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Mapping of Air Pollutants Within Urban Canyons of Alexandria City Fabric

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Abstract

Human health and the environment are both threatened by increased air pollution, which is a major issue on the global agenda. Recognizing the importance of addressing this issue, the research field emphasizes the urgent need to improve air quality, serving not only to mitigate climate change but also to restrain emissions and protect public health. Focusing on the urban context in Egypt, characterized by high traffic density and vehicular emissions, the prevailing urban fabric contributes significantly to increased concentrations of pollutants. Despite this, there is a lack of monitoring of localized pollutant concentrations, which directly impacts the well-being of citizens. This research aims to measure, on a localized scale, and map the most critical pollutants, namely PM2.5, PM10, CO, and CO2, inside a representative urban canyon of Alexandria. Hence, it introduces a novel layer to the existing spatial database, offering a comprehensive understanding of air quality dynamics within this specific urban environment. The study employs measurement campaigns, which are conducted using a handheld portable smart air quality detector. The measured concentrations are subsequently compared against both local and international standards. The concentrations of PM2.5 and PM10 are found to definitely exceed the international WHO ranges, while they sometimes exceed the limit values set by the EPA and the Egyptian ambient air quality standard. Whereas, the findings indicate that CO and CO2 exhibit no notable risks, with values largely falling within WHO limits. The study also delves into identifying and analyzing variables that have a significant influence on pollutant concentrations. The research findings affirm that seasonal variations and geospatial parameters distinctly influence the concentration levels of pollutants within urban canyons. Consequently, this study provides crucial insights for informed urban planning and environmental management strategies.

Keywords: urban canyon ; air pollution ; PM concentrations ; survey ; mapping

1. Introduction

Ensuring clean air is a fundamental necessity for both human health and environmental well-being. Air pollution has evolved into a pressing global concern, posing substantial risks to health and the environment. According to the World Health Organization (WHO), diseases linked to air pollution, such as heart disease, lung cancer, chronic obstructive pulmonary disease, and stroke, contribute to an estimated seven million premature deaths annually [1]. A staggering 91% of the global population resides in areas where air quality exceeds WHO limits for hazardous pollutants like particulate matter (PM2.5 and PM10), ozone (O3), nitrogen dioxide (NO2), and sulfur dioxide (SO2) [2]. This highlights the pervasive nature of air pollution making it the greatest threat to environmental health in recent times.

Particulate Matter (PM) has become a focal point in research due to its significant contribution to global [2] and local [3] health risks, and deterioration of the built environment [4]. PM exists in various categories, notably PM2.5 and PM10. PM2.5 refers to fine particles that are 2.5 micrometers in diameter or smaller, while PM10 refers to coarse particles up to 10 micrometers in diameter. Due to its notable high persistence in the atmosphere, particular focus is placed on PM2.5. This fine particulate matter has the ability to deeply penetrate the lungs, enter the bloodstream, and pose a significant threat to human health.

In outdoor environments, the main sources of particulate matter are location-specific and typically include traffic and transportation, industrial activities, power plants, construction sites, waste burning, fires, or agricultural fields [2]. With this regard, the World Health Organization [1] has developed the WHO Global Air Quality Guidelines (AQG) to address the

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health risks associated with key air pollutants. The air quality index rating, shown in Table 1 [5] [6], is taken into account for the assessment of ambient (outdoor) air quality in this study.

Table 1. Air quality index (AQI) values, with PM2.5 and PM10 concentration ranges (Source: [5]; adapted [6]).

AQI Value Of Index	Levels of Health Concern	$PM_{2.5}$ Conc. (μg/m³)	PM_{10} Conc. (μg/m³)	Daily AQI Color	Air Pollution Level
0–50	Good	0–12	0–54	green	Level 1
51–100	Moderate	12.1–35.4	55–154	yellow	Level 2
101–150	Unhealthy for sensitive groups	35.5–55.4	155–254	orange	Level 3
151–200	unhealthy	55.5–150.4	255–354	Red	Level 4
201–300	Very unhealthy	150.5–250.4	355–424	Purple	Level 5
301 and Higher	Hazardous	250.5–Higher	425–Higher	Maroon	Level 6

The increasing urbanization tendencies and the growth of global population have led to a rise in exposure to traffic emissions. The transit-oriented developments, vital for the connectivity of the city, bring traffic activity closer to people's residences, exposing the urban population to the negative effects of air pollution [7]. According to the European Commission, transportation (23.2 %) is the second-largest source of greenhouse gas emissions in the EU after energy (23.3 %), accounting for around a quarter of all emissions [8]. In general, field measurements on air quality in near high-volume roadways [9] have shown that the highest concentration of air pollutants is within 100 to 150 meters from the road, then it decreases gradually. Yet, some pollutants are found as far as 300 to 500 meters away from the traffic emissions.

In Egypt, and according to the 2019 State of Global Air report [10], the annual average exposure to PM2.5 is 68 μg/m3 [11]. This level of exposure poses substantial environmental and health risks to the city's population. It falls into the unhealthy category (AQI Level 4), indicating that some members of the public may experience adverse health effects, while sensitive groups may face more severe health issues.

Unlike in most developed countries where advanced monitoring technologies are utilized to generate information and guide policy-making, Egypt faces challenges in obtaining accurate, comprehensive, and up-to-date air quality data. Moreover, over the past decade, there has been a limited number of studies focusing on the assessment of outdoor spaces in the Egyptian context, with limited results examining the adjustment of the urban fabric, the integration of green infrastructure, and the assessment of urban air quality. Hence, the scarcity of data and information on real-time air quality monitoring in Egypt hinders the development of effective strategies for mitigating urban air pollution.

The main sources of pollution in Alexandria (case study) are attributed to urban development, population growth, increased vehicular emissions, and the detrimental impact of the "wall effect" on air ventilation and pollutants' dispersion rate, which is caused by the alignment of high-rise buildings in complex clusters. Such clusters produce poorly ventilated areas with slower pollutant removal, resulting in pollutant accumulation and higher concentrations.

Street canyon is the fundamental geometric unit of urban environments, which significantly influences microclimatic conditions. These canyons have been classified based on the ratio of their height (H) to width (W), denoted as the aspect ratio (H/W), which helps in categorizing the flow across canyons into three distinct regimes [12] (Figure 1). Several studies have investigated the effect of urban morphology on the dispersion of air pollutants within cities. Chan et al. [13] conducted research that revealed wider streets and lower buildings promote the dilution of pollutants within street canyons. In a similar manner, Sagrado et al. [14] embarked on both numerical and experimental modeling endeavors to examine the dispersion of pollutants within street canyons. Their investigations unveiled a phenomenon wherein a recirculating bubble forms inside the street canyon, hindering pollutants from escaping and thus trapping them in the corners of the street (Figure 1 - red circles). Furthermore, several state-of-the-art reviews [15-16-17-18-19] highlighted the multitude of influencing variables, such as urban geometries, greenery parameters and meteorological conditions, having significant effect on improving urban microclimatic conditions and air quality.

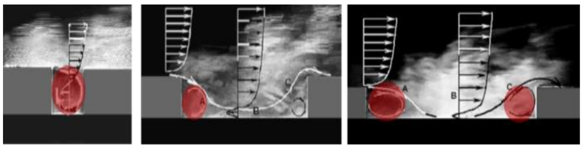

Fig. 1. Canyons airflow analysis, a) Skimming Flow – deep canyon, b) Wake Interference Flow – moderate canyon, c) Isolated Roughness Flow – shallow canyon (source: adapted from [12]).

The aim of this study is to 1) measure and map the most critical pollutants inside a representative urban canyon of Alexandria, 2) compare the concentration levels with local and international standards, and 3) evaluate the variables that have a significant influence over the pollutants' concentration. This research presents an expansion from the common analysis found in literature, by comparing the collected data according to four criteria: a) per gases, b) per national and international standards, c) per season, d) per sector. The researcher adopts an experimental research method to investigate the effect of seasonal and geospatial variations (independent variables) on the values of pollutant concentrations (dependent variable).

2. Materials and Methodology

2.1. Case Study

The city of Alexandria is selected as a case study due to the prevalence of deep urban canyons in its urban fabric, creating the “wall effect”. These urban canyons contribute to the trapping of Traffic-Related Air Pollution (TRAP) within a recirculating bubble, blocking the dispersion of pollutants outside the street boundaries. The formation of such urban typology began in 2010, characterized by the proliferation of illegal ramping-up of buildings, due to population increase, violation of the building codes, and a lack of effective government surveillance. These factors collectively contribute to the imperative necessity for comprehensive urban planning and environmental interventions to address the deteriorating health conditions in Alexandria.

Considering the current state of the city, an in-depth examination of air quality within urban canyons is essential. Abu Qir Street emerges as an ideal representation of an Alexandrian canyon (Figure 2) due to its unique characteristics. Stretching along the majority of the city's West-East axis, the street aligns parallel to the sea line and is mostly perpendicular to the prevailing wind direction. Moreover, Abu Qir Street has undergone significant transformations over time, marked by the proliferation of several illegal ramping-up of buildings. Consequently, its urban typology has experienced substantial changes, effectively encapsulating various urban canyon typologies, including deep, moderate, and shallow canyons (referenced in Figure 1). Furthermore, it is one of the most popular commercial streets, with a dense urban morphology, complex land use, and high traffic density. This street thus serves as a valuable case study for understanding the complexities of urban canyons in Alexandria.

Within this artery urban canyon, four sectors have been selected for this study, representative of the different typologies (Figure 2). The selection of the sectors is based on constant, controlled, independent, and dependent variables. The constant variables were chosen to provide consistency between sectors, they remain unchanged throughout the study. For instance, the four sectors were chosen from the same street which has a consistent orientation to the prevailing wind direction, approximately equal distance from the seashore, and mostly similar presence of traffic density. Whereas the controlled variables were chosen based on the need to investigate the relationship between dependent and independent variables. These include the date of the experiment, duration of the experiment, location of monitoring, and elevation of the monitoring device.

Hereafter, this study investigates the effect of seasonal and geospatial variations (independent variables) on the values of pollutants’ concentration (dependent variable). An urban morphology analysis was conducted to extract the geometric dimensions of the selected street sectors. Two main urban geometric aspects were considered: 1) the ratio between the surfaces covered by buildings (B) and the total surface (T), known as built-up footprint (B/T), and 2) the geometric average values of the buildings' height (H) to the streets' width (W), known as urban canyon's aspect ratio (H/W). The chosen sectors are delineated based on the availability, accessibility, and durability of their related data.

2.2. Data Collection

Measurement campaigns were carried out over one year from winter 2022 to autumn 2023, during representative days of the four seasons, to gain an insight about the seasonal variations. Selected days for measurements were chosen based on their characterization of the season with representative values of temperature, humidity, wind speed, and precipitation.

The sampling was performed at four static locations inside each sector. The four locations are equally distributed along the sector, with two locations on each sidewalk of the street sector. Samples were taken at each location during the rush hours and routine daily activities, to focus on the worst-case scenario during the selected representative days of each season. Readings were recorded at a time interval of one minute for a total average duration of 45 minutes daily, repeated four times every season.

The samples were collected from a fixed height of 1.5m above the ground (breathing zone), to measure the impact of pollutants on sidewalkers. Prominent air pollutants PM2.5, PM10, CO, and CO2 were monitored using the handheld portable smart air quality detector Oceanus OC-1000 (details in Table 2).

Additionally, a more precise monitoring of the pollutants’ evolution along the urban canyon was performed with an additional dynamic reading on a representative summer day. The monitoring device was in motion across the four sectors with an average human speed. This dynamic monitoring aims to measure the slight variations across the sectors.

2.3. Data Analysis

The data gathered from the field is meticulously presented through tables, graphs, and maps for comprehensive visualization. The initial analysis focuses on variations in gases and is assessed against both national and international standards Subsequently, a comparative analysis is undertaken to evaluate the impact of independent variables, namely seasons and geospatial variations, on the dependent variable, which is the concentration levels of air pollutants.

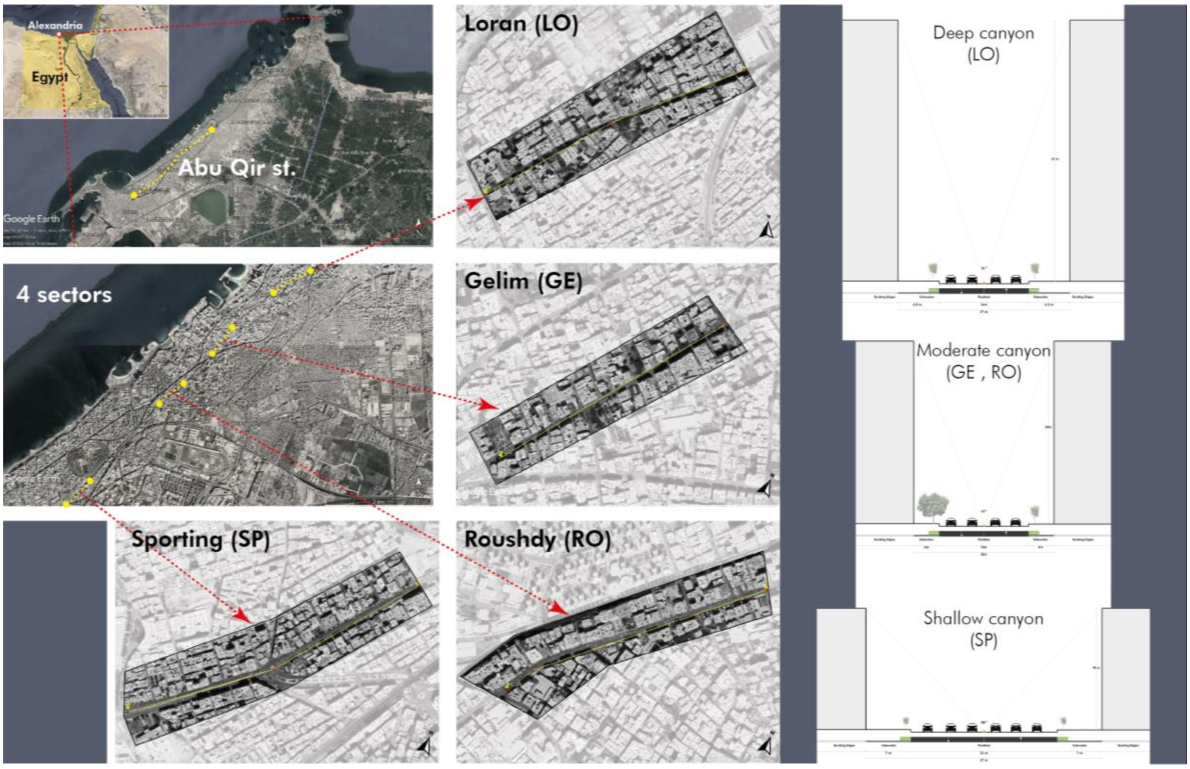

Fig. 2. Satellite images of the selected study area and the four sectors (Source: Google Earth).

Table 2. Properties of the air quality detector (Source: [20]).

Measurement Instrument	Measuring Parameter	Range	Resolution	Accuracy	Photo
Oceanus oc-1000	PM2.5 concentration	0~999 ug/m^3		±3%F.S	
	PM10 concentration	0~999 ug/m^3		±3%F.S	
	CO	0~1000 PPM	1PPM	±3%F.S	
	CO_2	0~10000 PPM	1PPM	±3%F.S	
	VOC	0~10 PPM		±3%F.S	
	Air Temperature	-40~120℃	---	---	
	Relative humidity	0~100% RH	---	---	
Dimensions	220*88*55mm				
Sensor-type	Electrochemical sensor				
Sampling	Pump				
Model	OC-1000				
Coverage radius	Approx. 15m				

This analytical approach aims to discern patterns and relationships within the dataset, contributing to a greater comprehension of the variables influencing air pollution levels within urban canyons.

3. Results and Discussions

3.1. Concentration Levels of Air Pollutants

a) Per gases

To begin with, according to Table 3 and referencing Table 1, it is noticeable that PM2.5 is the most critical pollutant with values exceeding WHO limits significantly. Following, PM10 warrants examination, particularly for surpassing values to a moderate level. Whereas, CO and CO2 exhibit no notable risks, with values largely falling within WHO limits. Hence, the field measurements confirm the findings from the previous researches, reaffirming PM2.5's critical status, due to its high persistence in the atmosphere and its deep penetration into the human bloodstream.

Table 3. Annual average of pollutants.

Gases average			
PM2.5	PM10	CO	CO2
49.3	63.3	4.4	417.9

b) Per national and international standards

According to the Central Agency for Public Mobilization and Statistics (CAPMAS) national reports, the annual average exposure to pollutants in the city of Alexandria are PM2.5=33 µg/m3 and PM10=101 µg/m3 [21]. The annual average of pollutants collected during field measurements (Table3) are not totally aligned with these readings, indicating higher pollutants concentrations than the ones reported. In fact, the measured annual average of PM2.5 exceeds the reported average by 1.5 times. Whereas the measured annual average of PM10 is found to be 0.6 times lower than the reported value. This variance is explicated by having a difference in readings between the micro-scale (urban canyon) and the macro-scale (city). The State of Global Air [11] has noted in their report that "PM2.5 concentrations reported are estimated using a combination of satellite data, ground air quality monitoring data, and chemical transport models. These estimates can be more uncertain where ground monitoring data are limited or not available". These initial findings, supported by the last statement, reinforce the goal of this study to investigate urban air pollution at a more local scale in relation to the localized changing variables.

In more depth, the measured concentrations of PM2.5 and PM10, exhibited in Table 4, definitely exceed the WHO acceptable limits (PM2.5=0-12 µg/m3; PM10=0-54 µg/m3) [2]. While they sometimes exceed the limit values set by the EPA (PM2.5=35 µg/m3; PM10=150 µg/m3) [22], and the Egyptian ambient air quality standard (PM2.5=50 µg/m3; PM10=70 µg/m3) [23].

With reference to the international WHO ranges, the measured annual average concentrations of PM2.5 in moderate canyons (GE and RO), and in the shallow canyon (SP) stand at level 3 "unhealthy for sensitive groups", while in the deep canyon (LO) it transcends to level 4 "unhealthy". As for the measured annual average concentrations of PM10, it remains within level 1 "good" in GE and RO sectors, while surpasses to level 2 "moderate" in SP and LO sectors. Additionally, CO levels in SP and LO sectors also stand at level 2 "moderate". In contrast, the CO2 levels in all sectors remain within the allowed limits of WHO (400-600 ppm). These findings verify that the PM2.5 concentrations always surpass the WHO limits and exceed the average values found in national reports. The findings also highlight the local variations within the urban microscale, which directly affects users of the urban space, negatively impacting their health.

Table 4. Annual average of pollutants by sector.

Sector	Gas	Yearly Average
Gelim	PM2.5	44.14
	PM10	52.31
	CO	3.87
	CO2	416.36
Roushdy	PM2.5	47.64
	PM10	49.89
	CO	3.99
	CO2	417.27
Sporting	PM2.5	44.30
	PM10	68.27
	CO	5.50
	CO2	414.69
Loran	PM2.5	60.96
	PM10	82.63
	CO	4.22
	CO2	423.20

c) Per season

The changing weather conditions throughout the seasons show an intense variation of PM values. Table 5 displays the seasonal variations and annual average concentrations of pollutants. It is noticed that the highest concentrations of PM2.5 occur in the summer season, while the lowest concentration of all pollutants is found during the spring season.

A primary analysis of the findings reveals that the summer season is the worst in terms of air quality. This season is associated with high temperatures, high humidity, low wind speed, and no rainfall. These meteorological conditions have direct effects on airflow patterns within the canyon, thus aggravating the pollution concentration in the summer season. It thus has the highest particle suspension rate.

Table 5. Annual average of pollutants by season.

	Seasonal average			
Season	PM2.5	PM10	CO	CO2
Winter	46.0	50.5	4.0	430.5
Spring	27.1	32.9	2.8	395.2
Summer	63.4	66.0	5.7	415.2
Autumn	60.9	69.8	4.5	429.5
Annual average	49.3	63.3	4.4	417.9

Unexpectedly, the autumn season witnesses the second-highest PM concentrations. Due to climate change, the autumn season now presents mild temperatures, low wind, and low rain, hence particles are not dispersed nor disposed in the canyon.

Additionally, a thorough investigation of the citizens' behavior shows that the autumn season is associated with the highest traffic volume and traffic congestion due to people's movement to work and schools during rush hours.

On the other side, spring and winter seasons, even though they uphold the same citizens' behavior schedule as in autumn, present high winds combined with abundant precipitation. Therefore, particles are least suspended during these seasons. In fact, spring exhibits the best air quality, with all pollutants' values falling within the WHO limits. This is mostly due to the highest wind speed among seasons, allowing a higher dispersion rate of pollutants through the streets perpendicular to the urban canyon.

d) Per sector

In alignment with the previous section, Figure 3 shows a strong correlation between multiple sectors across the different seasons. This is due to the consistency of the independent variables mentioned earlier. The maximum seasonal concentrations of PM2.5 was recorded in LO sector during the summer season (83 µg/m3). While the lowest concentration was found in SP sector during spring (22.7 µg/m3). The overall high concentration in LO sector is attributed to its urban typology.

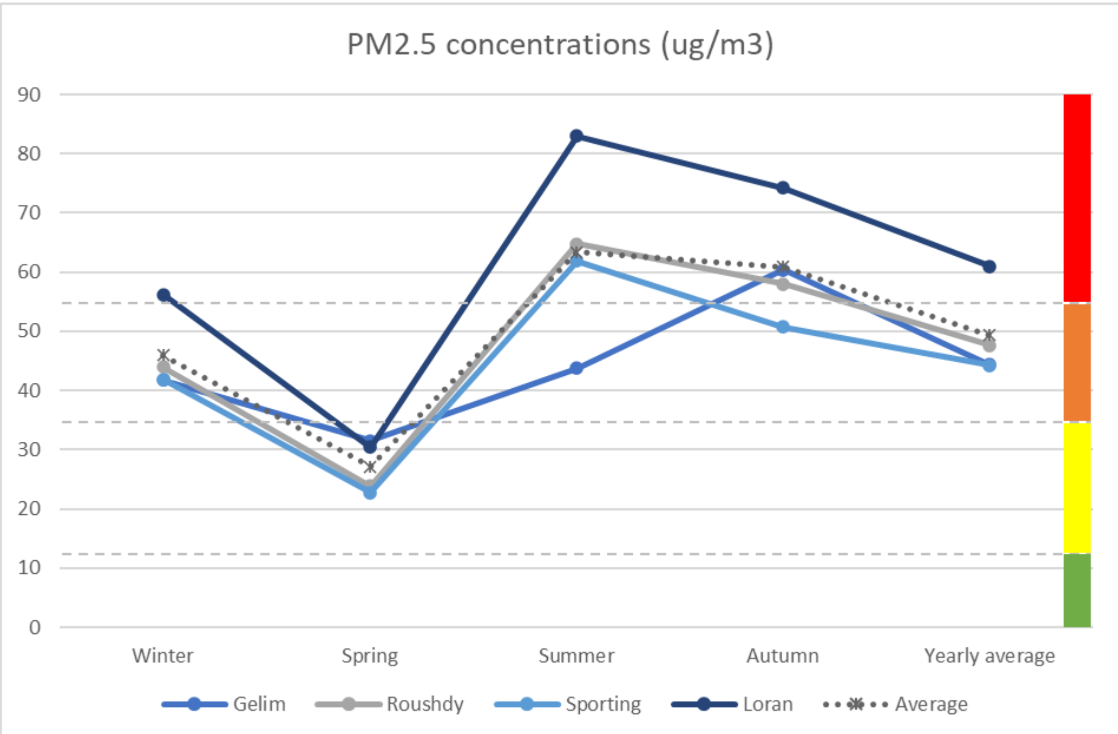

Fig. 3. Seasonal variation and annual average concentrations of PM2.5 in different sectors.

In terms of geospatial parameters, the H/W ratio has a significant impact on air quality. It is noticeable that in the deep canyon (LO) the Mean Monitoring Readings of PM2.5 are approximately 1.3 times higher than other canyons (GE, RH, and SP). This is due to the re-circulating bubble inside the deep canyon blocking the pollutants from moving out of the street. Moreover, high moderate canyon (RO) has frequently higher PM2.5 values than shallow canyons (SP), this is due to the position of the re-circulating vortex next to the leeward wall, increasing the concentration on sidewalks. As for the low moderate canyon (GE), it is almost in analogy except during the summer season, where it has a distinctive representation of values. Such difference is attributed to land use, with GE sector being mostly residential, it has a higher PM2.5 value during autumn than during summer. This is attributed to the people's movement for work and schools during rush hours, while in summer there is a lack of commercial activities and hence lower traffic.

3.2. Distribution of Data (dynamic readings)

The differences in pollutant concentrations inside the urban canyon are not solely attributed to variations in seasons and geospatial parameters. The researcher argues that pollutants' evolution along the urban canyon is also affected by localized changes in the urban geometry, land use, and activities. To fortify this claim, a more precise monitoring of PM2.5 evolution along two urban canyons (RO and SP) is performed using a dynamic reading on a representative summer day. It aims to plot the slight variations across each sector. The distribution of different concentrations of air pollutants is plotted on the plan of the different sectors, displaying local variations.

Localized variations are observed in Figure 4 and Figure 5, where a slight drop of the PM2.5 curve is associated with the change in the urban geometry, particularly by the presence of vacant land. This suggests that open spaces or specific urban layouts contribute to a reduction in PM2.5 levels, due to increased dispersion rate. Whereas, an instant peak in the PM curve is connected to a high traffic density, typically occurring near gas stations, signal lights, drop-off zones, and street squares. This spike is directly linked to the elevated presence of stationary vehicles, suggesting that vehicular emissions significantly contribute to localized air pollution. The juxtaposition of these contrasting patterns highlights the complex interaction of urban elements, traffic dynamics, and pollutant sources in shaping the spatial distribution of pollutants along the urban canyon.

4. Conclusions

Prominent air pollutants (PM2.5, PM10, CO, and CO2) were monitored inside four sectors of a representative urban canyon of Alexandria, to evaluate air pollution profile. The results indicated that concentration levels of PM2.5 pollutant always exceed the permissible thresholds of WHO. PM10 pollutant occasionally exceeds the permissible limits. Whereas, CO and CO2 exhibit no notable risks, with values largely falling within WHO limits.

The findings suggest that seasonal variations have a significant impact on pollution concentrations. Summer season notably exhibits the highest levels, due to its meteorological conditions. Followed by autumn having the second highest concentration levels, due to citizens' travel behaviors. While winter and spring display lower concentration levels, due to high winds and abundant rainfall.

Moreover, the outcomes of the static and dynamic measurements indicate the considerable influence of geospatial variations over the pollutants' concentration profile along the urban canyon. The urban typology has a substantial impact on pollutant concentrations, particularly represented by the aspect ratio (H/W) of the canyon. Likewise, urban air quality is affected by localized changes in the urban geometry, land use, and activities.

The data collected on air quality inside the urban space adds a novel layer to the existing spatial database of Alexandria. The generated information plays a crucial role in guiding policy-making, developing suitable customized responses, and addressing the issues brought on by poor air quality. Developing pollution reduction strategies could include promoting public transportation use, enforcing emission standards for vehicles, implementing temporary traffic restrictions during summer months, implementing green infrastructure initiatives, and enhancing urban planning regulations to minimize pollution hotspots.

Finally, this research provides a basis for improving the air quality in Alexandrian urban canyons, and similar urban and meteorological typologies, in order to mitigate the health risk on citizens and improve their well-being. Further research could study the potential effect of Urban Green Infrastructure (UGI) in reducing air pollutions inside cities. Complementary research could be elaborated based on the comparison between the results of this study and of other cities around the world with comparable climatic circumstances.

5. Conflicts of interest

There are no conflicts to declare.

6. Formatting of funding sources

There is no funding received to assist this research.

7. Ethical Approval

All Data in the current study was collected in accordance with the ethical standards. For this type of study formal consent is not required.

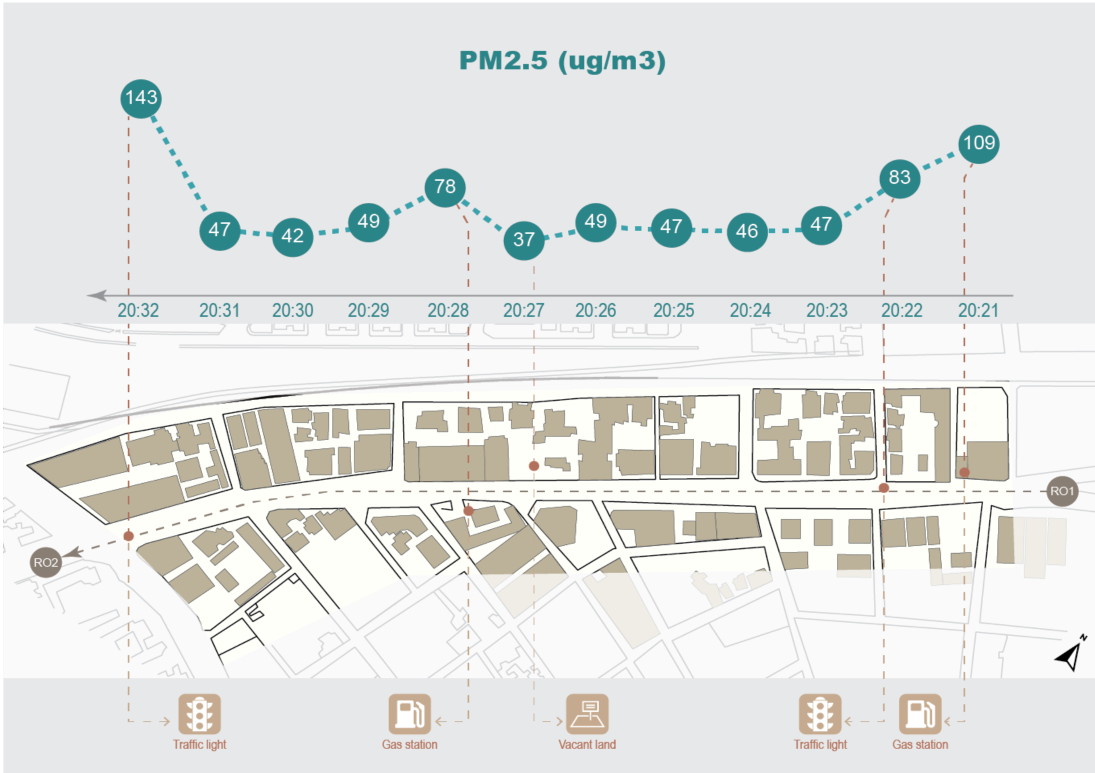

Fig. 4. Localized variations of PM2.5 concentrations in RO sector.

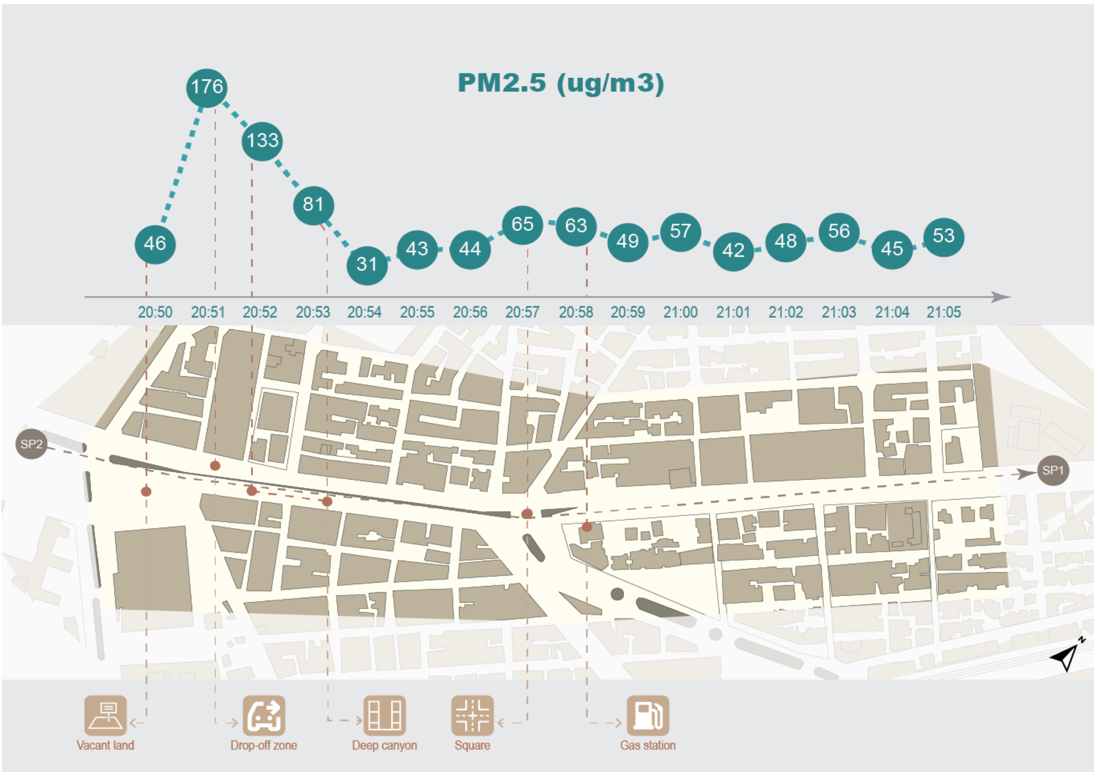

Fig. 5. Localized variations of PM2.5 concentrations in SP sector.

8. Data availability statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

9. Acknowledgments

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