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Air Pollution in Cities With Unplanned Urban Growth, a Case Study of Toluca Valley: Trends and Health Impacts Compared With Mexico City

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Abstract

Unplanned urban growth is occurring in many cities around the world in developing countries and is associated with social and environmental problems such as air pollution. The case study of the Metropolitan Area of Toluca Valley (MATV) provides a clear example of disorganized urban growth and high levels of air pollution. Since 2019, the IQAir platform has ranked MATV as the city with the worst air quality in Mexico, in terms of $PM_{2.5}$. Based on this scenario, ten-year (2011-2021) monitoring databases of air criteria pollutants (ACP) from six MATV monitoring stations were processed to establish seasonal and spatial distributions and to estimate the mortality proportion attributable to $PM_{2.5}$ exposure. The results were compared with the evolution of ACP concentrations and the proportion of mortality attributable to $PM_{2.5}$ of Mexico City. In addition, COVID-19 lockdown impact on ACP concentrations was also assessed. $PM_{2.5}$ and PM_{10} are the main ACP that worsen air quality in MATV and exceed the WHO Air Quality Guidelines (AQG) almost the entire year risking health population. The estimated mortality proportion due to natural deaths (ICD-10) associated with $PM_{2.5}$ exposure in 2019 for MATV was 11.97% (7.98-15.55) as for Mexico City, 6.95% (4.59-9.1). MATV presented higher levels of ACP and lower reduction percentages than Mexico City Metropolitan Area over the ten-year period, PM and O_3 patterns are very similar between cities, suggesting that air pollution is shared. COVID-19 lockdown in 2020 showed a reduction of all ACP concentrations except for O_3.

1. Introduction

Pollutants of major public health concern include particulate matter, carbon monoxide, ozone, nitrogen dioxide and sulfur dioxide, known as air criteria pollutants. The combined effects of ambient and household air pollution are associated with 6.7 million premature deaths annually (WHO, 2022). The relevance given by the WHO to the worldwide monitoring of air quality in large urban centers and metropolises has generated great interest from the scientific community and the media (de Vasconcellos et al., 2022). Air pollution is also linked to climate change (Ramanathan and Feng, 2009) as well as negative impacts on global economy (Aguilar-Gómez et al., 2022).

Urban and economic development is causing the functional areas of many cities around the world to transcend their political borders with labor, service and financial markets, as well as the physical extension of these cities across the jurisdictional territories of several neighboring municipalities (Gómez-Álvarez et al., 2017). The informal urban growth represents a defect in urban development in cities, the absence of design and planning standards together with the uncontrolled application of organizing laws lead to severe problems as the insufficiency of services, facilities and infrastructure (Bek and Elkafrawy, 2018). Environmental problems, such as low efficiency in solid waste management, fresh water supply and wastewater treatment, as well as poor air quality, are also related to unplanned urban growth which also increases public health risks.

Mexico City has transcended its State limit to the surrounding municipalities of the State of Mexico forming the Mexico City Metropolitan Area (MCMA). This is also the case of MATV, which is currently integrated by 15 municipalities (SEDATU, 2018). Both cities have grown without a proper process of planned urbanization, but instead there has been rapid urban expansion, diffuse and fragmented growth, and a conurbation with small and medium-sized peripheral settlements (Cruz-Bello, Galeana-Pizaña and González-Arellano, 2023). Despite the fact that MATV is located 60 km west from MCMA, it has been impacted by the immigration of labor and various industries, as well as by the increase in traffic density with the consequent related environmental problems (Iracheta, 2017). MATV has currently become the city with the highest $PM_{2.5}$ concentrations in Mexico since 2019 (IQ Air 2023).

MATV is located between north latitude 18°59'07" and 19°34'47" and parallels, 99°38'22" and 99°56'13" west longitude (Fig. 1a) and has a territorial extension of 2,410.5 km^2 (SEDATU, 2018). According with the last 2020 census, MATV has a population of 4,188,804 inhabitants (INEGI, 2021). Some of the MATV air quality problems are related to geophysical factors such as its high average altitude of 2,610 masl, being one of the highest cities of Mexico, were the atmospheric oxygen concentration is lower with respect to sea level, causing a less efficient combustion (Wang et al., 2013); in addition, MATV is partially surrounded by mountains affecting the air pollutants dispersion and increasing thermal inversions occurrence and high pressure systems (SMAGEM, 2012). Toluca Valley has three weather seasons: Dry-cold (DC) season, from November to February, Dry-hot (DH) season from March to May and Rainy (Ra) season, from June to October (SMAGEM, 2012).

Since 1960, Toluca Valley had an industrialization process promoted by the government and based on the offer of land, low-cost energy and water supplies with virtually no environmental regulations, resulting in the establishment of several industrial enterprises, the consequent increase in traffic density, as well as labor immigration (Orozco Hernández et al., 2003). Currently, there are more than 11,000 manufacturing economic units registered (SMAGEM, 2012) and 1,047,661 registered motor vehicles in circulation (INEGI, 2021) with a

rate of 250 vehicles per 1000 habitants. This large amount of vehicles is related to the absence of a massive transport system due to the unplanned historical expansion of the metropolitan area provoking a high amount of scattered suburban areas (CMM, 2014).

There are relatively few research publications analyzing the MATV air pollution phenomena, even so, serious health risks have been evidenced, as the presence of bioaerosols (pollen, spores, microorganisms, fragments and diatoms) with aerodynamic sizes of 0.3 μm to 45 μm (Romero-Guzmán et al., 2021). Ávila-Pérez et al., (2019) found a significant enrichment of Pb followed by Zn, Cu and Cr accumulated in mosses biomonitors. Romero-Guzman et al., (2018) reported high concentrations of heavy metals in rainwater TSP in the Northern zone of Toluca Valley. Unlike MATV, MCMA has been the subject of several studies to analyze the trends of air pollutants, their impact on public health and their emission sources (Mugica et al., 2009; Molina et al., 2010; Cromar et al., 2021).

The present study aims to contribute to the understanding of the serious air quality problems in cities with unplanned urban growth through the case study of MATV, by analyzing ten years (2011–2021) of ACP monitoring data, describing temporal and spatial distributions to identify the areas with higher risk to the population, in compliance with the WHO AQG. A comparison between MATV and MCMA ACP evolution levels was made along these 10 years to analyze the effects of the application of environmental policies taken by the Mexico City government and not in MATV. The impact on public health was assessed through the estimation of the number of natural deaths associated with $PM_{2.5}$ exposure using the AirQ + software developed by WHO for MATV and Mexico City. The changes in the ACP emissions in MATV related to the COVID-19 lockdown were analyzed to identify which pollutants were significantly reduced in relation to the decline in economic activities.

2. Methodology

2.1 Data bases

Air criteria pollutant monitoring data from six monitoring stations was provided by the air monitoring network of MATV. Hourly averages of PM_{10}, $PM_{2.5}$, O_3, NO_2, SO_2 and CO were analyzed from January 2011 to December 2021. Hourly averages of meteorological parameters were also analyzed to elaborate wind rose diagrams. The monitoring stations were selected based on data availability during the period of study. The selected sites are geographically distributed along the metropolitan area (Fig. 1b) in order to analyze the spatial distribution of ACP. Table 1 summarizes the codes, names and location of the 6 sites analyzed.

MCMA ACP monitoring data bases from 2011–2021 were obtained from Mexico City Air Monitoring Network website (SIMAT, 2022) for the comparative analysis between MCMA and MATV. Population and epidemiological data to feed the AirQ + model for both cities was obtained from the National Institute of Statistics and Geography website (INEGI, 2023).

The air monitoring networks from both cities operates under standardized procedures, the analyzers used meet the characteristics required for the US EPA reference and equivalent methods, which ensures reproducible and traceable results. In addition, both monitoring networks are subjected to audit processes by national environmental authorities and in the case of the MCMA monitoring network by personnel certified by the US EPA (SIMAT, 2023).

Table 1
Monitoring stations selected

Code	Name	Municipality	Location
SC	San Cristóbal Huichochitlán	Toluca	19° 19’ 38.0” N 99° 38’ 3.44” W
OX	Oxtotitlán	Toluca	19° 17’ 0.40” N 99° 41’ 0.56” W
CE	Toluca Centro	Toluca	19° 16’ 41.1” N 99° 39’ 23.1” W
CB	Ceboruco	Toluca	19° 15’ 37.1” N 99° 38’ 44.6” W
MT	Metepec	Metepec	19° 16’ 12.7” N 99° 35’ 42.7” W
SM	San Mateo	San Mateo Atenco/Lerma	19° 16’ 49.5” N 99° 32’ 30.0” W

2.2 Seasonal and spatial distribution analysis

The 24-h average was calculated for each ACP, except for the 8-h average for O_3, in order to establish a comparison between sites and seasons. The ACP data was separated within three weather seasons DH (Mar-May), Ra (Jun-Oct) and DC (Nov-Feb). The wind rose

diagrams were elaborated by using WR-PLOT Lakes Environmental Software and wind vectors were considered to discuss spatial distribution. ACP 24-h averages were compared to 2021 WHO AQG to identify the areas and seasons associated with higher risk to the population. To establish data indicators comparisons, significance test were perform in IBM SPSS software. Kruskal-Wallis test was perform to demonstrate significant differences between sites and seasons at a significant level of 5%, this since the ACP data concentrations can be represented by continuous random variables with unknown probability distributions (Zhao et al., 2018).

2.3 MATV and MCMA comparison

The monthly ACP medians for MATV and MCMA were calculated from the concentrations of all their respective monitoring stations during 2011 to 2021. A comparative analysis between cities of the evolution of each ACP was carried out in contrast to the differences in environmental policies adopted in each city. As a quality control assurance of data, monthly medians were calculated considering a 75% data sufficiency criteria to maintain representativeness. The significance of the differences between cities was evaluated using the Mann-Whitney U test.

2.4 $PM_{2.5}$ associated mortality estimation

The estimation of the mortality proportion in the adult population (< 30 years) attributable to $PM_{2.5}$ exposure as well as the associated number of natural deaths (ICD-10) was calculated using the AirQ + model. This software was developed by the WHO Regional Office for Europe to estimate the magnitude of the impacts of air pollution on the health of a given population. All calculations performed by AirQ + are based on methodologies and concentration-response functions established in epidemiological studies and these functions are based on a systematic review of all available studies and their meta-analysis (WHO 2020). AirQ + has been used in several countries to make impact estimates (Rovira et al., 2020; Mirzaei et al., 2021; Naghan et al., 2022). Comparative studies have been carried out on the use of AirQ + with respect to another software used for the same purpose of estimating mortality from exposure to air pollutants, which is US EPA BenMAP, finding that the results calculated with AirQ + and BenMAP agree well for similar input data (Mirzaei et al., 2021; Sacks et al., 2020)

AirQ + quantifies the impact of PM exposure using an attributable proportion (AP) function, defined in Eq. 1. AP is defined as the fraction of the health endpoint in a defined population attributable to exposure to an air pollutant, assuming a demonstrated causal relationship between exposure and the health issue and with no significant confounding effects on this association (Arregocés, Rojano and Restrepo, 2023). Where RR is the relative risk for the health endpoint in a determined exposure to air polluted by PM and P is the fraction of the population under exposure.

Eq 1

$$AP = \frac{\Sigma\,(RR-1)\times P}{\Sigma RR \times P}$$

An annual analysis was carried out from 2018 to 2019 to avoid the period of deaths from COVID-19 that began in 2020. To compare the results obtained for MATV, the model was also run for epidemiological, demographic, and $PM_{2.5}$ monitoring data from Mexico City during 2019. In addition, results from similar studies that used AirQ + in other cities around the world were used for comparison with the proportion of deaths attributable to $PM_{2.5}$ estimated for MATV.

For the MATV analysis, the population and epidemiological data were limited to the four MATV municipalities with air monitoring sites (Lerma, Metepec, San Mateo Atenco and Toluca), as shown in Table 1, to maintain the representativeness of the measured ambient concentrations of $PM_{2.5}$ and the population actually exposed to them. As for Mexico City, the epidemiological, demographic and air monitoring data was limited to the 16 municipalities of Mexico City State, without considering the neighboring municipalities of the State of Mexico included in the MCMA, in order to maintain separation of epidemiological records by State. The relative risk factors preloaded in AirQ+, 1,062 (1.04-1,083), were used for the impact analysis as the $PM_{2.5}$ means were within range (WHO, 2020).

2.5 COVID lockdown impact assessment

To analyze the impact of the COVID-19 lockdown on the ACP emissions, the lockdown period was determined by the start of the National Campaign of Healthy Distancing established by the Mexican government to reduce the number of infections by suspending non-priority economic activities, which took place from March 23rd to May 28th 2020. The daily ACP averages from this period were compared to the respective averages of the same dates (March 23rd to May 28th) but from the previous four years (2016–2019) as a reference of the typical MATV ACP levels. The 2021 ACP data, of the above mentioned period, was considered to analyze the emissions changes of the

transition from the complete lockdown to the so-called "new normality" stage, where the economic activities were restored, but many people continued in the home office mode as well as for the educational activities remained remote as well. The significance of the differences among the three periods was evaluated by Kruskal-Wallis test.

3. Results and Discussion

3.1 Seasonal and spatial distribution analysis

From the 2021 meteorology data base, Wind Rose diagrams were plotted for each monitoring station in the WRPLOT software (Fig. 1b). MATV wind speed is influence by air turbulence and surface roughness (Rivera et al., 2017). It was observed that the predominant wind direction in the stations on the periphery of MATV (SC, SM and OX) the wind blows mainly from Southeast and wind speed is less than 5.7 m s-1, which is consistent with the findings of (Ortiz et al., 2021). At MT station, wind blows from Northeast and this site is clearly downwind of the industrial area. The CB and CE stations have the lowest wind speed values (< 3.6 m s-1) and the wind vectors are more dispersed due to terrain elevations near the sites. The analysis of the spatial and temporal distribution of the six ACP is illustrated in Fig. 2. The results of the Kruskal-Wallis test of the differences between sites and seasons, showed all p-value less than 0.05, indicating significant spatiotemporal heterogeneity.

The highest values of $PM_{2.5}$ occurred during the DH season which is related to agricultural burning during March to May to prepare farmland for planting (SMAGEM, 2018), weather conditions of this season are also related, as the high pressure systems causes' air pollutants accumulation and high solar radiation favors aerosol secondary formation (Sbai et al., 2021). SC and SM sites have the highest $PM_{2.5}$ concentrations, both sites receive wind currents from industrial areas and are close to agricultural fields. All the monitoring stations medians are above WHO 24h $PM_{2.5}$ AQG (15 $\mu g/m^3$) almost the entire year.

In the case of PM_{10}, most of the sites have slightly higher values during the DH season in relation to the agricultural emissions described above, while SC has clearly higher PM_{10} concentrations during the DC season, due to the local practice of wood burning for home heating during cold winter as described in London by Fuller et al., (2014). SC and SM are also the sites with the highest PM_{10} concentrations, these sites receipt emissions from industry and wind erosion (Romero-Guzman et al., 2018). With respect to WHO 24h PM_{10} AQG, most of the sites fit partially the AQG during the Ra season, but exceed the limit the rest of the year.

As for the O_3 values distribution, 75% of the 8-hour means are below the WHO O_3 AQG. In general, the DH season presents the highest values due to the higher solar radiation during this period, 24% higher than DC season. MT station has slightly higher concentrations that can be related to be downwind the industrial area which is a source of O_3 precursors, but this precursors are also emitted within the MT area by the several clay craft workshops with high consumption of varnishes, solvents and furnace fuel (Núñez, 2022).

The higher concentrations of NO_2 are present at town center in CE station and followed by SM, especially during Dry-cold season. Both stations are surrounded by roads with high traffic, an important source of NO_2 (Anttila et al., 2011). Regarding WHO NO_2 AQG, all the sites are above the limits during the entire year.

CO values at all the sites and during the whole year are clearly below WHO CO AQG. The DC season is the period with the highest values due to the thermal inversions during the season. SC has the highest CO concentrations, followed by SM, CB and CE, at these sites there are intensive vehicular traffic and CO is a vehicle emissions indicator (Oakes et al., 2014) but also CO is emitted by biomass burning (Chan and Qin, 2017) which is an important factor in SC and SM since at these sites surroundings biomass burning is a common practice for cooking and heating.

SM station presents the highest values of SO_2, followed by CE and SC during the dry-cold season. SM and SC receives wind currents from the industrial areas where the combustion of fuel oil is an important source of SO_2 (Sosa et al., 2020). Diesel combustion in heavy-duty vehicles, such as busses and trucks, are also a significant source of SO_2 (Zavala et al., 2017) and these three monitoring stations are near of heavy traffic roads. SO_2 24-h average concentrations are below WHO SO_2 AQG.

The spatiotemporal distribution of the ACP in MATV is related to the heterogeneity in land use (agricultural, industrial and residential) which is a consequence of the urban growth of MATV without the proper urban organization standards. More and more farmers are selling their farmland at affordable prices for the construction of industrial parks, as well as to private builders of housing complexes of social interest close to the workplaces, but this situation end up increasing traffic since the roads are not adapted for a greater flow of

vehicles, in addition to causing insufficiency of resources such as drinking water, efficient sewerage, total absence of wastewater treatment and increased air pollution.

3.2 MATV and MCMA comparison

The results of the comparison of the 10-year evolution of the monthly medians of MATV regarding MCMA for the six ACP are presented in Fig. 3. The Mann-Whitney U test resulted in p-values below 0.05 for $PM_{2.5}$, PM_{10}, CO and SO_2, while O_3 and NO_2 p-values were 0.056 and 0.321, respectively, indicating there was no significant difference between the medians of these two ACP due to common emission sources.

$PM_{2.5}$, PM_{10} and O_3 showed similar tendencies, this can be associated to the exportation of air pollution between cities but mostly from MCMA to MATV, this is confirmed by the National Institute of Ecology and Climate Change from the analysis of wind surface trajectories in the vicinity of the urban areas of MCMA (INECC, 2016). The MATV tendency of $PM_{2.5}$ has remained relatively constant along the 10 year analysis, whereas in MCMA a 25% reduction in the tendency has been observed (Fig. 3a). PM_{10} tendencies have both reductions of 57% and 64%, for MATV and MCMA, respectively (Fig. 3b). MATV and MCMA O_3 concentrations have the same tendency line which has a 13% increment along the study period (Fig. 3c). Both cities have reduced their NO_2 levels in 34% in MATV and 30% in MCMA (Fig. 3d). CO concentrations have being reduced in 15% and 55% in MATV and MCMA, respectively (Fig. 3e). SO_2 MATV concentrations were double than MCMA along the ten years. MATV has a reduction of 35% in its SO_2 concentrations and 47% reduction in MCMA (Fig. 3f).

In general, MATV APC concentrations have been higher than MCMA along the 10-year period analyzed, also the reduction rates are lower regarding to MCMA. This can be attributed to several actions taken by MCMA government such as emissions control technologies and environmental audit programs for vehicles and industries, driving restriction strategies and improvements in public transportation infrastructure and availability (Molina et al., 2019). Currently, MATV does not have a mass transportation system, neither weekly vehicular driving restrictions, since vehicle exhaust emissions are not mandatory measured. Although MATV recognizes the “Program for Atmospheric Environmental Contingencies” when ACP levels are above critical threshold, the reduction of vehicular circulation is only suggested and the environmental surveillance is insufficient to verify the reduction in industrial activities for specific atmospheric sources during the high pollution days. An important factor to be considered is the agriculture related emissions from the surrounding rural areas of MATV, such as burnings and soil re-suspension during land preparation and harvest activities.

3.3 $PM_{2.5}$ associated mortality estimation

The input data used in AirQ + software as well as the results obtained by the model for MATV and Mexico City are summarized in Table 2

Table 2
AirQ + input data and model results

INPUT DATA	MATV*		Mexico City**
	2018	2019	2019
Annual Ave. $PM_{2.5}$ ($\mu g/m^3$)	30.4	31.2	21.97
Total Population	1 402 409	1 419 587	9 031 213
> 30 years population	687 443	704 344	5 257 052
Number of cases (natural deaths ICD-10, > 30 years)	5666	5816	57 090
AIRQ + Model RESULTS	MATV		Mexico City
	2018	2019	2019
Estimated number of attributable cases	654 (436–851)	696 (464–905)	3966 (2618–5297)
Estimates attributable proportion	11.55% (7.69–15.01)	11.97% (7.98–15.55)	6.95% (4.59–9.1)

*MATV population and epidemiological data were limited to the four MATV municipalities with air monitoring sites (Lerma, Metepec, San Mateo Atenco and Toluca)

**Mexico City population, epidemiological and $PM_{2.5}$ monitoring data was limited to the 16 municipalities of the State.

The long-term impact analysis of the AirQ + model showed that 2019 was the year with the highest number of cases of natural deaths associated with $PM_{2.5}$ exposure in MATV due to the higher environmental concentrations of $PM_{2.5}$. The MATV health impact analysis results of the previous years (2015–2017) can be consulted in Neria-Hernandez et al., (2022). The number of natural deaths attributable to exposure to $PM_{2.5}$ for MATV is proportionally consistent with the results of the analysis carried out by the State Center for Epidemiological Surveillance and Disease Control of the State of Mexico (CEVECE, 2020). Exposure to respirable particles can affect both short-and long-term effects on morbidity, and mortality. Numerous scientific studies have linked particle pollution exposure to ischemic heart disease, cerebrovascular disease, heart failure; systemic inflammation, oxidative stress and alteration of the electrical processes of the heart; respiratory effects (including aggravated asthma, decreased lung function, and symptoms such as coughing); infections; diabetes; impaired neurological development in children; “brain aging” and neurological disorders in adults (ASTDR, 2020).

The comparative analysis between MATV and the State of Mexico City for 2019, showed that 696 deaths could have been avoided in MATV if the ambient concentrations of $PM_{2.5}$ had not exceeded 10 $\mu g/m^3$, as for Mexico City State, 4027 cases. This large gap is related to the fact that the number of natural deaths associated to $PM_{2.5}$ exposure is estimated in proportion to the amount of exposed population, and the population of the State of Mexico City is six times greater than that of the four MATV municipalities considered. In terms of estimated mortality proportion, Mexico City is close to half the attributable proportion of MATV, as ambient $PM_{2.5}$ concentrations in Mexico City are 30% lower than those of MATV. Table 3. Summarizes the annual average of $PM_{2.5}$ and the attributable proportion estimated by AirQ + from similar studies conducted in other cities of the world to compare the results obtained for MATV and the State of Mexico City.

Table 3
Comparison of the mortality proportion of MATV with other cities in the world.

	MATV 2019	Mexico City 2019	Keran, Iran 2017 (Malakootian and Mohammadi, 2020)	Mukono, Uganda 2020 (Mukooza and Kizza-Nkambwe, 2022)	Konya, Turkey 2017 (Filiz, 2023)
Annual Average $PM_{2.5}$ ($\mu g/m^3$)	31.2	22.16	24.05	30.97	48.71
Estimated attributable proportion	11.97% (7.98–15.55)	6.95% (4.59–9.1)	9.29% (6.16–12.12)	11.34% (7.54–14.74)	20.77% (14.09–26.56)

The studies considered for the comparison used AirQ + for the mortality proportion estimations.

The annual $PM_{2.5}$ concentrations of the five compared cities are all above the WHO annual AQG for $PM_{2.5}$ of 5 µg/m3 (WHO, 2021). Ambient concentrations of $PM_{2.5}$ from MATV are similar to Mukono, Uganda, whose main emission sources are vehicles, as well as emissions from paved and unpaved roads (Mukooza and Kizza-Nkambwe, 2022). While in the case of Konya, it is a more urban environment with high traffic density and industrial emissions (Bugdayci and Kunt, 2023), so the mortality proportion is high as it is one of the most polluted cities in the world. Mexico City turned out to be the city with the lowest $PM_{2.5}$ concentrations and the lowest proportion of mortality attributable to $PM_{2.5}$ exposure within the comparison. Mukono, Keran and Konya are also clear examples of cities with unplanned urban growth as well. The WHO recognizes the unplanned growth can lead to detrimental health consequences (WHO, 2010)

3.4 COVID lockdown impact assessment

The analysis of the impact of COVID-19 during complete lockdown (March, 29 to May, 28, 2020) on ACP concentrations is presented in Fig. 4. Kruskal-Wallis test method results showed significant differences between the pre, during and post lockdown periods, since all p-values were lower than 0.05.

Except for O_3, the rest of ACP medians concentrations were reduced during the complete lockdown period in 2020 regarding the four year reference on the same days and months. The reductions were 43% for SO_2, 25% for CO, 23% for PM_{10}, 16% for $PM_{2.5}$ and 14% for NO_2. In the case of O_3, the median of the 8h averages during the complete lockdown grew 17% respect to the four-year reference, with a significant difference value ($p < 0.05$). The considerable reduction of SO_2 can be attributed to the reduced traffic circulation of diesel vehicles such busses and trucks, as well as the reduced industrial activity and respective fuel oil consumptions. PM_{10} detriment is related to reductions in industrial activity and $PM_{2.5}$ reduction to lower mobile and industrial emissions, although $PM_{2.5}$ secondary formation continued. NO_2 and CO reductions are mainly related to lower mobile emissions. Since O_3 is a secondary pollutant, the increased median of O_3 could be explain by a NOx-sensitive regime (higher ratio of VOC/NOx), where the reduction of NOx emissions will lead to an increase in ozone concentrations (Fu et al., 2020) and despite of the confinement, the VOC area sources emissions continued. By 2021, all the ACP median concentrations grew respect to the 2020 complete lockdown, but in comparison to the four year reference period, $PM_{2.5}$, NO_2, CO and SO_2 the medians were still bellow as evidence that economic activity was still diminished, mainly due to many inhabitants remained doing home-office. PM_{10} grew considerably due to agriculture related emissions.

These results are consistent with the general trend found by Adam, Tran, and Balasubramanian (2021), who reviewed more than 30 studies conducted in different cities around the world that analyzed changes in air pollution as a result of the COVID-19 lockdown. The highest percentages of air pollutant reductions were observed in cities with known problems of urban organization in developing countries, while in cities of developed countries the average percentage reduction was lower, it was also evidenced that and ozone concentrations grew in some cities despite the COVID-19 confinement due to VOC/NOx ratio variations.

4. Conclusions

The air quality of MATV has been diminished mainly by PM; in the case of $PM_{2.5}$, the WHO 24h $PM_{2.5}$ AQG is exceeded almost the entire year at all monitoring stations coverage areas, which represents a risk for the health of the population, especially in the northern part of MATV, due to the prevailing wind direction from SE to NW dragging mobile and industrial emissions. A mayor proportion of high concentrations of PM and O_3 occur during the dry-hot season due to emissions from agriculture and the formation of secondary pollutants in relation to the higher solar radiation from the season. Mobile, industrial and biomass burning sources are also important. PM composition studies from recent samples are necessary to perform source identification and apportionment analysis. The ten-year comparative analysis between MATV and MCMA showed that MATV has higher levels of ACP and lower reduction percentages than MCMA, due in part to the application of environmental policies taken by Mexico City government and not yet in MATV, such as massive transportation systems and environmental audit programs for vehicles and industries, but also the emissions from rural activities in MATV is an important factor to be consider. The air pollution export from MCMA to MATV and vice versa was also evidenced. The $PM_{2.5}$ associated mortality estimations by AirQ + in MATV during 2018 and 2019, were 11.55% and 11.97%, respectively, while in Mexico City, 6.95% in 2019, since the ambient $PM_{2.5}$ concentrations in Mexico City are 30% lower than those of MATV. The analysis of the impact of the COVID-19 lockdown showed that the reduction in mobility and economic activities improved the air quality even to meet WHO AQG, except for $PM_{2.5}$ and NO_2. The results of the present study highlight the severity of the air quality problem in MATV, the consequent risk to the population and the urgent need for the government to take more stringent actions and develop urban solutions, such as the creation of massive transportation systems and improvements in traffic efficiency and industrial environmental monitoring. The MATV case study provides context for understanding the social and environmental problems associated with unplanned urban growth that is occurring in many cities around the world in developing countries. The continuous and standardized monitoring of air pollutants is an important tool to generate evidence through the data necessary to evaluate the exposure of the population to air pollution, as well as to evaluate the efficiency of the application of environmental policies.

Declarations

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Availability of data and materials. The datasets used and/or analyzed during the current discussion are available and from the corresponding author upon reasonable request.

Ethics approval and consent to participate. Not applicable

Consent for publication. Not applicable

Competing Interests. The authors declare that they have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

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Figures

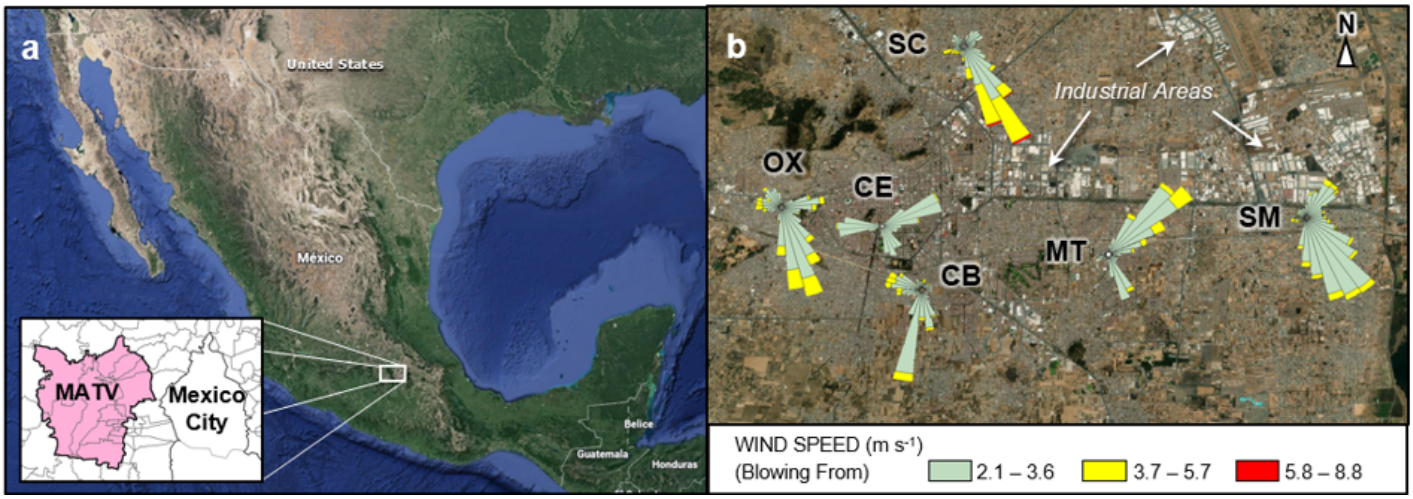


Figure 1

a. Metropolitan Area of Toluca Valley location. (Satellite map from Google Earth®)

b. Monitoring stations location and 2021 wind rose plots (Satellite map from Google Earth®)

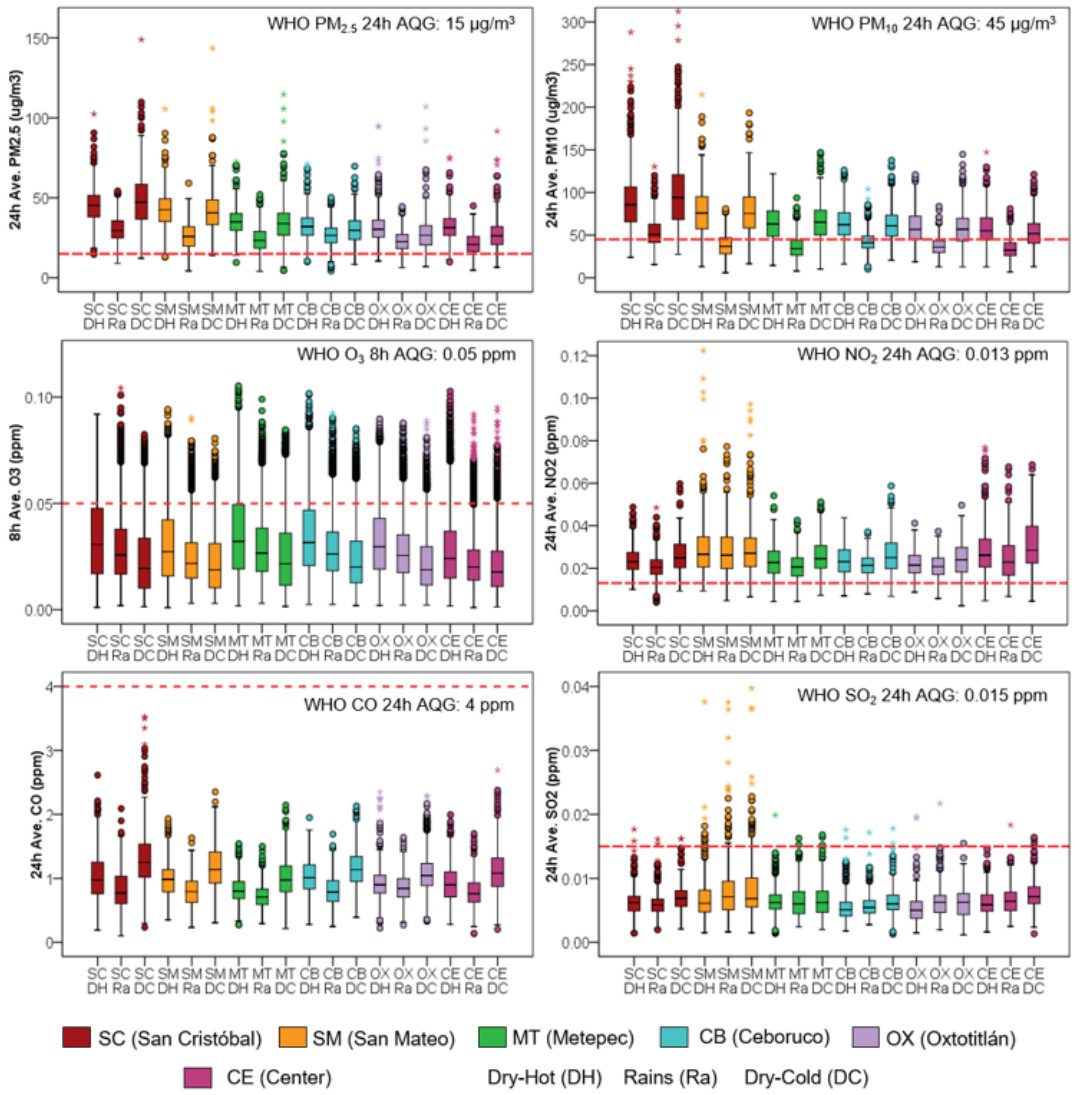


Figure 2

Analysis of spatial and temporal distribution of the six air criteria pollutants in MATV from the 2011-2021 data bases and comparison with the 2021WHO AQG.

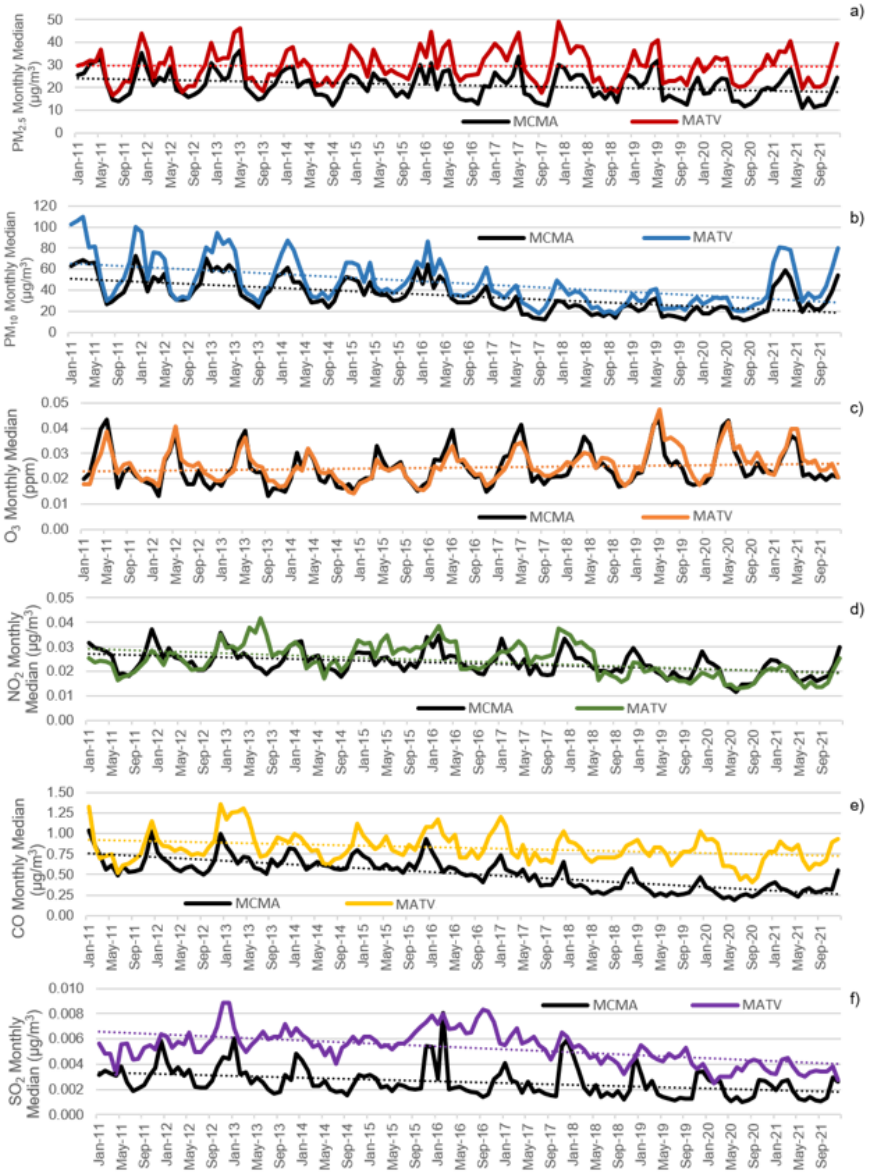


Figure 3

Time series of the monthly medians of the ACP from Jan 2011 to Dec 2021 of the MATV and MCMA

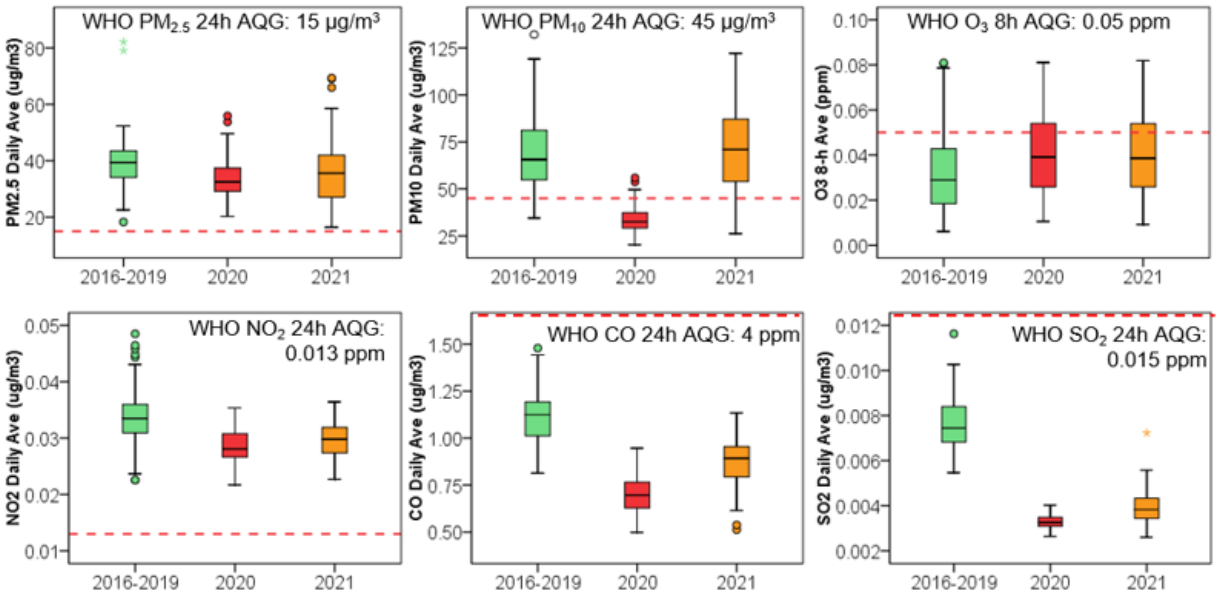


Figure 4

Comparison of daily averages of the MATV ACP concentrations during the complete lockdown period (red boxes) from March 23rd to May 28th, 2020 in comparison to a four-year reference (2016-2019) of data during the same days (green boxes) and after the complete lockdown "new normality" (orange boxes) during the same days in 2021.