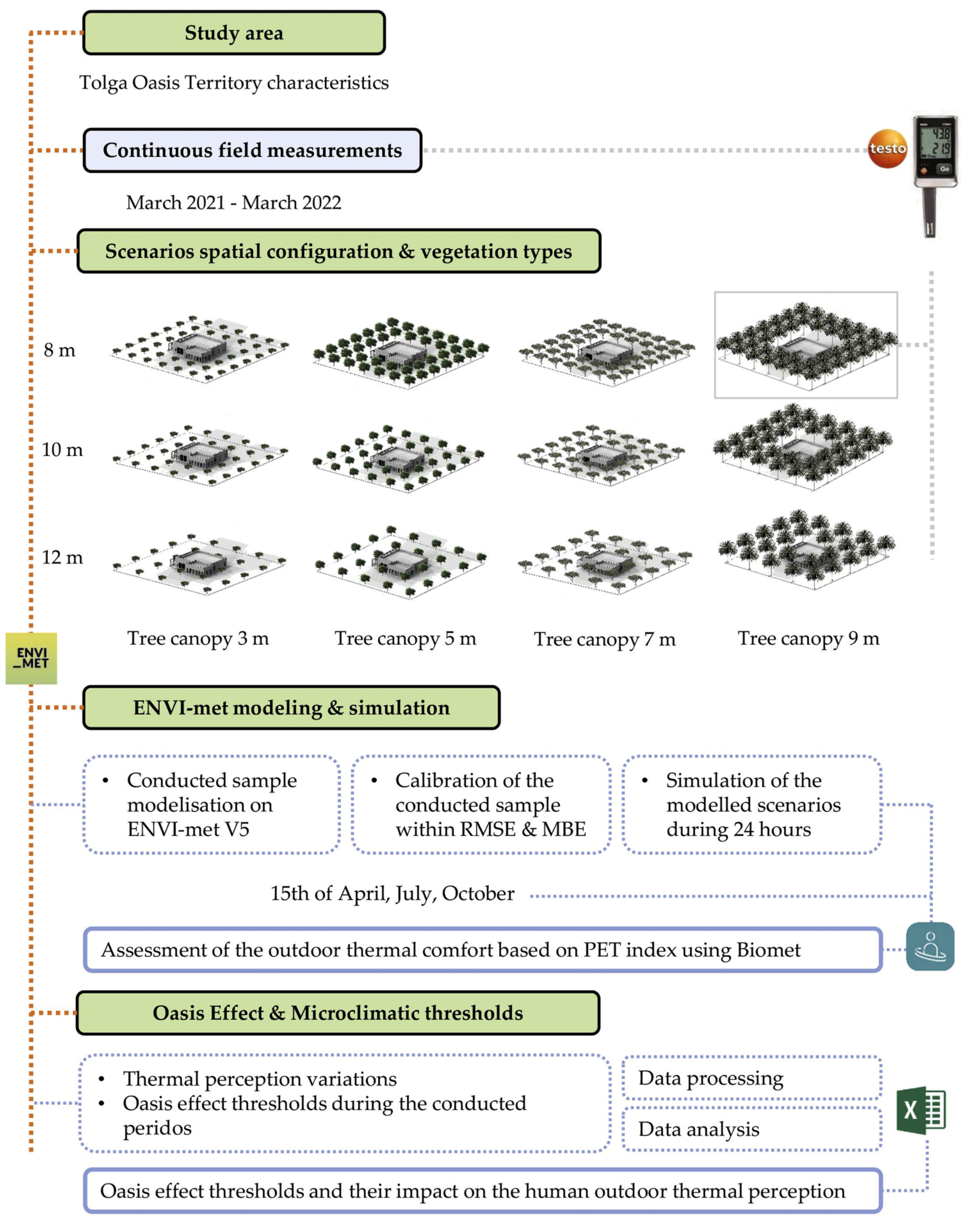



**Fig. 3.** Study conceptual framework

Additionally, the totality of the oasis territories in North Africa is living under a common hot and dry climate (Coté, 2005; Côte, 2012; Bisson, 1993).

The study is conducted in Tolga Oasis Territory, in Biskra Province, in the southern part of Algeria's most populated area, at the foot of the Saharan Atlas Mountains (Matallah et al., 2021; Matallah et al., 2022). The territory is located on the northern Saharan plains in North Africa and is characterized by a strong coexistence between the built environments and the palm groves (Fig. 4). Tolga Oasis Territory cover is a large palm groves area with more than 4.6 million productive Date Palm trees (Faci and Benziouche, 2021). It makes the region first rank most productive oasis settlements in North Africa.

The territory is known for very high temperatures. Between 1958 and 2021, the studied area registered a yearly average temperature and relative humidity of 22.4°C and 47.1 %, respectively. The yearly maximum air temperature reached 46.8°C (Fig. 5) (Center for the Built Environment (CBE)). Therefore, outdoor thermal comfort is affected by thermal heat stress around 6 months in the year.

Further, Tolga Oasis Territory recorded a strong deficient rainfall, with a low annual average (<126 mm) between 1995 and 2017. Additionally, during the last 30 years, the yearly average of heating degree-days (HDD) was estimated to be about 218 per year, and the average of cooling degree-days (CDD) was 1780 per year.

### 2.2. Continuous field measurements

The current study recorded a continuous hourly field measurement inside a real agricultural oasis settlement (palm grove) between the 25$^{th}$ of March 2021 and the 25$^{th}$ of March 2022. Thus, the study is primarily based on three successive seasons (spring, summer and fall), each of which these seasons are representative of the phenological cycle of the palm grove during the year (Matallah et al., 2022).

The agricultural oasis settlement was selected as an experimental area due to the well-cultivation of several typical plants that can lead to determining the relationship between the oasis effect phenomenon and human thermal comfort. This settlement also contains a typical farm building in the middle of the vegetated area. Therefore the meteorological instrument was shielded and implemented upon the outdoor gallery arches of the farm building. The instrument was projected two meters away from the outdoor gallery arches to avoid any radiation or convection effects from walls. The area is dominated by Date Palm trees (*Phoenix Dactylifera L.*), with few fruit trees such as fig, pomegranate and vine.

The air temperature ($T_{air}$) and the relative humidity ($R_H$) were measured using Testo 175 H1 data logger (accuracy ± 0.4°C and ± 1.0 %, respectively) on a height of 2.10 m from the ground to avoid any soil heat exchange or water evaporation effects due to irrigation (Fig. 6). To manage the device's recorded datasets, a complementary tool was set up, 'Comfort Software Basic 5.0,' compatible with the used instrument. The air velocity ($V_{air}$), solar radiation, rainfall, and hourly datasets were taken from the regional weather station with reference WMO 605265 in Biskra, Algeria.

### 2.3. Scenarios spatial configuration & vegetation types

By the use of the SPACES and ALBERO modules on ENVI-met 5.1.0 software (Bruse, 2004; ENVI-met software, 12 May 2023), 12 ideal scenarios of an agricultural oasis settlement were designed based upon

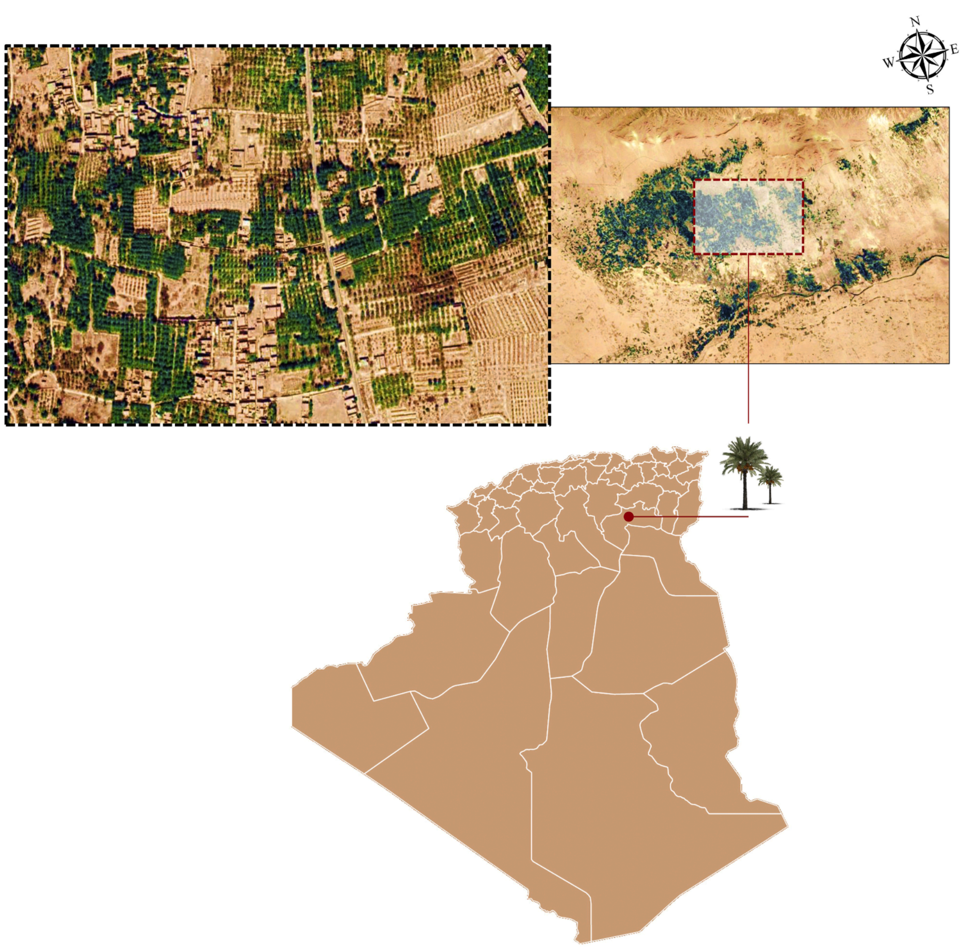



**Fig. 4.** Geographic location of the study area in Algeria

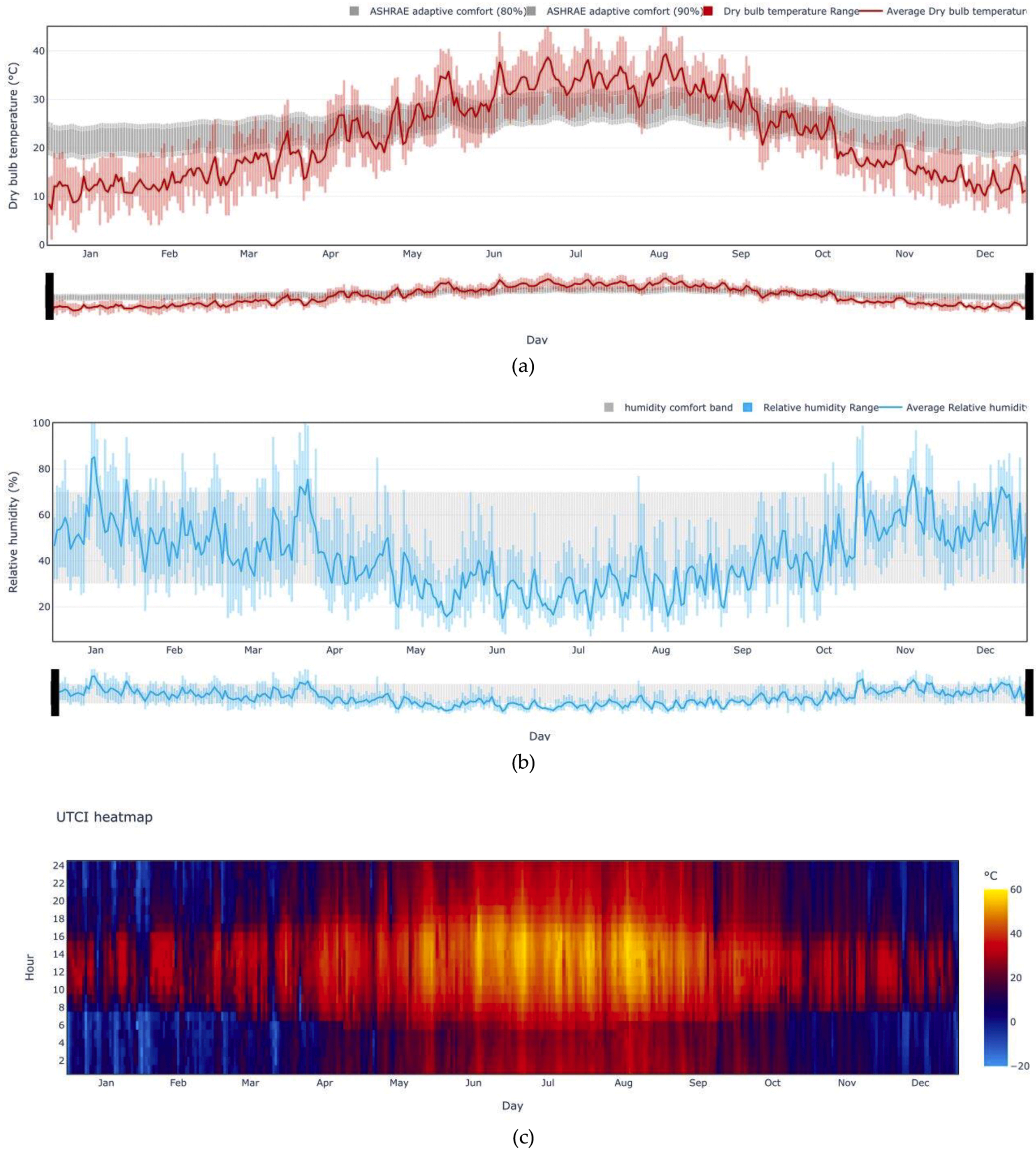
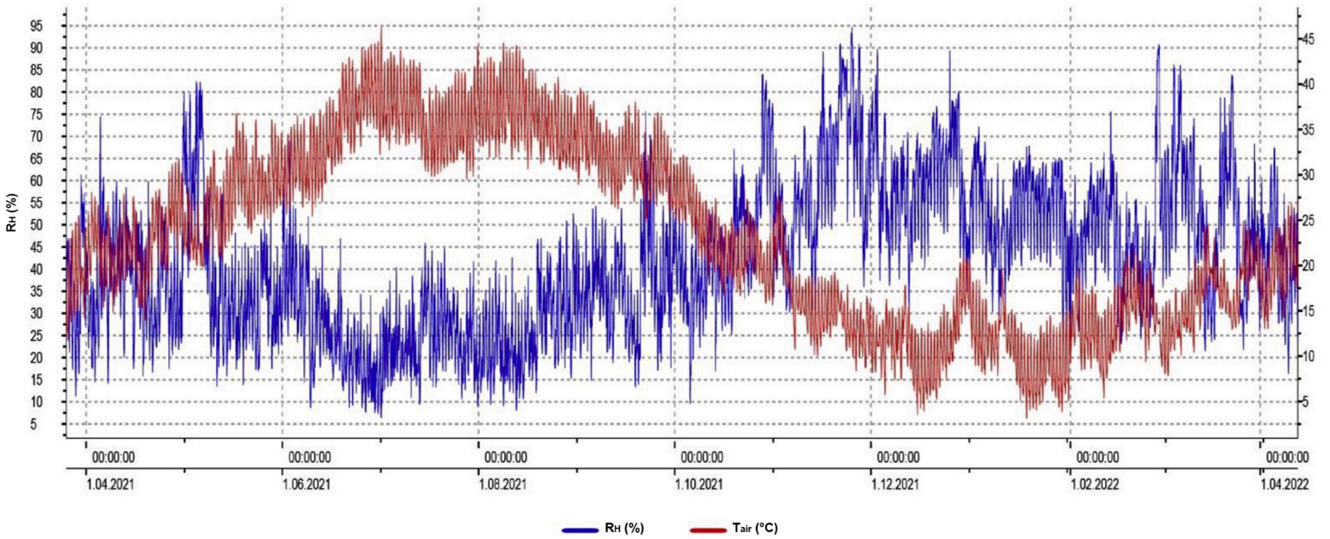



**Fig. 5.** Climatic conditions of the study context: (a) air temperature; (b) relative humidity; (c) UTCI index Heatmap

three different spatial configurations (grids) and four main trees (plants). Therefore, the trees were chosen depending on the main available trees in the study. The modeled grids are designed in Configuration 1: tree spacing of 8 m, Configuration 2: tree spacing of 10 m, and Configuration 3: tree spacing of 12 m. The spacing distances are primarily based on the local-used agricultural grids for *Phoenix Dactylifera L.* (Date Palm Tree). The area of each scenario is 2500 $m^2$.

The choice of tree species is based on the existing agricultural settlement in Tolga Oasis Territory, tree canopy characteristics, tree physiology and contextual aspects (Table 2). Hence, the trees were selected based on the following criteria: the tree's canopy (height, medium, and small) and the nature of the tree (evergreen or deciduous, and their growing under similar microclimatic conditions).

Further, every grid consists of one specific oasis tree: (i) trees with large canopies of 10 m (*Phoenix Dactylifera*) and 7 m (*Prosopis Juliflora)*, (ii) trees with medium canopy of 5 m (*Ceratonia Siliqua*), and (iii) tree with small canopy of 3 m (*Ficus Retusa*). The following abbreviations were assigned to each scenario: PD8, PD10, PD12 refer to Phoenix




**(a)**

**(b)**

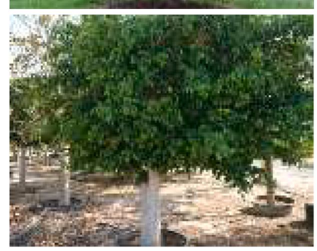
**Fig. 6.** (a) field measurements of air temperature ($T_{air}$) and relative humidity ($R_H$) variations from 25th March to 25th March 2022 inside the conducted site; (b) measurements data logger

Dactylifera; PJ8, PJ10, and PJ12 refer to *Prosopis Juliflora* within; CS8, CS10, CS12 refer to *Ceratonia Siliqua*; FR8, FR10, and FR12 refer to *Ficus Retusa,* within Configurations 1, 2, and 3 respectively. All the modeled scenarios contain the same building model, shaped in the middle of the vegetated area, to imitate the farm building in the study area. The building was designed similarly to the real house, presenting the residential housing archetype. The (PD8) presents the real conducted sample, which was taken as a reference scenario.

### *2.4. ENVI-met modelisation & simulation*

In the current study, the microclimatic conditions of the 12 oasis scenarios sampling were modeled and simulated using CFD ENVI-met 5.1.0 software. ENVI-met software is a three-dimensional simulation model with high reliability (Simon, 2016). Over the last few years, this model has gained increasing recognition and adoption among scholars involved in urban climate studies. ENVI-met's calculation modules encompass a wide range of scientific disciplines, spanning from fluid dynamics and thermodynamics to plant physiology and soil science (Salata et al., 2016; Chatzidimitriou and Yannas, 2017; Muniz-Gäal et al., 2020; Ali-Toudert and Mayer, 2006; Nasrollahi et al., 2021). This comprehensive coverage enables the model to effectively address various environmental simulation aspects. Compared to other numerical models, ENVI-met requires few input data. However, it yields highly accurate output data, including air and surface temperatures, relative humidity, wind speed, solar radiation, mean radiant temperature and more (Deng et al., 2023). It is important to note that the ENVI-met model focuses solely on the interactions between the atmosphere, buildings, soils, vegetation and water bodies. As a result, certain factors like anthropogenic heat, which significantly contributes to the urban heat island (UHI) effect, are not considered during the simulation (Deng et al., 2023). The simulation was carried out based on field measurements specific to the 15th of April, July and October 2021, with 24 hours of continuous running simulation. As the main part of the process, the validation of the baseline numerical model PD8 (reference scenario) was done within 48 hours on the 14th/ 15th of April, July, and October 2021.

**Table 2**
Selected trees from the local agricultural settlement

| Tree species | Description | Figure | Reference |
|---|---|---|---|
| Phoenix Dactylifera | • Commonly associated with oasis environments in desert regions and is cultivated in many dry worldwide regions. It is more typically under 20 m in cultivation.<br>• The trunk is round, stout and covered in overlapping, upward-pointing leaf bases that persist after the old leaves are shed.<br>• The leaves are up to 7 m long and typically palm-like, with pairs of grey-green leaflets arranged along their length. |  | Meunier, 1973; Munier, 1973; Chao and Krueger, 2007; Gros-Balthazard et al., 2013 |
| Prosopis Juliflora | • An evergreen leguminous tree, typical of arid and semi-arid regions, growing up to 10 m in height. The crown is large, and the canopy is open.<br>• Leaves are pinnately compound with 13-25 pairs of leaflets arranged on 1 or sometimes 2 pairs of pendulous rachis. Fruits are flattened, curved, indehiscent pods (4 mm thick, 1-1.5 cm wide and 15-20 cm long). |  | Pasiecznik et al., 2001 |
| Ceratonia Siliqua | • The tree can reach 6 to 10 m height. The crown is broad and semi-spherical, supported by a thick trunk with brown rough bark and sturdy branches.<br>• Leaves are 10 to 20 cm long, alternate, pinnate, and may or may not have a terminal leaflet. Most carob trees are deciduous. |  | Winer, 1980; Battle and Tous, 1997 |
| Ficus Retusa | • It is a rapidly growing, rounded, broad-headed, evergreen shrub or tree that can reach 10 m in height with an equal spread.<br>• The tree has glabrous obovate leaves, usually longer than 10 cm and spirally arranged. It has a gray to reddish bark dotted with small, horizontal flecks. |  | Chebouti et al., 2021; Sahli and Belhiouani, 2022 |

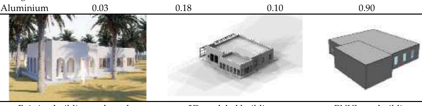
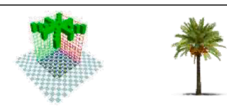
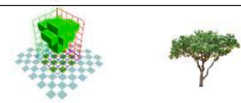
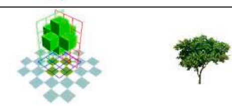
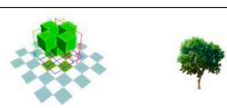
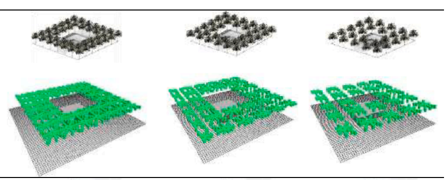
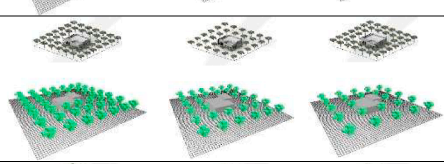
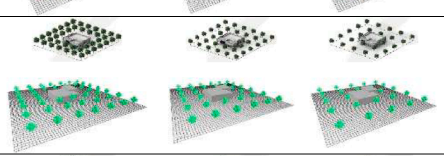
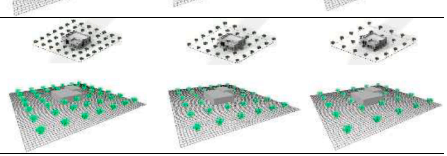
The validation is crucial to ensure the accuracy of all scenarios output datasets acquired from the simulation.

In order to assess the impact of the oasis cooling effect on human thermal comfort, the modeling process is established following the steps:

1. Continuous field measurements within the conducted oasis settlement over a year.
2. A holistic model was used to shape the numerical models using ENVI-met software (Xue et al., 2019; Boudjellal and Bourbia, 2018). Therefore, the scenarios were designed by SPACES and ALBERO modules (Table 3). ALBERO is a toolbox to define new 3D plant geometries introduced in ENVI-met software.
3. A full forcing of weather data was implemented based on CSV datasets of the $14^{th}$ and $15^{th}$ of April, July, and October 2021.
4. The simulation process uses to obtain the main microclimatic parameters for the quantification of the outdoor thermal comfort by PET index (Potchter et al., 2018; Potchter et al., 2022). The simulation comprises two essential steps: space modeling and utilization of weather data when the latter is based on the CSV full forcing datasets. The modeling and simulation were performed at the Sustainable Building Design Lab at the University of Liege, using a workstation, Super COmputeR ProcessIng wOrkstatioN (SCORPION). The workstation uses computing power and performance with 6 cores processor, 128 threads, and a 256 MB cache. SCORPION has 128 GB of RAM and a 24 GB graphics card, making it highly proficient in scientific applications (Amaripadath et al., 2023).
5. After simulation, the validation of the numerical model composed of buildings and trees. Hence, the validation was performed based on statistical metrics, using the root-mean-square error (RMSE) (Willmott, 1981) and mean bias error (MBE) (Willmott, 1982) standard error indices (ASHRAE, 2014; Stunder and Sethuraman, 1986), along with linear regression ($R^2$). The validation of the reference scenario aimed to assess the deviation between the simulated from the measured datasets (Fig. 7).
6. The PET index was calculated using Biomet, a post-processor tool designed to compute the human thermal comfort indices from ENVI-met model output simulated datasets. Biomet is established upon the 'Standard Human' according to ISO 7730 (Olesen and Parsons, 2002).

It is important to note that among 165 thermal indices, Potchter et al. (2018) (Potchter et al., 2018) have considered the PET index as one of the most reliable thermal indices and widely used for arid climate zone studies. Moreover, Cohen et al. (2019) (Cohen et al., 2019) conducted a study in Beer Sheva, Israel, where they modified the PET index scale specifically for the arid climate (BWh). This adaptation proved beneficial in achieving more accurate results relevant to the current study.

**Table 3**
Input data for the models in ENVI-met software

| | | | | | |
|---|---|---|---|---|---|
| **SPACES** | | | | | |
| **Main Model Area Grid size in meter** | 80 m x 80 m x 35 m | | 80 m x 80 m x 35 m | 80 m x 80 m x 35 m | |
| **$D_x$ = size of X grid** | $d_x$= 1 | | $d_x$= 1 | $d_x$= 1 | |
| **$D_y$ = size of Y grid** | $d_y$= 1 | | $d_y$= 1 | $d_y$= 1 | |
| **$D_z$ = size of Z grid** | $d_z$= 1 | | $d_z$= 1 | $d_z$= 1 | |
| **Building material** | Position/Material | Thickness | Emissivity | Absorption | Reflection |
| | Wall: brick wall (burned) | 0.30 | 0.90 | 0.60 | 0.40 |
| | Roof: light weight concrete | 0.25 | 0.90 | 0.70 | 0.30 |
| | Specific materials: | | | | |
| | Plexiglass | 0.03 | 0.90 | 0.05 | 0.05 |
| | Aluminium | 0.03 | 0.18 | 0.10 | 0.90 |
| **Building 3D Model** |  | | | | |
| | Existing building and nearby environment | | 3D modeled building | ENVI-met building | |
| **Soil** | Profiles | Albedo | Emissivity | Surface is irrigated | |
| | Loamy soil | 0.0 | 0.90 | True | |
| | Sandy loam | 0.0 | 0.90 | True | |
| | Pavement concrete | 0.5 | 0.90 | False | |
| **Vegetation / Albero Characterization** | **Physical Properties** | | **Albero 3D model** | **Tree** | |
| **Phoenix Dactylifera** | Palm Tree;<br>Height (m): 10.00<br>Canopy (m): 9.00<br>Number of Cells: 9 x 9 x 12 (1 x 1m)<br>Leaf Type: Conifer<br>Foliage Shortwave Albedo: 0.18 | |  | | |
| **Prosopis Juliflora** | Prosopis Juliflora;<br>Height (m): 7.00<br>Canopy (m): 7.00<br>Number of Cells: 5 x 5 x 7 (1 x 1m)<br>Leaf Type: Evergreen<br>Foliage Shortwave Albedo: 0.18 | |  | | |
| **Ceratonia Siliqua** | Ceratonia Siliqua;<br>Height (m): 5.00<br>Canopy (m): 5.00<br>Number of Cells: 3 x 3 x 5 (1 x 1m)<br>Leaf Type: Deciduous<br>Foliage Shortwave Albedo: 0.18 | |  | | |
| **Ficus Retusa** | Ficus Retusa;<br>Height (m): 3.00<br>Canopy (m): 3.00<br>Number of Cells: 3 x 3 x 3 (1 x 1m)<br>Leaf Type: Deciduous<br>Foliage Shortwave Albedo: 0.18 | |  | | |
| **Vegetation grids/Canopy** | | **8x8 m configuration** | **10x10 m configuration** | **12x12 m configuration** | |
| **Phoenix Dactylifera (Palm tree)** | Vector / Raster |  | | | |
| **Prosopis Juliflora** | Vector / Raster |  | | | |
| **Ceratonia Siliqua** | Vector / Raster |  | | | |
| **Ficus Retusa** | Vector / Raster |  | | | |
| **Position** | | | | | |
| **Latitude [+N; -S] (°)** | 34.73 | | same | same | |
| **Longitude [-W; +E] (°)** | 5.39 | | same | same | |
| **Start and duration of the model** | | | | | |
| **Date of simulation** | 15/04/2021 | | 15/07/2021 | 15/10/2021 | |
| **Start time** | 00:00 | | 00:00 | 00:00 | |
| **Total simulation time (h)** | 24 | | 24 | 24 | |
| **Initial meteorological conditions** | | | | | |
| **Full forcing** | CSV data | | same | same | |

*2.4.1. Modeling of the conducted sample on ENVI-met v5 software*

*2.4.2. Validation of the conducted sample within RMSE and MBE.* Numerous studies validated their numerical models designed with ENVI-met software based on statistical metrics such as RMSE and MBE. For instance, Liu et al. (2021) systematically reviewed modeling and validation methods using ENVI-met software (Liu et al., 2021). Their research further supported the software's credibility in simulating urban environments. Yang et al. (2021) also verified the ENVI-met thermal environment simulation of Yanzhong Square Park in Shangai (Yang et al., 2021). Hence, many previous studies validated their models within different timing, such as 20 hours (Sharmin et al., 2017) and 28 hours (Taleghani et al., 2015). In the current study, the aim was to align with two relevant works of the study scope. Sodoudi et al. (2018) investigated the impact of green areas' spatial configuration on thermal comfort, and Hien et al. (2012) conducted a comparison between STEVE and ENVI-met models for the air temperature prediction, where their numerical models were calibrated under 48 hours running simulation.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (\mathrm{Sim}_i - \mathrm{Obs}_i)^2} \quad (1)$$

$$\mathrm{MBE} = \frac{1}{n} \cdot \sum_{i=1}^{n} (\mathrm{Sim}_i - \mathrm{Obs}_i) \quad (2)$$

All the study datasets comprise the field measurements, and simulation results are reported in Matallah et al. 2023 technical report (Appendix A).

Table 4.

*2.4.3. Assessment of the outdoor thermal comfort based on PET index*

As explained, the 12 models are simulated for a typical day of three seasons (spring, summer and fall). Fig. 8 depicts the baseline simulations' mapping of three different hours: 6:00 a.m., 2:00 p.m. and 10:00 p.m. during three seasons. It should be noted that the average PET values were obtained within the entire agricultural oasis perimeter, including the farm building, treating the entire area as a unified composition.

## 3. Results

The investigation of the potential oasis cooling effect and its impact on human thermal comfort (HTC) was carried out basically on 12 oasis settlements scenarios across one typical day of three different periods: spring (April), summer (July) and fall (October) within the agricultural oasis settlement. Fig. 9 shows the thermal comfort perception and levels' variations during 24 hours. In every scenario, the typical summer day does not represent any comfortable thermal zone (neutral), indicating a very hot thermal heat stress varied from 25 % to 41.7 %, equal to 06 and 10 hours, respectively, per day. Therefore, during July, the hot thermal stress zone shows percentages lower than 10%, referred to in Configurations 2, 3, and FR8 from Configuration 1. Accordingly, thermal heat stress was quickly changeable from warm to hot during the daytime. *Ceratonia Siliqua* and *Ficus Retusa*'s 10 m and 12 m grids showed the highest heat stress rates, equaling 37.5% and 41.7%.

Otherwise, April holds the comfortable period in all scenarios, with a neutral thermal stress average of 41.6%, followed by October with 22.9% and July with 0.0% of the neutral thermal stress zone. Thus, the comfortable thermal duration in spring reaches a rate of 54.2%, lasting for approximately 13 hours per day. Phoenix Dactylifera's scenarios PD8, PD10, and PD12 showed the highest neutral thermal zone rates compared to the rest of the scenarios reaching 50%, 54.2% and 45.8%, respectively, in April and 33.3%, 25%, and 21%, respectively in October.

Over all the agricultural oasis' scenarios, the $T_{air}$ maxima's values were 28.2°C, 24.4°C, and 37.4°C versus minima's values equal to 18.4°C, 18.7°C, and 30.8°C in April, October and July, respectively. Moreover, $R_H$ rates varied between maxima's values of 59.8%, 58.1%, and 56.8% versus minima's values of 22.8%, 31.8%, and 29.3% in April, October and July, respectively. In contrast, $V_{air}$ varied through maxima's values of 6.00 m/s, 3.00 m/s, and 4.50 m/s to minima's values of

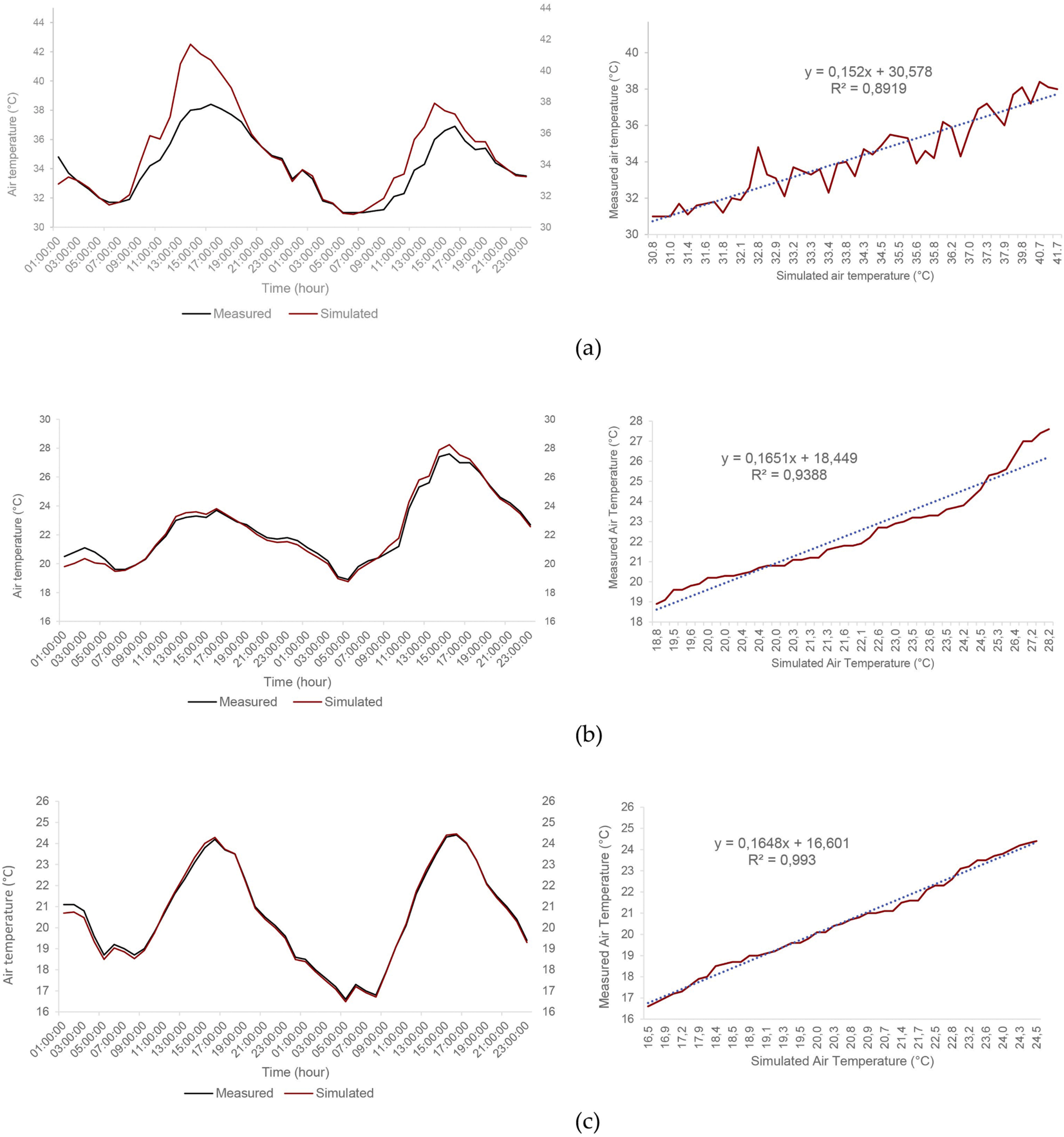



**Fig. 7.** Validation of the numerical baseline model created on ENVI-met: (a) July; (b) April; (c) October

**Table 4**
Validation of the numerical model with statistical metrics

| Site | Indices | Validation statistical metrics | |
|---|---|---|---|
| July | RMSE | 1.21 | 3.48 % |
| | MBE | 0.51 | 1.47 % |
| April | RMSE | 0.92 | 4.09 % |
| | MBE | 0.02 | 0.09 % |
| October | RMSE | 0.15 | 0.71 % |
| | MBE | - 0.05 | - 0.25 % |

0.9 m/s in April and 1.20 m/s in October and July, respectively. $T_{mrt}$ (Sinsel et al., 2022) reveals variations between maxima's with 59.8°C, 54.5°C, and 67.9°C and minima's with 8.0°C, 8.1°C, and 23.2°C in April, October and July, respectively.

### *3.1. Oasis effect and outdoor thermal comfort*

By comparing the baseline oasis settlement (PD8) to the rest of the scenarios featured in Table 5, the oasis cooling effect was remarkably obtained during nighttime hours (6:00 a.m. and 10:00 p.m.) with a significant decrease in levels of human thermal stress. In these scenarios,

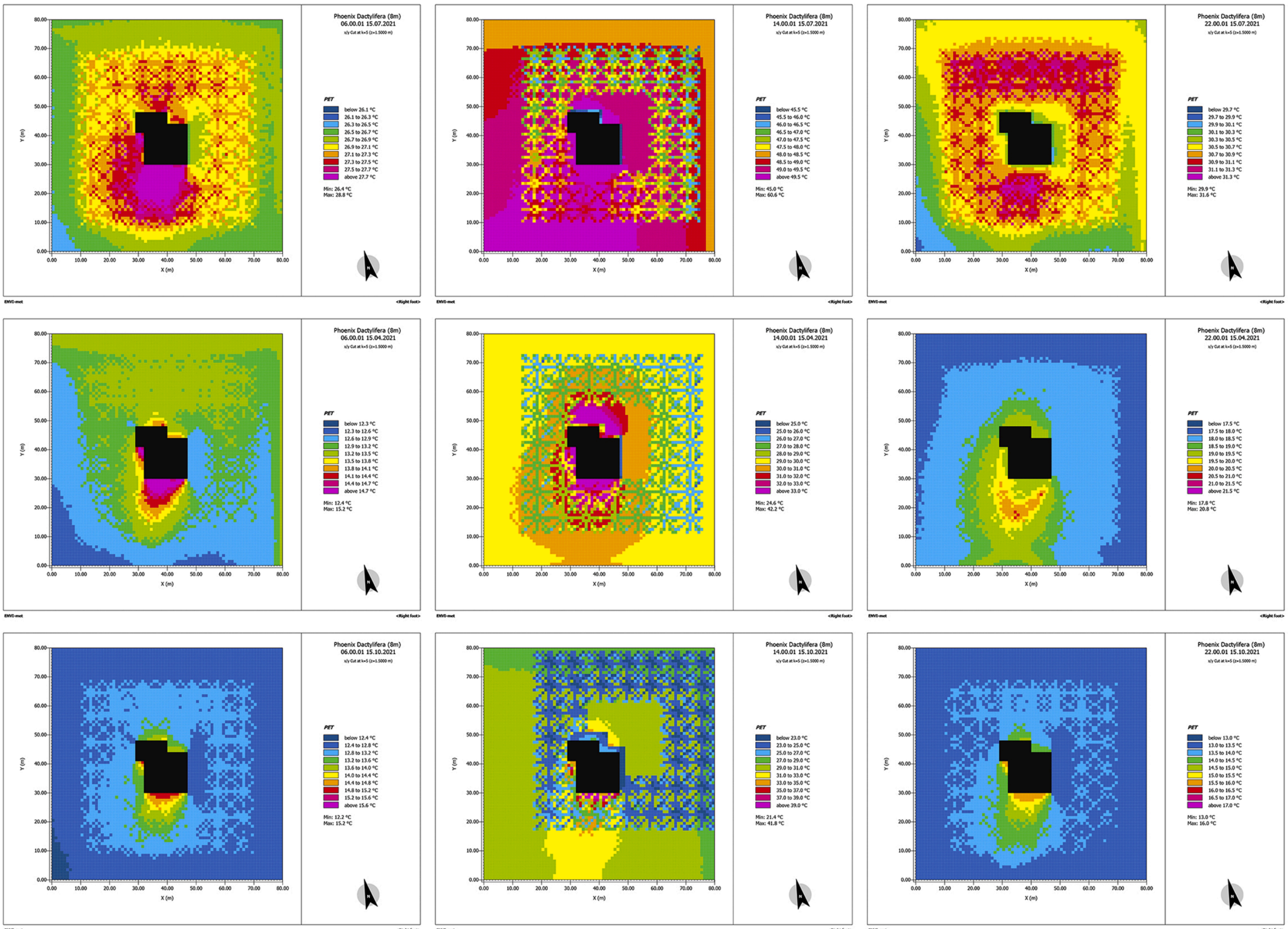


**Fig. 8.** PET values of the baseline via ENVI-met Leonardo mapping interface

the oasis cooling differences upon the HTC were low (< 3°C). The highest mean value appears at 2:00 p.m., reaching 2.2°C in the PD12 scenario, while the lowest appears at 6:00 a.m. with 0.1°C in the PD10 scenario. Hourly differences in oasis effects between scenarios increase before sunrise and after sunset, whereas differences decrease and become warming effects, specifically at noon. Notably, results showed that all scenarios warmed up at 2:00 p.m. compared to the baseline scenario, with differences' values reaching 8.6°C in the FR8, except the PD12, which experiences a cooling effect compared to the baseline scenario in the three typical periods. The Ficus Retusa's scenarios, within all spacing configurations, reveal the warmest scenarios during noon hours.

The decrease in the HTC levels during summer was very low, specifically in mild daytime until late noon hours. The lowest thermal stress zone was the slightly warm, three to five hours before sunrise. Therefore, the nighttime cooling effect inside the oasis settlements during April and October caused a perceived cool down to cool thermal stress felt, reaching 05 and 06 hours in April and 07 hours to 09 hours in October. However, the oasis settlements positively affect HTCs during daytime hours in April before midday and after sunrise to midnight, such as in October during the early morning and afternoon hours.

In parallel, April represents the most affected period by the warming effect through all oasis settlements' scenarios, with warming difference's values varying between 1.2°C to 8.6°C (Fig. 10).

## 4. Discussion

This section provides an overview of the main recommendations, strengths and limitations, and implications for practice and future work based on the research findings.

There is a large confusion between the oasis cooling effect and human outdoor thermal comfort, and almost no common evaluation within the oasis settlements in arid areas.

Towards a novel methodology, this study aimed to determine the oasis effect inside multi-agricultural oasis settlements grids during three seasons on the human thermal comfort in arid climates. The modeled scenarios were based on the current main findable species in the investigated territory. We acknowledge that the huge lands of deserts around the world have a distinct lifestyle that is closely linked to Saharan environments. However, none of the previous studies dedicated sufficient spatial standards and microclimatic ranges to maintain neutral human well-being in these areas passively.

Despite the variety of species, configurations, and timeframes, in the conducted context, the oasis cooling effect has not been found during a typical summer day. Certain configurations, particularly those featuring small canopies (3 m and 5 m), have been shown to increase human thermal stress levels.

In comparison to relevant studies on the oasis cooling effect caused by vegetation in arid climates in particular: Fan et al. (2017), Saaroni et al. (2004), Taha et al. (1991), the current outcomes show similarities to results reported by Potchter et al. (2008). This latter study indicated that the oasis cooling effect is not limited to air temperature reduction but involves other parameters such as relative humidity rate, air velocity and direct radiation. Moreover, the oasis cooling effect on human thermal comfort is supposed to be significantly perceived during the nighttime, unlike daytime hours. Accordingly, human thermal comfort


**Fig. 9.** Human thermal stress levels and fluctuations within all agricultural oasis settlements' scenarios

is strongly sensitive to oasis cooling effect variations positively or negatively at the same time. That means a reduction of air temperature or the rise of relative humidity inside an agricultural oasis settlement is insufficient to control thermal stress levels.

### 4.1. Findings and recommendations

1. The Phoenix Dactylifera's grids (10 and 12 m), characterized by a large canopy of 9m, represent the favorable scenarios for the oasis cooling down effect. Further, implementing Phoenix Dactylifera within these spatial grids can guarantee 12 hours of the neutral thermal zone under favorable microclimatic requirements. Consequently, in specific Phoenix Dactylifera's configurations with 10 m and 12 m grids, the human thermal stress can be reduced by 1.0°C and 2.0°C, respectively, throughout 12 hours a day.
2. Otherwise, small canopies with large spaced grids, such as Ceratonia Siliqua (10, 12 m) and Ficus Retusa (10, 12 m), should increase the perceived heat or cold thermal stress.

**Table 5**
Oasis cooling effect differences

| Configuration of scenarios | Time | Phoenix Dactylifera | | | Prosopis Juliflora | | | Ceratonia Siliqua | | | Ficus Retusa | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | July | April | October | July | April | October | July | April | October | July | April | October |
| 8 m | 6:00 a.m. | 27.0 | 13.2 | 12.6 | ▼ 0.4 | ▼ 0.2 | ▼ 0.2 | ▼ 0.6 | ▼ 0.2 | ▼ 0.2 | ▼ 0.5 | ▼ 0.4 | ▼ 0.4 |
| | 2:00 p.m. | 46.5 | 27.6 | 28.6 | ▲ 2.5 | ▲ 4.0 | ▲ 1.4 | ▲ 2.5 | ▲ 6.4 | ▲ 1.6 | ▲ 2.5 | ▲ 8.6 | ▲ 1.6 |
| | 10:00 p.m. | 30.7 | 18.2 | 13.2 | ▼ 0.3 | ▼ 0.4 | ▼ 0.0 | ▼ 0.4 | ▼ 0.2 | ▼ 0.2 | ▼ 0.4 | ▼ 0.8 | ▼ 0.2 |
| 10 m | 6:00 a.m. | ▼ 0.1 | ▲ 0.2 | ▲ 0.2 | ▼ 0.4 | ▼ 0.2 | ▼ 0.2 | ▼ 1.0 | ▼ 0.4 | ▼ 0.2 | ▼ 0.6 | ▼ 0.4 | ▼ 0.4 |
| | 2:00 p.m. | ▲ 2.3 | ▲ 3.4 | ▲ 1.4 | ▲ 2.3 | ▲ 3.6 | ▲ 1.8 | ▲ 2.5 | ▲ 3.8 | ▲ 1.6 | ▲ 2.5 | ▲ 8.4 | ▲ 1.6 |
| | 10:00 p.m. | ▼ 0.0 | ▼ 0.2 | ▲ 0.2 | ▼ 0.3 | ▼ 0.4 | ▼ 0.2 | ▼ 0.4 | ▼ 1.0 | ▼ 0.2 | ▼ 0.4 | ▼ 0.8 | ▲ 0.4 |
| 12 m | 6:00 a.m. | ▼ 0.2 | ▼ 0.0 | ▼ 0.2 | ▼ 0.5 | ▼ 0.2 | ▼ 0.2 | ▼ 0.5 | ▼ 0.2 | ▼ 0.2 | ▼ 0.6 | ▼ 0.2 | ▼ 0.4 |
| | 2:00 p.m. | ▼ 0.3 | ▼ 1.2 | ▼ 2.2 | ▲ 2.3 | ▲ 3.4 | ▲ 1.2 | ▲ 2.1 | ▲ 3.6 | ▲ 1.4 | ▲ 2.3 | ▲ 3.6 | ▲ 1.4 |
| | 10:00 p.m. | ▼ 0.2 | ▼ 0.4 | ▼ 0.0 | ▼ 0.3 | ▼ 0.6 | ▼ 0.2 | ▼ 0.3 | ▼ 0.6 | ▼ 0.2 | ▼ 0.4 | ▼ 0.6 | ▼ 0.2 |

3. Overall the human thermal stress levels, $T_{mrt}$, reveals the main acting microclimatic factor upon the neutral human thermal comfort related to an oasis cooling effect inside an agricultural oasis settlement with a rate of 53%. Therefore, $T_{air}$, $R_H$ and $V_{air}$ gradually affect the neutral human thermal comfort by 33%, 30% and 17%, respectively.
4. Based on the study, it has been found that the human neutral thermal stress within agricultural oasis settlement can be assured into ranges of 29°C to 37°C, 19°C to 20°C, 55% to 58%, and 1m/s to 2m/s upon the $T_{mrt}$, $T_{air}$, $R_H$ and $V_{air}$ respectively.
5. Therefore, assessing the human thermal comfort within several agricultural oasis settlements' grids has revealed distinct thresholds linked to various microclimatic parameters. Achieving these thermal thresholds can passively ensure a neutral outdoor thermal perception within similar areas. Table 6 depicts the microclimatic parameters' ranges related to different thermal stress levels relevant to an agricultural oasis settlement. Consequently, these ranges are useful for determining the PET index values relevant to oasis settlement areas.
6. On the other hand, the air velocity up and below 2m/s frequency represents a crucial factor that affects elevation on heat and cold thermal stress, and it can quickly generate cool, warm or hot thermal stress depending on the season.

### *4.2. Strength and limitations*

1. The paper's main strength lies in determining guiding rules of the configuration for oasis grids to ensure a longer neutral thermal perception duration. Previous studies searched the oasis cooling effect variations without modifying the initial palm grove grids primarily covered by palm trees. The value of the current study is the foundation of the basics of urban planning in arid environments (Fig. 2).
2. Determining the optimal utilization of climatic parameters to enhance the microclimate in an oasis setting in an arid climate. By calculating the PET values for a series of parametric scenarios of oasis configurations, the study succeeded in defining the optimal and nearly optimal thermal comfort thresholds.
3. The varied combinations and solutions for the spatial, climatic and plant parameters explored in this study are rich and comprehensive. Consequently, the results were able to define the oasis design and planning configurations that can lead to the maximum cooling conditions during extreme heat events in spring, summer and fall. To our knowledge, no existing studies defined the spatial configuration in palm groves that can maintain the maximum neutral comfort hours during summers in arid climates.
4. The study used a coupled methodology combining on-site continuous field measurements and a high-quality calibrated numerical model using ENVI-met software based on ASHRAE 14 Guideline (ASHRAE, 2014). The primary approach of the methodology was on the validation of the numerical model, which required 510 hours for the validation step on software. Subsequently, the study involved over 2000 hours of computational time (Appendix A). The study ensured that simulations were accurate and reliable. It is crucial for providing insights into the oasis cooling effect and its potential benefits for human health and well-being in arid environments.
5. However, it is important to note that this study has several limitations. For instance, our reference case does not fully capture all the characteristics of the oasis settlement, such as the presence of irrigated canals or secondary vegetated areas (vegetable gardens) alongside the primary trees. These factors would have been crucial in better analyzing the leaf temperatures of trees and the heat and vapor exchanges between plants and the atmosphere. We could not obtain the solar radiation requirements to enhance our dataset analysis due to insufficient instruments.

### *4.3. Implication on practice and research*

No planning guidelines exist for spatial configurations of oasis palm groves and the urban integration of built-up habitats.

The study findings hold great potential in guiding the oasis settlements areas' agriculture departments, local units, and centers specialized in Date palm cultivation, such as the Desert Research Center (DRC) in Egypt and the Scientific and Technical Research Centre on Arid Regions (CRSTRA) in Algeria, by incorporating the main microclimatic thresholds and agricultural oasis grids into urban planning.

The coexistence of palm groves within these environments is crucial due to their significant economic value for human life in oasis settlements. Therefore, the Algerian government aims to gain 400 million dollars by 2025 through Date palm exports.

Like many countries, the Algerian government must update urban guidelines documents, specifically the Master Plan of Development and Urban Planning (PDAU) and the Land-Use Plan (POS) guidelines. The research outcomes provide a solid foundation for shaping oasis urban planning, focusing on Nature-based urban planning. Furthermore, standardization of the spatial aspects and the microclimatic thresholds are key tools in optimizing livability inside the worldwide oasis areas.

Our findings hold significant value and have the potential to make valuable contributions to the United Nations Human Settlements Programme (UN-Habitat) and the World Green Building Council (World GBC) co-developed the Guidelines for Sustainable Reconstruction and Urban Regeneration in the MENA Region.

In light of the principles established in this study, future work will incorporate parametric studies to refine further and define the optimal design configurations for urban settlements.

Moreover, upcoming research will investigate the role of water and irrigation as systems in passive cooling strategies' monitoring. Understanding the impact of these systems on passive cooling will be crucial for implementing effective, sustainable practices in urban environments.

## 5. Conclusion

This study aims to develop a methodological approach to evaluate the impact of the oasis cooling effect on human thermal comfort in Tolga Oasis, with its arid climate (Koppen-Geiger BWh classification). Twelve

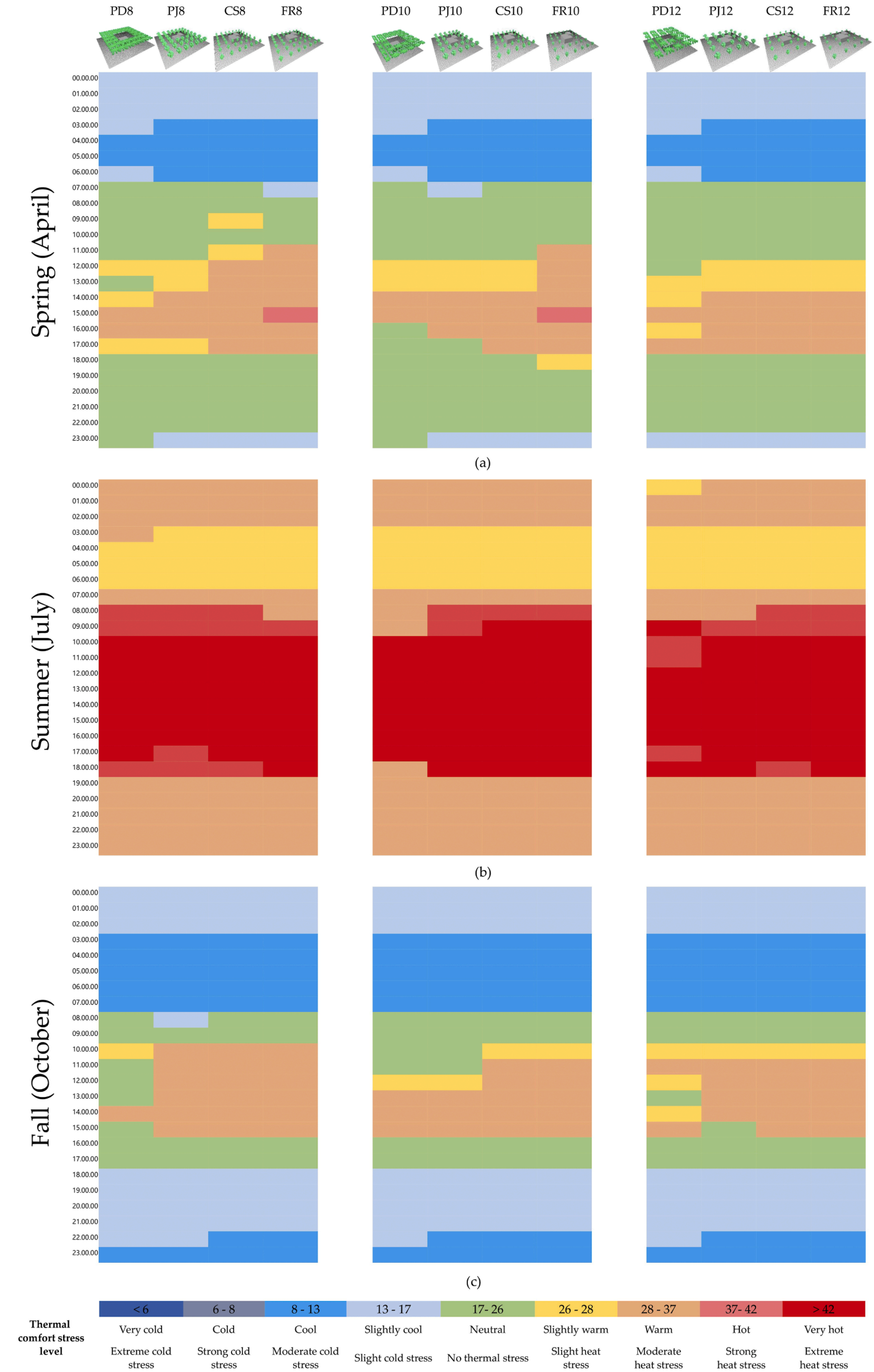



**Fig. 10.** Mean daily PET values of a typical day in: (a) spring (April), (b) summer (July) and (c) fall (October) within all scenarios

**Table 6**
Summary of the main findings

| Thermal stress | PET index [BWh] (°C) | $T_{air}$ thresholds (°C) | $R_H$ thresholds (%) | $V_{air}$ thresholds (m/s) | $T_{mrt}$ thresholds (°C) |
|---|---|---|---|---|---|
| Very cold | < 6 | - | - | - | - |
| Cold | 6 - 8 | - | - | - | - |
| Cool | 8 - 13 | 19 - 20 | 54 - 56 | ≥ 2 | 9 - 10 |
| Slightly cool | 13 - 17 | 20 - 21 | 50 - 53 | ≥ 2 | 10 - 11 |
| Neutral | 17 - 26 | 19 - 20 | 55 - 58 | 1 - 2 | 29 - 37 |
| Slightly Warm | 26 - 28 | 26 - 32 | 40 - 53 | 2 - 4 | 25 - 43 |
| Warm | 28 - 37 | 25 - 28 | 38 - 50 | 2 - 3 | 45 - 51 |
| Hot | 37 - 42 | 30 - 33 | 41 - 56 | ≤ 2 | 54 - 59 |
| Very hot | > 42 | 32 - 33 | 44 - 51 | ≤ 2 | 59 - 62 |

agricultural oasis settlements were modeled according to spatial, climatic and plant characteristics to define the suitable oasis grids and the optimal microclimatic thresholds to ensure for longer the neutral thermal zone of an oasis settlement inhabitants. This comprehensive study indicates a need for more research and deeper investigation, particularly regarding the gaps between the parametric urban design studies within the agricultural oasis areas and global warming. A research methodology is a quantitative approach that combines field measurements and high-quality numerical modeling via ENVI-met software.

Integrating the palm groves' grids within the built environment is essential for the long-term sustainability of urban development in arid environments. Implementing the Phoenix Dactylifera tree can significantly enhance the neutral human thermal perception during 12 hours under favorable microclimatic conditions. Therefore, a tree canopy is preferable above 5 m providing additional shaded areas for individuals. In parallel, the human neutral thermal zone can be ensured into ranges of 29°C to 37°C, 19°C to 20°C, 55% to 58%, and 1m/s to 2m/s upon the $T_{mrt}$, $T_{air}$, $R_H$ and $V_{air}$, respectively.

Combining oasis grids, plants' characteristics and climatic parameters offers optimal oasis settlement design alternatives. Future work should focus on parametric study for the urban settlements design in oasis territories. Furthermore, the water and irrigation systems should be further developed to incorporate passive cooling systems for urban mitigation strategies.

## Author Declaration

We hereby certify that this paper consists of original, unpublished work not under consideration for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfy the criteria for authorship but are not listed. Furthermore, we confirm that all authors have approved the order in which they are listed in the manuscript.

## Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

## Data availability

Data will be made available on request.

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## Appendix A

To download the technical report: https://hdl.handle.net/2268/302134.

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