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Assessment of Urban Outdoor Comfort Variation in a Northwestern Moroccan City – Toward the Implementation of Effective Mitigation Strategies

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ABSTRACT

Studying urban outdoor comfort has become a necessary approach to achieving sustainability at multiple levels. Today, many urban projects incorporate new mitigation strategies such as green and blue patterns when it is difficult to modify urban configuration and density. This study aims to investigate urban outdoor comfort variation in a northwestern Moroccan city, where urban planning is rapidly evolving due to local socio-economic dynamics. Various urban areas were analyzed during summer conditions from two perspectives. The first one focused on studying the air quality and involved the use of Google Earth Engine platform to extract data on air pollutants (NO_2, CO, formaldehyde and aerosols). Second, in-situ monitoring was carried out using four main parameters (temperature, humidity, solar illuminance and sound levels). Other factors such as urban density, urban greening and water components were also assessed. Air quality findings revealed that the main sources of air pollution were concentrated in the industrial zone and the backwater. This led to a significant impact on the air quality of the city center. The results also indicated minor effect of vegetation on the density of the pollutants studied. Based on the in-situ monitoring, results highlighted variations between different sites, which can be attributed to differences in urban morphology and the use of various plant species for urban vegetation and the water proximity. We have identified four main species on the site: Populus nigra and Platanus orientalis are deciduous trees that provide significant shade and contribute to outdoor urban comfort, resulting in a decrease of temperature by 0.8 °C compared to open bare lands where palm trees provide minimal shading. Furthermore, areas with deciduous trees experience a noise reduction of 4.6 dB compared to open bare lands. Grass and linear bushes only produce evapotranspiration benefits. In addition, we have found that proximity to water sources can reduce outdoor temperature. Green and blue strategies play an essential role in optimizing urban comfort. However, their urban implementation is not entirely effective, focusing more on aesthetic aspects than functional factors to optimize outdoor comfort. Results from the present study can be used to better influence future mitigation strategies and implement new sustainable tools.

Keywords: sustainability, urban vegetation, urban studies, urban comfort, northwestern Morocco.

INTRODUCTION

The rate of urbanization is currently very high, leading to rapid changes in the composition, configuration and quality of urban spaces. Furthermore, these changes also contribute to global warming caused by the increase in greenhouse gases and heat waves during summer months (Aleksandrowicz, 2017; Mazdiyasni, 2017). Additionally, global warming affects urban quality and public, resulting in human discomfort and health issues (Alcoforado and Andrade, 2008).

The decrease in the percentage of urban green spaces and natural landscapes is leading to several problems at the city level and affecting public health. The search for urban outdoor comfort has become fundamental for planning, evaluating and improving the urban environment. Urban outdoor spaces represent a living and interactive "place" in which people live and practice all the time. Woolley (2003) explains that outdoor spaces provide various benefits, including physical, environmental, economic and social benefits. Hirano and Fujita (2012) and Davies et al. (2008) note that improving the outdoor thermal environment can create opportunities for energy savings. As a result, the cooling load of buildings can be reduced due to lower urban temperatures.

Urban outdoor comfort (UOC) is defined as a "condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (Ramspeck et al., 2004). This definition integrates two major parts, the first part is related to the thermal aspect that refers mostly to the urban heat island (UHI) and the second part is related to their user experience and perception. The UHI indicates the high temperature in the air and surface of urban centers (Santamouris, 2013) and represents the focus of various studies.

In addition to abiotic and biotic ecological factors, the urban outdoor environment is influenced by four significant factors. These include urban structure, which encompasses the dimensions of buildings and spaces between them; urban cover, which refers to the proportions of buildings, paved or vegetated surfaces, bare soil, and water; urban materials, encompassing both building and natural materials; and urban metabolism, which involves factors such as heat, water, and pollutants resulting from human activity (Alberti, 2008). Added to these factors, thermal comfort is related to the usage of outdoor spaces (Hassid et al., 2000).

The increasing concern regarding air quality has led to a rising interest in integrating it into the study of urban comfort processes. This is particularly relevant as a majority of urban areas currently exceed recommended exposure levels for two major health-damaging air pollutants, namely particulate matter (PM) and nitrogen dioxide (NO_2), as highlighted by World Health Organization. Among the environmental issues faced by metropolitan areas, air pollution is considered one of the most severe and significant problems affecting cities on a larger scale, even globally. It is a growing concern for numerous international organizations due to its adverse impact on human health. The World Health Organization and other similar international organizations have long recognized air pollution as a serious public health issue. According to the United Nations Environment Program over one billion people are exposed to pollution annually, resulting in one million premature deaths. Pollutants such as nitrogen oxides (NO_x), $PM_{2.5}$ and PM_{10} particulate matter can enter the body and cause a range of cardiovascular and respiratory illnesses, leading to untimely demises (Boningari, 2016; Hoek, 2000).

To reduce these effects, cities and urban planners are adopting various mitigation strategies following sustainable approaches, such as green and blue patterns, since morphological transformation and optimization of the current urban composition are very difficult to achieve due to high building density and social factors.

Many studies (Lai et al., 2019) confirm that when comparing the effect of various strategies specially on cooling the urban space and achieving urban comfort, urban geometry has a large effect, since it is hard to change the actual morphology, the urban vegetation is qualified as an effective strategy against climate change (Mills et al., 1991) followed by water bodies.

The study of outdoor comfort is focused on several issues affecting both urban policies and the use of urban space, when it is important to emphasize the benefits of green strategies as an effective mitigation strategy to achieve outdoor comfort, regulate air temperature and help create micro-biodiversity within the city and reduce pollution levels in cities (Beckett, 1998; Bennett, 1973); however, it can be observed that urban vegetation, as integrated in the urban outdoor space, is not fully effective and does not give sustainable result.

This paper explored how urban models can be adapted, evaluated and reconfigured to improve urban comfort through green and blue strategies. The authors ask the questions: What are the most effective strategies that help achieving comfort through a sustainable approach? How can green and blue strategies help to make a sustainable choice for the city?

This study focused on analyzing urban outdoor comfort through 2-step approach, first extracting air quality data and focusing on the density of 4 common air pollutant (CO, NO_2, density of formalhydes and aerosols) and the second step involved experimental monitoring of different areas to measure four key parameters: temperature, humidity, sound levels and solar illuminance. This methodology enables to identify variations in comfort levels between different spaces across the city during summer conditions, particularly when the city experiences significant increase in tourist activity. Its primary objective is to comprehend the criteria and factors that characterize these areas. Additionally, the authors aimed to evaluate the effectiveness of green strategies as a tool for promoting sustainability and improving outdoor comfort. By examining the current green and blue configuration of the city, it is possible to gain insights into how this affects outdoor comfort and identify the opportunities for implementing effective mitigation strategies based on green infrastructures that can enhance comfort levels. Overall, the main goal was to provide valuable insights into the relationship between urban development, sustainability and outdoor comfort in order to contribute to the development of more effective mitigation strategies that prioritize sustainability and citizen's well-being.

MATERIALS AND METHODS

Study area

The present study was conducted in the city of Martil, which is located on the northwestern coast of Morocco, in the region of Tanger-Tetouan-Al Hoceima. The geographical coordinates of the city are latitude 35° 54' 60" N and longitude 5° 16' 60" W (Fig. 1). Martil has an estimated population of approximately 64,355 residents (High Commission for Planning, 2018). The city's key economic sectors consist of tourism, fishing, and agriculture. Additionally, there is an industrial area situated at the western entrance, as depicted in Figure 2. Moreover, Martil possesses a stagnant backwater in its southern region. These two characteristics have the potential to affect the urban air quality.

The city has a Mediterranean climate and a sub-humid bio-climate with warm winters and humid influences from the Mediterranean Sea, with a dominant wind patterns in the region exhibit an east-west orientation, with easterly winds prevailing during the period from May to October and westerly winds prevailing from October to February (EL Mrini A et al., 2008). The nearby mountains have a thermo-Mediterranean vegetation stage with altitudes ranging from 3 to 200 meters, which adds to the ecological characteristics of the area.

Data extraction and processing

Understanding the urban pattern composition

To better understand the composition of the urban pattern as well as identify the green and blue aspects of the map, an unsupervised classification of the area of interest was used (Fig. 2), as reported in a study on the comparison of land use classification methods incorporating remote

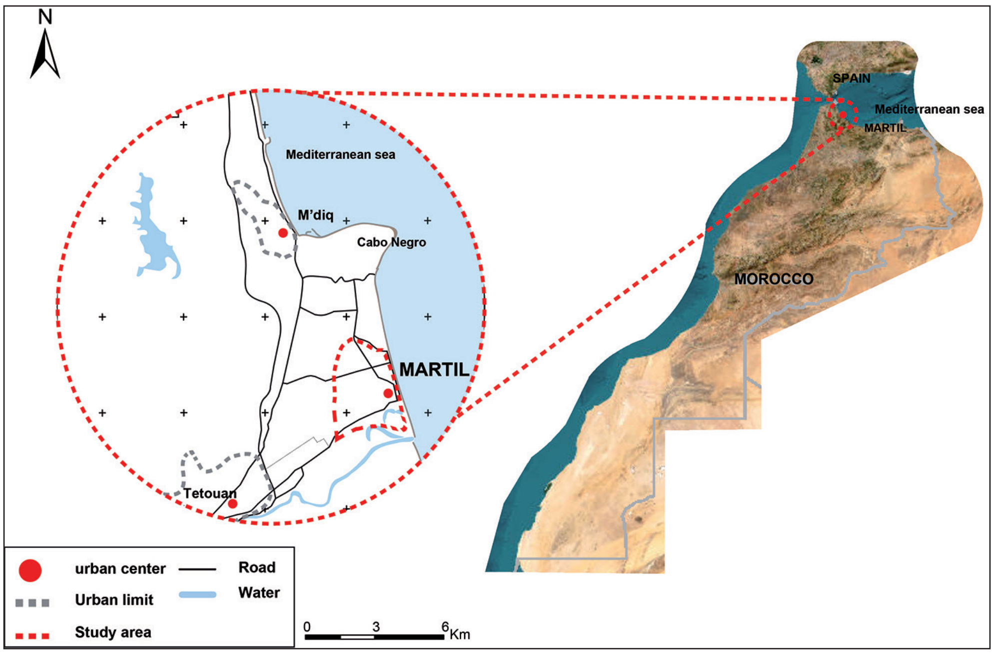

Figure 1. Location map of the study area

sensing and GIS inputs presented by Rozenstein and Karnieli (2011). They used a McNemer test in which confirms that the unsupervised classification is better than the supervised method, with an accuracy of 70.67% vs. 60.83%.

This method involves automated analysis of the raster pixels using GIS software to identify and group together pixels based on their spectral similarities. Although this method is fast to process, it takes time to identify the different components. Texture, patterns, light and context were analyzed to classify the raster of the study area into four classes, namely: water bodies, buildings, vegetation and bare land. Then, areas of these four classes were determined by converting them into polygons to analyze the urban model.

Air quality

Pollutants identification

Air pollution is a major concern in urban areas, as it can have significant impacts on both air

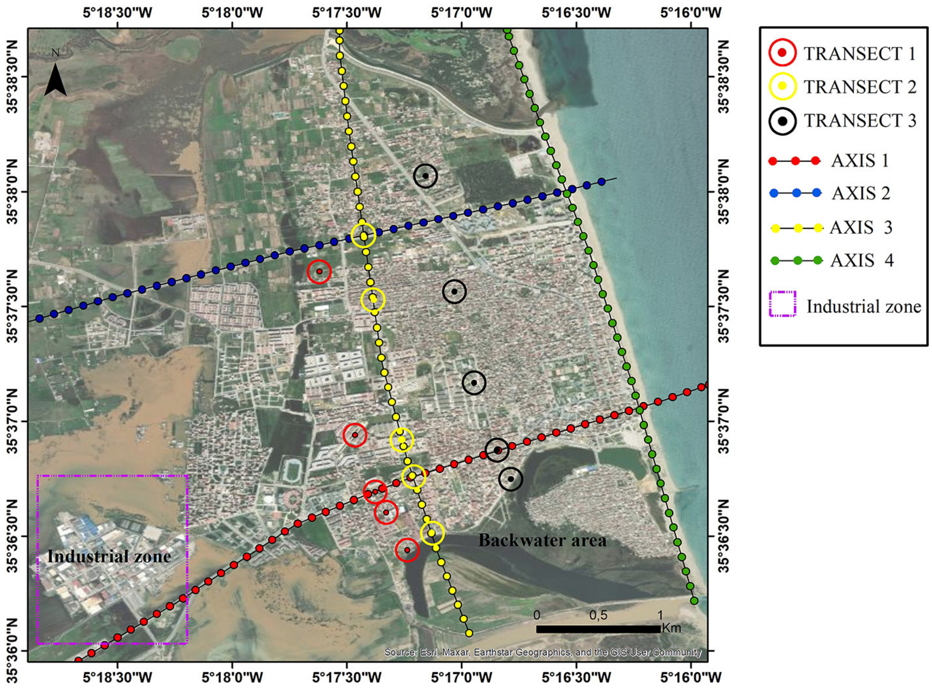

Figure 2. Aerial image (21-09-2020, source: Google Earth) of Martil city showing the 5 monitored points along three transects and the four axes used air quality assessment

Table 1. Bibliographical research on air pollutants and their data availability

Pollutants	Main Sources	Effect on air quality and human health	References	Data availability (source)
Nitrogen oxides (NO_2)	Vehicle exhaust, power plants, industrial processes	Causes respiratory problems, contributes to create fog and decreases air quality	(EPA, 2021), (Kumar, 2019)	Sentinel-5P OFFL NO_2
Aerosols (PM2.5)	Combustion of fossil fuels, vehicle exhaust, industrial processes, agricultural activities	Increases risk of respiratory (asthmas) and cardiovascular problems, reduces visibility and aesthetic appeal of landscapes	(World Bank, 2022)	Sentinel-5P OFFL AER LH
Carbon monoxide (CO)	Vehicle exhaust and combustion of fossil fuels, biomass burning and atmospheric oxidation of methane and other hydrocarbons	Increases risk of toxicity problems and cause the greenhouse effect	(EPA, 2021), (Khaniabadi, 2019), (Gao, 2019), (INERIS, n.d.)	Sentinel-5P OFFL CO
Formaldehyde	Photochemical oxidation of volatile organic compounds (VOC) of natural origin, Solar irradiation of humic substances present in water, Decomposition of plant residue in the soil	Concern also indoor air. Irritates eyes and respiratory tract	(INRS, 2022)	Sentinel-5P OFFL HCHO

quality and urban comfort. The authors focused on four common pollutants carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde and aerosols ($PM_{2.5}$). Table 1 summarizes main sources of these pollutants, their effects on air quality and on human health as well as their data availability.

Data analysis

To access and analyze diverse data for environmental monitoring and analysis, a comprehensive three-step process was followed.

Firstly, the GEE platform was utilized; thus is a cloud-based system that makes use of Google's powerful computing capabilities, it provides access to a large amount of publicly available remote sensing imagery. GEE allows users to analyze and visualize geospatial data in a sophisticated manner using high-speed parallel processing and machine learning algorithms, The development of this platform has generated great interest and dedication in the fields of remote sensing and geospatial data science. Within this study, custom JavaScript code was developed to import data from Sentinel-5P following the study area boundaries. Using this code, four types of air pollution data were extracted (NO_2, CO, Formaldehydes and Aerosols) during the period from 15/07/2022 to 01/09/2022.

Secondly, the obtained results were exported to personal storage space in "raster" image format in the world coordinate system (WGS84). With the use of the GEE platform and our code, efficient data access and analysis were achieved.

Finally, a comprehensive data analysis was performed utilizing ArcGIS software, resulting in the delineation of four primary axes (Fig. 2.):

- Axis 1: spans from the eastern coast to the western part of the study area and serves as the primary main avenue of the city, extending towards the industrial area.
- Axis 2: runs from the eastern coast to the western part of the study area and functions as the secondary main avenue of the city, connecting to the northern side.
- Axis 3: originates from the northern side of the city and extends to the southern part of the study area, serving as a significant avenue that connects to the coastal area.
- Axis 4: starts from the northern side of the city and reaches the southern part of the study area, representing a prominent avenue experiencing substantial growth.

The outcome of this analysis involved the creation of four maps that combine satellite imagery with the extracted air pollution data. These maps proved to be valuable tools for environmental monitoring and analysis. Additionally, four graphs were generated to illustrate the progression of air pollution across the city.

In-situ monitoring

The in-situ experimental monitoring involves recording four main parameters: temperature, humidity, solar illuminance and sound comfort. These parameters will enable to differentiate and identify variations in outdoor comfort under summer conditions among various urban areas and understand the impact of green (urban vegetation) and blue components (water bodies).

The sampling method used a reasoned choice approach that involves identifying criteria specific to each area. The points belonging to these areas are drawn on the same transverse transects parallel to the littoral and they have the same topographic character (flat), three main lines are drawn and classified by area as identified on the map (Fig. 2). These areas are grouped into five categories based on their common characteristics. The areas are represented by the following 3D view (Fig. 3).

- Area 1: Area with an abundance of open space and bare lands.
- Area 2: Semi-dense building area.
- Area 3: Grand avenue with the presence of urban vegetation.
- Area 4: Semi-dense with the presence of urban vegetation and water bodies.
- Area 5: High building density area with a nonlinear morphology.

At this point, a single device, the SAINT GOBAIN, was used to take measurements. This device is connected to a mobile application called "MC 350" which enables to record all four parameters simultaneously and view the results on the mobile interface. The device is also equipped with a tracking function, which allows us to track the measurements over time.

To obtain more precise results, several repetitions of the measurements were conducted. This approach enabled to minimize errors and improve the accuracy of the obtained findings. By utilizing this method, the comfort level of each area can be compared and contrasted as

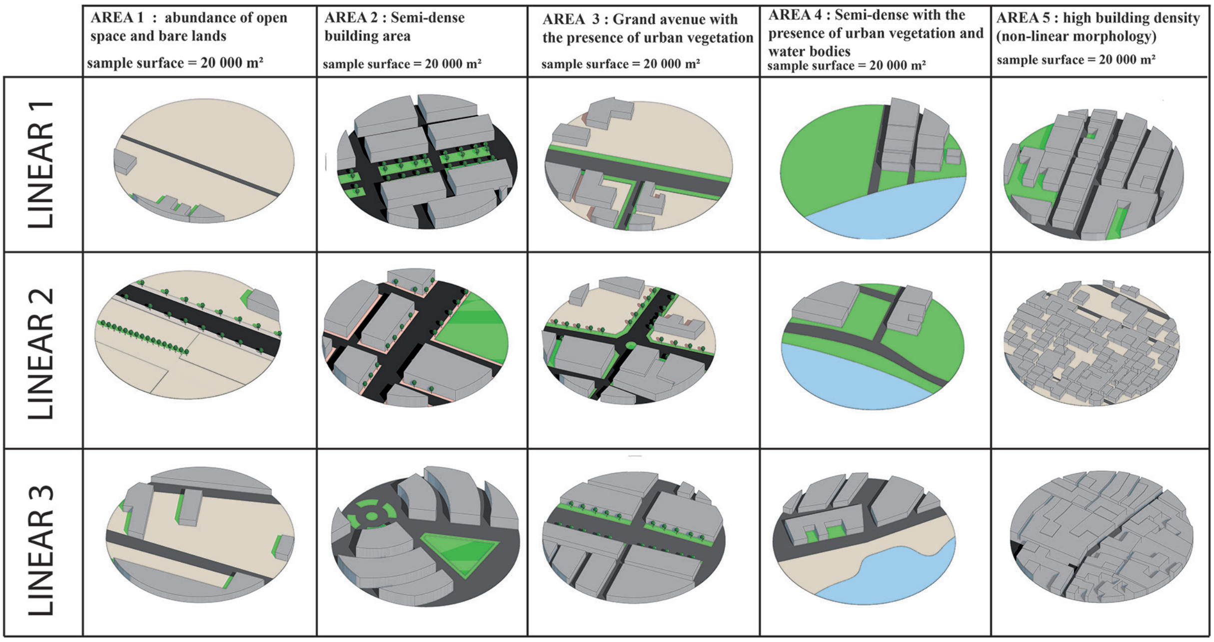

Figure 3. 3D model of each micro-site following the area classification

well as the factors that contribute to the differences in comfort can be identified.

Urban greening identification and analysis

Vegetation has a profound impact on urban sustainability and planting is a widely recognized and effective strategy for enhancing urban comfort. Plants serve as bio-filtering tools and contribute to thermal regulation, reducing pollutant levels and improving overall urban comfort. Considering these benefits, it becomes essential to analyze urban vegetation through the following aspects:

- Identification of the species used and their global characteristics;
- Assessment of size and appearance: the shape of the species and its shading area were identified;
- Evaluation of implementation and alignment with buildings.

By conducting this analysis, the authors were able to gain insights into the types of vegetation that are suitable for urban environments and how they can be effectively incorporated into city landscaping. The information obtained will be useful in guiding future green initiatives and promoting sustainable urban development. Finally, Figure 4 summarize the overall methodology implemented throughout this study.

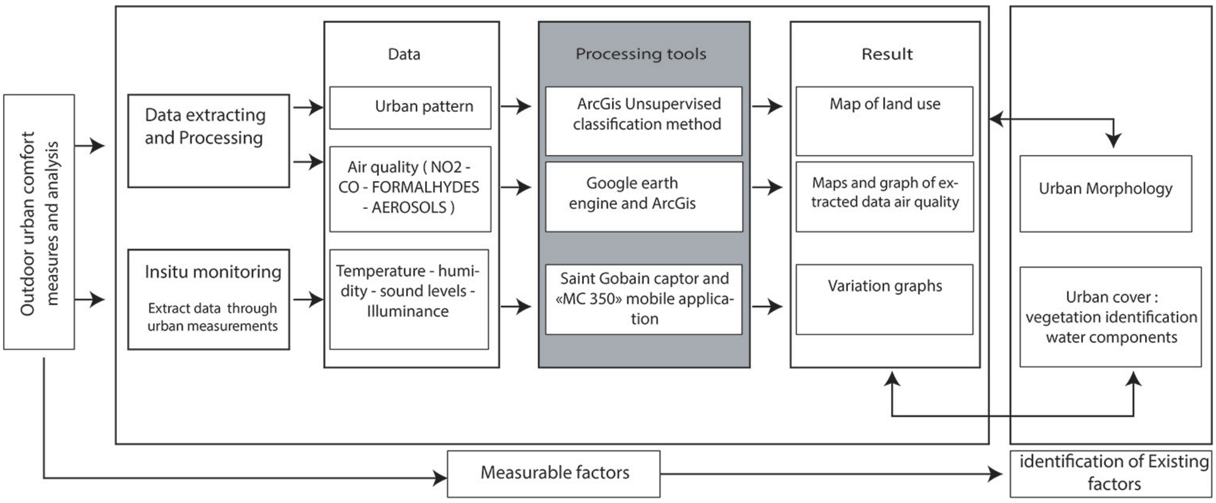

Figure 4. Overall methodological approach of the study

RESULTS

Aerial photograph analysis

To have a better understanding of urban patterns, the map component was divided into four major aspects. Figure 5 illustrates that buildings and construction represent 37% of the space, which is concentrated in the city center with a variety of urban tissue ranging from very dense to medium dense.

The vegetation represents 14% of the global surface, equivalent to less than half of the urban surface; it is distributed on the city limits and has few representations in the city's major avenues and neighborhoods. Bare lands represent 46% of the map component and are primarily located in the city's suburban areas; these areas represent an asset for future urban growth. The water component represents only 3% and is represented by the backwater located to the south of the city.

Air quality

Nitrogen dioxide (NO_2) and aerosols ($PM_{2.5}$)

The following analysis presents an overview of the patterns and variations observed in NO_2 and aerosol concentrations in the studied area, as well as an examination of the consistency of monitoring values across different sampling points, Figure 6 illustrated that the patterns of NO_2 and aerosols were closely related. Along axis 1 and 2, a gradual increase in concentrations from the coast to the industrial area was observed, with high concentrations present, the NO_2 pattern exhibited particular strength, extending towards the city center. On the other hand, when considering

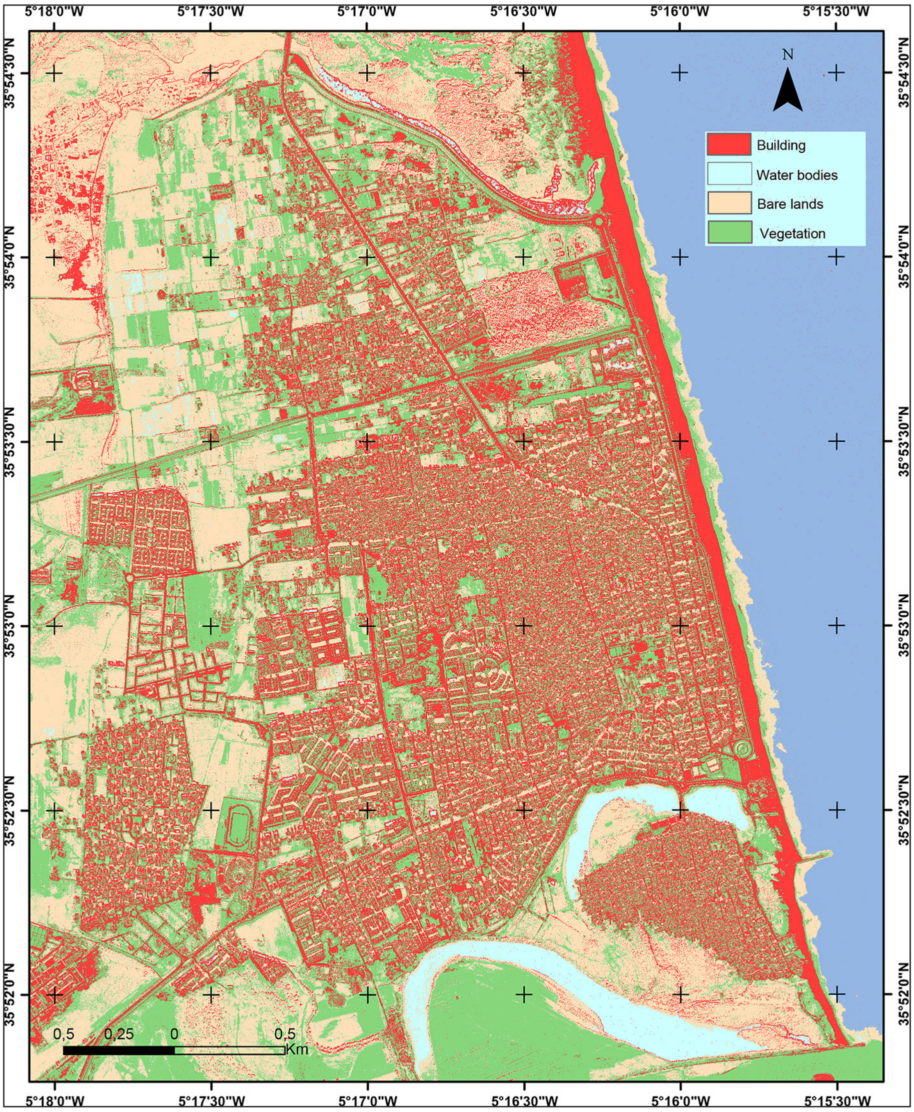

Figure 5. Map of the land use

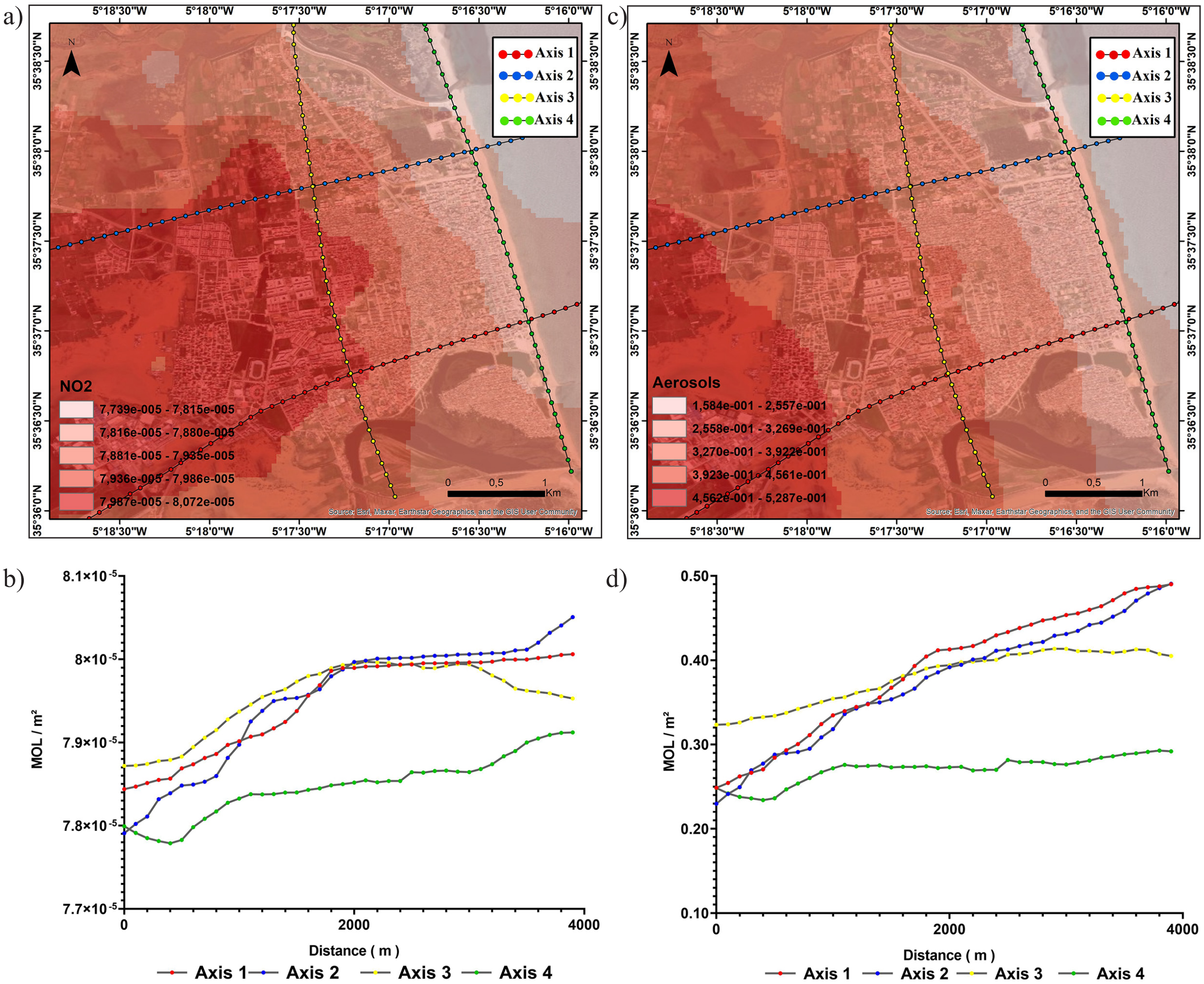

Figure 6. Results of the extracted air pollution data for nitrogen dioxide and aerosols; a) map of the combined satellite image with the extracted nitrogen dioxide data; b) graph of the extracted nitrogen dioxide data variation; c) map of the combined satellite image with the extracted aerosols data; d) graph of the extracted aerosols data variation

axis 3 and 4, which represented a transversal line crossing the city from north to south, minimal variations were noted.

Regarding the determination of monitoring values for each axis, it is observed that both axis1 and axis 2 exhibit similar growth curves, indicating a gradual increase in values from east to west. Specifically, axis 1 demonstrates an average difference of 0.24 mol/m² between the highest and lowest aerosol density values and 1.6×10^{-6} mol/m² for NO_2 density values. Similarly, axis 2 shows an average difference of 0.026 mol/m² for aerosol density and 2.6×10^{-6} mol/m² for NO_2 density, conversely, axis 2 and axis 3 display minimal or negligible variations. Axis 3 has an average difference of 0.09 mol/m² for aerosol density and 1.3×10^{-6} mol/m² for NO_2 density, while axis 4 has an average difference of 0.06 mol/m² for aerosol density and 1.3×10^{-6} mol/m² for NO_2 density.

Carbon monoxide and formaldehyde

According to the obtained findings in Figure 7, elevated levels of carbon monoxide (CO) are observed in the northern part of the study area, with sporadic hotspots in the western areas that can be attributed to bare lands and agricultural activities. Furthermore, higher concentrations of formaldehyde in the southeast area, which gradually decrease towards the city center following the axis 1 and 2, were noted. It is worth noting that the formaldehyde pattern is having a significant impact on the study area, with high values being linked to a stagnant backwater area.

Regarding the assessment and characterization of monitoring values for each axis, it is observed that all four axes exhibit similar growth curves for CO, indicating a consistent increase in values from north to south. The average difference between the highest and lowest CO density values is $2,039\times10^{-4}$ mol/m². However, there is

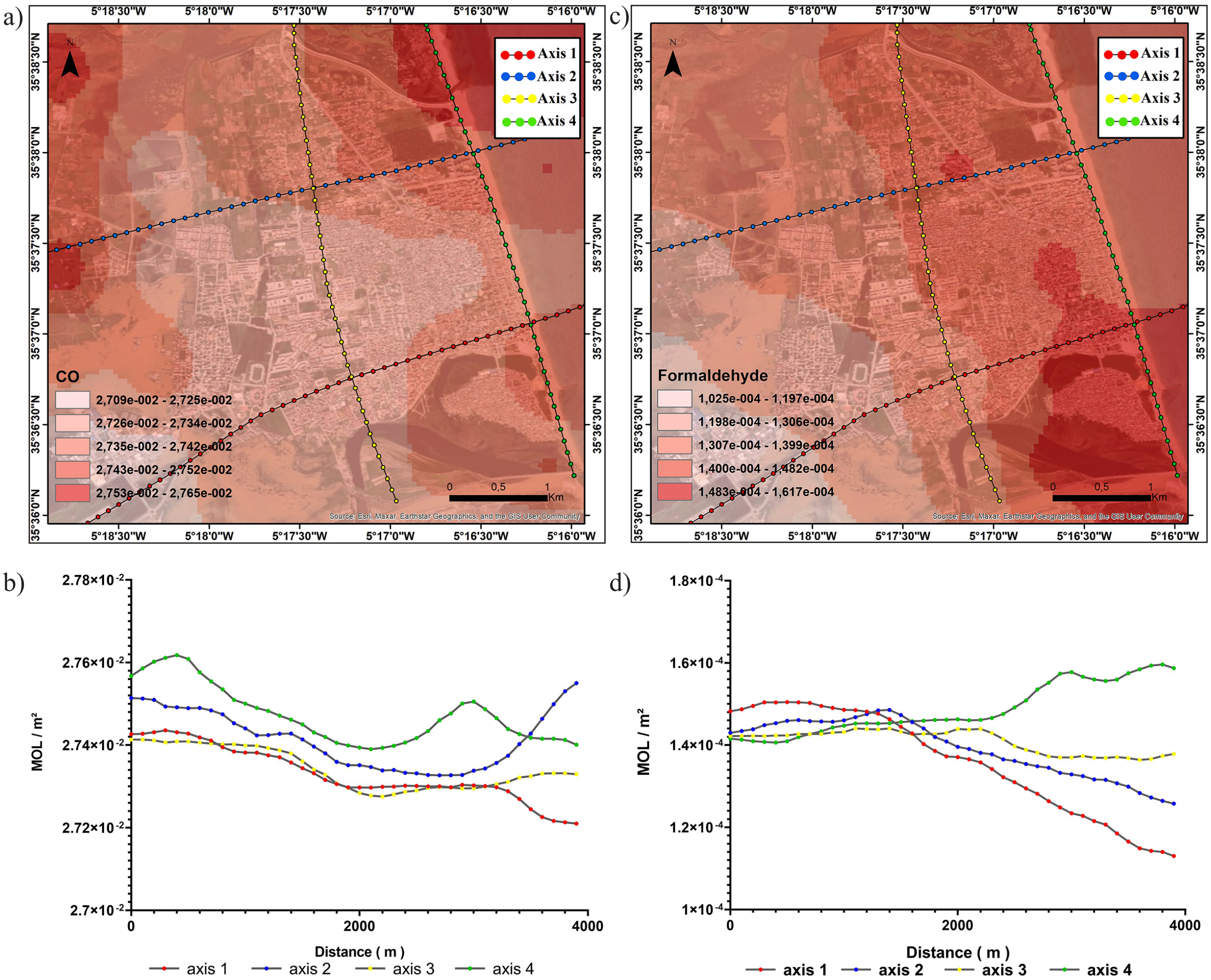

Figure 7. Results of the extracted air pollution data for CO and formaldehydes; a) map of the combined satellite image with the extracted CO data; b) graph of the extracted CO data variation; c) map of the combined satellite image with the extracted formaldehydes data; d) graph of the extracted formaldehydes data variation

a contradiction with formaldehyde, as it demonstrates a decreasing trend for axis 1 and axis 2, extending from the east coast to the west. The average difference in formaldehyde density is 3.74×10^{-5} mol/m² for axis 1 and 2.28×10^{-5} mol/m² for axis 2. Conversely, axis 2 and axis 3 show minimal or negligible variations. Axis 3 has an average difference of 7.65×10^{-6} mol/m², while axis 4 has an average difference of 1.9×10^{-5} mol/m².

In situ monitoring variation

Temperature and humidity

The temperature parameter is a key component of the concept of urban comfort. The authors focused on three factors that influence this parameter: the presence of aquatic spaces, urban morphology (density factor) and the presence of vegetation, as shown in Figure 8. The results indicate that there is variation in temperature across different urban areas. The highest temperature was observed in "Area 1," which is characterized by low building density, a large percentage of open space and agricultural or bare lands with some greenery. Conversely, the lowest temperature indicating comfort in exterior spaces was observed in "Area 4," which has a medium building density and features vegetation and water components. Areas with medium values were those with medium-density buildings, average vegetation cover and no water component.

The analysis of temperature data collected from the areas studied reveals a linear relationship between temperature and location. Specifically, the average temperature difference between area 1 and area 4 is found to be 1.8 °C, while the difference between area 1 and area 3, which has a higher vegetation cover, is on average 0.8 °C.

Figure 9 shows that there is variation in relative humidity across different urban area, based on their landscape characteristics. The distributions of

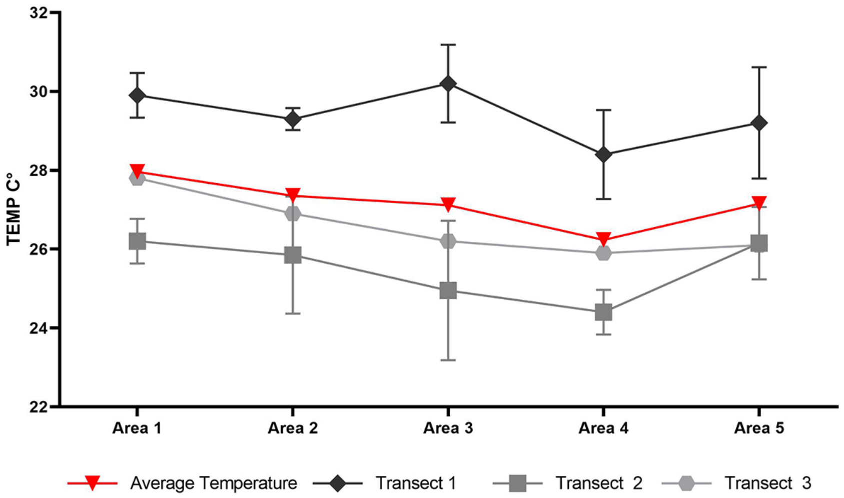

Figure 8. Temperature variation in the study area following the three transects

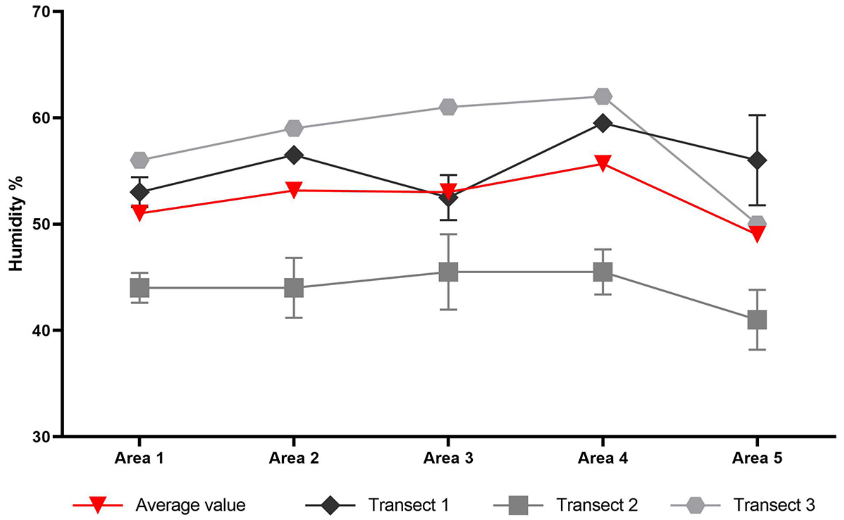

Figure 9. Humidity variation in the study area following the three transects

relative humidity were found to differ in these areas. The highest humidity value was observed in area 4, which contains the backwater and has proximity to the waterfront and vegetation, as shown in Figure 8. Conversely, the lowest value was measured in Area 5, where the density is very high and there is no presence of vegetation and in Area 1, where there is open space and high temperature values.

The examination of the collected humidity data from the studied areas illustrates a linear correlation between humidity and geographic location. In particular, the average humidity difference between area 4 and area 5 was determined to be 6.6%, while the average difference between area 4 and area 3, which features more vegetation, was found to be 2.6%. These results can be compared to the temperature findings, where high temperature levels were associated with lower humidity levels.

Sound level

Figure 10 illustrates the variations in sound levels, which can be attributed to three major factors: building density, vegetation and essentially human activities. The highest sound levels were recorded in area 3, where the building density is moderate and the area is characterized by heavy traffic and commercial activity.

The analysis of the sound data collected from the studied areas indicates that there is a variation in sound levels between the different locations. Specifically, the average difference in sound levels between area 3 and area 1 was found to be 10.2 decibels (dB), while the average difference between area 3, which features the presence of *Platanus orientalis* trees and area 1, which contains palm trees, was determined to be 4.3 decibels (dB).

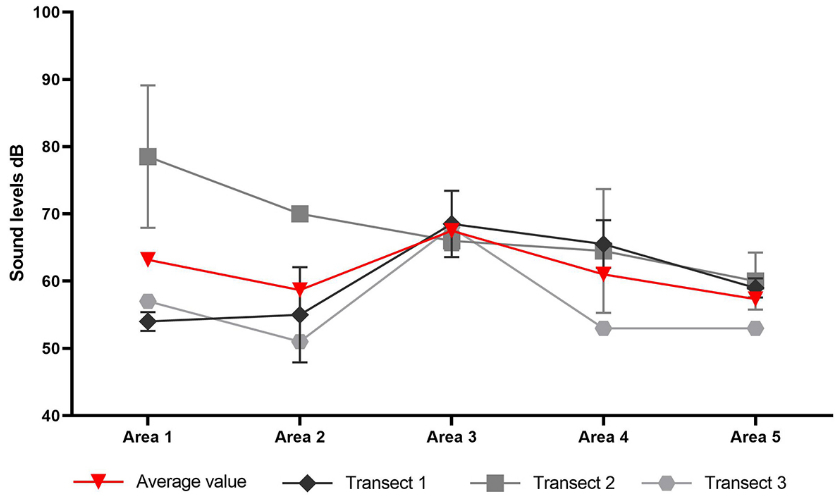

Figure 10. Sound levels variation in the study area following the three transects

In area 1, high sound levels are observed due to two main factors: traffic noise from cars and wind turbulence, as the area is open and unprotected. The lowest sound levels were measured in area 5 and area 2, which are residential area with calm activities and where tree lines are present. The noise levels from cars and commercial activities were found to be the main contributors to sound levels in the study area.

Solar illuminance

Figure 11 shows how solar illuminance varies across different areas in the study area. It indicates that the presence of vegetation and building density are two major factors that affect solar illuminance. Area 1 has the highest solar illuminance values, which is due to its open spaces and the presence of palms that do not provide significant shading. In contrast, area 5 has the lowest solar illuminance values due to the dense residential buildings that create shade and the absence of vegetation. Areas 2, 3 and 4 have medium solar illuminance values, which are closer to providing a comfortable level. These areas are characterized by medium building density and the presence of urban trees (*Populus nigra and Platanus orientalis)* that provide a shading effect.

Understanding the urban greening

Through our in-situ monitoring results, the presence of four main species has been observed in different areas. "Area 1" is characterized by the presence of Washingtonian palms. "Area 2" and "Area 4" feature *Populus nigra* trees along with shrubs and grass. In "Area 3," *Platanus orientalis* trees are accompanied by grass. The analysis of urban greening enhances the understanding of the overall variations observed.

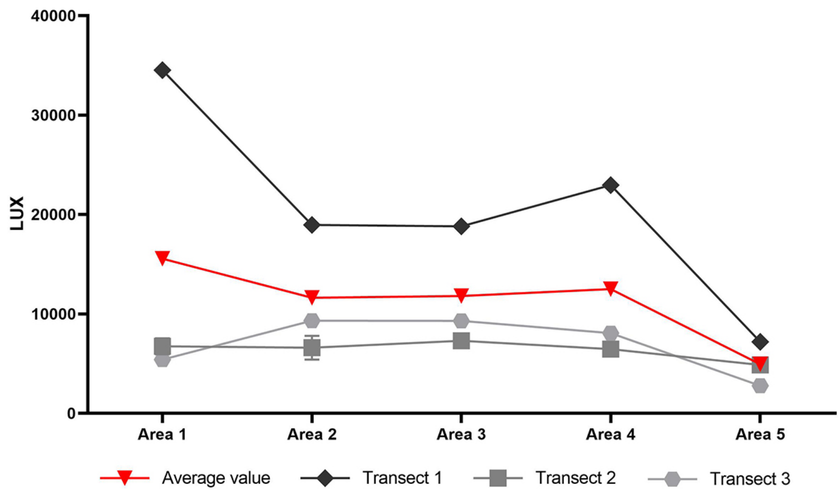

Figure 11. Solar illuminance variation in the study area following the three transects

Vegetation characteristic of area 1

In area 1, the presence of Washingtonian palms, which are planted along the road with a distance of 10 meters between every two consecutive palm trees, has been observed (Fig. 12). The Washingtonian palm belongs to the Arecaceae family and is evergreen palm foliage with a height of 4 meters and very light palmate leaf density. The shading area created by this palm species does not exceed a radius of 1.5 meters and the water requirement for this type of tree is very low, making it suitable for a drought climate.

Vegetation characteristic of area 2

In this area, the presence of *Populus nigra* from the Salicaceae family has been noted. These trees create a shading area with a radius ranging from 2 to 4 meters (Fig. 13) along the road with a distance of 10 meters. The shading area created by this tree species ranges from 2 to 4 meters in radius. Along with *Populus nigra* trees, the presence of shrubs and grass has been noted. Shrubs are present in form of a line that represents a barrier in the urban space with a high not exceeding one meter.

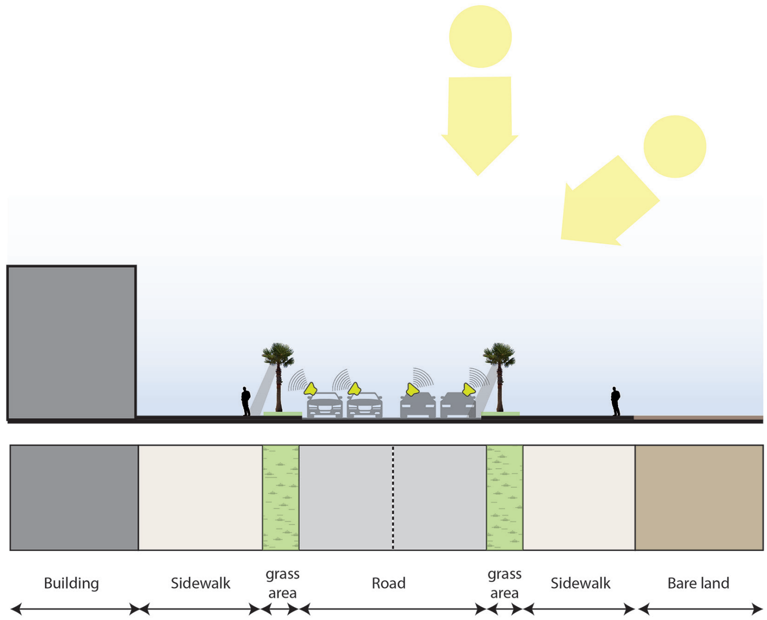

Figure 12. Urban section illustrating area 1

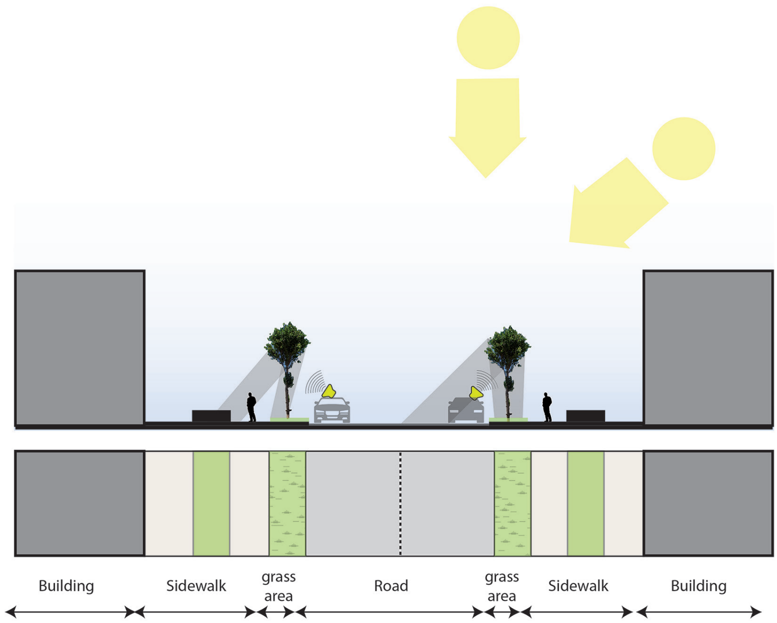

Figure 13. Urban section illustrating area 2

Vegetation characteristics of area 3

In this area, the presence of green grass and *Platanus orientalis* has been noted; the latter, belonging to the *Platanaceae* family, is a tree with deciduous foliage with a rapid growth. The shading area created by this tree species ranges from 2 to 10 meters in radius (Fig. 14). *Platanus orientalis* has also a medium water requirement and needs fresh, aerated and moist soil. Its roots are also capable of absorbing moisture from groundwater or streams.

The grass covers an area of 1.5 meters in width along the entire length of the road and has a green aspect throughout the year. Although it does not provide shade, it requires permanent maintenance and has a very high water requirement. However, the contribution of grassed area to the temperature reduction parameter studied seems minimal as the turf only affects the evaporation flow.

It should be noted that the study area is experiencing declines in water supply due to periods of low rainfall. This is an important factor to consider when assessing the impacts of urban components on temperature and humidity.

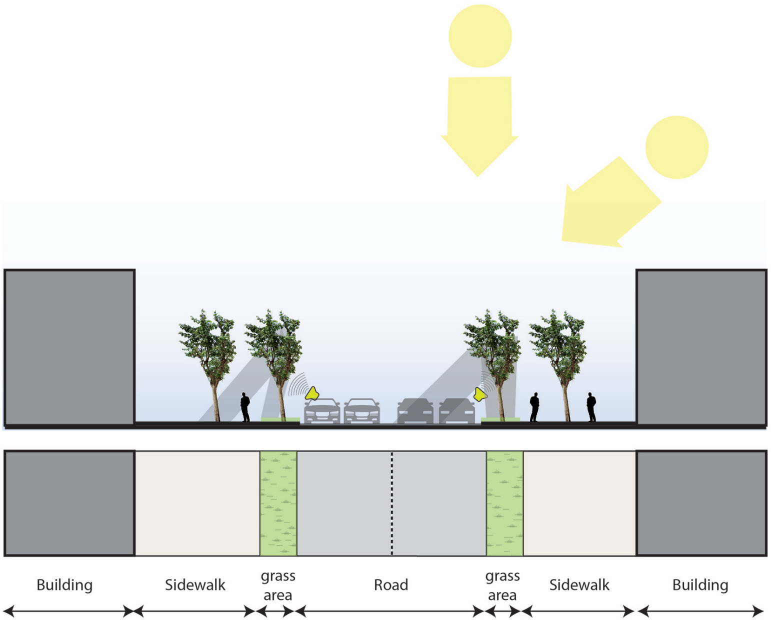

Figure 14. Urban section illustrating area 3

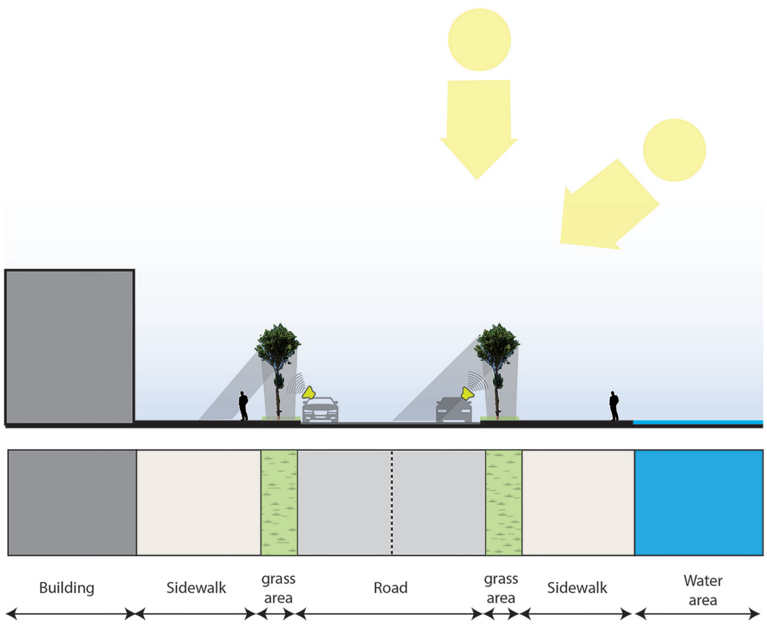

Figure 15. Urban section illustrating area 4

Vegetation characteristics of area 4

In this area, the presence of *Populus nigra* trees, strategically located near the backwater area, has been observed. This proximity contributes to soil moisture, aiding in the healthy growth of the trees (Fig. 15). The *Populus nigra* trees not only offer shade but also enhance the visual appeal of the urban space, making it more appealing for pedestrians.

DISCUSSION

This study aimed to analyze urban outdoor comfort by addressing two main aspects: air quality and the factors that affect pedestrians' comfort when using outdoor spaces, defined as temperature, humidity, sound levels and solar illuminance.

First, the composition of the study area showed a dominant presence of urbanized areas, accounting for 23% on average between green and urban aspects, which significantly affects the city's temperature and creates variations in temperature between the different investigated sites. A study conducted by Brunet (2017) in Rotterdam compared a thermographic map to an urban pattern map and found that green spaces resulted in a decrease in temperature, while high-temperature values were observed in the densely populated urban center. This demonstrates the degree of impact of green aspects on reducing Urban Heat Island (UCI).

On the basis of air quality findings, a significant impact of the four common pollutants has been observed. In particular, high concentrations of NO_2 and aerosols were detected in the industrial area along axis 1, with a percentage increase of 49% for aerosol density and 2% for NO_2 density. Similarly, axis 2 showed a 53% increase in aerosol density and a 3.2% increase in NO_2 density. Axis 3 and 4 exhibited minimal or negligible variations. Additionally, elevated levels of formaldehyde associated with a stagnant backwater in the area were identified, while CO levels were linked to bare lands and agricultural activities along axis 1, with a percentage increase of 0.8% for CO density and 25% for formaldehyde density. Axis 2 showed a 0.8% increase in CO density and a 15% increase in formaldehyde density. Axis 3 and 4 displayed minimal or negligible variations.

Numerous studies confirm that vegetation can help to reduce air pollution, Baradaran Motie et al., (2023) found that planting trees on the median strip, away from sidewalks, can effectively decrease air pollution deposition at the pedestrian level. Their study also showed that deciduous trees are better than coniferous trees at reducing air pollution, specifically $PM_{2.5}$ particles, and improving thermal comfort. However, in the study area, we did not observe a significant difference in air pollution reduction between areas with vegetation, even with the presence of deciduous trees such as *Populus nigra* and *Platanus orientalis*. This raises questions about the configuration and species used in those areas. Additionally, observational studies have shown that NO_2 concentrations are lower under tree cover than in open spaces with similar exposure to traffic pollution (Klingberg et al., 2017).

Other studies have focused on identifying effective vegetation species and factors that influence their effectiveness in air pollution reduction. Alsalama et al., (2021) evaluated conifer species based on criteria such as gender selection and appropriate site matching, while Tallis et al., (2011) and Tiwary et al., (2009) found that coniferous trees outperformed evergreen broadleaf and deciduous species in capturing particulate matter (PM). Green space density, described in terms of relative tree cover, has been positively associated with the mitigation of PM and NO_2 (Escobedo and Nowak, 2009; Nowak et al., 2014) Additionally, (Paoletti et al., 2011) reported that pollutant removal rates of trees increase over time as they grow in size.

It has been observed that the implementation of tree lines along roads focused primarily on aesthetic purposes without considering crucial modifying variables such as wind and precipitation, that a play a fundamental role in the effectiveness of green spaces for air pollution mitigation. Research by (Alonso et al., 2011), Srivanit, (2013) suggests that air quality improvements are more likely under windy conditions, as wind enhances ventilation and reduces pollutant concentrations; however, it is important to note that wind can also become stagnant in street canyons, potentially leading to increased pollution concentrations. Furthermore, increased precipitation positively contributes to the ability of urban vegetation to remove particulate matter (PM) by washing particles from leaf surfaces (Nowak et al., 2013).

It is important to consider the negative impacts as well. Pugh et al., (2012) found that while street trees can reduce street-level PM, they might increase NO_2 concentrations in highly polluted canyons. However, in streets with moderate or low emissions, trees have shown an overall beneficial effect.

Regarding the findings from the in-situ monitoring, the authors focused on analyzing four parameters that affect the exterior comfort and the quality of the urban space; it was noted that area with the presence of vegetation and water components experience a decrease in temperature values, while open spaces experience high temperature values and low humidity values. This result is similar to the study conducted by Thani et al., (2013), which confirmed that open surfaces record higher temperatures and lower humidity levels than area covered by tree canopies or shadowed by buildings. Moreover, (Bigorgne, 2013) explains that vegetation contributes to reducing air temperature through evapotranspiration. The results observed confirm the conclusion made by Shashua-Bar and Hoffman, (2000) that the shading effects provided by trees could provide significant comfort in thermal experience. In their study, McDonnell et al., (2009) specified that the portions of public space that have benefited from a good level of shade during the day do not heat up and do not store solar energy, thus staying fresh.

When comparing trees and grass, it was found that grass surface composition has little impact on globe temperatures. However, tree shading has been shown to reduce globe temperatures by 5 to 7 degrees Celsius and provide significant relief from heat stress (Armson et al., 2012). Trees are considered more effective than shrubs and grass in cooling urban areas, as they show stronger correlations with urban cool islands, especially during warm seasons (Chen et al., 2014).

Among tree types, deciduous trees are recognized as crucial for providing thermal comfort in parks. They offer shade during hot months without blocking the warming sunlight in cold months (Hwang et al., 2011). Both deciduous and evergreen trees contribute to cooling effects during summer, but evergreen tree parks tend to be cooler in winter, falling below the “neutral” comfort conditions (Zhang et al., 2013). However, it is important to note that the cooling effect of plants on air temperatures can be limited if ideal water and soil conditions required for evapotranspiration are not met (Vidrih and Medved, 2013) which reflect the actual challenges that occur in the study area.

It was also noted that Hirsch (2015), in his study of ICU characteristics in Paris, describes water as a “heat trap” that absorbs heat and stays relatively fresh, which explains that water, as a physical component, helps reduce air temperature and create an ambient micro-climate. (Campbell, 2012) and (bigorgne, 2013) affirm that in the summer season, water temperature is lower and has a refreshing effect. Moreover, water can consume energy in the form of heat through evaporation, which reduces temperature. The result obtained is also similar to the study made by Maughan (2014), which analyzed the effect of the presence of a river on the temperature and humidity of an urban area, where temperature levels were on average 1 °C reduced at a 30-meter distance from the river and spaces that give directly to the river are most affected by it; it was also noted that studies conducted by Thani et al., (2013) confirm that dense urban area have high-level temperatures and low humidity while area near water components are fresher.

In terms of sound comfort, it was observed that shrubs are considered optimal due to their linear arrangement, which creates a vegetation barrier to sound. *Populus nigra*, with its dense foliage, is also effective in sound absorption and protection. However, the Washingtonian palm does not contribute significantly to sound comfort. However, the authors observed that the effect of vegetation is minimal, as established by Fang (2003), who noted that a tree line can reduce urban noises slightly. At the same time, Kragh (1979) reported that the effect of vegetation is minimal through several species and the effect on urban traffic is almost absent. However, (Ver, 2005) reported that when a noise meets a barrier, a noise shadow area appears behind the barrier. The noise attenuation is high inside the shadow area, but it is lower outside the shadow area (Beranek and Ver, 1992)

Regarding solar illuminance, Building density and vegetation play an important role to reduce it. In area with high building density and absence of vegetation, there is less solar illuminance reaching the ground, resulting in lower solar illuminance values (Santamouris, 2014). On the other hand, an area with medium building density and presence of urban trees provide medium shading, resulting in medium values of solar illuminance (Liu et al., 2018).

Vegetation creates shading by blocking a portion of the direct sunlight, reducing the amount of solar illuminance that reaches the ground and therefore the solar illuminance values. The shading effect of vegetation depends on the species, foliage density and the orientation of the sun. Urban trees with dense foliage like *Populus nigra and Platanus orientalis* provide optimal shading, while palms with light foliage density do not provide significant shading (Akbari et al., 2001).

CONCLUSIONS

Studying outdoor urban comfort has become a necessity in today's world to optimize energy usage and mitigate climate change. As cities continue to grow and develop, the need for sustainable urban design becomes increasingly crucial. Studying outdoor urban comfort can provide insights into how more sustainable and energy-efficient urban environments – that are better equipped to mitigate the effects of climate change – can be created.

This assessment has revealed the vulnerability of urban areas in terms of air quality and four crucial parameters identified through the conducted in-situ monitoring Firstly, the urban pattern and building density have a significant impact on urban comfort. An area with calibrated green/buildings and medium-density buildings provides optimal results. Secondly, the presence of urban vegetation and the species used also affects urban comfort. *Populus nigra* and *Platanus orientalis* have been found to have a beneficial impact, while other vegetation species enhance the aesthetic perception and social impact. Thirdly, the water component plays a vital role in reducing the temperature effect. It is imperative for urban planning strategies to consider these aspects to achieve good results.

The obtained findings have significant implications for urban planning, as they highlight the need for a more holistic approach to urban planning that considers outdoor urban comfort as a fundamental aspect of sustainability. Integrating this perspective into urban policies can help create more livable and resilient cities that are better equipped to tackle the challenges posed by climate change.

The selection of appropriate tree species plays a pivotal role in enhancing air quality within urban environments by effectively capturing pollutants. It is highly recommended to opt for the tree species that exhibit resilience to urban conditions, necessitate minimal maintenance, demonstrate drought tolerance and possess inherent resistance to diseases, once the optimal green infrastructure and its strategic placement have been identified; meticulous attention to implementation details becomes imperative for achieving successful outcomes. Factors such as wind patterns and precipitation should be carefully considered, as they significantly influence the efficacy of green installations in mitigating environmental challenges.

Additionally, it is essential to approach green implementation in a case-specific manner, taking into account the unique characteristics and requirements of each location. This tailored approach ensures that the full potential of green interventions is harnessed, thus maximizing their effectiveness in ameliorating air quality in urban settings.

Urban planners can use the findings obtained in this study to guide their decisions when designing green spaces and selecting vegetation species for urban landscapes. They can also use this information to optimize building design and placement to improve thermal comfort, reduce energy consumption, minimize the urban heat island effect and reduce air pollution.

Furthermore, policymakers can leverage the findings of this study to develop guidelines and regulations that promote sustainable and comfortable urban environments. By incorporating these results into their decision-making processes, they can encourage the adoption of best practices in urban planning and design and facilitate the implementation of sustainable and climate-resilient urban projects.

This research underscores the importance of considering outdoor urban comfort in urban planning and design. By doing so, it is possible to create more sustainable, livable and resilient cities that are better equipped to mitigate the negative impacts of climate change and provide a high quality of life for their residents.

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