Environmental impact of fireworks during the celebration of New Year's Eve on the air quality in an urban region: Queretaro, Mexico

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Abstract

The high concentrations of particulate matter (PM) in the atmosphere have adverse effects on both the environment and human health, as well as on urban and faunal biodiversity. Short-term events, such as the burning of fireworks, attributable to human activity, result in a significant and rapid increase in PM concentration levels within the atmosphere. We present findings derived from observations made using low-cost PM sensors deployed as part of the Environmental Monitoring Network in Querétaro, Mexico. These sensors utilize the Environmental Geo Monitoring Stations (EMGA) device, developed by the Institute of Geosciences at UNAM. The observation period spanned from December 10, 2023, to January 10, 2024, encompassed the Christmas and New Year holidays, and focused on $PM_{2.5}$ concentrations, and a comparison with a similar period from February 10, 2024, to March 10, 2024, considered a typical activity period in the area. The results reveal a substantial increase in PM2.5 concentrations over time and spatial distribution during this period, with notable increases observed during the festive season. Specifically, prolonged periods exceeding up to 6 hours were noted on festivities dates. This research offers insight into the effects, trends, and spatial-temporal distribution of pollutants within the city of Queretaro, which may be used as a reference for other cities around the world. Furthermore, a comparison between $PM_{2.5}$ data recorded by the EMGA devices and infrasound data was conducted complementarity to explore potential correlations between these two types of data.

1. Introduction

Fine Particulate Matter (PM) with an aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) has garnered global attention due to its effects on air quality, human health, and climate (Li et al., 2016). Under normal atmospheric circumstances, natural dust constitutes the primary component of $PM_{2.5}$, however, in urban areas, it also contains significant concentrations of inorganic and organic components, including black carbon, Potentially Toxic Elements (PTE), and Polycyclic Aromatic Hydrocarbons (PAH) (Chen et al., 2022; Feng et al., 2019; Li et al., 2016), all of which pose health risks. Once emitted into the atmosphere, this complex mixture of pollutants can transform aerosols based on ambient conditions and interactions among $PM_{2.5}$ components and air as well as gaseous pollutants (e.g., SO_x, NO_x, CO_x, and volatile organic compounds). The atmospheric particulate system is particularly intricate in urban areas due to (i) large emissions volumes of $PM_{2.5}$ components, (ii) gasses released by anthropogenic sources, (iii) widespread distribution of emission sources, (iv) and climate. Hence, it is crucial to monitor short-term events to identify dates and spatial patterns of pollutant sources for environmental management and risk assessment (Chen et al., 2022; Chhabra et al., 2020). Although technological sensors provide detailed information on PM concentration over time, complementarily, environmental networks using biological indicators can also provide particle pollution data recorded over months, years, or seasons (McIntosh et al., 2007; Paoli et al., 2017; Castañeda Miranda et al., 2020; Chaparro et al., 2024).

New Year's Eve is among the globally celebrated festivals as it marks the transition from the old year to the new year in the Gregorian calendar. In major cities, such celebrations directly impact the local environment, particularly the air quality (Lin, 2016; Ambade, 2018). The

bursting and burning of firecrackers during festivities release substantial concentrations of $PM_{2.5}$ and gasses into the atmosphere. Previous studies have documented the adverse effects of fireworks on air quality worldwide, for example, the significant increase in $PM_{2.5}$ levels during the Diwali festival in India due to fireworks (Ambade, 2018). Moreover, there are regional and global effects of this anthropogenic activity, as the resultant atmospheric aerosols can alter Earth's climate balance through direct (scattering and absorption of solar and longwave radiation), semi-direct (evaporation of cloud droplets due to solar absorption), and indirect (modification of cloud optical properties, lifetime, and albedo) influences (Chhabra et al., 2020).

The primary objective of burning fireworks as a recreational activity is to produce sound, gasses, and smoke effects. Most common pyrotechnic mixtures comprise an oxidizer, a fuel, a source of carbon, and various additives such as chlorine donors to enhance color and other chemicals to modify appearance or sound (Rossol, 2014). Compounds affecting human health, such as hazardous pollutants (e.g., $PM_{2.5}$ or dust), toxic gasses (SO_x, NO_x), and almost any PTE, can be present in pyrotechnic emissions. The use of commercial low-cost monitoring devices, such as Purple Air sensors, Smart Citizen Kit (Ardon-Dryer, et al., 2020; Barkjohn et al., 2020; Camprodon et al., 2019; Farooqui et al. 2023), both devices using the Plantower PMS5003 sensor, have created new opportunities for local and regional air quality monitoring. Although less precise than traditional monitoring equipment, these devices provide a cost-effective and accessible solution for environmental surveillance, enabling increased citizen participation in data collection and decision-making. Studies like those conducted have demonstrated the usefulness and feasibility of low-cost $PM_{2.5}$ sensors in monitoring air quality, providing valuable data for understanding air pollution and its impact

on public health and environmental policies (Stravoulas et al., 2020; Mousavi et al., 2021; Farooqui et al. 2023). This study aims to measure and analyze changes in $PM_{2.5}$ concentration during the intense pyrotechnic burning activity on Christmas and New Year's Eve in Querétaro City (Mexico), using low-cost $PM_{2.5}$ sensors. This research will contribute to a better understanding of fireworks' impact on urban air quality and may provide valuable information for designing and implementing public policies aimed at mitigating their adverse effects.

2. Materials and methods

2.1 Study area

The study was conducted in the urban area of Santiago de Queretaro City and its Metropolitan Area (Figure 1), which serves as the primary industrial and commercial hub of the El Bajio region. A macroregion located within the central Mexican plateau, approximately 250 km northwest of the Mexico City megalopolis. Queretaro's urban area is situated on a plain at an elevation of 1900 meters above sea level. The urban area is home to approximately 1.5 million inhabitants (INEGI, 2020), concentrated across three municipalities: (i) Querétaro, (ii) Corregidora, and (iii) El Marqués. The study area experiences a semi-arid climate (BSh), classified in Köppen climate classification. The average annual temperature ranges from up to 15 to 22°C, with an average annual precipitation *ca.* 528 mm.

The city hosts significant industrial activity, with around 28 industrial parks scattered throughout the metropolitan area. Moreover, owing to its strategic central location within the country, Queretaro serves as a major transportation hub, experiencing heavy traffic of cargo transport vehicles bound for Mexico City and other regions, as well as substantial local

121 vehicle traffic. Industrial operations and the high volume of vehicular traffic represent
122 potential sources of atmospheric pollutants, which vary depending on temporal and
123 geographical variations in human activity. In addition, Queretaro is immersed in a heavily
124 industrial and agricultural region towards the west, which can contribute to the air pollutants
125 measured in its atmosphere.
126
127 *2.2 Instrumentation and data acquisition*
128 In-situ measurements were gathered from 11 stations within the Environmental Monitoring
129 Network of the Metropolitan Area of Queretaro City (Table 1) initiated by the Instituto de
130 Geociencias-Universidad Nacional Autonoma de Mexico, shown in Figure 1. This network
131 is comprised of Environmental Geo Monitoring Stations (EMGA) designed and developed
132 by the CGEO-UNAM, which continuously monitor eight environmental variables in real-
133 time: Particulate Matter (PM): PM2.5, PM10, and PM1 concentrations in $\mu g/m^3$, temperature,
134 atmospheric pressure, relative humidity, environmental noise, and intensity of the Earth's
135 magnetic field. Data is collected every 4 minutes and promptly transmitted to a data
136 processing, storage, and visualization platform via the Internet. All EMGAs are installed
137 outdoors, typically near streets, at an average height ranging from 2 to 3 meters above ground
138 level. For this study, PM concentration data were specifically obtained on the particulate
139 matter at sizes of 2.5 μm determined in $\mu g/m^3$, as well as temperature and relative humidity,
140 continuously recorded over a period of up to 30 days spanning from December 10, 2023, to
141 January 10, 2024. As a comparison with a similar period from February 10, 2024, to March
142 10, 2024, considered a typical activity period in the area were performed.
143 The EMGAs use a commercial low-cost Plantower PMS5003 optical particulate matter
144 sensor for sizes of 2.5, 10, and 1μm where their concentrations are determined in $\mu g/m^3$. The

use and performance of these sensors have been scrutinized and discussed by various researchers (e.g., Kuula et al., 2020; Giordano et al., 2021; Kaur et al., 2023; Searle et al., 2023), who propose diverse methodologies for evaluating their accuracy and precision. The reliability of the data obtained with these sensors is subject to debate, particularly when compared with high-precision reference equipment. Nonetheless, multiple studies agree that data obtained from these sensors, although lacking the precision of high-performance equipment, are valuable as references for detecting atmospheric pollutants. Unlike high precision equipment, which incurs substantial installation and maintenance costs, these sensors, due to their affordability, facilitate the establishment of dense air quality monitoring networks at a reduced expense, enabling the observation of spatial discrepancies and seasonal variations in urban environments. These sensors are the ones integrated into low-cost commercial equipment networks like Purple Air, which boasts thousands of devices installed across the USA, with their performance and validity assessed in various studies (Ardon-Dryer et al., 2020; Barkjohn et al., 2020; Stavroulas et al., 2020; Farooqui et al. 2023).

In this study, raw mass concentration ($\mu g/m^3$) data were selected from each sensor for $PM_{2.5}$ with raw data collected every 4 minutes on the original time series. The data series underwent hourly averaging for each sensor, followed by the application of a correction factor per hour to mitigate the standard error of underestimation in the sensor model, described by Searle et al. (2023). Subsequently, an statistical analysis was conducted with an algorithm, applied to the data series to filter out outliers, excluding from the calculation of hourly averages any data points that deviated beyond a σ (sigma) of the standard deviation of the data set. This process effectively eliminated outlier data from the time series, enhancing its quality and reliability, eliminating less than 10% of the data.

Additionally to the EMGA network, a network of 5 infrasound sensors was installed in the City of Queretaro. The infrasound stations are equipped with Raspberry Shake Boom instruments. These instruments have a flat response ranging from 0.1-50Hz, and sampling rate of 100Hz. All the data is transmitted in real-time to the Institute of Geosciences and is managed using the Seiscomp software. The objective of the infrasound network is monitoring urban noise at infrasound and audible levels in the metropolitan area of Querétaro. Infrasound data could be used as a source of comparison for human activity and the incidence of environmental changes from anthropogenic origin and could be compared with data collected from the EMGA stations.

3. Results

3.1 Time series

For the time series analysis and for comparison, three reference points were selected (Figure 2): the station with the highest values (STATION-10), a station with intermediate values (STATION-19), and the station with the lowest values (STATION-13). Additionally, a comparison was made with a time series from the station with the highest values recorded in this study, but for a subsequent period of equal duration. This was done to establish a pattern of variation among the spatially obtained results.

Figures 2a and 2b, corresponding to STATION-10 and STATION-19, depict the temporal records of hourly averages, exhibiting typical variations for different days of the week, with $PM_{2.5}$ values averaging below 50 $\mu g/m^3$. The blank spaces represent periods during which the equipment did not record data attributable to specific site-related issues. Within the time

series, two peaks are evident, showing a significant increase during the early hours of December 25, 2023, and January 1, 2024, considerably exceeding 150 μg/m³ and 300 μg/m³, respectively. These increases persist for at least 6 hours during these specific events. These peaks align with the Christmas and New Year festivities, with the elevated $PM_{2.5}$ recordings directly linked to fireworks burning in the vicinity. During these times and dates, traffic and industrial activity (among other factors) do not substantially contribute to $PM_{2.5}$ generation in the environment, with average $PM_{2.5}$ concentrations below 30 μg/m³.

Figure 2c illustrates the time series for STATION-10 from February 10 to March 10, 2024, displaying peaks with high $PM_{2.5}$ concentration values, albeit sustained for no more than 30 minutes. These peaks are primarily associated with traffic activity, and sustained increases over several hours, as observed during the previously mentioned dates and times, are not apparent. Figure 3 presents a comparison among three stations with the highest, intermediate, and lowest values (STATION-10, STATION-19, and STATION-13, respectively). For STATION-10 and STATION-19, a similar trend of increased $PM_{2.5}$ concentration was observed, albeit in varying proportions, on December 25, 2023, and January 1, 2024.

3.2 Meteorological conditions and PM2.5 relationship

As shown in Figure 4a, the comparison between the time series of the data record from STATION-10 and the temperature record, where the temperature has a similar behavior during this period, varies from 10° C to 20° C during the day. No specific dependence on the significant increase in $PM_{2.5}$ concentrations is observed for December 25 and January 1. Furthermore, during the period studied, there was no rainfall, and wind speeds varied within

a range of 0-40 km/h. Figure 4b shows no variation associated with changes on humidity records are related to the increasing of the $PM_{2.5}$ concentrations. This suggests that the abrupt increase in these values is not correlated with a natural phenomenon (meteorological conditions), indicating that the high concentrations of $PM_{2.5}$ recorded are of an anthropic origin, associated with the firework burning.

3.3 Daily trends

Based on the typical patterns of $PM_{2.5}$ emission into the atmosphere, the results were grouped by day of the week to examine the daily impact of human activities on $PM_{2.5}$ levels in the city. This involved estimating hourly averages and filtering out outliers, as previously described. The data were then organized by day of the week, from Monday to Sunday, and further segmented by time of day, from 0 a.m. to 11:59 p.m.

Figure 5d illustrates the daily $PM_{2.5}$ records from February 10 to March 10, 2024, representing typical activity patterns over four consecutive weeks. The graph highlights the days of the week that, on average, contribute to higher levels of $PM_{2.5}$ in the environment, with notable peaks corresponding to peak traffic hours in the city.

In contrast, Figures 5a and 5b, representing STATION-19 and STATION-10 respectively, depict a notable increase in $PM_{2.5}$ concentration during the late hours of Sunday and the early hours of Monday. This pattern coincides with observations in the time series of the same stations during events characterized by high pyrotechnic activity. Figure 5c, showing the

lowest records for the studied period, exhibits a similar trend to Figure 5d, indicating that pyrotechnic activity in this area was lower and less significant.

3.4 Hourly trends

To understand the specific variations per day for each station according to the time of day, the same methodology of averaging within 1-hour intervals was employed. The results were graphed in polar form, enabling visualization of hourly variations from 0 to 11:59 p.m. for each day within the date range of this study.

Figures 6a and 6b depict the polar graphs illustrating the hourly behavior of stations STATION-10 and STATION-19, respectively. Two curves can be observed, with a noticeable increase from 9 p.m. to 11 p.m. on one curve, representing data from a single day. This increase continues into a new curve, corresponding to a new day, from 0 to around 7 a.m. This period coincides with the initiation of pyrotechnic burning from 9 p.m. on December 24, 2023, continuing until around 7 a.m. on January 2, 2024. This aligns with observations from the comparison of time series data for the study period. Figure 6c displays the polar projection for the STATION-13 sensor, which recorded the lowest concentration of $PM_{2.5}$ during the studied period. As shown in Figure 6, the burning of pyrotechnics was considerably lower compared to other stations in the city. Figure 6d shows the polar projection for the period between February 10, and March 10, 2024. Although the daily trends differ from those of the STATION-13 station, as they correspond to different social environments, a similarity in maximum averages can be observed. Neither of the two

projections exhibits sustained peaks for several hours, as observed in STATION-10 and STATION-19.

3.5 Histograms

To observe the statistical impact of these short-term events, which nonetheless have a high environmental significance (Gouder & Monterfort, 2014; Lin, 2016), histograms were constructed for each station within the period of this study. $PM_{2.5}$ concentrations were grouped into ranges of $PM_{2.5}$ concentration of 5 µg/m³ each. A Gaussian (normal) distribution curve was fitted to the histogram to show the distribution of occurrence density for each $PM_{2.5}$ concentration range.

Figures 7a, 7b, and 7c present the histograms for stations: STATION-19, STATION-10, and STATION-13, respectively, over the timeframe period. It is observed that in STATION-19 and STATION-13, the distribution of $PM_{2.5}$ concentrations extends up to 40 and 50 µg/m³, with very similar distributions. In the case of station STATION-10, concentrations extend up to 50 and 60 µg/m³, with its distribution, although slightly higher, still similar to that of STATION-19 and STATION-13. Figure 7d illustrates the histogram of data recorded between February and March 2024 for station STATION-10, representing ordinary human activity. A distribution with a similar trend is observed, but the 95% limits are reduced to 40 and 50 µg/m³. This demonstrates that in longer time series, these short-lived events become diluted and challenging to detect, yet their environmental impacts remain significant.

3.6 Spatial distribution of $PM_{2.5}$

The spatial analysis focuses on $PM_{2.5}$ peaks during the early hours of January 1, 2024, from 00:00 and up to 07:00 (GMT-6). During this timeframe, EMGA sensors observed a notable increase in $PM_{2.5}$ recordings, some of them up to 1000% higher than the usual values on the same hours. For the analysis, the maximum mean values from each of the 11 stations utilized in this study were considered (Figure 8). Data analyzed correspond to the period from December 10, 2023, to January 10, 2024. Outlier data were excluded by filtering to calculate the averages, as mentioned in Sect. 2.2. Figure 8a displays the maximum values recorded for February 12, 2024 (Monday), considered a random typical day of activity in the city. Figure 8b illustrates the spatial distribution of $PM_{2.5}$ records, highlighting the highest readings observed at STATION-10, located in the central area of the city. This region is recognized as one of the most densely populated areas in the city and is adjacent to two significant industrial zones. Additionally, it is characterized by nearby neighborhoods where various regional and local festivities, such as religious festivals, occur more frequently than in other parts of the city. Conversely, the lowest readings correspond to STATION-13, located in the southwest area of the city. This site is positioned between the Bernardo Quintana Industrial Park and the Cimatario National Park ecological reserve and boasts one of the lowest population densities in the city. Despite experiencing intense activity on regular working days and hours, human activity, including both traffic and industrial activities, is notably diminished during the early hours of January 1, compared to other parts of the city, resulting in the lowest $PM_{2.5}$ recordings among all stations during that period. Table 1 presents the maximum $PM_{2.5}$ concentration values recorded by the stations for January 1 and February 12.

3.7 Infrasound data

In addition to analyzing particulate matter concentrations, an examination of infrasound data was conducted to identify trends associated with the burning of pyrotechnics. For this purpose, data from an infrasound station installed at the same location as station STATION-10 were analyzed from December 19, 2023, to January 6, 2024. Figure 9a displays the time series of the normalized data, where no significant difference is observed for January 1. To discern specific trends, a seasonal trend decomposition (STL) analysis was employed. This statistical technique separates the trend, seasonality, and noise components of a given time series dataset (Shumway, 2017; Hyndman, 2018). Figure 9b presents the graph generated with the trend adjustment obtained by STL, indicating a trend towards an increase in activity during the late hours of December 31, 2023, continuing into the early hours of January 1, 2024, before normalizing for the rest of the day. This trend aligns with observations in $PM_{2.5}$ records from EMGA stations during the same timeframe. Figure 9c compares the original normalized time series with the STL trend data, highlighting the noticeable trend towards increased activity, which can be associated with the rise in pyrotechnic burning.

4. Discussion

The use of low-cost sensors presents a feasible and economical alternative for monitoring air quality in urban settings exposed to various sources of pollution. While these sensors may not offer the same level of precision as reference equipment, they serve as valuable tools for

identifying the sources and dispersion of contaminants stemming from human activities, as well as their correlation with climatic variables like temperature, humidity and other climate conditions (Badura, 2018; Tryner et al., 2020; Nguyen et al., 2021; Karaoghlanian et al., 2022; Jaffe et al., 2023). The data presented in this study highlight contamination sources from burning pyrotechnics, occurring over several hours and distributed across the city.

Real-time recordings provided by sensors enable the observation of varying environmental conditions (deterioration of air quality), including changes in particulate matter concentration. Short-term fluctuations, spanning from minutes to hours, are frequently linked to human activity, which can exert significant short- and medium-term impacts on the environment. In this study, we analyze the substantial increase in atmospheric $PM_{2.5}$ concentration resulting from fireworks burning. Spatially, Figure 4b illustrates station distribution and their peak values recorded during the early hours of January 1, 2024, showing considerable increases across most stations compared to typical values depicted in Figure 4a. The spatial distribution identifies areas where fireworks burning was more intense during that period, associating it as a source of contamination during short-term events.

Complementing spatial distribution, time series analysis reveals $PM_{2.5}$ concentration variations over time. A significant increase is observed in $PM_{2.5}$ concentrations recorded on December 25 and January 1 across most stations, indicating a substantial rise in atmospheric pollutants generated within a few hours due to fireworks burning. Each station's location reflects changes corresponding to predominant human activity in its area. For instance, STATION-13, situated in an industrial area, exhibits no significant increase in $PM_{2.5}$ concentrations during the indicated dates, suggesting lower human activity compared to

residential areas like stations 10 and 19. This underscores the anthropogenic influence on $PM_{2.5}$ concentration during short-duration events.

Weekly and hourly trends display a consistent pattern aligned with human activity, with $PM_{2.5}$ concentration fluctuations marked by peak times of anthropogenic activity such as vehicular traffic and industrial operations. However, as depicted in Figures 7a, 7b, 8a, and 8b, pyrotechnic activity disrupts these trends, substantially elevating $PM_{2.5}$ concentrations compared to periods of lower activity.

Real-time monitoring proves crucial, allowing for the recording and characterization of short-lived events in time and space. Despite their brief duration, such events significantly impact environmental conditions, potentially affecting human health and urban fauna diversity. Figure 8 demonstrates how high $PM_{2.5}$ concentrations may go statistically unnoticed in longer-term records, with only more frequent concentrations observed in the normal distribution. This fact underscores the challenge of quantifying and associating short-term effects with other anthropogenic and environmental issues, such as forest fires, waste burning outdoors, accidental fires, and barbecues, among others.

Furthermore, analyzing $PM_{2.5}$ data in conjunction with other parameters, such as infrasound (Figure 9), can reveal trends indicating pollution increases associated with anthropogenic activity, as recorded by other monitoring devices like seismic or geomagnetic stations.

The bursting and burning of firecrackers during festivities can cause significant damage to human health every year. Consumer firework-related physical injuries can be devastating,

leading to permanent vision loss, limb amputations, and, in some cases, death (Puri et al., 2009; Tandom et al., 2012; Turgut et al., 2022). On the other hand, exposure to $PM_{2.5}$ can cause acute and chronic health problems, as evidence shows that exposure to the particulate is linked to cardiovascular disorders such as heart attacks, heart failure, arrhythmias, and strokes (Krittanawong et al., 2023; Garcia et al., 2023). More critical are the respiratory effects, such as asthma attacks and exacerbated respiratory symptoms like sneezing, wheezing, and shortness of breath, as exposure to $PM_{2.5}$ is associated with those respiratory disorders (Ren et al., 2017; Cao et al., 2018; Garcia et al., 2023). As a general diagnosis of the air quality situation in Queretaro during New Year's Eve, it can be said that the urban area presents a spike of $PM_{2.5}$ values that can cause an increase of cardiovascular risk factors but especially a high number of cases of respiratory disorder.

In the case of pets and urban fauna, health issues manifest as cardiopulmonary problems, alongside visual and auditory overstimulation that disrupts behavior. Elevated concentrations of $PM_{2.5}$ and PM_{10} particles impact airway epithelial cells and vascular endothelial cells, resulting in lung inflammation within the initial 24-hour period post-inhalation. Research conducted in laboratories has shown that $PM_{2.5}$ particles exert a more pronounced effect on mammalian health, escalating the production of reactive oxygen species (Hickey et al., 2020). While these molecules typically play roles in cellular functions, heightened levels can induce oxidative stress, causing potential damage to cellular structures or genetic material. The sudden loud noises and intense brightness of fireworks trigger fear and confusion among animals. Pet dogs often display signs of fear, particularly in response to noise, such as heightened activity, panting, vocalizations, blinking, and seeking out hiding spots (Gähwiler

et al., 2020). It's worth noting that not all individuals respond identically to stress, which may explain why some do not exhibit obvious signs of fear (Gähwiler et al., 2020).

Regarding urban fauna, birds are sensitive to loud noises and intense light (Shamoun-Baranes et al., 2011; Hoekstra et al., 2024). Observations suggest that in open fields or agricultural areas, birds seek shelter and gather in large numbers (Shamoun-Baranes et al., 2011; Hoekstra et al., 2024). In Querétaro, where the highest pyrotechnic activity is recorded, the site is adjacent to open fields, indicating that birds, mammals, and other organisms such as insects will react and congregate in this area (Shamoun-Baranes et al., 2011; Hoekstra et al., 2024; see Figure 10). Although there is insufficient information regarding the effects on insects and other invertebrates, it is presumed that similar to vertebrates, inhaled particles affect their respiratory system, while loud noises, shock waves, and light impact their auditory system, leading to confusion due to their positive phototropism. This latter point is closely linked to their transversal orientation system, utilized by different organisms such as moths to navigate their environment with the Moon as a reference point (Warrant & Dacke, 2010).

5. Conclusions

The recording of environmental pollution through the use of low-cost sensors provides valuable data for monitoring human activity. Particularly this study highlights short-term events such as fireworks burning. These brief events may go unnoticed in long-term time series. Additionally, the importance of low-cost environmental monitoring networks is demonstrated, providing data over long periods and enabling spatial analysis, thereby inferring anthropogenic impacts on environmental conditions. In this study, it was shown

how two events lasting approximately 10 hours resulted in particulate matter concentrations up to 10 times higher than on a regular day. This could have negative consequences for human health and urban fauna diversity. Analyzing these events can facilitate the design of mitigation measures to reduce environmental damage.

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Data availability

Data available on demand.

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Statement

Alejandro Rodríguez-Trejo: conceptualization, writing, interpretation, figures, technical development and programming of the device and the visualization platform; Héctor Enrique Ibarra-Ortega: technical development of the equipment, reviewing; Harald Böhnel: Conceptualization, reviewing, technical development of the device; Reneé González-Guzmán: writing, interpretation, reviewing, figures; Luis Enrique Sánchez-Ramos: writing, interpretation, reviewing, figures; Ana Gabriela Castañeda-Miranda: writing, interpretation,

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Competing interest declaration

The authors declare that there is no competing interest in the present work.

References

Ambade, B. (2018). The air pollution during Diwali festival by the burning of fireworks in Jamshedpur city, India. *Urban climate*, *26*, 149-160.

Ardon-Dryer, K., Dryer, Y., Williams, J. N., & Moghimi, N. (2020). Measurements of PM2.5 2.5 with PurpleAir under atmospheric conditions. *Atmospheric Measurement Techniques*, *13*(10), 5441-5458.

Badura, M., Batog, P., Drzeniecka-Osiadacz, A., & Modzel, P. (2018). Evaluation of low-cost sensors for ambient PM 2.5 monitoring. *Journal of Sensors*, *2018*.

Barkjohn, K. K., Gantt, B., & Clements, A. L. (2020). DeveloPM2.5ent and Application of a United States wide correction for PM2.5 2.5 data collected with the PurpleAir sensor. *Atmospheric Measurement Techniques Discussions*, *2020*, 1-34.

Camprodon, G., González, Ó., Barberán, V., Pérez, M., Smári, V., de Heras, M. Á., & Bizzotto, A. (2019). Smart Citizen Kit and Station: An open environmental monitoring system for citizen participation and scientific experimentation. *HardwareX*, *6*, e00070.

Cao, Q., Rui, G., & Liang, Y. (2018). Study on PM2. 5 pollution and the mortality due to lung cancer in China based on geographic weighted regression model. *BMC public health*, *18*, 1-10.

Castañeda-Miranda, A.G., Chaparro, M.A.E., Pacheco-Castro, A., Chaparro, M.A.E., Böhnel, H.N., 2020. Magnetic biomonitoring of atmospheric dust using tree leaves of *Ficus benjamina* in Queretaro (Mexico). Environ. Monit. Assess. https://doi.org/ 10.1007/s10661-020-8238-x.

Chaparro, M.A.E.; Buitrago Posada, D.; Chaparro, M.A.E.; Molinari, D.; Chiavarino, L.; Alba, B.; Marié, D.C.; Natal, M.; Böhnel, H.N.; Vaira, M., 2024. Urban and suburban's airborne magnetic particles accumulated on Tillandsia capillaris. Sci. Total Environ. 907, 167890. https://doi.org/10.1016/j.scitotenv.2023.167890

Chen, L., Pang, X., Li, J., Xing, B., An, T., Yuan, K., ... & Chen, J. (2022). Vertical profiles of O3, NO2 and PM in a major fine chemical industry park in the Yangtze River Delta of China detected by a sensor package on an unmanned aerial vehicle. *Science of the Total Environment*, *845*, 157113.

Chhabra, A., Turakhia, T., Sharma, S., Saha, S., Iyer, R., & Chauhan, P. (2020). Environmental impacts of fireworks on aerosol characteristics and radiative properties over a mega city, India. *City and Environment interactions*, *7*, 100049.

Farooqui, Z.; Biswas, J.; Saha, J. Long-Term Assessment of PurpleAir Low-Cost Sensor for PM2.5 in California, USA. Pollutants **2023**, 3, 477–493. https://doi.org/10.3390/pollutants3040033

Feng, B., Li, L., Xu, H., Wang, T., Wu, R., Chen, J., ... & Huang, W. (2019). PM2. 5-bound polycyclic aromatic hydrocarbons (PAHs) in Beijing: Seasonal variations, sources, and risk assessment. *Journal of Environmental Sciences*, *77*, 11-19.

Gähwiler, S., Bremhorst, A., Tóth, K., & Riemer, S. (2020). Fear expressions of dogs during New Year fireworks: a video analysis. *Scientific reports, 10(*1), 16035.

Garcia, A., Santa-Helena, E., De Falco, A., de Paula Ribeiro, J., Gioda, A., & Gioda, C. R. (2023). Toxicological effects of fine particulate matter (PM2. 5): health risks and associated systemic injuries—systematic review. *Water, Air, & Soil Pollution*, *234*(6), 346.

Giordano, M. R., Malings, C., Pandis, S. N., Presto, A. A., McNeill, V. F., Westervelt, D. M., ... & Subramanian, R. (2021). From low-cost sensors to high-quality data: A summary

of challenges and best practices for effectively calibrating low-cost particulate matter mass sensors. *Journal of Aerosol Science*, *158*, 105833.

Gouder, C., & Montefort, S. (2014). Potential impact of fireworks on respiratory health. *Lung India*, *31*(4), 375-379.

Hickey, C., Gordon, C., Galdanes, K., Blaustein, M., Horton, L., Chillrud, S., Ross, J., Yinon, L., Chen, L. C., & Gordon, T. (2020). Toxicity of particles emitted by fireworks. *Particle and fibre toxicology, 17*, 1-11.

Hoekstra, B., Bouten, W., Dokter, A., van Gasteren, H., van Turnhout, C., Kranstauber, B., van Loon, E., Leijnse, H., & Shamoun-Baranes, J. (2024). Fireworks disturbance across bird communities. *Frontiers in Ecology and the Environment, 22*(1), e2694.

Hyndman, R. J., & Athanasopoulos, G. (2018). *Forecasting: Principles and Practice*. OTexts.

Instituto Nacional de Estadística y Geografía (INEGI). 2020. Censo de población y vivienda 2020. México: Instituto Nacional de Estadística y Geografía. https://www.inegi.org.mx/programas/ccpv/2020/

Jaffe, D. A., Thompson, K., Finley, B., Nelson, M., Ouimette, J., & Andrews, E. (2023). An evaluation of the US EPA's correction equation for PurpleAir sensor data in smoke, dust, and wintertime urban pollution events. *Atmospheric Measurement Techniques*, *16*(5), 1311-1322.

Jiao, W., Hagler, G., Williams, R., Sharpe, R., Brown, R., Garver, D., Judge, R., & Caudill, M. (2015). Community Air Sensor Network (CAIRSENSE) project: evaluation of low-cost sensor performance in a suburban environment in the southeastern United States. *Atmospheric Measurement Techniques*, 8(4), 1443-1460.

Karaoghlanian, N., Noureddine, B., Saliba, N., Shihadeh, A., & Lakkis, I. (2022). Low cost air quality sensors "PurpleAir" calibration and inter-calibration dataset in the context of Beirut, Lebanon. Data in Brief, 41.

Kaur, K., & Kelly, K. E. (2023). Laboratory evaluation of the Alphasense OPC-N3, and the Plantower PM2.5S5003 and PM2.5S6003 sensors. *Journal of Aerosol Science*, *171*, 106181.

Krittanawong, C., Qadeer, Y. K., Hayes, R. B., Wang, Z., Thurston, G. D., Virani, S., & Lavie, C. J. (2023). PM2. 5 and cardiovascular diseases: State-of-the-Art review. *International Journal of Cardiology Cardiovascular Risk and Prevention*, 200217.

569 Kuula, J., Mäkelä, T., Aurela, M., Teinilä, K., Varjonen, S., González, Ó., & Timonen,
570 H. (2020). Laboratory evaluation of particle-size selectivity of optical low-cost particulate
571 matter sensors. *Atmospheric Measurement Techniques*, *13*(5), 2413-2423.
572
573 Li YouPing, L. Y., Zhang ZhiSheng, Z. Z., Liu HuiFang, L. H., Zhou Hong, Z. H.,
574 Fan ZhongYu, F. Z., Lin Mang, L. M., ... & Xia BeiCheng, X. B. (2016). Characteristics,
575 sources and health risk assessment of toxic heavy metals in PM2.5 at a megacity of southwest
576 China. *Environmental geochemistry and health*, 2016, vol. 38, p. 353-362.
577
578 Lin, C. C. (2016). A review of the impact of fireworks on particulate matter in ambient
579 air. *Journal of the Air & Waste Management Association*, *66*(12), 1171-1182.
580
581 McIntosh, G.; Gómez-Paccard, M.; Osete, M.L. (2007). The Magnetic Properties of
582 Particles Deposited on Platanus x hispanica Leaves in Madrid, Spain, and their Temporal and
583 Spatial Variations. Sci. Total Environ., 382, 135–146
584
585 Mousavi, A., Yuan, Y., Masri, S., Barta, G., & Wu, J. (2021). Impact of 4th of July
586 fireworks on spatiotemporal PM2. 5 concentrations in California based on the PurpleAir
587 Sensor Network: Implications for policy and environmental justice. *International journal of*
588 *environmental research and public health*, *18*(11), 5735.
589

Nguyen, N. H., Nguyen, H. X., Le, T. T., & Vu, C. D. (2021). Evaluating low-cost commercially available sensors for air quality monitoring and application of sensor calibration methods for improving accuracy.

Paoli, L., Winkler, A., Guttova, A., Sagnotti, A., Grassi, A., Lackovicova, A., Senko, D., Loppi, S., 2017. Magnetic properties and element concentrations in lichens exposed to airborne pollutants released during cement production. Environ. Sci. Pollut. Res. 24 (13), 12063–12080. https://doi.org/10.1007/s11356-016-6203-6.

Puri, V., Mahendru, S., Rana, R. and Deshpande, M., 2009. Firework injuries: a ten-year study. *Journal of Plastic, Reconstructive & Aesthetic Surgery*, *62*(9), pp.1103-1111.

Ren, M., Fang, X., Li, M., Sun, S., Pei, L., Xu, Q., ... & Cao, Y. (2017). Concentration-Response Relationship between PM 2.5 and Daily Respiratory Deaths in China: A Systematic Review and Metaregression Analysis of Time-Series Studies. *BioMed research international*, *2017*.

Rossol, M. "Arts, Crafts, Theater, and Entertainment." (2014): 317-322.

Searle, N., Kaur, K., & Kelly, K. (2023). Identifying a performance change in the Plantower PM2.5S 5003 particulate matter sensor. *Journal of Aerosol Science*, *174*, 106256.

612 Shamoun-Baranes, J., Dokter, A. M., van Gasteren, H., van Loon, E. E., Leijnse, H.,
613 & Bouten, W. (2011). Birds flee en mass from New Year's Eve fireworks. *Behavioral*
614 *Ecology, 22*(6), 1173-1177.

615

616 Shumway, R. H., & Stoffer, D. S. (2017). *Time Series Analysis and Its Applications:*
617 *With R Examples*. Springer.

618

619 Sousan, S., Koehler, K., Hallett, L., & Peters, T. M. (2016). Evaluation of the
620 Alphasense Optical Particle Counter (OPC-N2) and the Grimm Portable Aerosol
621 Spectrometer (PAS-1.108). *Aerosol Science and Technology*, 50(2), 135-144.

622

623 Stavroulas, I., Grivas, G., Michalopoulos, P., Liakakou, E., Bougiatioti, A.,
624 Kalkavouras, P., ... & Gerasopoulos, E. (2020). Field evaluation of low-cost PM2.5 sensors
625 (Purple Air PA-II) under variable urban air quality conditions, in Greece. *Atmosphere*, *11*(9),
626 926.

627

628 Tandon, R., Agrawal, K., Narayan, R. P., Tiwari, V. K., Prakash, V., Kumar, S., &
629 Sharma, S. (2012). Firecracker injuries during Diwali festival: The epidemiology and impact
630 of legislation in Delhi. *Indian journal of plastic surgery*, *45*(01), 097-101.

631

632 Tryner, J., L'Orange, C., Mehaffy, J., Miller-Lionberg, D., Hofstetter, J. C., Wilson,
633 A., & Volckens, J. (2020). Laboratory evaluation of low-cost PurpleAir PM monitors and in-

field correction using co-located portable filter samplers. *Atmospheric Environment*, *220*, 117067.

Turgut, Ferhat, Alexandra Bograd, Brida Jeltsch, Adrian Weber, Petra Schwarzer, Iulia M. Ciotu, Joao Amaral et al. "Occurrence and outcome of firework-related ocular injuries in Switzerland: a descriptive retrospective study." *BMC ophthalmology* 22, no. 1 (2022): 296.

Warrant, E., & Dacke, M. (2010). Visual orientation and navigation in nocturnal arthropods. *Brain Behavior and Evolution*, *75*(3), 156-173.

Table

	January 01, 2024	**February 12, 2024**
Station Name	**Max $PM_{2.5}$ ($\mu g/m^3$)**	
STATION-19	160	28
STATION-12	265	50
STATION-10	346	42
STATION-11	267	52
STATION-18	178	43
STATION-13	56	39
STATION-01	198	51

STATION-03	112	34
STATION-17	231	26
STATION-07	274	53
STATION-22	255	58

Table 1. Maximum $PM_{2.5}$ concentrations recorded at monitoring stations for January 1st and February 12th, 2024, illustrate the significant difference between recordings on two different days.

Captions

Figure. 1 Location of Querétaro city compared to other cities in central Mexico (left). The spatial location of the EMGA stations from the environmental monitoring network of Querétaro city (right).

Figure. 2 Time series showing increases in PM2.5 concentrations at three monitoring stations. (a) Displays the values recorded at STATION-10; (b) The values recorded by STATION-19; (c) Shows the recordings from STATION-13.

Figure 3. Comparison among three time-series showing increases in $PM_{2.5}$ concentrations at three monitoring stations. Series 1 (red) displays the values recorded at STATION-10; series 2 (blue) shows the values recorded by STATION-13; and series 3 (green) depicts the recordings from STATION-19.

667

668 Figure 4. Comparison with temperature (up) and humidity (down) dependence of the $PM_{2.5}$
669 concentration.

670

671 Figure 5. Trends by day of the week from Monday to Sunday, and by hour of the day. The
672 graph illustrates the hourly and daily trend of $PM_{2.5}$ concentration during the study period.

673

674 Figure 6. Polar representation showing trends of $PM_{2.5}$ concentration in hourly averages.
675 Each color indicates hourly averages for a full day of data.

676

677 Figure 7. Histograms of $PM_{2.5}$ concentrations grouped into 5 $\mu g/m^3$ ranges and fitting to a
678 normal distribution.

679

680 Figure 8 Spatial distribution of maximum $PM_{2.5}$ concentrations recorded in the monitoring
681 network for February 12th, 2024 (a); and for January 1st, 2024 (b). The inset (below) displays
682 the ranges of $PM_{2.5}$ concentrations in $\mu g/m^3$.

683

684 Figure 9. Infrasound data recorded at STATION-10 between December 29th, 2023, and
685 January 6th, 2024. (a) Shows the time series plot of normalized data; (b) Trend plot of the
686 Seasonal Decomposition of Time Series (STL) applied to the time series; (c) Comparison
687 between the trend plots and the infrasound time series.

688

689 Figure 10. Areas within the city of Querétaro where records of insects and birds have been
690 documented. The red heat points represent the locations of EMGAs (Ecological Monitoring

and Management Areas) and their corresponding maximum values. Lighter shades of red indicate lower values, while darker shades indicate higher values. GBIF Occurrence Download https://doi.org/10.15468/dl.emurnt.

Figures

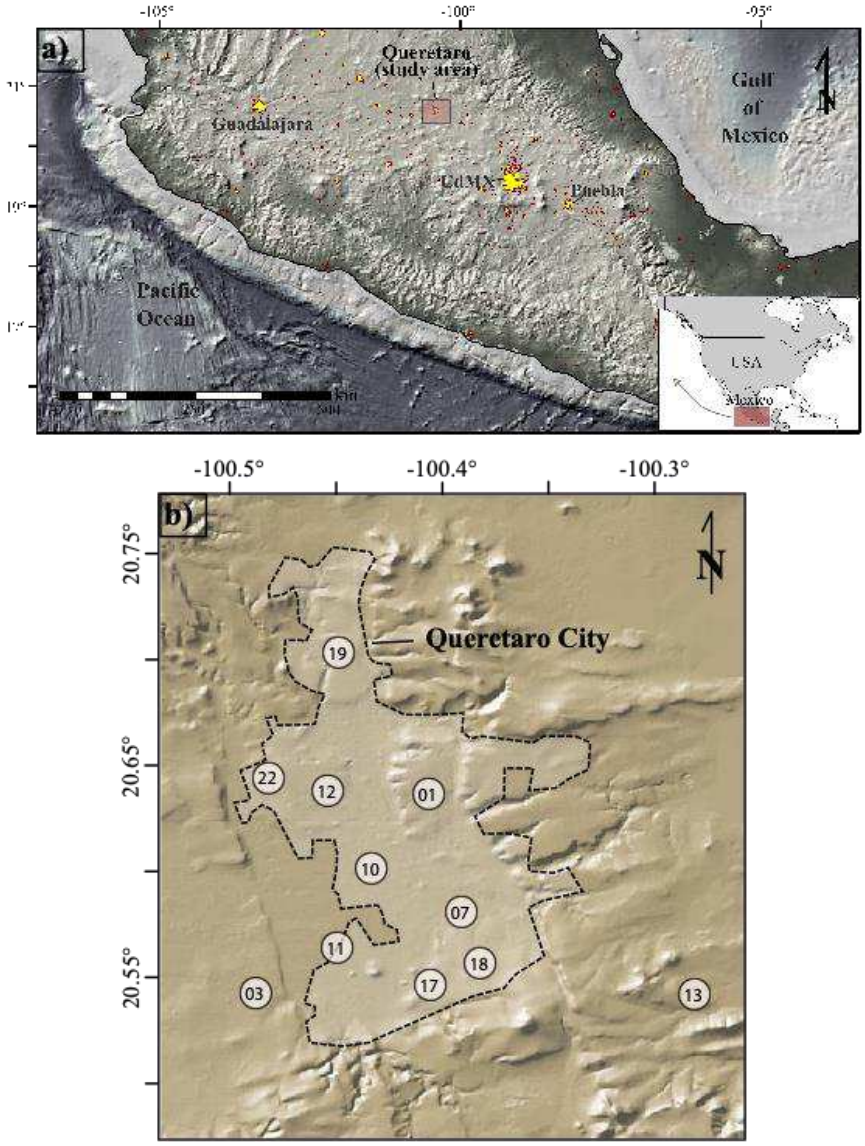


Figure 1

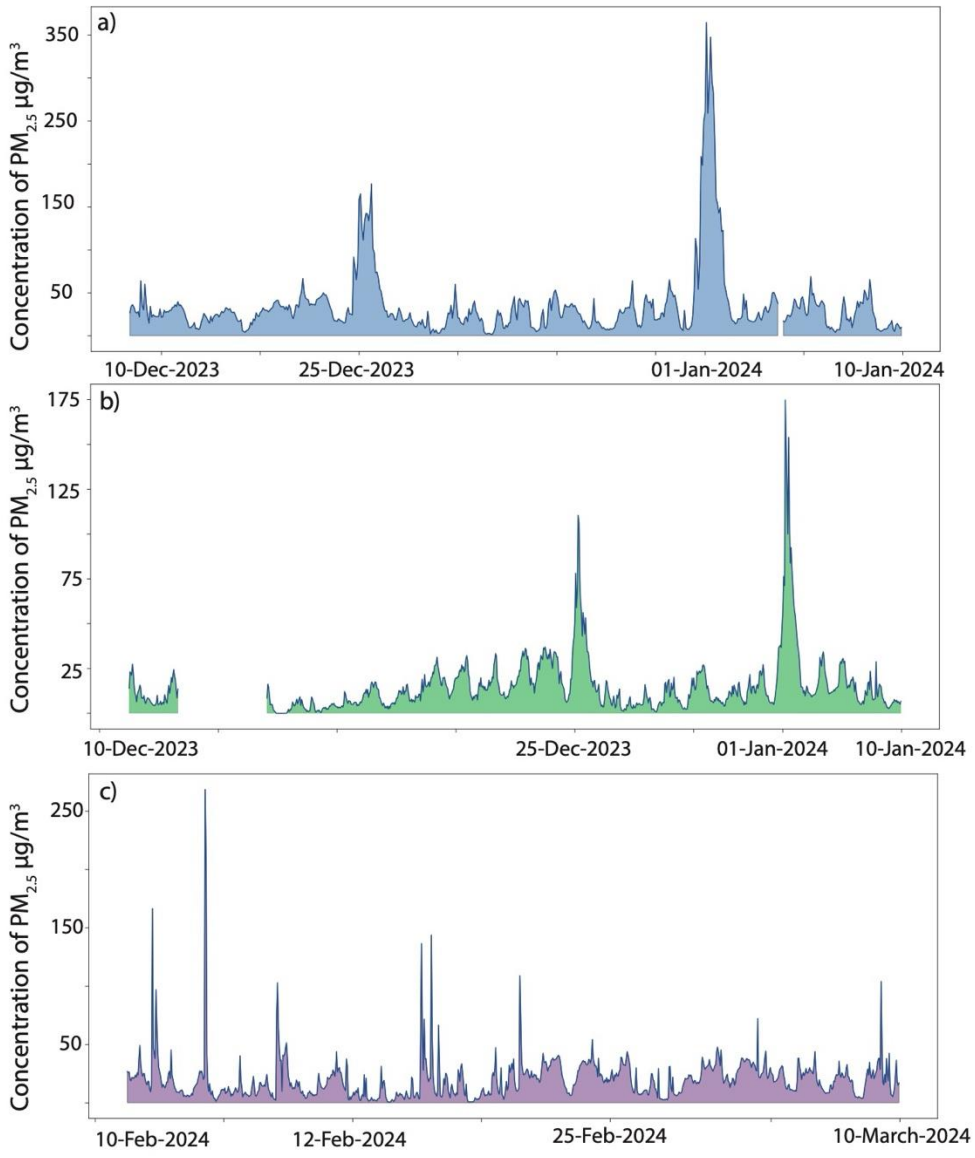

a)
Concentration of PM2.5 µg/m3
350
250
150
50
10-Dec-2023
25-Dec-2023
01-Jan-2024
10-Jan-2024
b)
Concentration of PM2.5 µg/m3
175
125
75
25
10-Dec-2023
25-Dec-2023
01-Jan-2024
10-Jan-2024
c)
Concentration of PM2.5 µg/m3
250
150
50
10-Feb-2024
12-Feb-2024
25-Feb-2024
10-March-2024

Figure. 2

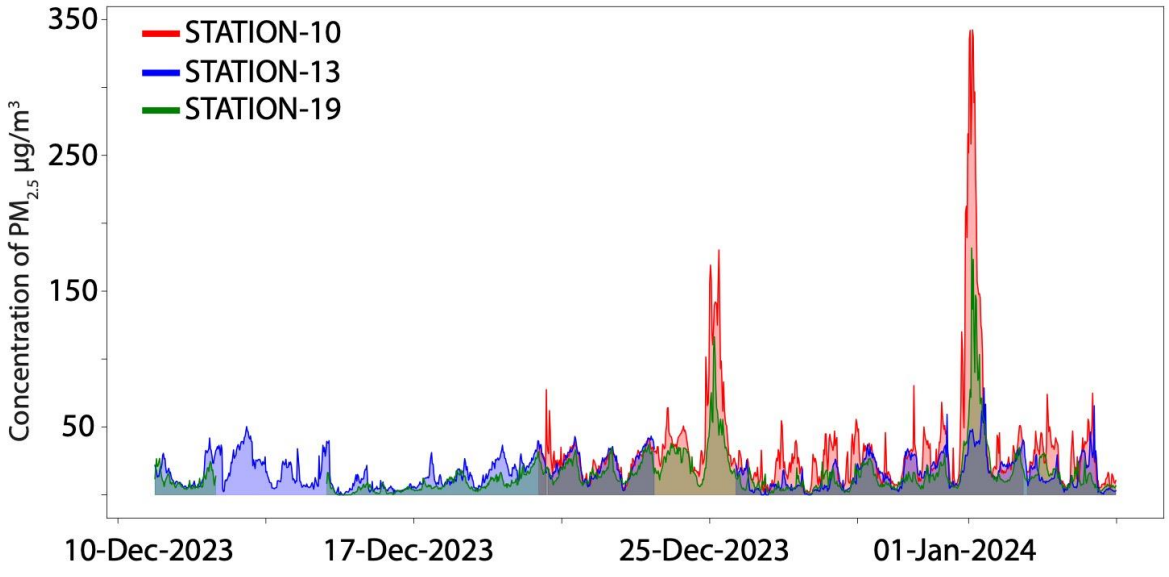

STATION-10
STATION-13
STATION-19
Concentration of PM2.5 µg/m³
350
250
150
50
10-Dec-2023
17-Dec-2023
25-Dec-2023
01-Jan-2024

Figure. 3

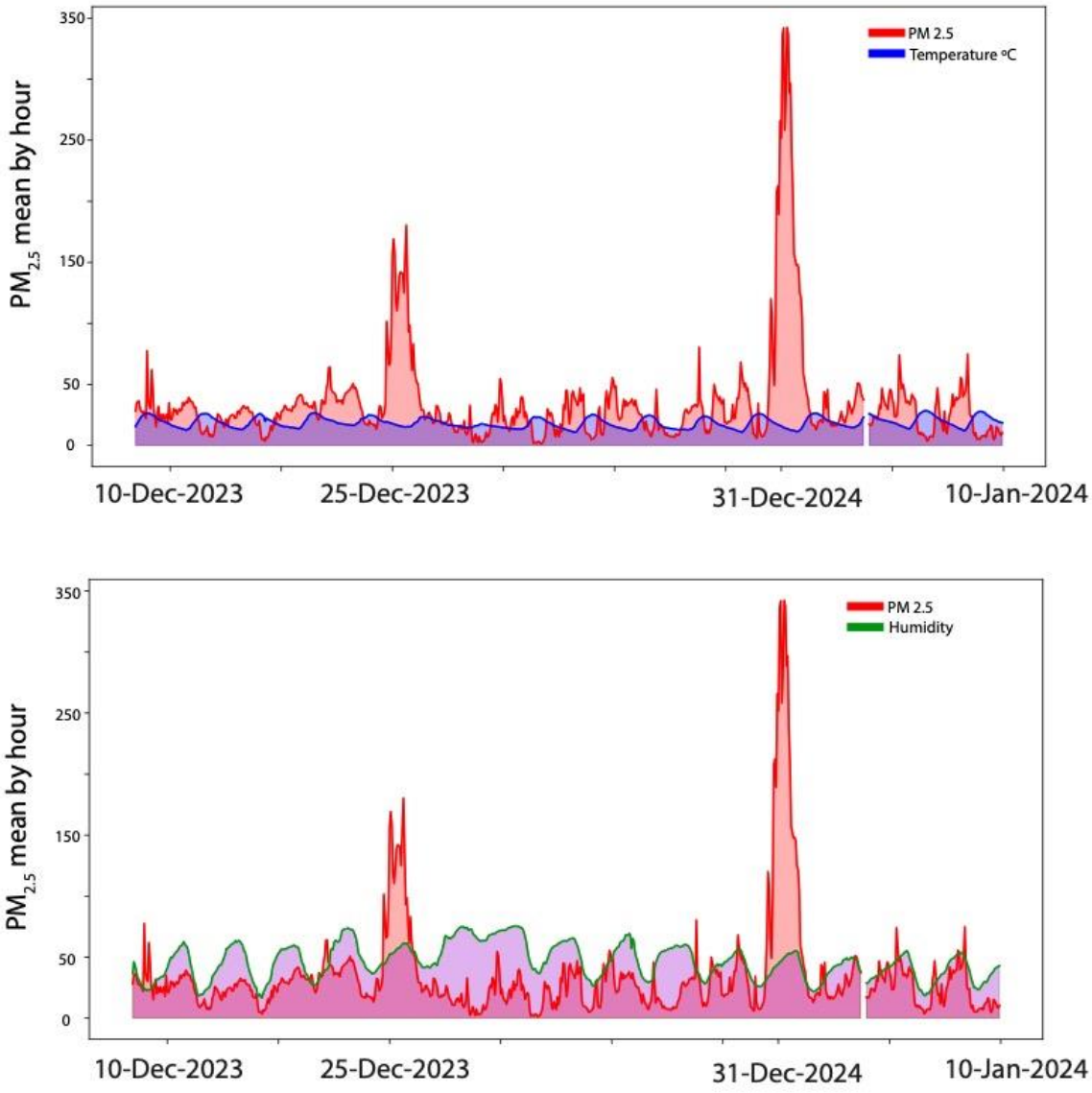

PM 2.5
Temperature °C
PM2.5 mean by hour
350
250
150
50
0
10-Dec-2023
25-Dec-2023
31-Dec-2024
10-Jan-2024
PM 2.5
Humidity
PM2.5 mean by hour
350
250
150
50
0
10-Dec-2023
25-Dec-2023
31-Dec-2024
10-Jan-2024

Figure. 4.

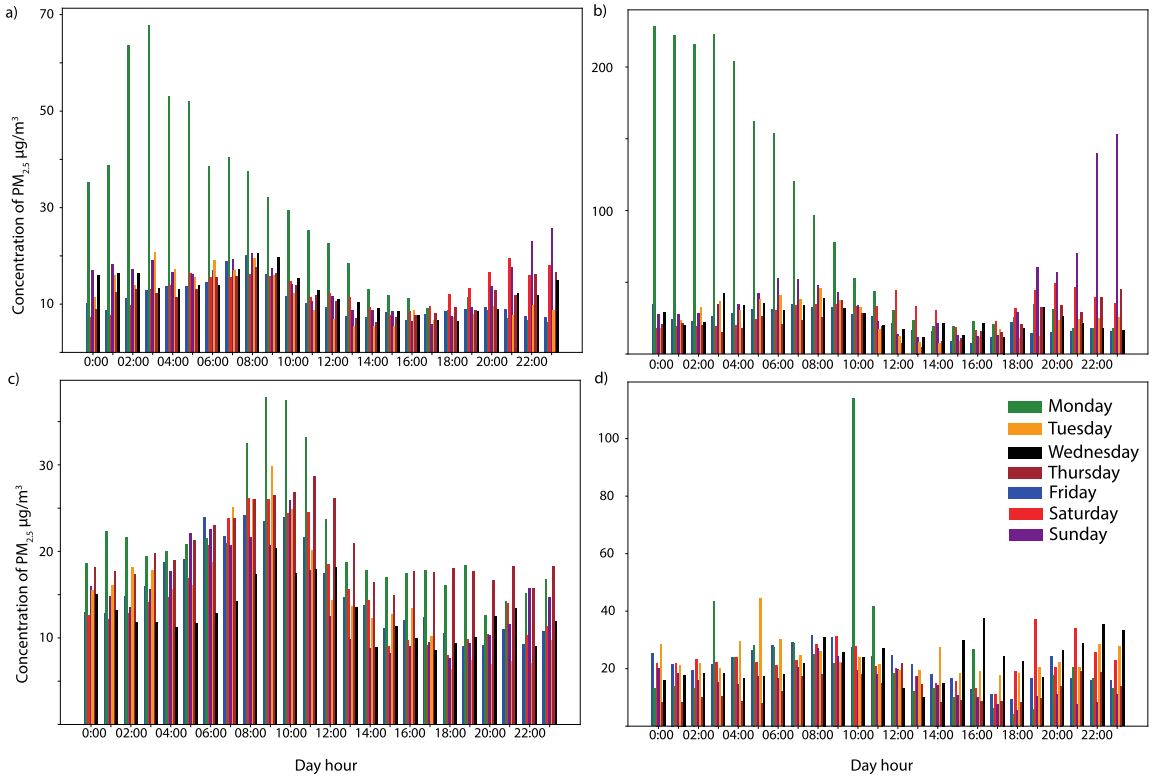

a)
b)
c)
d)
Concentration of PM2.5 µg/m3
Concentration of PM2.5 µg/m3
Day hour
Day hour
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday

Figure. 5

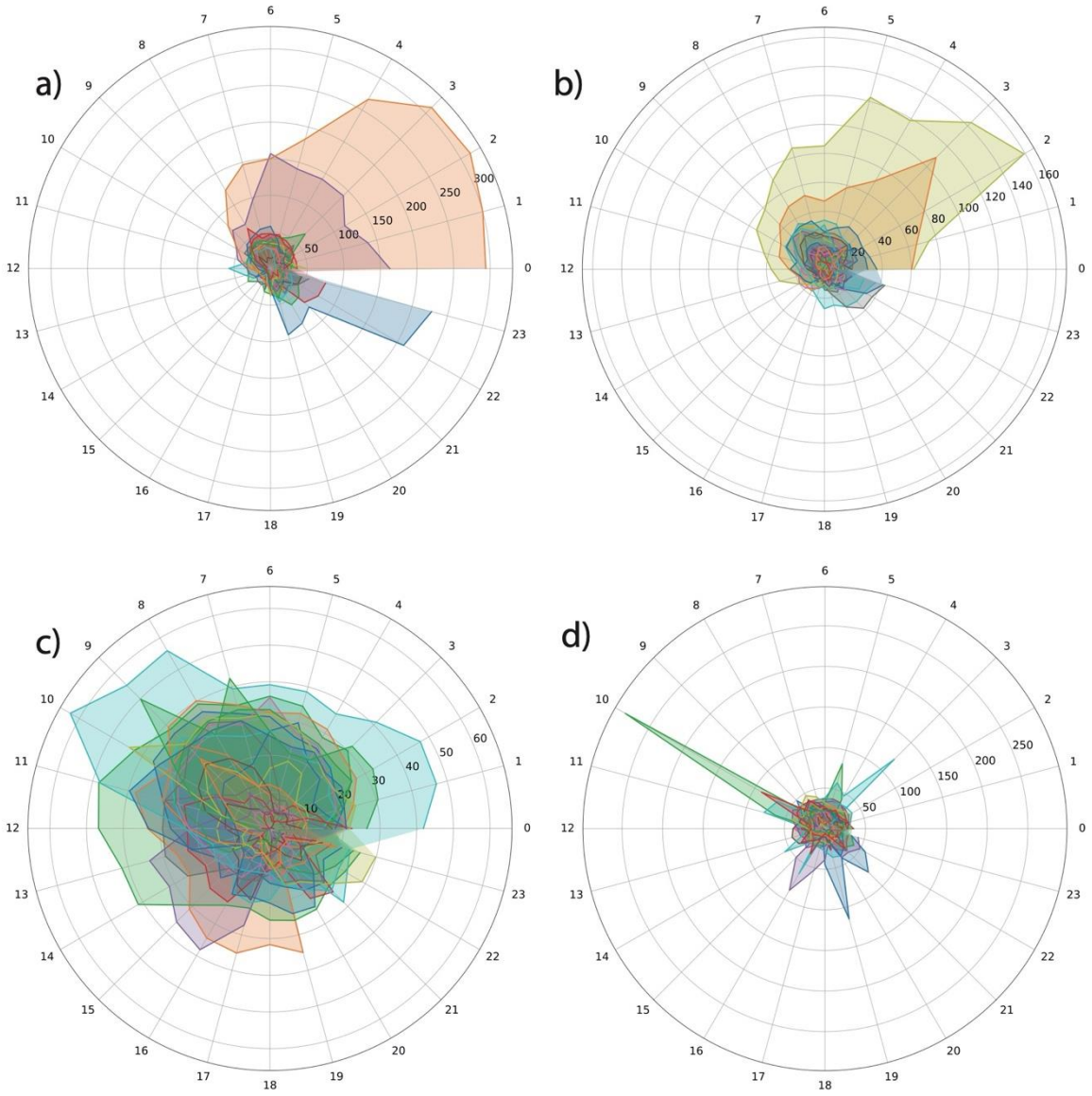


Figure. 6

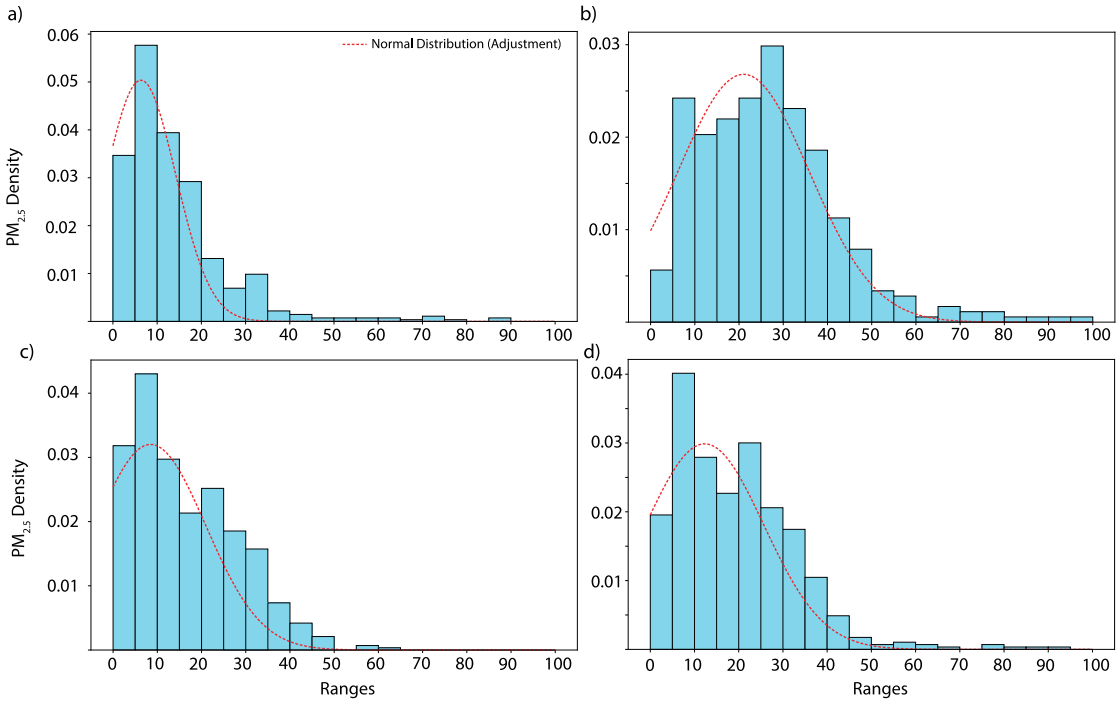

a)
b)
c)
d)
Normal Distribution (Adjustment)
PM2.5 Density
Ranges
0.06
0.05
0.04
0.03
0.02
0.01
0 10 20 30 40 50 60 70 80 90 100

Figure 7

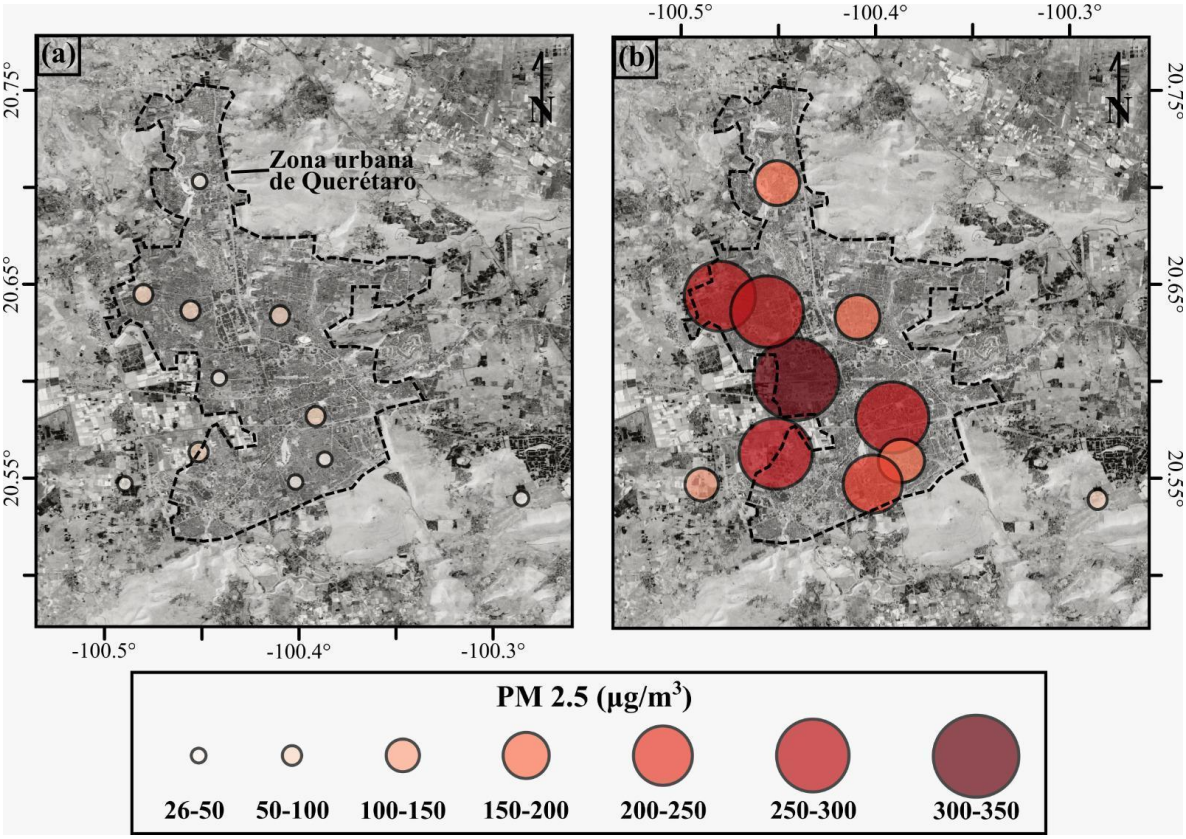
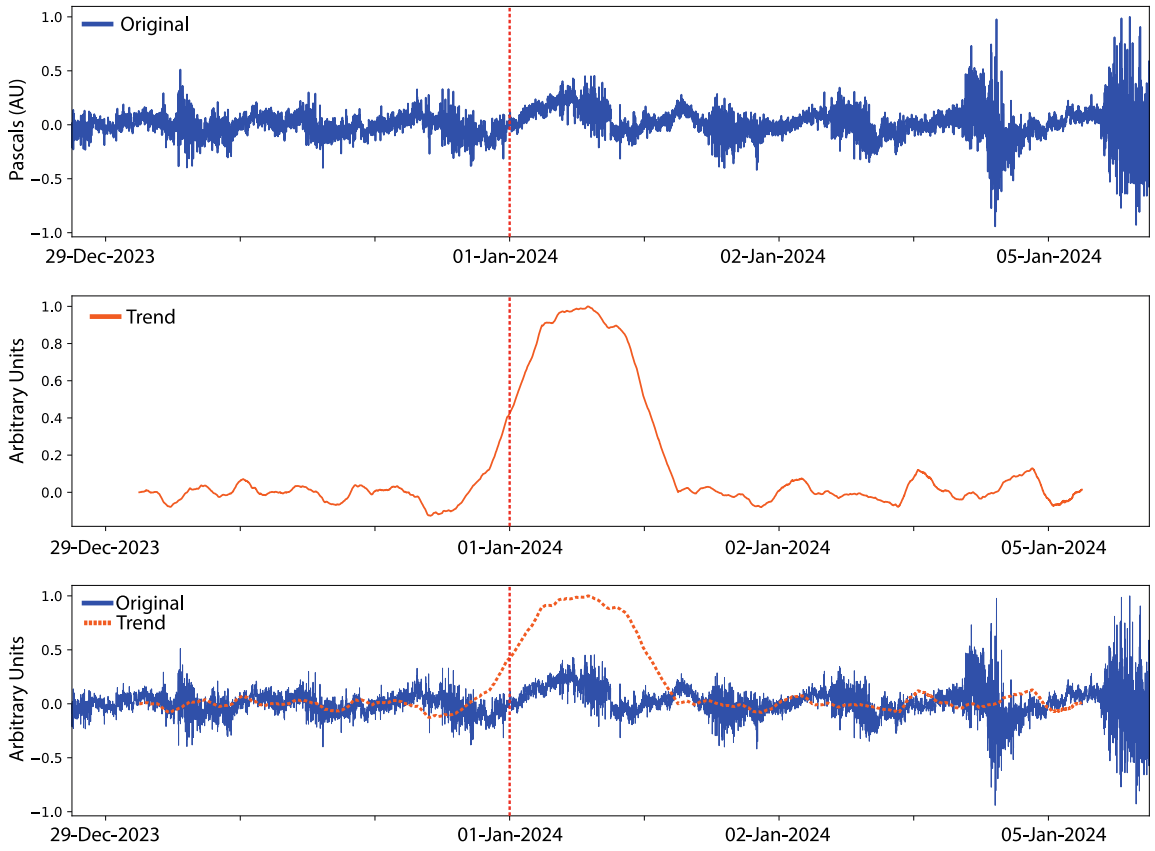
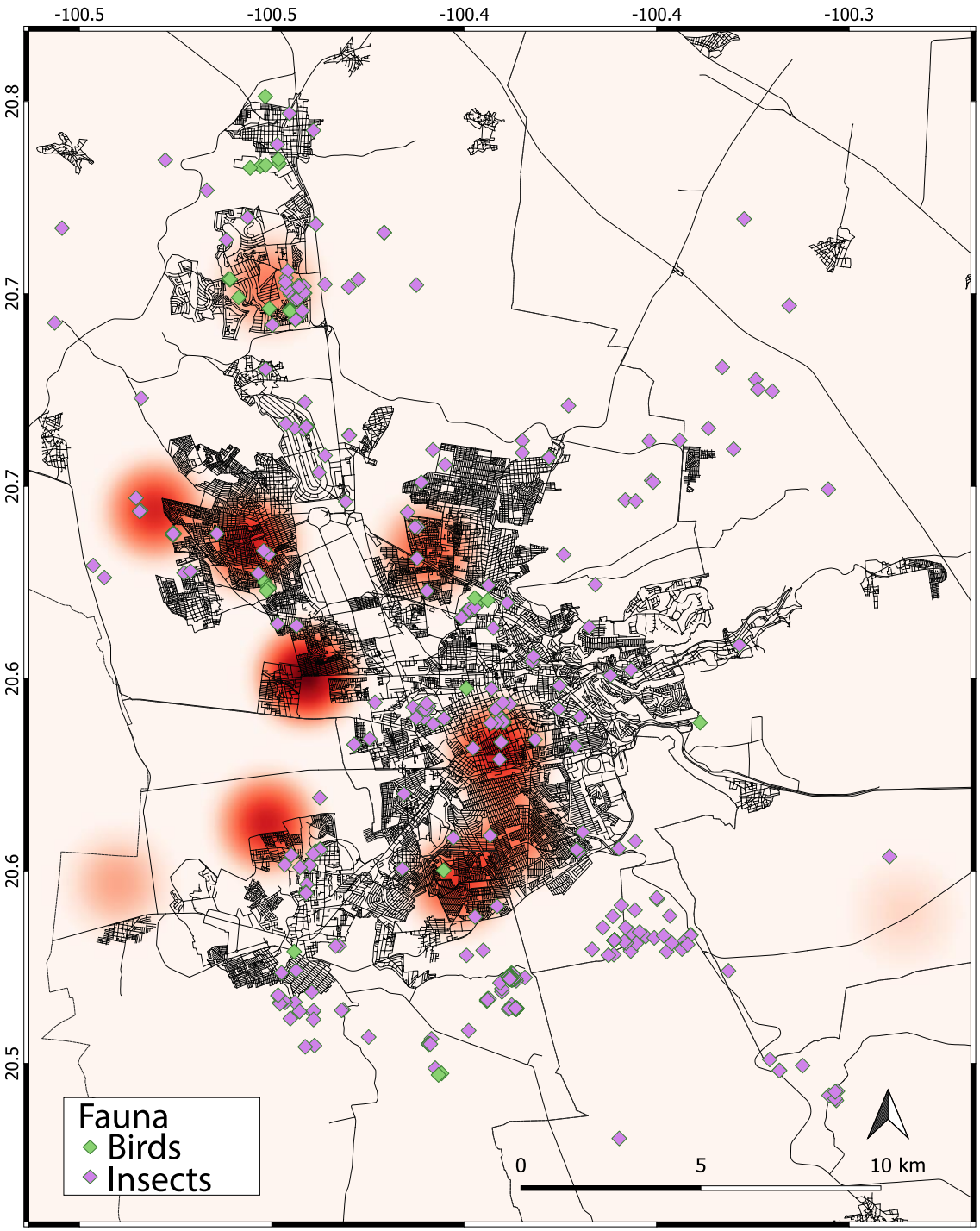

(a)
(b)
Zona urbana
de Querétaro
N
-100.5°
-100.4°
-100.3°
20.75°
20.65°
20.55°
PM 2.5 (µg/m3)
26-50
50-100
100-150
150-200
200-250
250-300
300-350

Figure 8



764

765 Figure 9



766

767 Figure 10