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Research Article

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Why Small Built Parks Matter: Evidence that Small Urban Vegetation Improves Thermal Comfort in Hyper-arid Cities

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Abstract

Muscat, the capital of Oman is a hyper-arid city characterized by intensive solar radiation for most part of the year similar to the neighboring Gulf cooperation countries (GCC). Outdoor Thermal Comfort (OTC) is critical for livability, was assessed. A field survey was carried out in vegetated and non-vegetated area in summer where objective and subjective parameters were simultaneously collected. The former represents environmental parameters measured using a Kestrel 5400 Heat Stress Tracker, while the later was assessed through a structured face-to-face questionnaire. A total of 415 respondents were involved to assess their thermal sensation vote (TSV) and environmental parameters preference using ASHRAE 7-point scale and Mclntyre scale respectively. The computation of the Physiological Equivalent Temperature (PET) was performed via RayMan pro version 3.1 software. The Physiological Equivalent Temperature (PET) range of 23.6°C- 30.8°C and neutral PET of 27.2°C was obtained. PET is moderately correlated ($R= 0.7$, $R^2 = 0.50$) with thermal sensation votes and it is significant at the 0.01 level (2-tailed). A linear regression model specific to the country's climatic zone and the national dress code of the citizens was established as: $TSV= (0.14\times PET) -3.8$. The majority of respondents (96.2%) in vegetated area felt, the temperature to be more thermally acceptable and comfortable, while the percentage fall to quarter in non-vegetated area. This study emphasizes the importance of human thermal comfort in urban areas contributing to knowledge on the influence of microclimate in hot arid climatic zones, and cities in those zones can adapt by transforming the urban spaces.

Keywords: Urbanization; Outdoor thermal comfort; Thermal sensation votes; Physiological equivalent temperature; microclimate

1 Introduction

More than half of the world's population now lives in cities, prompting researchers, engineers, architects, and urban planners to center their efforts on urban microclimate and outdoor thermal comfort (Fang et al., 2018; Salata et al., 2016). Accordingly, the quality of outdoor spaces in urban settings is critical to the quality of life in cities. Furthermore, the rising urbanization of cities in recent years has raised the need for the provision of more outdoor areas for people's relaxation and leisure activities.

(Makaremi et al., 2012). In fact, the outdoor microclimate is an essential component among several that impact the quality of outdoor places (Chen and Ng, 2012). Additionally, pleasant micrometeorological conditions may encourage people to spend more time outside, which could result in a decrease need for air conditioners and subsequent reduction in energy consumption. Furthermore, the impact of microclimate on human well-being needs to be taken into account (Golasi et al., 2018) in attaining thermal comfort to make cities livable.

The "state of mind in which a human feel satisfied within the thermal environment" is known as human thermal comfort (ANSI, 2004). Numerous elements, such as the air temperature (*Ta*), humidity (*RH*), mean radiant temperature (*Tmrt*), and air movement (*v*), affect human thermal satisfaction. In the end, non-climatic variables including garment insulation, activity level, age, gender, physical appearance, subcutaneous fat, and fitness also affect how people perceive their surroundings (Aram et al., 2020; Pantavou et al., 2020).

In contrast to studies on thermal comfort in interior settings, outdoor thermal comfort (OTC) is a comparatively recent topic of study (Aghamolaei et al., 2020). Recently, the number of OTC studies has been rising up on a worldwide scale. These studies' methodologies are based on field surveys or computer simulations (Canan et al., 2019; Baruti et al., 2024). Field studies for assessing OTC might be conducted for a short period or over multiple seasons and can be complemented by questionnaire surveys (Nasrollahi et al., 2021). And also, could be either transversal (i.e., surveys in which each participant only took part once) (Canan et al., 2019; Canan et al., 2020) or Longitudinal (i.e., a small number of participants were subjected to various microclimates at various times throughout the survey (Cheng et al., 2012; Salata et al., 2016; Xu et al., 2023).

Many indices have been used so far to assess thermal comfort, but an often-applied one is the Physiological Equivalent Temperature (PET) (Klemm et al., 2015; Potchter et al., 2018). This bioclimatic thermal index refers to the air temperature at which a human can maintain their energy budget while keeping skin temperature, core temperature, and sweat rate comparable to those found in the test setting (Binarti et al., 2020). It is a measure of human thermal sensations and is based on the Munich Energy-balance Model for Individuals (MEMI) (Lindner-Cendrowska and Błażejczyk, 2018). Since this index is applicable in changing outdoor environments and involves most meteorological elements (Zhang et al. 2022), many researchers rely on it for conducting their studies, covering different climatic zones, e.g., humid subtropical (Cfa) in China (Wang et al. 2018; Su et al. 2024), Mediterranean (Csa) in Turkey (Canan et al. 2019) and Italy (Salata et al. 2016), marine west coast (Cfb) in Netherlands (Klemm et al. 2015), and Poland (Lindner-Cendrowska, 2013), Tropical Savanna (Aw) in Tanzania (Ndetto and Matzarakis, 2016) , tropical rainforest (Af) in Singapore (Heng and Chow, 2019), mid-latitude Steppe and desert (Bsh) in India (Manavvi and Rajasekar, 2019), tropical and subtropical steppe (Bsk) in Syria (Yahia and Johansson, 2012), tropical and subtropical desert (BWh) in Egypt (Mahmoud, 2011; Elnabawi et al. 2016). The majority of these studies were conducted in climates that ranged from temperate to tropical, in contrast to arid and semi-arid regions, which account for approximately

one-third of both the land surface and the population of the globe (Cohen et al., 2019).

The quality of life in urban areas is greatly influenced by the design and management of built environments (Aghamolaei et al., 2020). The microclimate within an urban setting is directly influenced by built-up places. Every urban area produces its own microclimate, which cause spatial variations of microclimate and, as a result, outdoor thermal comfort (Baruti et al., 2024). For example, Urban parks are fundamental components of urban ecosystems and landscapes, as well as vital elements of outdoor open space (Xu et al., 2018). Green spaces are typically cooler than their built-up surroundings (Quadros and Mizgier, 2023). Wang et al. (2017) mentioned that the microclimate and human thermal comfort in a nearby urban area were greatly impacted by urban greenery infrastructure. Thus, the microclimate scale must be the primary focus of research.

Outdoor thermal comfort (OTC) is harder to assess than indoor thermal comfort because outdoor settings comprise a greater spectrum of related factors. This is the first study in Oman aiming to develop index for the country's climatic zone and the national dress code of the citizens. It attempted to get, for the first-time thermal sensation and environmental preference and, ultimately, thermal comfort condition of people, using a measurable microclimatic parameter (objective assessment) and inhabitant's perception (subjective assessment). Globally, researchers have investigated OTC in a wide range of cities across a spectrum of climates (Mahmoud, 2011; Eludoyin and Adelekan, 2012; Yahia and Johansson, 2012; Lindner-Cendrowska, 2013; Tsitoura et al., 2014; Klemm et al., 2015; Wu et al., 2015; Giannakis et al., 2016; Elnabawi et al., 2016; Ndetto and Matzarakis, 2016; Salata et al., 2016; Aljawabra and Nikolopoulou, 2018; Wang et al., 2018; Canan et al., 2019; Heng and Chow, 2019; Manavvi and Rajasekar, 2019). Due to the exposure to excessive thermal loads, it is crucial to assess how people feel the heat in hyper-arid cities like Muscat. In an effort to better understand how land uses can affect thermal comfort, this research also explores the differences in people's thermal comfort perception in vegetated and non-vegetated area on their potential in regulating microclimate. The overall outcome of this study may provide a better knowledge of the effect of microclimate on people's perceptions, and governments can make it a priority when establishing projects or altering land use in the city for development purposes.

2 Materials and methods

2.1 Study site

Oman's summer season lasts at least seven months, from April to October (Lawati et al., 2022). The study was performed in Muscat Governorate, the capital of Oman, which according to Köppen classification has "hot and dry" climate (BWh) (Al-Rasbi & Gadi, 2021). The average annual temperature was 28.3°C for the period (2000 - 2019) with maximum temperature of

48.4 °C and a minimum of 11.3°C in summer and winter respectively. The average annual rainfall was 77.7 mm with maximum precipitation of 309 mm in 2007 during the tropical Gonu cyclone. The average annual relative humidity for the same period was 60.5 % (CAA,2020). Muscat is the biggest city in term of population consists of six sub-cities (Wilayates) with a total of 1,302,440 inhabitants, according to the latest e-census conducted in 2020. Majority of them (478,517) reside in A'seeb sub-city and representing about 36.74 % of Muscat governorate (NCSI, 2020). Two contrasting land-use in A'seeb were chosen to conduct the survey, vegetated (Al-Sahwa park-627614E, 2609369N) and nearby commercial non-vegetated area (622583E, 2608859N). Figure 1 shows the boundary of the study area. Figure 2 and 3 show location of measurement point and field survey photos in vegetated area (park) and non-vegetated area (commercial) respectively. The study was carried out from 15 August to 4th September 2021, which encompasses a period of 20 days from the usual hot condition of Muscat city. To draw attention to the outdoor thermal comfort in the hot and semiarid to hyper-arid environment, microclimatic measurement and questionnaire field survey were taken simultaneously from (09-11:30 AM), and from (3:30-6:00 PM) local time.

2.2 Data collection

2.2.1 In-situ microclimatic measurements

The climatic parameters were measured using the Kestrel 5400 Heat Stress Tracker. Every five minutes, the air temperature (T_A), globe temperature (T_{GLOBE}), wind speed (WS), and relative humidity (RH) were automatically recorded at a height of 1.1 meters above the ground (Hadianpour et al., 2018; Elnabawi et al., 2016; Kumar and Sharma, 2022), which equates to the average adult's center of gravity. Table 1 presents details of the sensors that were utilized to measure the microclimate. The layout of research methodology is illustrated in Figure 4.

2.2.2 Survey

In conjunction with measuring microclimatic parameters a questionnaire survey was performed. The outdoor thermal comfort was assessed using a transversal field survey. This implies that each responder took the survey only once (Salata et al., 2016). Face-to-Face interviews were carried out with participants, who were willing to take part in the study upon request while they were in the study sites. The participants are met within 3 meters away from sensors and their feeling responses were recorded (Yao et al., 2018). Given that the survey was carried out throughout the COVID-19 pandemic, all appropriate safety measures were implemented, such as sanitization and mask usage. Residents of Muscat who were at least 15 years old and visited the study sites during the survey period were the target population. Data from respondents was collected automatically in a Google spreadsheet using a web-based survey created with Google Forms.

According to the (Golasi et al., 2018), the minimum respondents depend on the population size. Accordingly, 415 respondents were surveyed to express their feelings about thermal comfort and preferences for various environmental parameters. This was obtained using the following equation

$$n = \frac{N \times (\frac{1}{E^2})}{N + (\frac{1}{E^2})} \quad (1)$$

Where n is the minimum size of the sample, N the population of the A'seeb sub-city (478517) and E is the sampling error (assumed to be 5 %).

To comply with ISO 10551 and ASHRAE standard 55, Supplementary file display the questionnaire, that includes two parts. The opening section enquired about demographic and personal information including (gender, age, weight, height, clothing types, time of residency in Muscat, activity level in the past 30 minutes and at the moment while answering the questionnaire). While the second part involves asking respondents about their thermal feeling at the moment of taking meteorological measurements and rating it in a scale consists of 7-points (cold = -3, cool = -2, slightly cool = -1, neutral = 0, slightly warm = +1, warm = +2, and hot = 3 (Villadiego and Velay-Dabat, 2014; Salata et al., 2018; Sharmin et al., 2019; Larriva and Higueras, 2020). In addition, respondent's preference towards different meteorological parameters was assessed using the Mclntyre scale (3-point scale). That means thermal preference was rated as (cooler = -1, unchanged = 0, warmer = +1), Humidity preference was rated as (drier = -1, unchanged = 0, damper = +1), wind speed preference was rated as (weaker = -1, unchanged = 0, stronger = +1) and solar radiation preference was rated as (weaker = -1, unchanged = 0, stronger = +1) (Hadianpour et al., 2018; Larriva and Higueras, 2020).The final drawn information about respondent's comfort perception was assessed on a 3-point scale (uncomfortable = -1, acceptable = 0, comfortable = 1) (Kumar and Sharma, 2022).

2.2.2 Data processing and thermal comfort assessment

The physiological equivalent temperature (PET), a steady-state assessment technique based on thermo-physiological heat balance, was used to determine the outdoor thermal comfort (Lin et al., 2019; Xu et al., 2018; Cohen et al., 2019). According to the input parameters, the PET value for each respondent was calculated using the RayMan Pro version 3.1 software (Matzarakis et al., 2009; Simath and Emmanuel, 2022). Some of these parameters can be used directly to feed the software, but others can be drawn from other parameters by specific equations and then utilized as input. These parameters were the mean radiant temperature (*Tmrt*), activity level (metabolic rate) and insulation of the cloth (*I cl*) wearing by respondents. With the aid of the black globe temperature (*Tg*), wind speed (*WS*), and air temperature *(Ta)*, the mean radiant temperature (*Tmrt*)

was calculated by the following equation (Canan et al., 2019; He et al., 2020; Kumar and Sharma, 2022).

$$MRT = \left[(T_{GLOBE} + 273.15)^4 + \frac{1.1 \times 10^8 \times WS^{0.6}}{\varepsilon . D^{0.4}} . (T_{GLOBE} - T_A \right]^{0.25} - 273.15 \quad (2)$$

Where ε and D are the emissivity (0.97) and the diameter (0.0254 m) of the black globe.

Activity level was determined by calculated metabolic rate which involves many steps prior, and the following equations were fundamentals for this process (Canan et al., 2020; Salata et al., 2016).

$$Dubois\ area = 0.202 \times (W^{0.425} \times H^{0.725}) \quad (3)$$

$$BF\ (Body\ fat) Male = 0.685 \times W - 5.86 \times H^3 + 0.42 \quad (4)$$

$$BF\ (Body\ fat) Female = 0.737 \times W - 5.15 \times H^3 + 0.37 \quad (5)$$

$$FFM\ (Fat - free\ body\ mass) = Weight - BF \quad (6)$$

$$MB\ (Basal\ metabolic\ rate\ ) = 0.0484 \times (19.7 \times FFM + 743) \quad (7)$$

$$M\ (metabolic\ rate\ evaluated\ during\ survey\ ) = (0.7 \times M_{1(activity\ at\ answering\ the\ survey)} + (0.3 \times M_{2\ (activity\ in\ the\ past\ 30\ minutes)}) \quad (8)$$

$$Metabolic\ rate\ in\ Watt = (MB + M) \times Dubois\ area \quad (9)$$

People's clothing plays a role in thermal comfort assessment procedure, so that the determination of clothing insulation (I_{CL}) is critical. Since Muscat's residence includes citizens and expatriates especially from South Asia, therefore all predicted wearing garments have been introduced in the questionnaire. Since the lack of data availability about Omani traditional dress insulation for both genders. Therefore, this study relies on ISO 9920 as a guide, in addition to published insulation values for various Arabian Peninsula ensembles, which is at large extent similar in gulf cooperation countries (GCC) (ASHRAE, 2017; Havenith et al., 2015; Newsham et al., 1997; Yao et al., 2018). Values of cloth insulation are presented in the (Supplementary Table 1). The metabolic rate is computed as 1 MET for sitting, 1.2 MET for standing, 2.0 MET for walking, and 2.2 MET for exercising (Albdour and Baranyai, 2019).

Since assessing thermal comfort condition solely based on environmental parameters is insufficient, personal data beside values of clothing insulation and activity levels is required. Consequently, Physiological Equivalent Temperature (PET) as index used in this study involves inputs of measured air temperature, relative humidity, and wind speed as well as the computed mean radiant temperature. A version of RayMan Pro 3.1 was utilized to calculate the PET value. This procedure involves entering data of each respondent individually including personal information (height, weight, age, gender, clothing insulation, metabolic rate), measured environmental parameters (air temperature, wind speed, relative humidity), and computed mean radiant temperature. Taking into consideration, geographic information (latitude, longitude, altitude) of the place, the date and time of filling out the questionnaire to be entered in the software.

3 Results and Discussion

3.1 Microclimatic characteristics

During the field survey and measurements, the maximum air temperature was 40.6℃, and a minimum temperature of 30.0℃ with an average of 32.3℃ in vegetated area. In contrast these values are higher by about 5.0℃ for maximum, and 3.0℃ for the minimum in non-vegetated area. Generally, these two locations were differed by about 6.0 ℃ in the mean. Both the maximum and minimum relative humidity was recorded at higher level in vegetated area with values 84.0 % and 32.9 % respectively. These values drop to 63.8 % and 18.7 % in non-vegetated area, with a difference in the mean value by 27.6 %. These two locations exhibit higher relative humidity fluctuations and reaches its peak of about 51.1% and 45.0% for vegetated and non-vegetated area. Humidity can be affected by changes in air temperature, that means any changes in air temperature can have an influence on humidity. These findings provide an explanation for the link between humidity and air temperature, showing that a rise in one parameter causes a decrease in the other and vice versa. With a maximum speed of 3.5 m/s, the mean wind speed was higher in vegetated area by about of 0.8 m/s, while a maximum of 2.5 m/s was measured in non-vegetated area. Globe temperature was at its peak in the non-vegetated area, reaching 57.3°C with a mean of 47.4°C, whereas in the vegetated area it was 42.9°C with a mean of 34.2 °C. As it is important to take into consideration, indirect measured parameter have an impact in outdoor thermal comfort assessment. The computed mean radiant temperature from measured environmental data reached a maximum of 59.0°C and 42.9°C in non-vegetated and vegetated areas, respectively. Vegetated area showed lower minimum mean radiant temperature by 2.9°C compared to non-vegetated area. Various parameters and their statistical values are displayed in Table 2.

3.2 Personal and demographic parameters

Participation in the survey was limited to residents of Muscat City who had resided there for a minimum of six months and were willing to express their feelings and preference about microclimatic environmental parameters. A total of 415 face-to-face questionnaires were collected randomly during the field survey from both locations. Citizens made up 58.3% of the participants, while expatriates made up 41.7%. The biological sex was unevenly distributed between male (72.0 %) and female. The age was widely distributed between 15 and 71, with a mean of 34 years old. In this study the age groups were classified according to the National Center for Statistics and Information, with the lowest category of 15-24 so that everyone who is lower than this is excluded. Almost 62.41% aged between 25-44, and who aged 55 and above representing only 3.37% from the total participants. The weights were varied between 38.0 kg and 140.0 kg with an average of 68.9 ± 0.7 kg. The height was 1.7 ± 0.004 m on average with a maximum of 1.9 m and a minimum of 1.4 m. Metabolic rate of participants ranges between 112.0 m /w^2 to 215.0 m /w^2 with an average of 167.0 ± 0.86 m /w^2. Cloth insulation varies between 0.2 Clo to 1.9 Clo with an average of 0.86 ± 0.03 Clo and 1.8 ± 0.21 Clo for male and female respectively. The anthropometric information is depicted in Supplementary Fig. 1.

3.3 Participants subjective assessment

Thermal feeling was ranked using the ASHRAE 7-point scale: "cold" (-3), "cool" (-2), "slightly cool" (-1), "neutral" (0), "slightly warm" (+1), "warm" (+2), and "hot" (+3). Thermal sensation votes varied between “slightly cool” (-1) and “hot” (+3). Majority of respondents (67.6 %) in non-vegetated area felt “hot” (+3). In contrast, (52.9 %) of participants in vegetated area felt “neutral” (0). Moreover, in vegetated area 16.3 % felt “Slightly warm” (+1), while only 4.8 % in non-vegetated area. Furthermore, votes of participants reversed in “warm” (+2) category recording high percentage in non-vegetated and accounted 24.6 %, while in vegetated area was lesser by about 5.8%. About 6.3 % of respondents felt “slightly cool” (-1) in vegetated area, whereas none in the non-vegetated area. Since this survey was performed during the summer season, there were no responses in “cool” (-2) and “cold” (-3) category. Percentage distribution of Thermal Sensation Votes (TSV) is shown in Supplementary Fig. 2.

3.4 Thermal preference vote

The lower temperature and less intense solar radiation are people’s main preferences to feel comfortable in summer season in this climatic zone. However, differences can be found within microclimatic niches among different landscape spaces. Therefore, people’s preference for air temperature and solar radiation varies among different landscape spaces. A majority of subjects (95.2 %) in non-vegetated area desired solar radiation to be less, while 70.7 % preferred to be kept unchanged at vegetated area, this is mainly due to the shading providing from trees that partially block the sun radiation in this microclimate.

As temperature is linked directly to solar radiation, almost 56.0 % of subjects in vegetated area preferred the air temperature to be 'less' than the measured average of 32.3 ± 1.2 ºC, and 43.0 % preferred to be 'unchanged'. In contrast, 96.0 % of subjects in non-vegetated area preferred a 'decrease' and to be less than 38.3 ± 2.8 °C, and only 3.0 %, preferred to be 'unchanged' measured temperature. This indicates that people in general prefer temperature to be less than 30.0 ºC in hot climatic zone. The analysis of subject's votes for wind speed showed that more than 60.0 % preferred to be more than 0.5 ± 0.03 m/s with a maximum of 2.5 m/s in non-vegetated area. In contrast more than 60.0 % in vegetated area preferred to be 'unchanged' at around 1.3 ± 0.09 m/s with a maximum of 3.5 m/s. These results showed that, in terms of wind speed, almost the same percentage of subjects desired to be stronger with a maximum of 2.5 m/s and a minimum of 0.5 m/s. Therefore, the average wind speed between 0.5 m/s and 1.3 m/s is the ideal wind speed that people feel comfortable in terms of wind speed. In terms of relative humidity preference, more than 90.0 % of subjects desired to be drier with an average of 42.3 ± 0.7 %, in non-vegetated area, while almost all subjects in vegetated area preferred to be 'drier 'or at least 'unchanged' with an average of 69.9 ± 0.3 %. It seems that the relative humidity between 40.0 % and around 70.0 % is the most preferable and accepted by subjects in hyper-dried countries like Oman. Figure 5 shows preference votes percentage (%) for different environmental parameters.

3.5 **Outdoor thermal comfort model**

The physiological equivalent temperature (PET) was calculated for each subject in the survey and the analysis is shown in Fig. 6. The highest average of PET was detected in non-vegetated area with a value of 44.5 ºC ± 0.3 ºC, while the minimum was found in vegetated area with a value of 33.1 ºC ± 0.1 ºC. For both location, an average of 38.8 ± 0.3 ºC was calculated. The hourly variations are observed in the two places since the solar radiation and air temperature beside other parameters can influence these changes (Supplementary Fig. 3).

The analysis was further investigated to determine neutral Physiological Equivalent Temperature (nPET), and comfort range of the subjects. A linear regression was performed to show the relationship between PET and the thermal sensation votes of the subjects. The regression model showed that PET with a moderate correlation (R= 0.7, R^2= 0.50) with sensation votes and it is significant at the 0.01 level (2-tailed). The slope was 0.14, which means there was 7.1 °C change in PET per TSV unit. The coefficient of determination (R^2) is comparable with findings (R^2=0.6) by Hadianpour et al. (2018), and highest compared to findings (R^2=0.2) by Sharmin et al. (2019) and lowest compare to the result (R^2=0.9) reported by Nasrollahi et al. (2021). In this study the correlation between the thermal sensation votes and PET is derived as follows:

$$TSV = (0.14 \times PET) - 3.8 \quad (10)$$

$R = 0.7$, $R^2 = 0.5$

Using this model, and substituting TSV with a value of 0, -0.5 and +0.5, the PET equal to 27.2 °C, 23.6°C and 30.8°C for neutral physiological equivalent temperature (nPET) and the comfort range respectively were determined. Subsequently, the PET intervals corresponding to the thermal perception categories for the city of Muscat, Sultanate of Oman were calculated (Table 3). Since this study was conducted in the summer season, the categories 'cool' (-2) and 'cold (-3)' are absent, meaning no response from the subjects.

The PET as an index is applied in different climate zones in different continents, in an effort by researchers to define the n-PET and categorize peoples' thermal perception. For example, In the middle east, Elnabawi et al. (2016) reported a value of 29.5°C in Cairo, Egypt. In addition, a value of 25.3°C reported by Nasrollahi et al. (2021) in Ahvaz, Iran, these were closest to the value calculated from this work. Both of these studies were conducted in the hot arid climatic zone (BWh) closer to this study. In contrast, Nasrollahi et al. (2017) reported 26.4 °C in Isfahan, Iran, and Hadianpour et al. (2018) found 25.1 °C in Tehran, Iran in an arid, desert, with cold winter climatic zone (BWk). Though there are limited studies in neighboring geographies for comparison, a recent study revealed that Muscat exhibits relatively lower thermal stress at macro-scale in comparison to cities located in Arabian Peninsula (Yasmin et al., 2026). However, in their study only satellite derived data was used to evaluate urban thermal discomfort without human subject assessment. The Supplementary Table 2 depicts the findings of this study and other studies on the subject of comfort PET ranges.

3.6 **Overall outdoor thermal comfort**

Only a quarter of subjects in non-vegetated area felt the temperature to be thermally acceptable and comfortable, when these parameter's average, 38.2 °C, 44.5 °C, 48.4 °C, 42.3%, 0.5, for air temperature (T_{air} °C), Physiological equivalent temperature (PET °C), mean radiant temperature (T_{mrt} °C), relative humidity (%), and wind speed (m/s), respectively. Conversely, the majority of subjects in vegetated area (96.2%) felt the microclimatic effect, thermally acceptable and comfortable. With an average temperature of 32.3 °C T_{air}, 33.1 °C PET, 34.7 °C T_{mrt}, relative humidity of 69.9%, and a wind speed of 1.3 m/s. According to Feng, 2018, the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE's) standard describes that thermal microclimate is acceptable if greater than 80% of the subjects consider it acceptable and comfortable.

In a non-vegetated area, the majority (74.9%) of subjects reported uncomfortable. However, in a vegetated area, the percentage drops substantially, 3.8% of them reported uncomfortable. Even though the relative humidity is higher in the vegetated area

compared to the non-vegetated area, the wind speed may have an effect on the subject' feeling. Despite the fact that the responses of the survey participants may be affected by a number of other factors. The percentage of each category is presented in the Fig. 7.

4 **Conclusion**

Although the urban outdoor thermal comfort as a public health concern received more attention globally, the awareness among the researchers is limited in many regions of the globe particularly in the Gulf Cooperation Council (GCC) countries. As thermal comfort as an indicator of public health is important in any part of the world, it is crucial in hot arid climatic zones. This work aimed to assess the thermal comfort of inhabitants in the city of Muscat in normal city location coupled with assessing the role of vegetation in mitigating discomfort. It was achieved by using approaches simultaneously that includes subjective and objective measurements to come up with neutral physiological equivalent temperature and the range of comfort specific to Muscat city and the predominant dress code of the country. The thermal sensation of subjects was found to be a moderate linear function (R^2, 0.5) with the nPET of 27.2 °C, and comfort range of 23.6 °C and 30.8 °C. The generated model from this study, also lead to predict thermal sensation categories. This model can be applied by urban designers in an arid and semi-arid area under similar microclimatic conditions particularly applicable neighboring GCC countries namely UAE, Saudi Arabia, Qatar, Kuwait and Bahrain.

Solar radiation plays a role in thermal comfort as this study revealed, a less intensity is highly preferred (95.2%) in non-vegetated area, while only 29.3 % of subjects preferred solar radiation to be less intense in vegetated area. Shading offered by tree vegetation in cities can heavily influence people's preferences. Additionally, the air temperature was preferred to be less by subjects in the two (Commercial and Vegetated) microclimatic areas, to be less than the measured average of 38.3 ± 2.8 °C in non-vegetated area, and the measured average of 32.3 ± 1.2 ºC in vegetated area, with 43.0 % preferred to be 'unchanged'. It gives an indication that air temperature below 30.0 °C could be preferable outdoor air temperature in Muscat city. Wind speed as another environmental factor has a solid impact on human thermal comfort, as in this study a wind speed between 0.5 m/s and 1.3 m/s is the preferable and ideal wind speed. Humidity is crucial and not to be ignored, it directly influences and affect human comfort especially in coastal area. This study revealed humidity between 40.0 % and 70.0 % is the acceptable range to feel more comfortable in hot-dry climatic zone like Muscat.

The results also reveal, high percentages of subjects (96.2%) feeling the comfortability and acceptability towards the microclimate in vegetated area. This percentage has dropped to a quarter in non-vegetated area, despite, the uniformity of dress code practiced by the people and activities they do. This was due to shading effect provided by vegetation, which undoubtfully

play significant contribution in reducing solar radiation, mean radiant temperature and the globe temperature, emphasize, the role of vegetation in urban area to increase the thermal comfort and reducing heat stress.

Since the governments worldwide are moving towards establishing sustainable cities, Sultanate of Oman recognizes, implementing the country's urban development as a pathway towards Oman vision 2040. It is therefore, imperative for city planners and policy makers to take into consideration thermal comfort of inhabitations. The finding of this is study will serve and provide input on human thermal comfort as one of the key priorities when implementing any city expansion or designing new city development projects.

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Supplementary information

Additional figures, tables and the survey questionnaire used in this study are provided in the supplementary material.

Authors' contributions

Hameed: Ideate the problem and conceptualize work integration, supervised the work.

Abdullah: Collect, analyze and curate the data, write the main manuscript.

Hameed and Abdullah: Planned and prepared the respondents survey, reviewed the manuscript.

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Data availability

The datasets used and analyzed during the current study are available to be collected from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

All research was conducted in accordance with the Declaration of Helsinki and ethical approval internally is directed by Humanities Research Centre of Sultan Qaboos University to seek an oral consent with the individuals before the interview. Every participant provided their consent after briefing the purpose of the study. Out of 450 participants approached, only eight percent were not willing to participate, citing lack of time.

Human Ethics and Consent to Participate: Not applicable

Consent for publication: Not applicable.

Competing interests: Both authors declared no conflict of interest.

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Table 1 Sensors properties in Kestrel 5400 Heat stress tracker pro used in measurements

Parameters	Sensors	Range	Accuracy (+/-)	Sensor's image
Air temperature (°C)	Kestrel 5400 Heat stress tracker pro (Air tem)	-29.0 to +70.0 °C	0.5°C	
Globe temperature (°C)	Kestrel 5400 Heat stress tracker pro (Globe tem)	-29.0 to 60.0 ºC	1.4 ºC 2.5 ºF	
Relative humidity (%)	Kestrel 5400 Heat stress tracker pro (Humidity)	10 to 90% 25ºC non-condensing	2% RH	
Wind speed (m / s)	Kestrel 5400 Heat stress tracker pro (Wind speed)	0.6 to 40.0 m/s	0.1 m / s	

Table 2 Statistic values of environmental parameters during field survey in vegetated and non-vegetated area

Location	Statistics	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Globe temperature (°C)	Mean radiant temperature (°C)
Vegetated area	Mean ± SE	32.3 ± 0.1	69.9 ± 0.3	1.3 ± 0.1	34.2 ± 0.1	34.7 ± 0.2
	Minimum	30.0	32.9	0.0	30.3	30.3
	Maximum	40.6	84.0	3.5	42.9	42.9
Non-vegetated area	Mean ± SE	38.3 ± 0.2	42.3 ± 0.7	0.5 ± 0.03	47.4 ± 0.3	48.4 ± 0.4
	Minimum	33.0	18.7	0.0	33.2	33.2
	Maximum	45.6	63.8	2.5	57.3	59.0

Table 3 PET intervals corresponding to thermal sensation categories in Muscat based on the model developed in the study.

Thermal sensation	PET °C
Cold	Not applicable
Cool	Not applicable
Slightly cool	16.5°C; 23.6°C
Neutral	23.6°C; 30.8°C
Slightly warm	30.8°C; 38.0°C
Warm	38.0°C; 45.2°C
Hot	45.2°C; 52.3°C

Fig. 1 Boundary of the study area

Fig 2 A map showing location of measurement point and field survey photos in vegetated area (park)

Fig. 3 A map showing location of measurement point and field survey photos in non-vegetated area (commercial)

Fig. 4 Layout of research methodology to calculate physiological equivalent temperature

Fig 5 Preference votes (%) for (a) air temperature, (b) solar radiation, (c) humidity and (d) wind speed in measurement locations

Fig 6. Identification of the PET comfort range in Muscat, Oman through applying the model from this study

Fig 7. Percentage (%) of each category (Uncomfortable, Acceptable, Comfortable) in vegetated and non-vegetated area

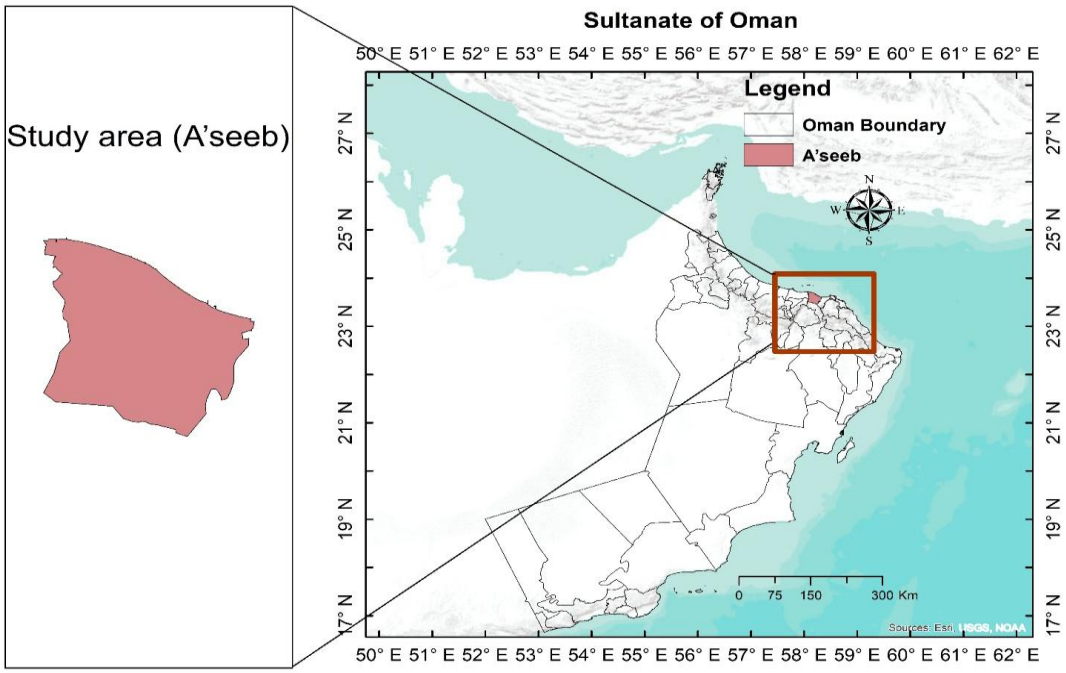
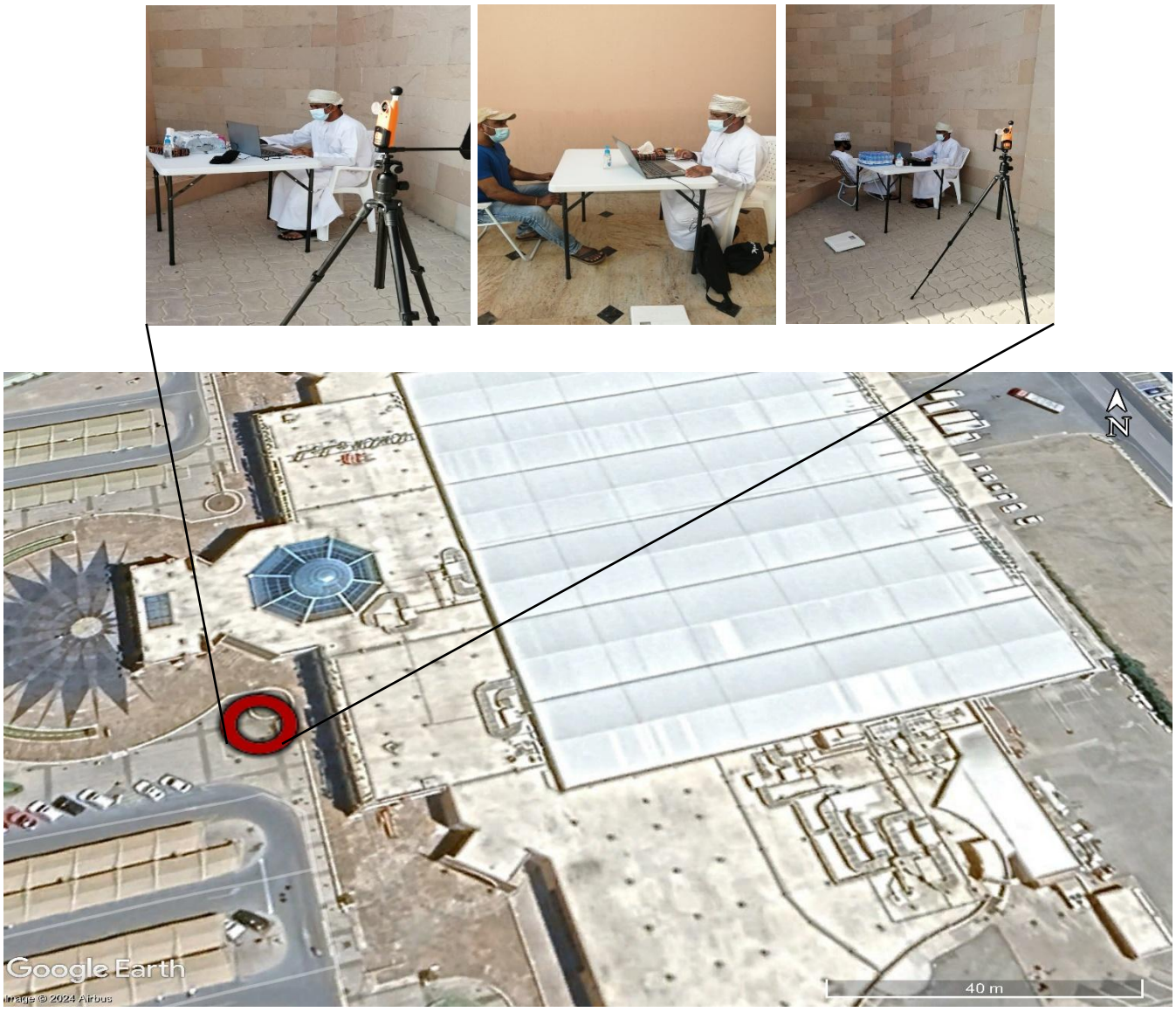

Study area (A'seeb)
Sultanate of Oman
50° E 51° E 52° E 53° E 54° E 55° E 56° E 57° E 58° E 59° E 60° E 61° E 62° E
Legend
Oman Boundary
A'seeb
N
W
E
S
27° N
25° N
23° N
21° N
19° N
17° N
0 75 150 300 Km
Sources: Esri, USGS, NOAA

Fig 1.


N
Google Earth
Image © 2024 Airbus
200 m

Fig 2.



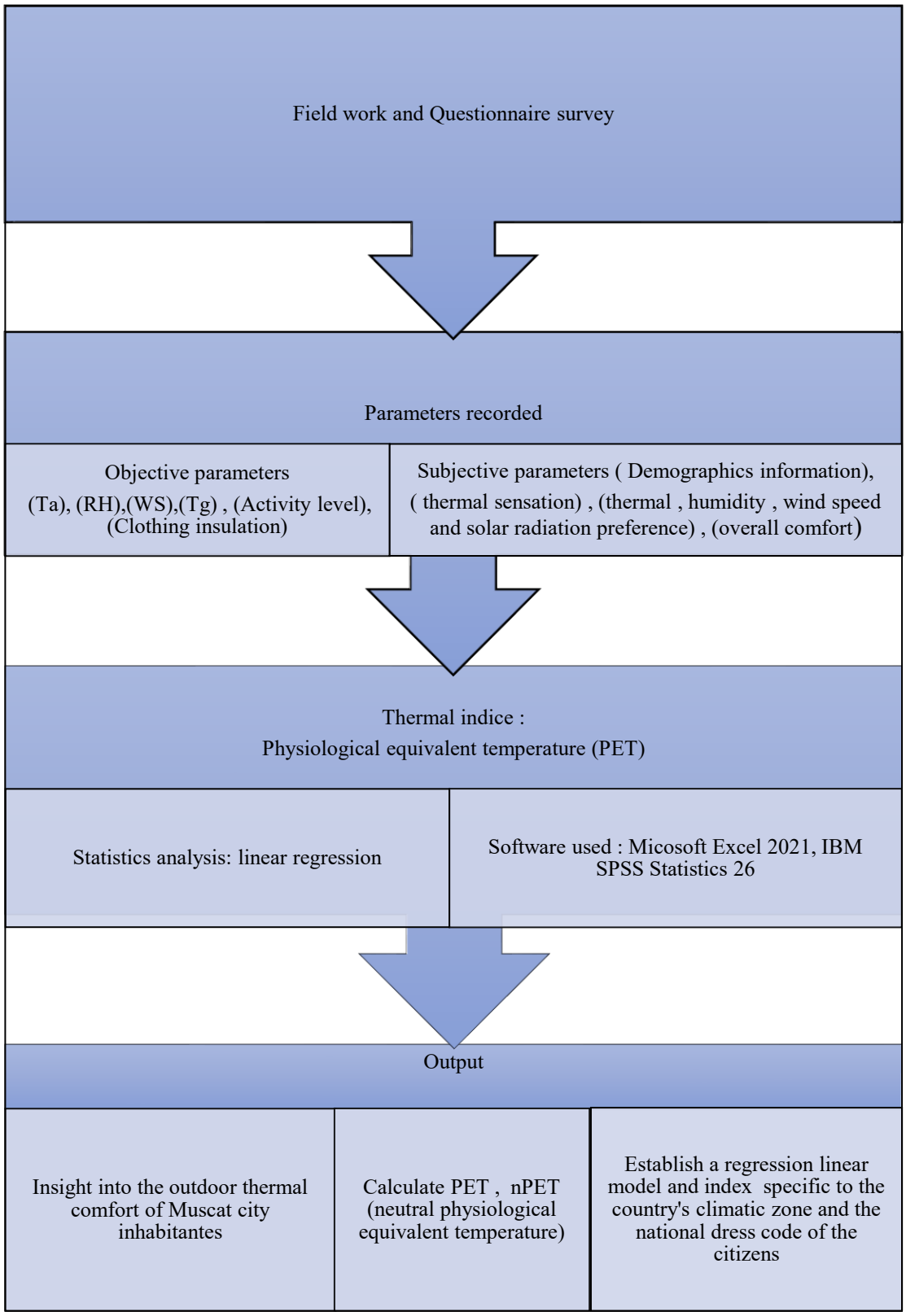
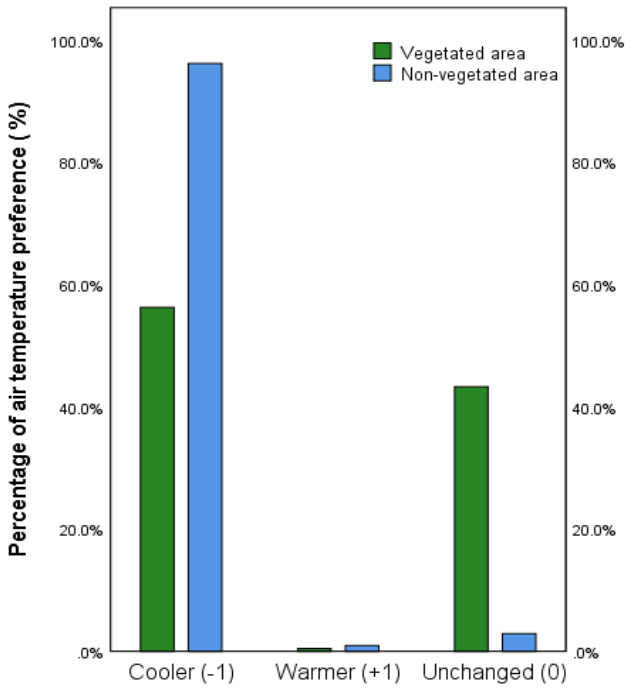
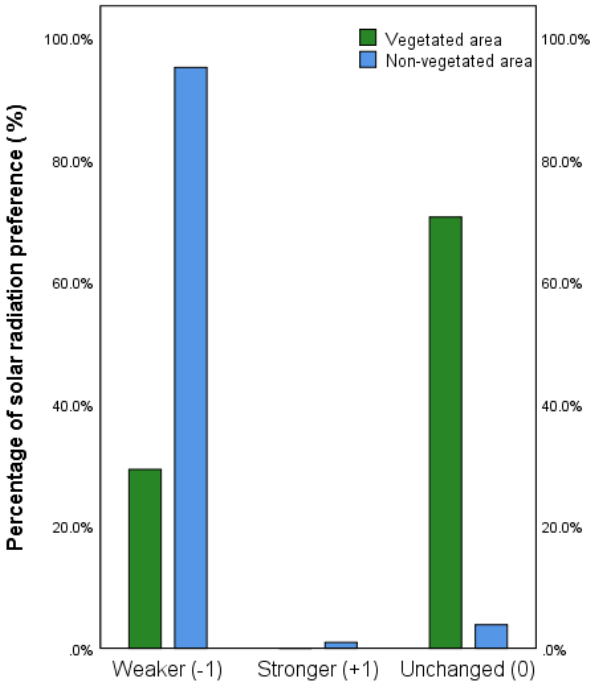

Field work and Questionnaire survey
Parameters recorded
Objective parameters
(Ta), (RH),(WS),(Tg) , (Activity level), (Clothing insulation)
Subjective parameters (Demographics information), (thermal sensation) , (thermal , humidity , wind speed and solar radiation preference) , (overall comfort)
Thermal indice :
Physiological equivalent temperature (PET)
Statistics analysis: linear regression
Software used : Micosoft Excel 2021, IBM SPSS Statistics 26
Output
Insight into the outdoor thermal comfort of Muscat city inhabitantes
Calculate PET , nPET (neutral physiological equivalent temperature)
Establish a regression linear model and index specific to the country's climatic zone and the national dress code of the citizens

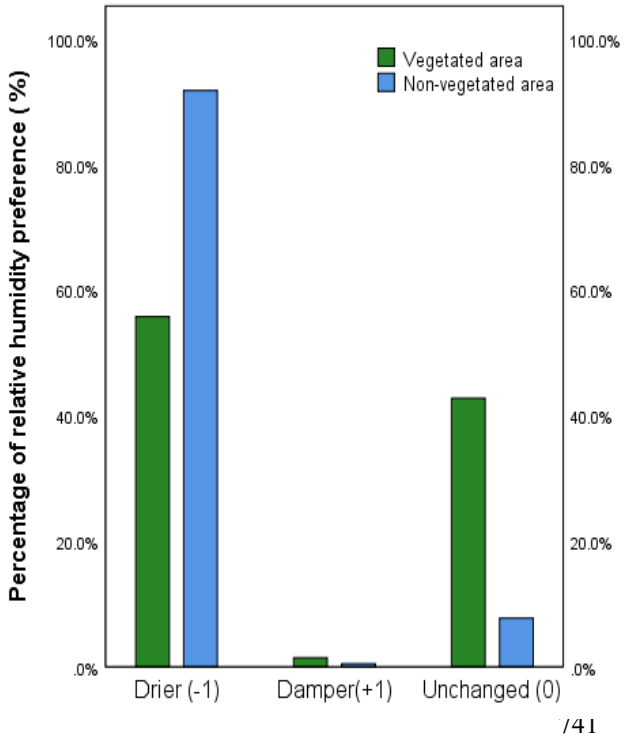
Fig 4.


Vegetated area
Non-vegetated area
Percentage of air temperature preference (%)
100.0%
80.0%
60.0%
40.0%
20.0%
.0%
Cooler (-1)
Warmer (+1)
Unchanged (0)

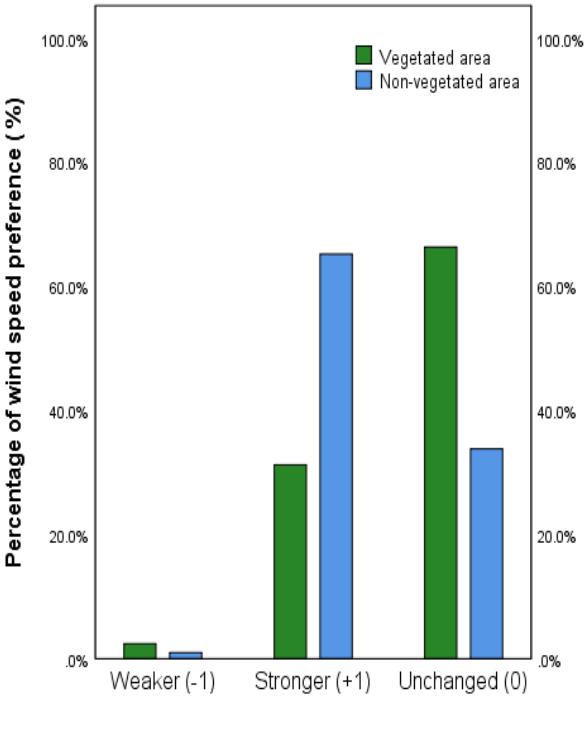
(a)


Vegetated area
Non-vegetated area
Percentage of solar radiation preference (%)
100.0%
80.0%
60.0%
40.0%
20.0%
.0%
Weaker (-1)
Stronger (+1)
Unchanged (0)

(b)


Vegetated area
Non-vegetated area
Percentage of relative humidity preference (%)
100.0%
80.0%
60.0%
40.0%
20.0%
.0%
Drier (-1)
Damper(+1)
Unchanged (0)

(c)


Vegetated area
Non-vegetated area
Percentage of wind speed preference (%)
100.0%
80.0%
60.0%
40.0%
20.0%
.0%
Weaker (-1)
Stronger (+1)
Unchanged (0)

(d)

Fig 5.

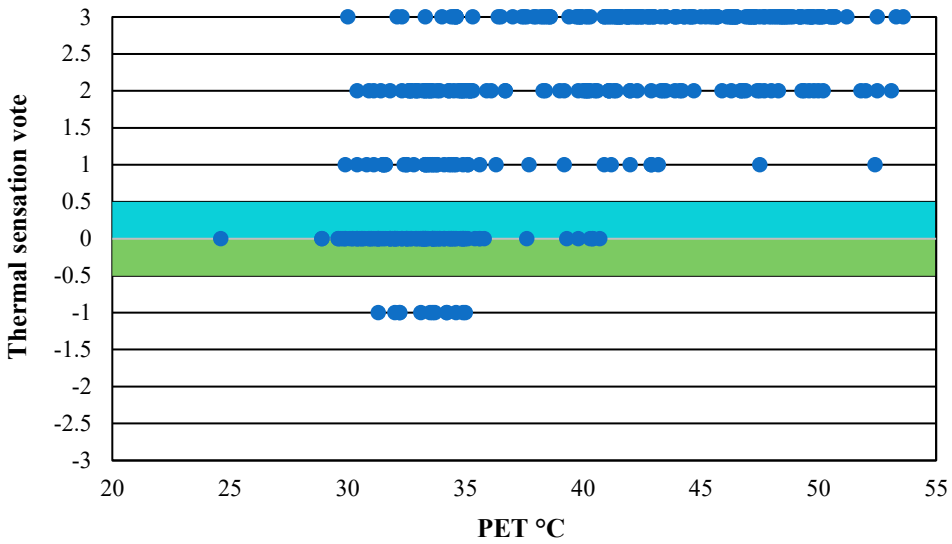

Thermal sensation vote
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
20
25
30
35
40
45
50
55
PET °C

Fig 6.

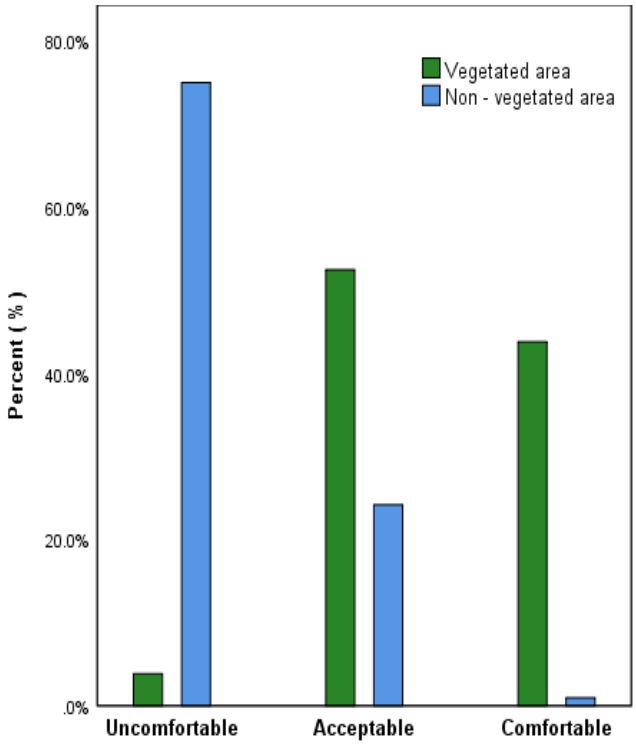

80.0%
60.0%
40.0%
20.0%
.0%
Percent (%)
Vegetated area
Non - vegetated area
Uncomfortable
Acceptable
Comfortable

Fig 7.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial.docx