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Atmospheric Pollutants in a Commercial Region of Fortaleza, Ceará, Brazil: Integration of Health, Environment and Economy in Urban Planning to Improve Air Quality

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Abstract

The accelerated growth of the vehicular fleet, the modernization of large urban centers, and the few adjustments to the road network in Fortaleza have intensified the problems of traffic and emissions of atmospheric pollutants, highlighting the necessity for strategic urban planning initiatives to address the escalating issues of traffic and pollution. With the objective of analyzing the indices of concentrations of atmospheric pollutants and estimating how these levels can affect human health, this work consists of a study of the analysis of air quality in the intense trade region of Fortaleza. For this, the analysis zone was divided into three perimeters (Major - Medium - Minor), where each perimeter was analyzed at 7 am, 12 noon and 5 pm. Concentrations of the type of O_3, particulate matter ($PM_{2.5}$ and PM_{10}), CO_2 and HCHO were collected. Our results demonstrate that most of the analyses are within the limits of current legislation; however, at certain times and perimeters, the analyses of CO_2 and HCHO exceeded the established limits. In view of the above, we conclude that public policies to control air quality are necessary to reduce the damage to human health and the environment caused by pollutants.

Keywords

Air Quality, Urban Planning, Particulate Material, Health Impacts

1. Introduction

The current challenges posed by high levels of pollutant emissions underscore the pressing need for effective planning and management of urban spaces. Anthropogenic activities over the years have contributed to atmospheric pollution, aggravated by factors such as disorganized traffic, uncontrolled pollutant emissions from both public and private transport, and the widespread use of individual vehicles by the population (McDuffie et al., 2020).

The concentration of people in large urban centers, driven by urbanization, policies encouraging automobile production, and inadequate urban planning, has resulted in an urban mobility crisis, particularly evident in deficiencies within the public transport system (Teixeira et al., 2015). Addressing these challenges requires strategic urban planning to create sustainable, efficient, and environmentally friendly transportation systems.

The rapid expansion of cities, as seen in the center of Fortaleza/Ceará, Brazil, necessitates a holistic approach to urban planning. Historical activities and the influx of people to tourist and commercial areas should be carefully managed to ensure a balance between economic development and environmental sustainability (Silva, 2013; Vasconcelos, 2008). Effective urban planning is crucial for mitigating the environmental impact of commercial activities while maintaining the vibrancy of the city.

The discussion of atmospheric components and pollutants highlights the importance of environmental planning in urban areas. The presence of pollutants like carbon monoxide and dioxide (CO and CO_2), ozone (O_3), sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) emphasizes the need for policies and planning aimed at reducing emissions and improving air quality (WHO, 2015).

Analyzing the consequences of pollutant exposure requires a comprehensive approach that integrates epidemiological studies. Such studies can inform urban planning decisions by providing insights into the health impacts of air pollution. Integrating health indicators into urban planning strategies becomes essential to create environments that promote both physical well-being and economic growth (Opoku et al., 2024; Botchwey et al., 2022).

It is possible to observe over the years the concern of society about the possible adverse health effects caused by exposure to air pollution, particularly in large urban centers (Goodsite et al., 2021). The amount of air pollutants inhaled causes serious damage to health; in relation to visual pollution, the main impacts are associated with the degradation and devaluation of the environment, which reflects on the local economy (BRASIL, 2018).

According to the IPLANFOR (2024), the Centro neighborhood has a population of 31,463 people, with a constant decrease in the number of residents. The urban structure in certain areas includes a large number of neglected buildings, while others are semi-demolished and have been converted into parking lots. Most of the buildings are subject to very low rents and are used by a vibrant popular commerce during the daytime hours. At night, establishments close their doors, giving rise to a forlorn urban nocturnal desert (PLANMOB, 2015).

Preventive measures to address pollutant emissions and mitigate the effects of atmospheric degradation are integral to achieving sustainable urban development. Balancing economic goals with environmental protection requires a multidimensional approach that includes public policies, territorial planning, and sectoral actions. This study contributes to this broader objective by analyzing atmospheric pollutants in a commercial area of Fortaleza, emphasizing the importance of integrating health indicators and urban planning considerations in achieving air quality goals.

In this context, the present work aims to analyze the concentration of atmospheric pollutants (PM, NO_x, CO, CO_2, O_3 and HCHO) in a commercial area of Fortaleza/Ceará, Brazil. For this, the analysis region was divided into points distributed along three perimeters (largest, medium and smallest). The analyses were performed at 7 am and 12 noon and 5 pm. In addition, some health indicators were mathematically estimated, through the analysis of PM deposition in the respiratory system and PM dose inhaled per body mass of people exposed to the analyzed environments.

2. Materials and Methods

2.1. Characterization of Analysis Zones

The study was carried out in a region of intense commerce located in the city of Fortaleza/Ceará, Brazil. The region was then divided into three different routes called: 1) greater perimeter; 2) average perimeter; and 3) smaller perimeter. The region of analysis is known for the great commercialization of products and offer of services, besides having the main access roads to the beaches of the east region of Fortaleza, presence of roads with intense flow of vehicles, access roads to noble neighborhoods of Fortaleza and mainly the intense circulation of people and vehicles of public and private transport.

For analysis of atmospheric pollutants in the region, the route of each perimeter was divided into monitoring points with intervals of approximately 500 m between them. Atmospheric analyzes were performed over a period of 5 minutes at each monitoring point. The perimeters were divided into points according to **Figure 1**.

The larger perimeter, with approximately 10.5 km, was divided into 17 monitoring points; the average perimeter, with approximately 3.7 km, in 9 points; and the smaller perimeter, with approximately 1.4 km, in 4 points, totaling 30 monitoring points. For the transfer during the analyses between the 30 points, a motorcycle was used.

This study was carried out to determine the feasibility of the analysis methodology developed, in addition to verifying whether the environment is harmful in terms of the exposure of people in that region to pollutants. The study was

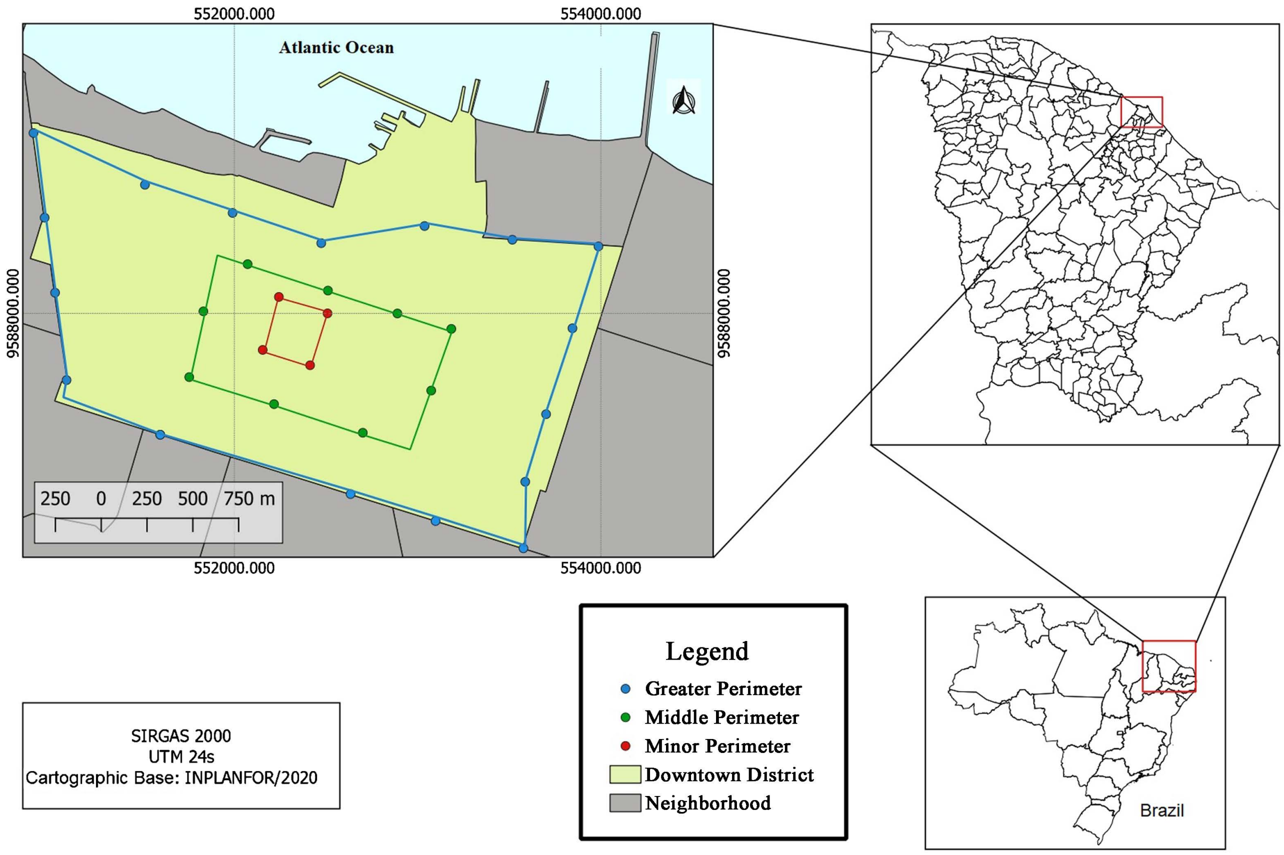

Figure 1. Analyzed Region location map.

carried out between November/December 2021 (for O_3 analyses) and April/May 2022 (for other analyses), when the atmospheric pollutant indices were analyzed in the three different perimeters of the center of Fortaleza and in their respective points of contact monitoring.

The collections were carried out during the period of 5 minutes in each of the 30 points of the three perimeters (Major-Middle-Smaller), during three consecutive days (Tuesday, Wednesday and Thursday), considered these for being typical days compared to Monday or Friday. Each perimeter was analyzed at 7:00 am, 12:00 noon and 17:00 pm.

Figure 1 represents the paths covered, where A characterizes the largest perimeter and 17 analysis points, B corresponds to the average perimeter and its 9 points, and C corresponds to the smallest perimeter with its 4 analysis points. This region is marked by the large commerce that operates strongly in the area, including schools, colleges, squares, hospitals, clinics, tram stations, homes and churches, among others. It is evident a large number of people and exposed to the intense flow of vehicles often marked by extensive traffic jams. Not to mention unexpected facts, for example, rain and collisions between vehicles.

2.1.1. Greater Perimeter

The analyses of the largest perimeter are divided into 17 points (1 to 17) with intervals of 500 m along the route, whose length is about 10.5 km, starting at Av. Padre

Ibiapina, 1802, Centro, Fortaleza, CE, 60035-130 (3˚43'50.534"S 38˚32'23.907"W). To cover the entire perimeter, it takes an average of 40 minutes. At each point, measurements were taken during an interval of 5 minutes. The last point of the route is at Rua Antônio Pompeu, 1381-1257, Centro, Fortaleza, CE (3˚43'58.767"S 38˚32'6.801"O).

This perimeter encompasses most of the elements that intensify the flow of vehicles that release pollutants into the atmosphere, commerce and local fairs, the flow of people, and residences, as well as banks, cultural centers, shopping malls, supermarkets, squares, tram stations, hospitals, clinics, health centers, as well as police stations, schools, colleges, churches and restaurants. It is a very busy region, as it grants access to other neighborhoods and beaches in the east of Fortaleza.

2.1.2. Average Perimeter

The second perimeter was divided into 9 points (18 to 26), starting at Av. Dom Manuel 362-500, Centro, Fortaleza, CE (3˚43'41.261"S 38˚31'15.970"W), the end of this route is at Rua Visconde Sabóia, 248, Centro, Fortaleza, CE (3˚43'38.178"S 38˚31'25.317"W), covering a total of 3.7 km. The characterization of this region is comprised of several lanes of intense flow of vehicles throughout the day and has large shopping centers that intensify the flow of people. Through its roads, it is possible to have access to the city center.

The journey from this perimeter takes an average of 15 minutes. Along this path, it is possible to find clinics, hospitals, health centers, schools, colleges, squares, theater, leisure areas, hotels, residential, commercial and residential buildings, churches, banks, small malls and mainly commercial establishments; are factors that contribute to a greater flow of vehicles and agglomeration of people.

2.1.3. Minor Perimeter

The smaller perimeter is one of the main regions of Fortaleza and, above all, well known by the people of Fortaleza, due to the large number of street vendors who sell their products in the streets of the city center. In addition to being characterized by the intense local commerce and the great traffic of people. This perimeter has a total length of 1.4 km and is normally covered in 8 minutes, without traffic and with few stops along the way.

This perimeter was divided into 4 points (27 to 30), whose trajectory begins at R. Senador Pompeu, 856, Centro, Fortaleza, CE (3˚43'35.420"S 38˚31'46.254"W) and completed at R. Floriano Peixoto, 671-563, Centro, Fortaleza, CE, 60025-131 (3˚43'38.281"S, 38˚31'37.708"W).

2.2. Pollutant Analysis

For pollutant analysis, a TEMTOP M2000-Elitech meter was used. This consists of a portable device with a high precision electrochemical sensor, laser particle sensor and carbon dioxide sensor based on Non-Dispersive Infrared Analyzers

(NDIR). This device detects particles of carbon dioxide and formaldehyde in the air and transforms the concentration of air pollutants into visual data. It is possible to detect the indices of the following particles and factors: $PM_{2.5}$, PM_{10}, CO_2, HCHO.

Together for the static analyses, the concentrations of ozone (O_3) were determined using the continuous analyzer model 202 from 2B Technologies in the pilot project. This analyzer uses an absorption cell that absorbs at a wavelength of 254 nm and has a pollutant detection range ranging from low ppb (~1.5 ppb accuracy) to 250,000 ppb (0 - 250 ppm).

2.3. Interpolated Spatial Representation of Pollutants

The spatial representation of the dispersion of analyzed pollutants was carried out through interpolated assistance. Interpolation is a method for calculating or finding a point between known values, based on experiments or a function. The need for this process arises due to the limitations of the nodal sensors employed in identifying the value of each analyzed pollutant. Various types of interpolation can be applied, such as linear interpolation, quadratic interpolation, and cubic spline interpolation.

In this study, cubic spline interpolation was used, where a point between four points is sought or calculated. The technique maximizes the use of available data, capturing non-linear variations between sampling points with adjustable precision and smoothing, presenting a more subtle appearance when compared to other interpolation techniques (Aràndiga et al., 2022; Tayebi et al., 2022; Roe & Brooks, 2021).

2.4. Health Risk Assessments

2.4.1. Respiratory Deposition Dose (RDD)

The concentrations of particles that deposited in the airways was estimated for three regions of the respiratory tract (upper, tracheobronchial and alveolar) of adults, considering the means of the different parameters for adult men and women (20 to 39 years old). Equation (1) shows the estimated respiratory deposition dose (*RDD*) calculation (Sousa et al., 2021; Segalin et al., 2017; Azarmi & Kumar, 2016; Kumar & Goel, 2016).

$$RDD = \left(VC \cdot f\right) \cdot DF_{ij} \cdot PM_i \tag{1}$$

where VC is the respiratory tidal volume (m^3/cycle), f is the respiratory rate (breaths per minute), DF_{ij} is the deposition fraction for each specific diameter, and PM_i is the measured concentration. Respiratory parameters VC and f for adults (men and women) were: 3.8×10^{-4} m^3 per respiratory cycle and 14 breaths per minute, respectively (Parreira et al., 2010). DF_{ij} was calculated based on the equations proposed by Hinds (1999).

2.4.2. Particulate Matter Inhalation Dose Calculation

The dose of MP inhaled per body mass was estimated, taking into account a worker (male or female) exposed to such an environment for 8 hours per day in each analysis perimeter, also considering the exposure time determined at 44 hours per week. The determination of the concentration of MP dose was calculated based on Equation (2) (Slezakova et al., 2018; Fonseca et al., 2014).

$$\text{Dose}(D) = (VM/m)\cdot C\cdot t \quad (2)$$

where VM is the minute volume (L/min); m is the body mass (kg); C is the PM concentration (μg/L) and t is the exposure time in minutes. An average body mass of 67 kg and VM of 5.15 kg L/min was considered for both men and women (Parreira et al., 2010).

3. Results and Discussion

3.1. Evaluation of Pollutants Analyses

Building on the static analyses, it is crucial to integrate urban planning and management considerations to address the average concentration levels of pollutants within each perimeter (Major - Medium - Minor) at different times (7:00 am, 12:00 noon, and 5:00 pm) as illustrated in **Figures 2-4**.

Examining the concentrations of $PM_{2.5}$ and PM_{10} in the larger perimeter at 7:00 am, 12:00 noon, and 17:00 pm (**Figure 2**), it becomes imperative to align these findings with urban planning initiatives. A comparison with the standards set by the National Council for the Environment (CONAMA) in resolution 491/2018 and the updated World Health Organization (WHO) guidelines for the year 2021 reveals crucial insights into the urban environment's air quality.

Analyzing variations in $PM_{2.5}$ concentrations in the largest perimeter emphasizes the need for spatial planning, especially noting that point 3 exhibits the highest average concentration at 17:00 pm. Similarly, for PM_{10}, concentration increases along the route, albeit within the acceptable limits established by CONAMA and WHO.

In the larger perimeter, point 1 holds strategic importance at the intersection of Avenida de Bezerra de Menezes, marking the exit loop of Parque Araxá and São Gerardo neighborhoods and the commencement of Centro neighborhood. Urban planning should consider this location's dynamics, which includes large supermarket chains, mechanical workshops, São Sebastião Market, known for its vibrant fruit and vegetable trade, commercial buildings, day care centers, small shops, residences, a bike lane, and an exclusive bus lane.

This perimeter's characteristics, such as the presence of faculties, a technical school, and residences, underscore the need for thoughtful urban planning to accommodate diverse activities. The flow of people, particularly during the beginning and end of classes, highlights the importance of synchronized transportation planning. Noteworthy establishments like the School for Sailors' Apprentices, various shops, restaurants, bars, and dental centers further emphasize the diverse urban landscape and necessitate comprehensive spatial management.

In **Figure 2**, the portrayal of average concentrations of CO_2, HCHO, and O_3 in the larger perimeter at various times emphasizes the importance of integrating

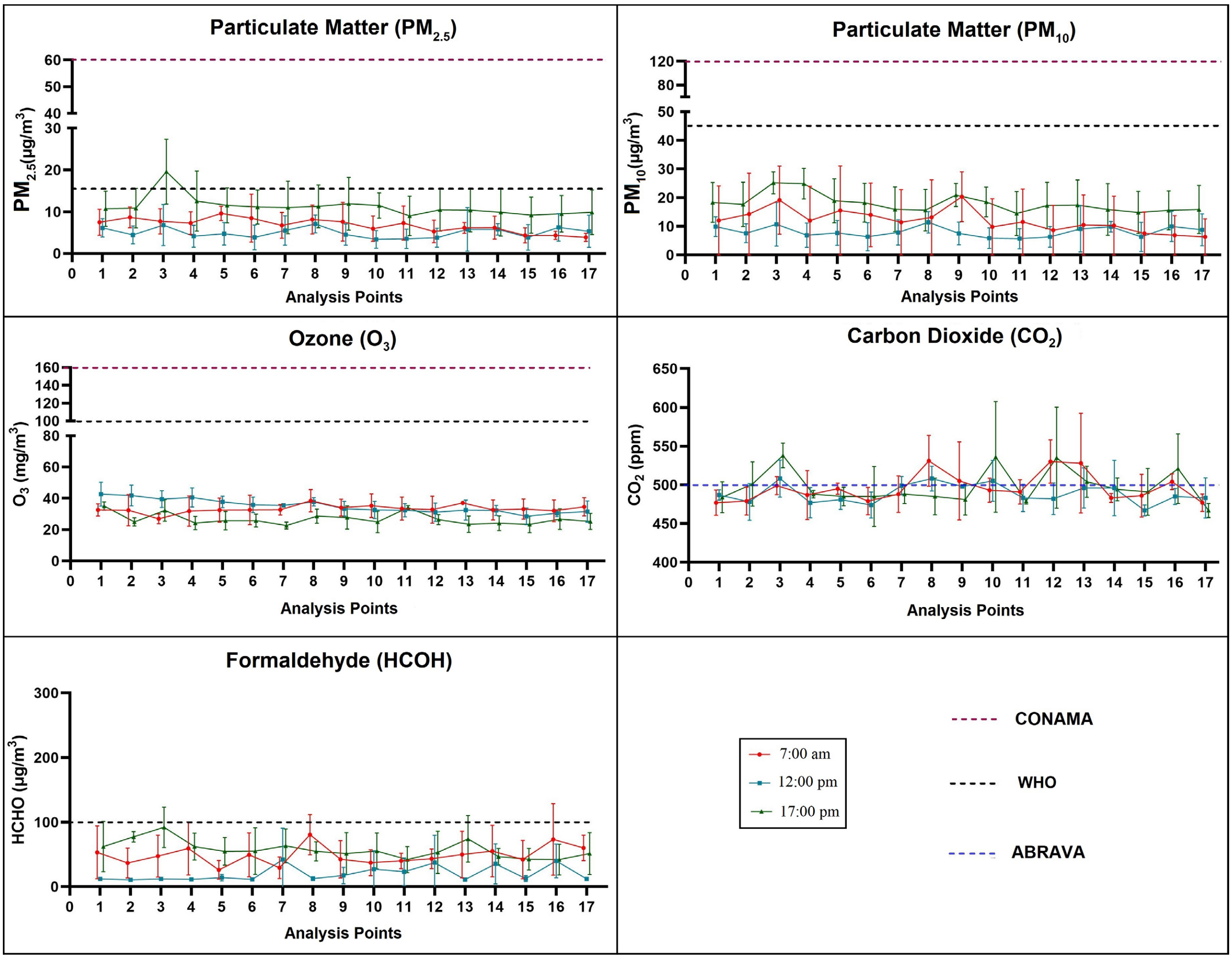

Figure 2. Pollutants Analysis in Greater Perimeter. $MP_{2.5}$, MP_{10}, CO_2, HCHO and O_3 emissions results for analyses carried out on 7:00 am, 12:00 noon and 17:00 pm.

urban planning and spatial management strategies to address these dynamic concentrations. The levels of external CO_2 concentrations were compared with the limit recommended by RN 02/2003 of the Brazilian Association of Refrigeration, Air Conditioning, Ventilation and Heating (ABRAVA), which corresponds to 500 ppm, according to ABRAVA, this is a traffic indicator very intense in urban areas, validating the influence of the large vehicular flow on the levels and concentrations of CO_2.

Regarding O_3 concentrations, the levels were compared with the limits established by the National Council for the Environment (CONAMA), according to resolution 491/2018 and the limit standards updated in 2021 recommended by the World Health Organization (WHO). Regarding the levels of HCHO, the averages of their concentrations were compared with limits determined by the WHO for indoor environments, due to the absence of specific legislation for levels of concentrations in outdoor areas. The highest CO_2 averages in the larger perimeter were evidenced at points 8, 12 and 13 at 7:00 am and at points 3, 10, 12 and 16 at 17:00 pm. Regarding O_3 and HCHO, they maintained their concentrations below the legislated standards that were compared, whereas CO_2 exceeded the limits recommended by ABRAVA.

In the characterization of the points, it is possible to identify elements that cause changes in concentration levels. Point 3 is characterized by a large shopping center with small shopkeepers that attracts a large number of people ranging from small wholesalers and retailers to customers in general, intense movement most of the day, schools, squares and small commercial buildings are also present. Point 8 corresponds to the Central Market of Fortaleza, other elements present are churches, few residential buildings, event houses, most of the local commerce is from street vendors and some wholesale establishments, this space has wide two-way lanes, thus vehicles that transit in this area come from both coastal neighborhoods and neighborhoods further away from the city center, traffic lights and speed cameras control the traffic in the area. Point 10 is located on Avenida Monsenhor Tabosa, an area characterized by the presence of large buildings, hotels, supermarkets, restaurants, bars, beauty centers, churches, schools, the presence of street vendors is not significant, the commerce in general is physical stores and quite miscellaneous.

Characterizing specific points in the larger perimeter reveals elements influencing concentration levels, such as the bustling activity at Point 3, the commercial and traffic dynamics at Point 8, and the diverse urban landscape at Point 10. These characterizations highlight the importance of spatial management and planning to accommodate various activities.

At point 13, the CO_2 level changed at 7:00 am, this point located on a one-way street that also gives access to the main avenues in the surroundings of the center, there are schools, faculties, hospitals, small clinics, residences and commercial buildings, in addition to multi-sports gyms, local commerce is dominated by vehicle workshops, restaurants and snack bars.

As for the time of 12:00 noon in the afternoon on the higher perimeter, the levels of concentrations of CO_2, O_3 and HCHO pollutants remained at the established standards.

Figure 3 shows the average concentrations obtained in the average perimeter at 7:00 am, 12:00 noon and 17:00 pm. Identifying changes in CO_2 concentrations along the route of the average perimeter, particularly at points 18, 19, 20, 22, 24, and 25, reinforces the need for spatial management strategies to address peak concentrations, especially at 7:00 am. The dominance of high concentrations at points 18, 22, and 24 at 12:00 noon and points 20 and 22 at 17:00 pm emphasizes the importance of strategic urban planning interventions. Point 22, in particular, demonstrates consistently high averages across all analysis times, suggesting the necessity for focused urban management.

For HCHO, the concentration variations at points 19 and 23 underscore the importance of targeted planning measures, especially during noon and 7:00 am, to ensure compliance with established standards. Conversely, O_3 did not exceed the limits recommended by CONAMA.

Regarding the variations in $PM_{2.5}$ concentrations in the average perimeter,

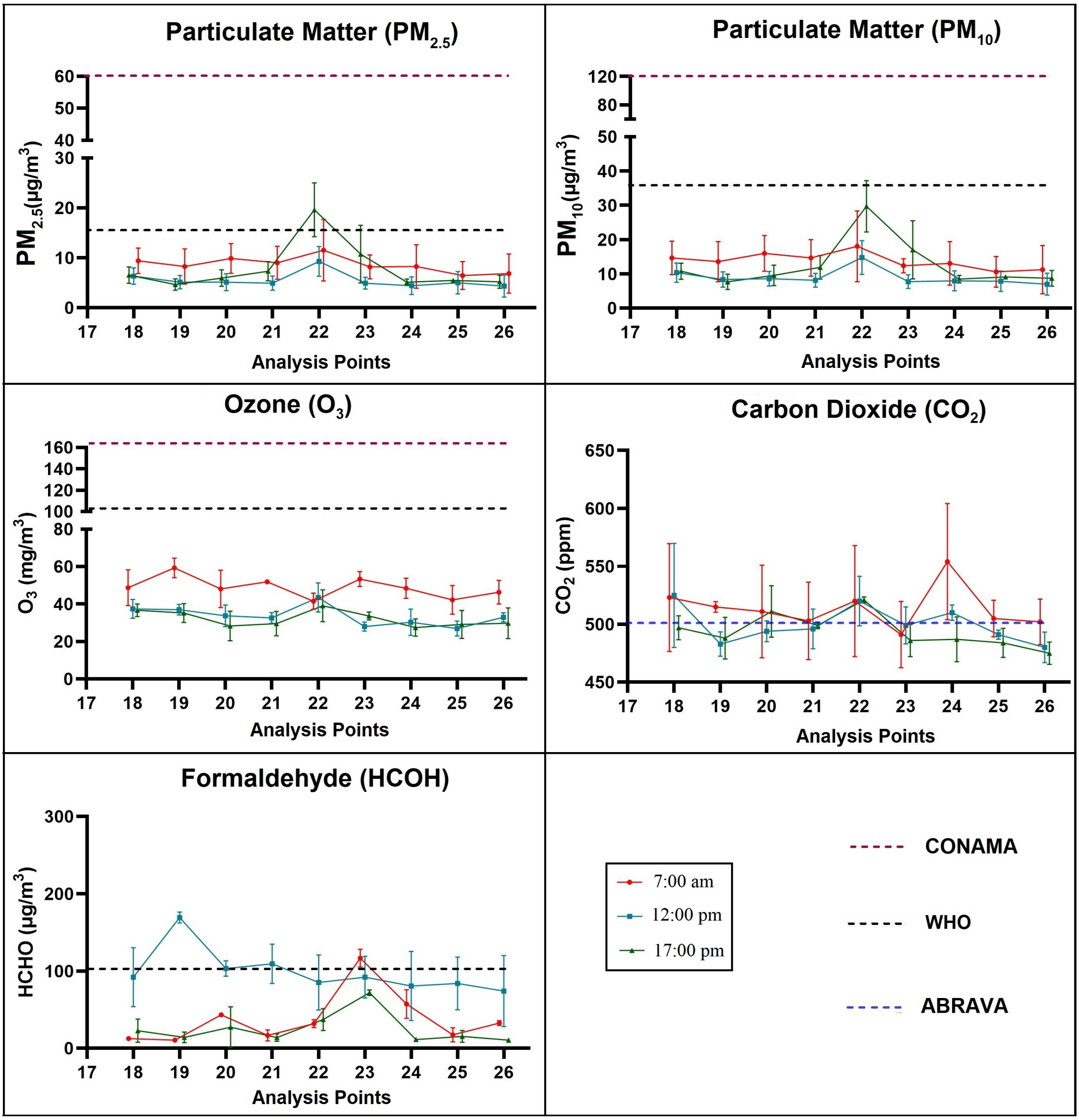

Figure 3. Pollutants Analysis in Middle Perimeter. $MP_{2.5}$, MP_{10}, CO_2, HCHO and O_3 emissions results for analyses carried out on 7:00 am, 12:00 noon and 17:00 pm.

point 22 presented the highest average concentration at 17:00 pm, exceeding the limit determined by the WHO, however the average concentrations did not exceed the standards defined by CONAMA, regarding PM10 its averages suffered an increase in concentration along the route, however the concentration values did not exceed the limits established by the limit standards required by CONAMA and WHO.

Figure 4 shows the average concentrations obtained in the smaller perimeter

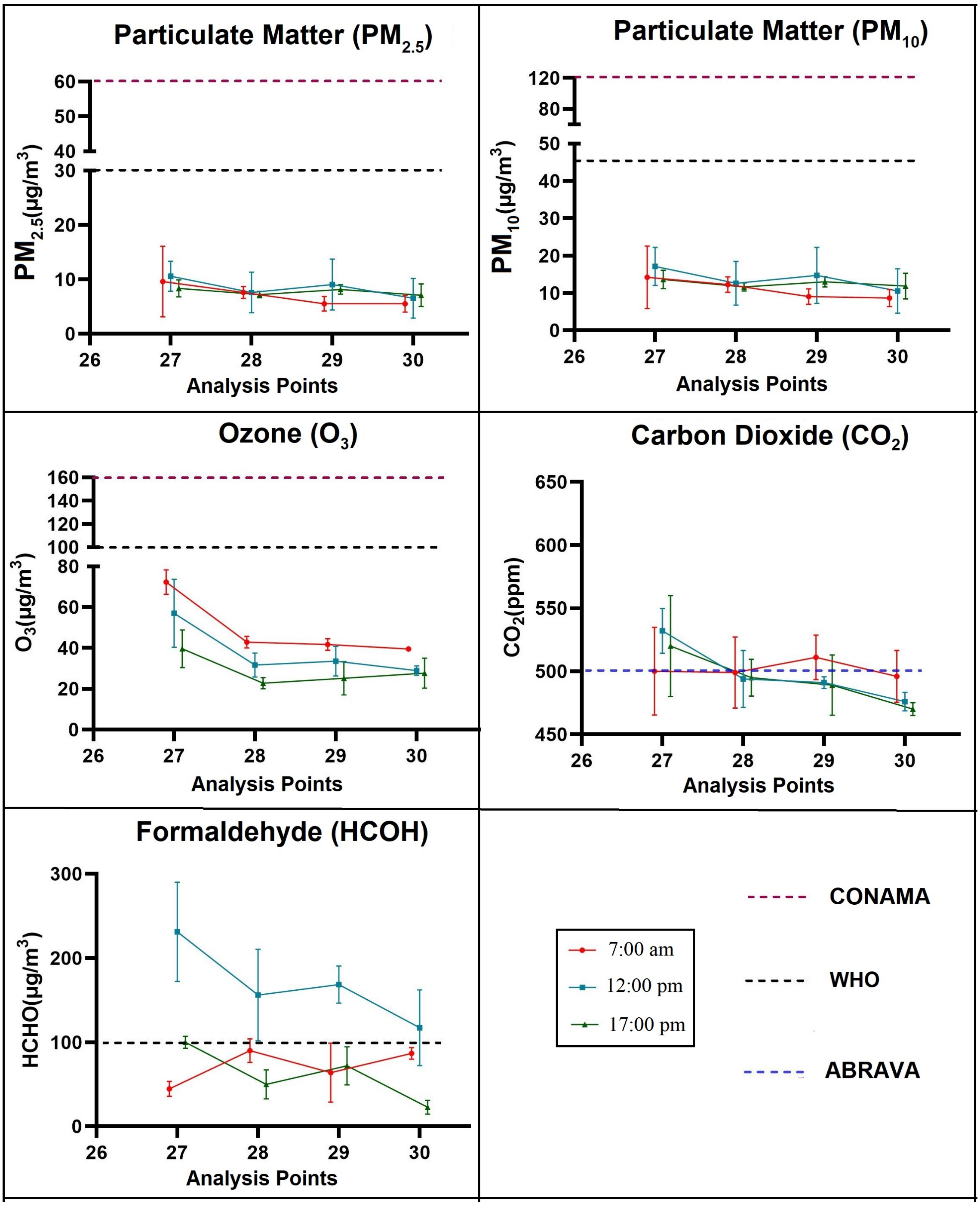

Figure 4. Pollutants Analysis in Minor Perimeter. $MP_{2.5}$, MP_{10}, CO_2, HCHO and O_3 emissions results for analyses carried out on 7:00 am, 12:00 noon and 17:00 pm.

at 7:00 am, 12:00 noon and 17:00 pm. It is possible to identify changes in the levels of CO_2 concentrations, where point 27 had the highest concentration level at 12:00 noon and 15:00 pm and point 29 had the highest concentration at 7:00 am, that is, both points exceeded the limits established by ABRAVA. In relation to the average concentrations of HCHO at 12:00 noon, all points exceeded the established limits when compared to the WHO levels, while at other times all points remained below the established. The mean concentrations of O_3 at the three times did not exceed the limit determined by CONAMA.

Regarding the average concentrations of $PM_{2.5}$ and PM_{10} in the smaller perimeter, no point exceeded the standards established by CONAMA and WHO, at the time of analysis.

Due to the high volatility of HCHO, the most affected are those who handle products that contain it in large quantities. High concentrations cause shortness of breath, breathing difficulties, headaches, eye irritation, pulmonary edema, laryngitis, bronchitis and pneumonia (Mendell et al., 2007).

Thus, humans exposed to these levels of HCHO can be affected in the eye region and upper airways (nasal cavity, oral cavity, pharynx and larynx). In addition, eye and upper airway irritations are more common features of people who live or work in environments where materials containing formaldehyde compounds are used in large amounts (Sakamoto et al., 1999).

The Air Pollution Monitoring Project was created in 2014 with the objective of meeting the demands and programming actions of circulation and traffic of urban transport in a city that reduce the influence on local atmospheric conditions, modifying the functional structures in the transport system allowing changes in air quality (PLANMOB, 2015).

The traffic problem is a reflection of the few adjustments made to Fortaleza's road network in view of the accelerated growth in the use of private cars. Measures aimed at planning and managing transport in the city were insufficient, aggravating the current situation. The private vehicle fleet increases every year, due to the increase in travel times, the decrease in fluidity, incidents or unexpected events on the road, accidents with victims and even the stress caused by traffic jams (PLANMOB, 2015).

In this way, changes in concentrations can be potentiated with the increase in traffic jams along the perimeters, as vehicles in congestion consume more fuel, that is, to operate when not in motion, the vehicle's engine needs fuel that burns and releases polluting gases. Together, there is a constant problem regarding traffic laws in Fortaleza, which results in traffic accidents and troubled relations between transport and drivers (PLANMOB, 2015).

Even knowing the types of vehicles, it is also necessary to define the pollutants to be analyzed, where it is necessary to identify the behavior and reaction of each pollutant when interacting with other substances present in the atmosphere. For local studies, pollutants that impact the health of the population can be prioritized, as at a global level, concern for the environment as a whole can prioritize the reduction of other types of pollutants (DIAS et al., 2016).

The mitigation of atmospheric pollution effects in large urban centers represents a complex and critical challenge, requiring an integrated approach to urban planning and management. As highlighted by Hanif et al. (2022), increasing urbanization and the growth of industrial activities have significantly contributed to the emission of atmospheric pollutants, directly impacting air quality. In this context, effective urban planning strategies become imperative to address this issue, considering the population density and the diversity of emission sources present in urban areas.

Efficient management of urban areas requires the implementation of policies that consider not only pollution sources but also sustainable development, urban mobility, and the promotion of green spaces. The introduction of low-emission zones, the expansion of public transportation networks, and the creation of urban green zones are examples of practices that not only reduce pollutant emissions but also promote a better quality of life for urban inhabitants (Flanagan et al., 2022; Verbeek & Hincks, 2022). Therefore, it is essential to recognize the interconnection between urban planning and air quality, integrating strategies that address the complex dynamics of modern cities towards more sustainable and healthy urban environments.

3.2. Analysis of Spatial Interpolation of Pollutants

Figure 5 shows 2D interpolations of the examined pollutants in the analysis region. Color changes become visible when pollutant data reaches a specific threshold value. Each type of pollutant exhibits a visually distinct map based on the analyzed data results.

Upon evaluation, it is observed that $PM_{2.5}$ and PM_{10} share focal points at 3 and 22, indicating higher concentrations of pollutants at these locations. This suggests that these points generate positive gradients for the dispersion of these pollutants into other areas. This trend is supported by the values presented in figures 2 and 3 for these points, with a notable emphasis on the 17:00 pm period.

Regarding O_3, point 27 appears to be responsible for its dispersion in the region, with concentration values reaching 57 μg/cm^3 on the contour plots. Higher O_3 values were observed at points 19 and 22 during morning periods (**Figure 2** and **Figure 3**), suggesting a more intense dispersion gradient during this time.

In the analysis of HCHO, contour plots of 210, 180, 150, and 120 μg/cm^3 were found around point 28 at radial distances of less than 0.2 km between these curves, indicating a pronounced positive dispersion gradient. Average values exceeding 150 μg/cm^3 of HCHO were found at points along the smaller perimeter during the 12:00 noon period (**Figure 3**), supporting the trend presented in the 2D interpolations of the region's points.

Interpolations in 2D of CO_2 unveiled five diffusion points for these pollutants (points 3, 12, 18, 22, and 27), with concentrations exceeding 500 ppm. The spreading dynamics of CO_2 in the region appeared chaotic, as contour plots, although originating from a relatively constant value, were directly influenced by the radial distance from the source. The dispersion gradient was more pronounced at points 27 and 22, being the main vectors for this pollutant in the region.

Although 2D interpolations successfully captured an average dispersal trend of the analyzed pollutants, external factors such as wind speed, diffusion coefficient of each pollutant, and the region's topology add complexity to predicting this behavior. Nevertheless, cubic spline interpolation modeling proves effective in recording the average concentration of each assessed pollutant in the region.

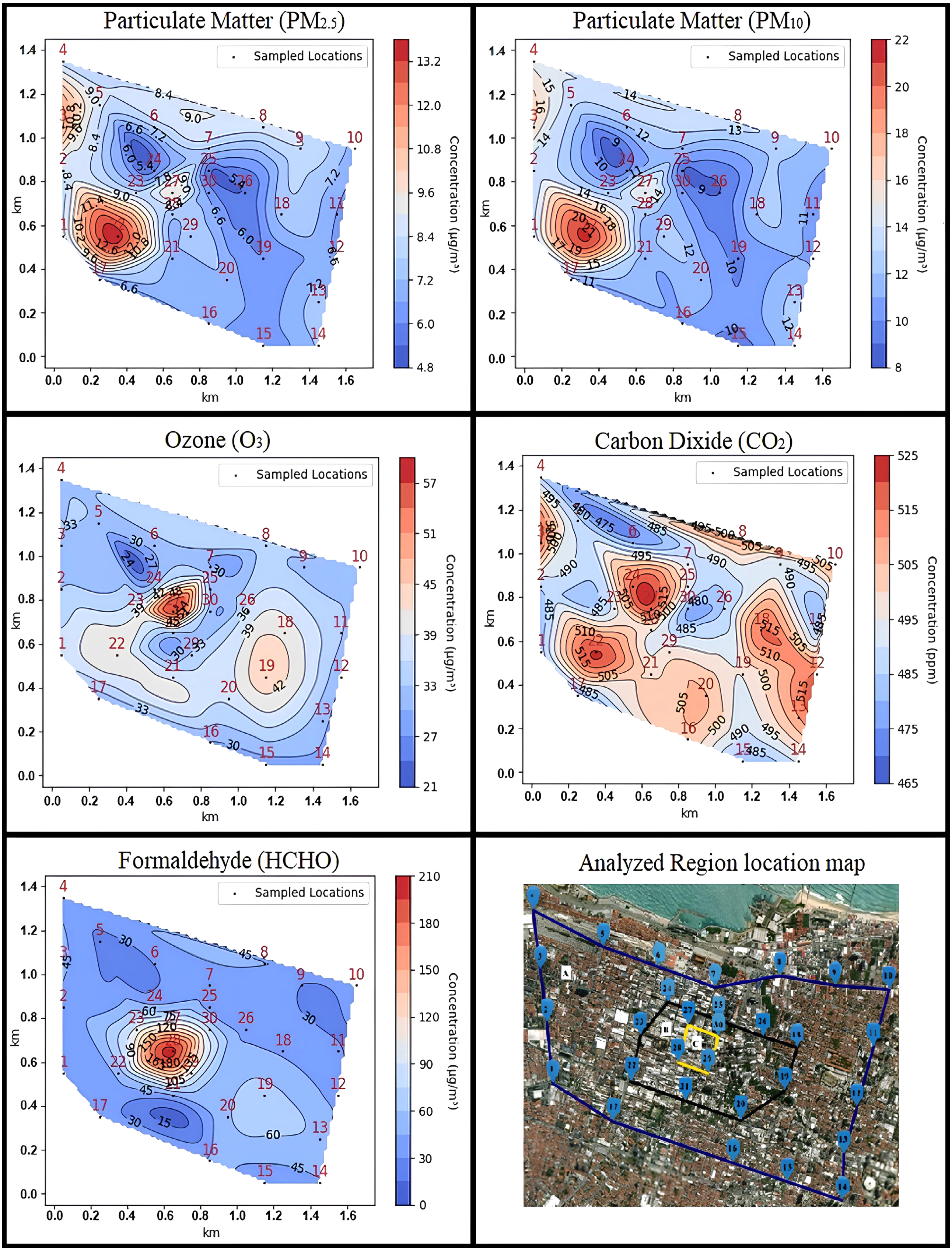

Figure 5. Visual map of interpolations of pollutants examined in the analysis region.

The temporal tracking of each analysis was crucial for proposing boundary conditions for the two-dimensional mapping.

3.3. Respiratory Deposition Dose (RDD)

The analysis of the inhaled dose of MP ($MP_{2.5}$ and MP_{10}) was estimated based on: 1) the average concentration of MP in each of the three analyzed perimeters; 2) physiological characteristics; and 3) the exposure time (44 h/month) of an adult working in the environment of the analyzed perimeters.

According to the analysis of the concentrations of $MP_{2.5}$ and MP_{10} (**Figure 6**), variability of the pulmonary dose received by humans was estimated, generating more realistic deposition results (Li et al., 2016). The lung structures are composed of subdivisions, which are classified by regions, such as: extrathoracic, tracheobronchial and pulmonary regions (Hussain et al., 2011), aiming to calculate the deposition of particles in the respiratory system (Upper, tracheobronchial and alveolar) of adults (Koblinger, 1990).

The highest concentrations of $PM_{2.5}$ and PM_{10} deposited in the respiratory system were obtained in the largest perimeter at 17:00 pm. The lowest concentrations of $PM_{2.5}$ and PM_{10} deposited in the respiratory system were also obtained in the larger perimeter at 12:00 noon.

In addition, we observed that most of the deposition of the inhaled particles ($PM_{2.5}$ and PM_{10}) is deposited in the upper region, in relation to the tracheobronchial and alveolar regions, due to the diameter of the $PM_{2.5}$ particles where they can be deeply fixed in the respiratory system reaching the lungs. For this reason, they are called thoracic particles PM_{10}, on the other hand, can pass through the nasal and oral cavities and penetrate to the larynx. In the case of ultrafine particles, $PM_{0.1}$ can pass from the pulmonary alveoli and reach the circulatory system (Brito et al., 2018). The particles can come from both biogenic and anthropogenic sources, where anthropogenic sources are generally composed of ultrafine particles, while biogenic sources are commonly composed of coarse particles (Avino et al., 2016).

Much of the air pollution from human particles is present in urban centers, coming from vehicular combustion (Karagulian et al., 2015). Diesel vehicles are the most worrisome compared to other automobiles, as their emissions occur mainly in the ultra-thin size range (Kittelson, 1998; Kittelson et al., 2002). It is worth mentioning that public transport is one of the diesel-powered vehicles and is quite present on the perimeter roads. According to Burtscher (2005), the particles emitted in the burning of diesel vary between 1 nm and 1 μm, and more than 90% are smaller than 0.050 μm.

The vast majority of these particles are agglomerates consisting mainly of spherical primary particles of about 15 to 40 nm in diameter. Another critical factor of the particles emitted in the burning of diesel is due to the large surface area they have and, for this reason, they can absorb several compounds suspended in the air that can be toxic, mutagenic and carcinogenic (Cohen & Nikula, 1999; Oravisjärvi et al., 2011).

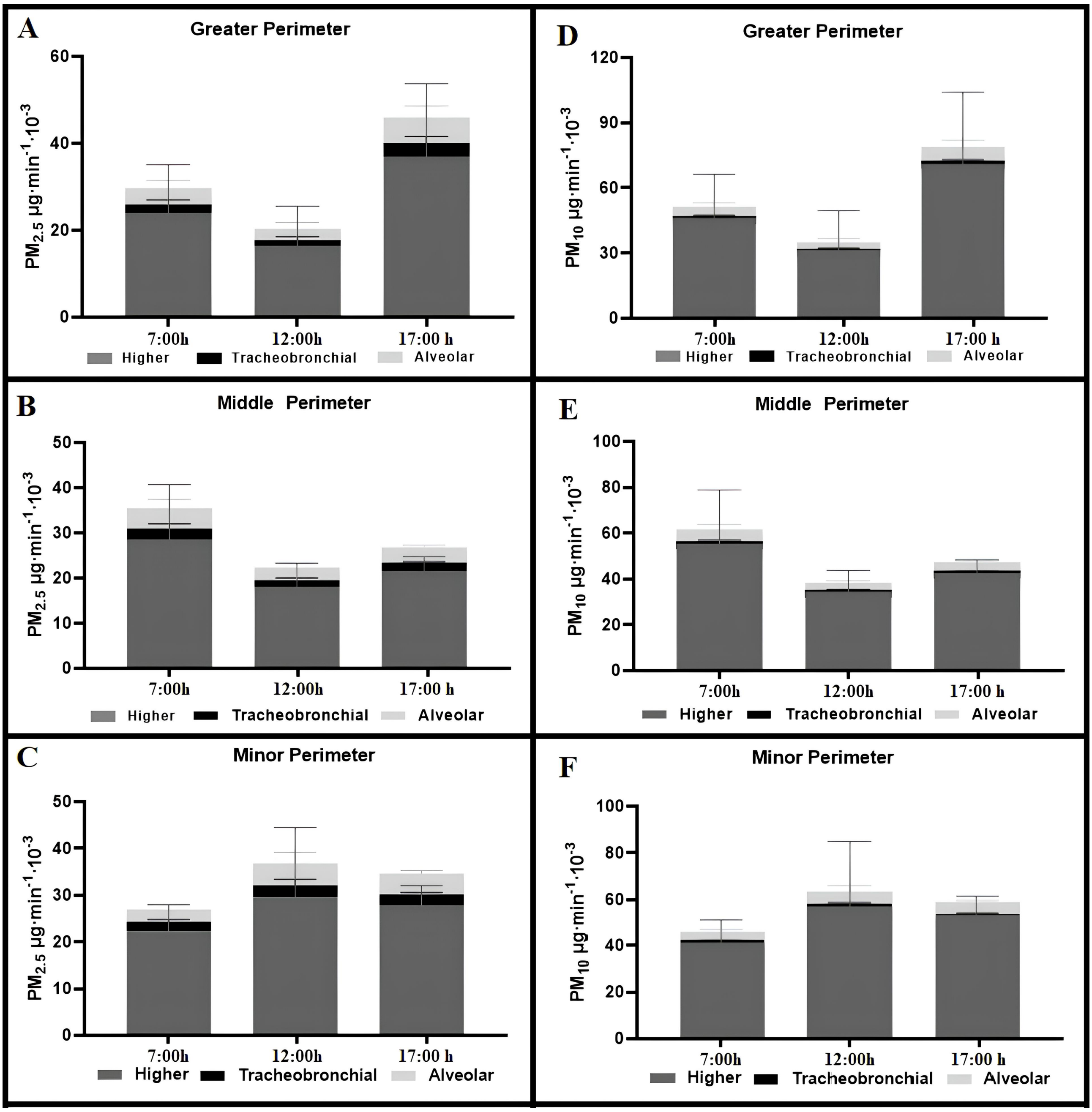

Figure 6. Particles Deposition in the Respiratory Tract ($PM_{2.5}$ and MP_{10}). Particles deposition concentration estimated for three regions of the respiratory tract (Upper, tracheobronchial and alveolar) of adults on Greather, Middle and Minor Perimeter, in 7:00 am, 12:00 noon and 17:00 pm.

3.4. Particulate Matter Inhalation Dose

The risks to human health arising from atmospheric pollutants evaluated, above all, by studies carried out in urban areas, concerned with atmospheric emissions from industrial or vehicular origin. Many studies adopt the conceptual framework of human exposure assessment. Exposure consists of contact between the person and a specific concentration of environmental contaminant, in a certain period of time. Human beings are constantly exposed to pollutants present in the atmosphere, personal exposure is the presence of a pollutant in the breathing zone of an individual (Ribeiro & Assunção, 2002).

Regarding the calculation of the inhaled dose per body mass, respiratory parameters of men and women aged 20 to 39 years were considered, using the concentrations of $PM_{2.5}$ and PM_{10} measured at each of the perimeters. As the inhaled dose is proportional to the exposure time, considering an individual who works (176 h/month) in the vicinity of each perimeter, where he is daily exposed to pollutants from that environment. The concentration of the inhaled doses is shown in **Figure 7**. To determine the inhaled dose of $MP_{2.5}$ and MP_{10}, it was performed from the average of the three analysis times for each perimeter.

According to the averages calculated in each perimeter, higher concentrations of inhaled dose are observed in the smaller perimeter and for the lowest concentrations of inhaled dose in the medium perimeter. The risk of mortality related to exposure to $PM_{2.5}$ (Li et al., 2018), among these, the increase in cardiovascular causes and diseases (Kim et al., 2020). Regarding exposure to PM_{10}, evidence was found between exposure to this pollutant and the risk of lung cancer (Consonni et al., 2018). Aerobic exercise practitioners can lead to a higher inhaled dose, in addition, children also receive potentially greater dose than adults as they have greater ventilation by body mass and are generally more active and spend more time outdoors (Commitee of the Environmental, 1996).

4. Conclusion

Reflecting on the results of the analyses conducted in the commercial region of Fortaleza, it becomes evident that a comprehensive approach to urban planning and spatial management is essential to address changes in pollutant emissions across the three perimeters at different analysis times.

In the larger perimeter, the observed changes in CO_2 concentrations at 17:00 pm, surpassing established standards, underscore the importance of strategic urban planning to mitigate the impact of vehicular emissions. Specific indices,

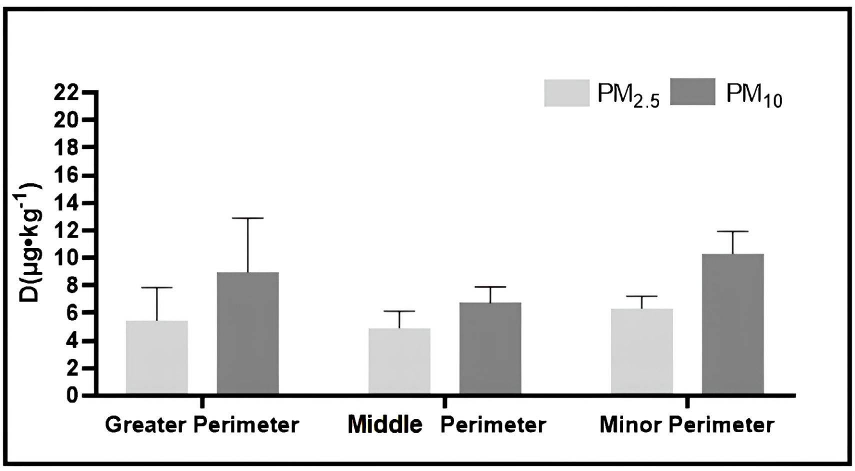

Figure 7. Inhaled particulate matter dose according to $PM_{2.5}$ and PM_{10} concentrations found on Greather, Middle and Minor Perimeter, in 7:00 am, 12:00 noon and 17:00 pm.

notably HCHO, O_3, $PM_{2.5}$, and PM_{10} concentrations, close to or exceeding recommendations, highlight the need for targeted interventions in pollutant hotspots.

In the average perimeter, point 22 presented the highest average concentrations of pollutants in the three analysis times, changes can be justified by the elements that make up this point aggravated by vehicular emissions. As for the smaller perimeter, the greatest changes in HCHO were identified at all points at 12:00 noon, and such levels can cause serious problems to human health.

The importance of evaluating indices at different periods lies in their direct impact on daily activities. These data can inform local traffic measures and serve as a database for educational campaigns and enforcement blitz by authorities. Identifying specific places with significant changes in pollutant indices during a given period allows for targeted interventions, showcasing the role of urban planning in improving air quality.

Furthermore, the evaluation of indices contributes not only to revising current environmental legislation but also highlights the necessity of aligning economic demands favoring motorized displacement with the imperative to enhance air quality. This emphasizes the interconnectedness of urban development, economic activities, and environmental sustainability, necessitating a holistic approach in urban planning and management.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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