Cleiseano Emanuel da Silva Paniagua
(Organizador)

MEIO AMBIENTE

E DESENVOLVIMENTO SUSTENTÁVEL:

DESAFIOS E SOLUÇÕES

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Meio ambiente e desenvolvimento sustentável: desafios e soluções

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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: *Introduction:* Unplanned urban growth is occurring in many cities in developing countries and is associated with social and environmental problems. The Metropolitan Area of Toluca Valley (MATV) began its disorganized expansion since the 1960s, and according to the IQAir platform, it has been the city with the worst air quality in Mexico, in terms of $PM_{2.5}$, since 2019. *Materials and methods:* Ten-year (2011-2021) monitoring databases of air criteria pollutants (ACP) from six MATV monitoring stations were processed to establish spatiotemporal variations and to estimate the mortality proportion attributable to $PM_{2.5}$ exposure using AirQ+ software. The evolution of ACP concentrations and the $PM_{2.5}$ mortality proportion between the MATV and Mexico City were compared. The COVID-19 lockdown impact on ACP was also assessed. *Results:* $PM_{2.5}$ 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 public health. The estimated mortality proportion 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. The COVID-19 lockdown in 2020 caused a reduction of all ACP concentrations except for O_3. *Conclusions:* MATV case study provides a reference scenario of the impact of unplanned urban growth on public health and the need for the government to develop solutions to improve urban mobility and environmental surveillance.
KEYWORDS: ACP, Health impact, COVID-19, Unplanned urban growth

LA CONTAMINACIÓN DEL AIRE EN CIUDADES CON CRECIMIENTO URBANO NO PLANIFICADO, ESTUDIO DE CASO DEL VALLE DE TOLUCA: TENDENCIAS E IMPACTOS A LA SALUD COMPARADOS CON LA CIUDAD DE MÉXICO

RESUMEN: *Introducción:* El crecimiento urbano no planificado está ocurriendo en muchas ciudades de los países en desarrollo y está asociado con problemas sociales y ambientales. La Zona Metropolitana del Valle de Toluca (ZMVT) comenzó su expansión desorganizada desde la década de los 60s, y de acuerdo con la plataforma IQAir, ha sido la ciudad con peor calidad del aire en México, en términos de $PM_{2.5}$, desde 2019. Materiales y métodos: Se procesaron las bases de datos de monitoreo de diez años (2011-2021) de contaminantes de criterio del aire (CCA) de seis estaciones de monitoreo de la ZMVT para establecer las variaciones espaciotemporales y estimar la proporción de mortalidad atribuible a la exposición a $PM_{2.5}$ utilizando el software AirQ+. Se comparó la evolución de las concentraciones de CCA y la proporción de mortalidad asociada a la exposición a $PM_{2.5}$ entre la ZMVT y la Ciudad de México. También se evaluó el impacto del confinamiento sanitario por COVID-19 en los CCA. *Resultados:* Las $PM_{2.5}$ y PM_{10} son los principales CCA que empeoran la calidad del aire en la ZMVT y superan las Guías de Calidad del Aire (GCA) de la OMS casi todo el año, poniendo en riesgo la salud pública. La proporción de mortalidad estimada asociada a la exposición a $PM_{2.5}$ en 2019 para la ZMVT fue de 11.97% (7.98-15.55) y para la Ciudad de México de 6.95% (4.59-9.1). La ZMVT presentó mayores concentraciones de CCA y menores porcentajes de reducción que el Área Metropolitana de la Ciudad de México en el periodo de diez años. Los patrones de PM y O_3 son muy similares entre ciudades, lo que sugiere que la contaminación del aire es compartida. El confinamiento por COVID-19 en 2020 provocó una reducción de todas las concentraciones de CCA excepto de O_3. *Conclusiones:* El estudio de caso de la ZMVT proporciona un escenario de referencia del impacto del crecimiento urbano no planificado en la salud pública y la necesidad de que el gobierno desarrolle soluciones para mejorar la movilidad urbana y la vigilancia ambiental.
PALABRAS-CLAVE: Contaminantes Criterio, Impacto a la salud, COVID-19, Crecimiento urbano no planificado

INTRODUCTION

The pollutants of major public health concern include particulate matter, carbon monoxide, ozone, nitrogen dioxide and sulfur dioxide are known as air criteria pollutants. The combined effects of ambient and household air pollution are associated with 6.7 million premature deaths annually [1]. 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 [2]. Air pollution is also linked to climate change [3] as well as negative impacts on global economy [4].

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 [5]. 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 [6]. 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 16 municipalities [7]. Both cities have experienced rapid urban expansion, diffuse and fragmented growth, and a conurbation with small and medium-sized peripheral settlements [8]. 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 and the consequent related environmental problems [9]. MATV has currently become the city with the highest $PM_{2.5}$ concentrations in Mexico since 2019 [10].

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 [7]. According with the last 2020 census, MATV has a population of 2,353,924 inhabitants [11]. 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, at this altitude, the atmospheric oxygen concentration is lower with respect to sea level, causing a less efficient combustion [12]; in addition, MATV is partially surrounded by mountains affecting the air pollutants dispersion and increasing thermal inversions occurrence and high pressure systems [13].

Since 1960, Toluca Valley has had an industrialization process promoted by the government offering to entrepreneurs land, low-cost energy and water supplies with virtually no environmental regulations, this resulted in the establishment of several industrial enterprises, the consequent increase in traffic density, as well as labor immigration [14]. MATV transformed from a rural town to a city that grew around industrial areas to house immigrant labor from other states looking for work. Currently, there are more than 1,000 manufacturing economic units registered [13] and 1,136,489 registered motor vehicles in circulation [15] with a rate of 483 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 [16].

There are relatively few research publications analyzing the MATV air pollution phenomena. Even so, serious health risks have been evidenced, such as the presence of bioaerosols (pollen, spores, microorganisms, fragments and diatoms) with aerodynamic sizes of 0.3 μm to 45 μm [17]. Significant enrichment concentrations of Pb, Zn, Cu and Cr have been found accumulated in mosses biomonitors [18]. High concentrations of heavy metals in rainwater samples in the Northern zone of Toluca Valley have been reported as well [19]. 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 [20, 21, 22].

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, for this purpose, ten years (2011-2021) of ACP monitoring data were analyzed to describe 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 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.

MATERIALS AND METHODS

Data

Air criteria pollutant monitoring data from the six sites selected 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 as shown in Fig. 1b, in order to analyze the spatial distribution of ACP. The codes, names and location of the six sites analyzed are summarized in Table 1.

MCMA ACP monitoring data bases from 2011-2021 were obtained from Mexico City Air Monitoring Network website [23] 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 [15]. 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 [23].

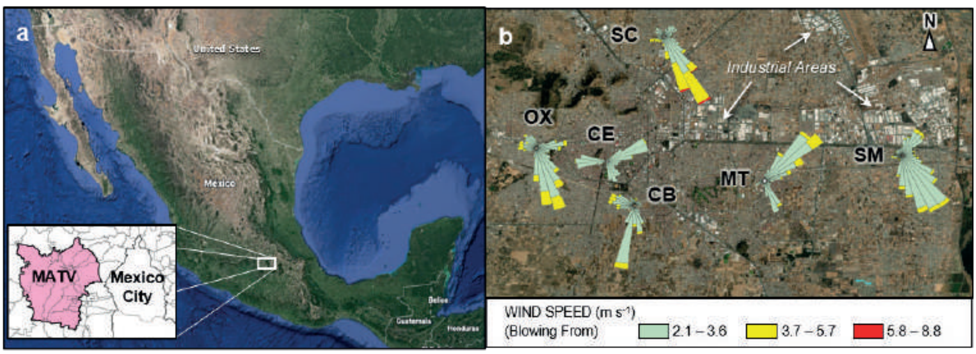

Fig. 1. a) Metropolitan Area of Toluca Valley location. (Satellite map from Google Earth®). b) Monitoring stations location and 2021 wind rose plots (Satellite map from Google Earth®)

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

Table 1. Monitoring stations selected

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 the three weather seasons observed in TVMA: Dry-hot (DH) season from March to May, Rainy (Ra) season, from June to October and Dry-cold (DC) season, from November to February [13]. 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 [24].

MATV and MCMA ACP trends 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 in the monthly medians between cities was evaluated using the Mann-Whitney U test.

$PM_{2.5}$ 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 [25]. AirQ+ has been used in several countries to make impact estimates [26, 27, 28]. 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 [27, 29]. AirQ+ quantifies the impact of PM exposure using an attributable proportion (AP) function, defined in Eq. 1.

$$AP = \frac{\sum(RR - 1) \; X \; P}{\sum RR \; X \; P} \qquad \text{Eq 1)}$$

AP corresponds to the fraction of the health endpoint in a defined population attributable to the 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 [30]. RR is the relative risk for the health endpoint in a determined exposure to the air pollutant and P is the fraction of the population under exposure.

An annual analysis was carried out from 2018 to 2019 to avoid the mortality rates of COVID-19 pandemic that began in Mexico 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 to compare 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 [25].

COVID lockdown impact assessment

To analyze the impact of the COVID-19 pandemic lockdown on the ACP emissions in MATV, 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 changes in the ACP emissions during 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 period was evaluated by Kruskal-Wallis test.

RESULTS AND DISCUSSION

Seasonal and spatial distribution analysis

From the 2021 meteorology data base, Wind Rose diagrams were plotted for each monitoring station by using the WRPLOT software and are presented in Fig. 1b. MATV wind speed is influence by air turbulence and surface roughness [31]. At the MATV periphery stations (SC, SM and OX) the wind blows mainly from the Southeast and the wind speed is less than 5.7 m s-1, which is consistent with the findings of Ortiz, Jiménez and Díaz (2021) [32]. 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 p-values (<0.05) of the Kruskal-Wallis test of the differences between sites and seasons, indicates 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 [33], another factor related is the weather conditions of this season, as the high pressure systems causes' air pollutants accumulation and high solar radiation favors aerosol secondary formation [34]. 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 (Fig 2a).

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 and coal burning for home heating during cold winter, similar conditions has been studied in London reporting high concentrations of PM_{10} [35]. SC and SM have the highest PM_{10} concentrations, these sites receipt emissions from industry and wind erosion [19]. With respect to WHO 24h PM_{10} AQG, most of the sites fit partially the AQG during the rainy season, but exceed the limit the rest of the year (Fig 2b).

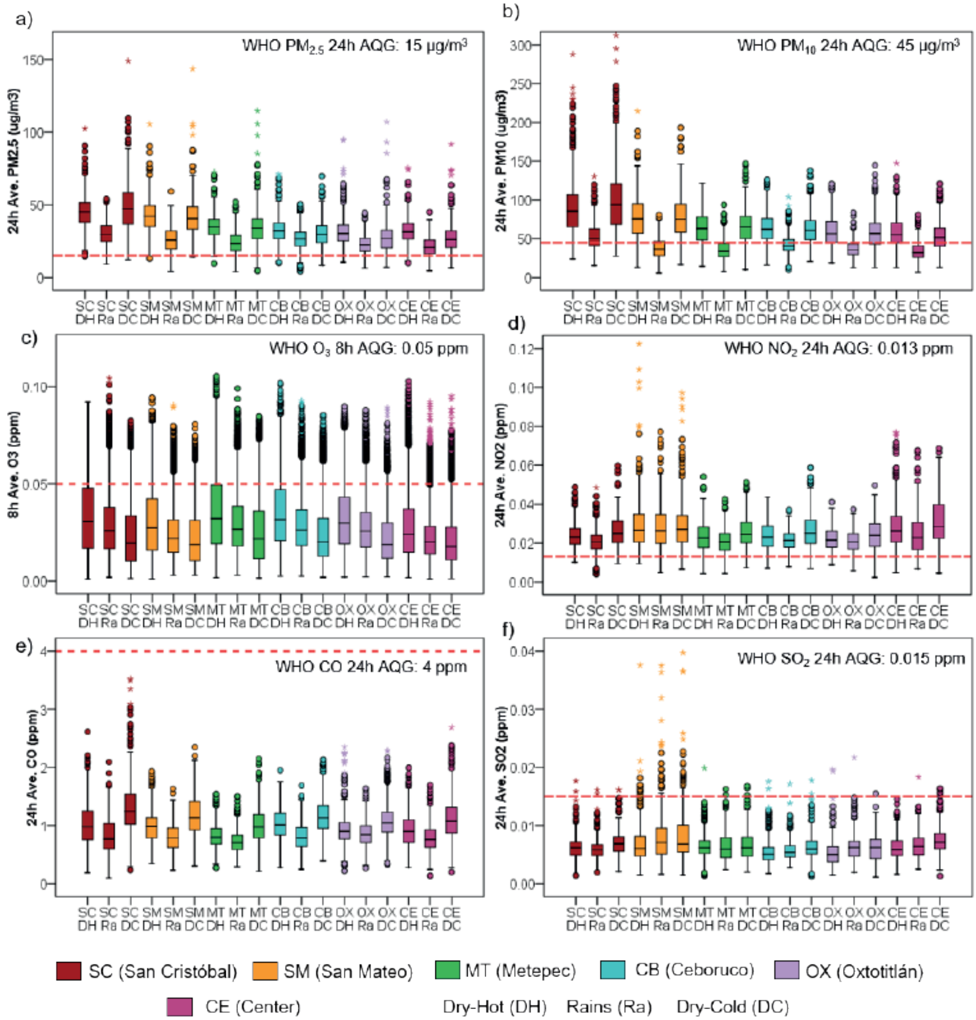

Fig. 2. Analysis of spatial and temporal distribution of the six air criteria pollutants in MATV from the 2011-2021 data bases and comparison with the 2021WHO AQG.

As for the O_3 values distribution, 75% of the 8-hour means are below the WHO O_3 AQG (Fig 2c). 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 of 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 [36].

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 vehicular traffic, an important source of NO_2 [37]. Regarding WHO NO_2 AQG, all the sites are above the limits during the entire year (Fig 2d).

CO values at all the sites and during the whole year are clearly below WHO CO AQG (Fig 2e). The DC season is the period with the highest values due to the thermal inversions during this 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 [38] but also CO is emitted by biomass burning [39] 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 [40]. Diesel combustion in heavy-duty vehicles, such as busses and trucks, are also a significant source of SO_2 [41] and these three monitoring stations are near of heavy traffic roads. SO_2 24-h average concentrations are below WHO SO_2 AQG (Fig 2f).

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

MATV and MCMA ACP trends comparison

The results of the comparison of the 10-year evolution of the monthly medians of MATV regarding MCMA for the six ACP are represented 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.

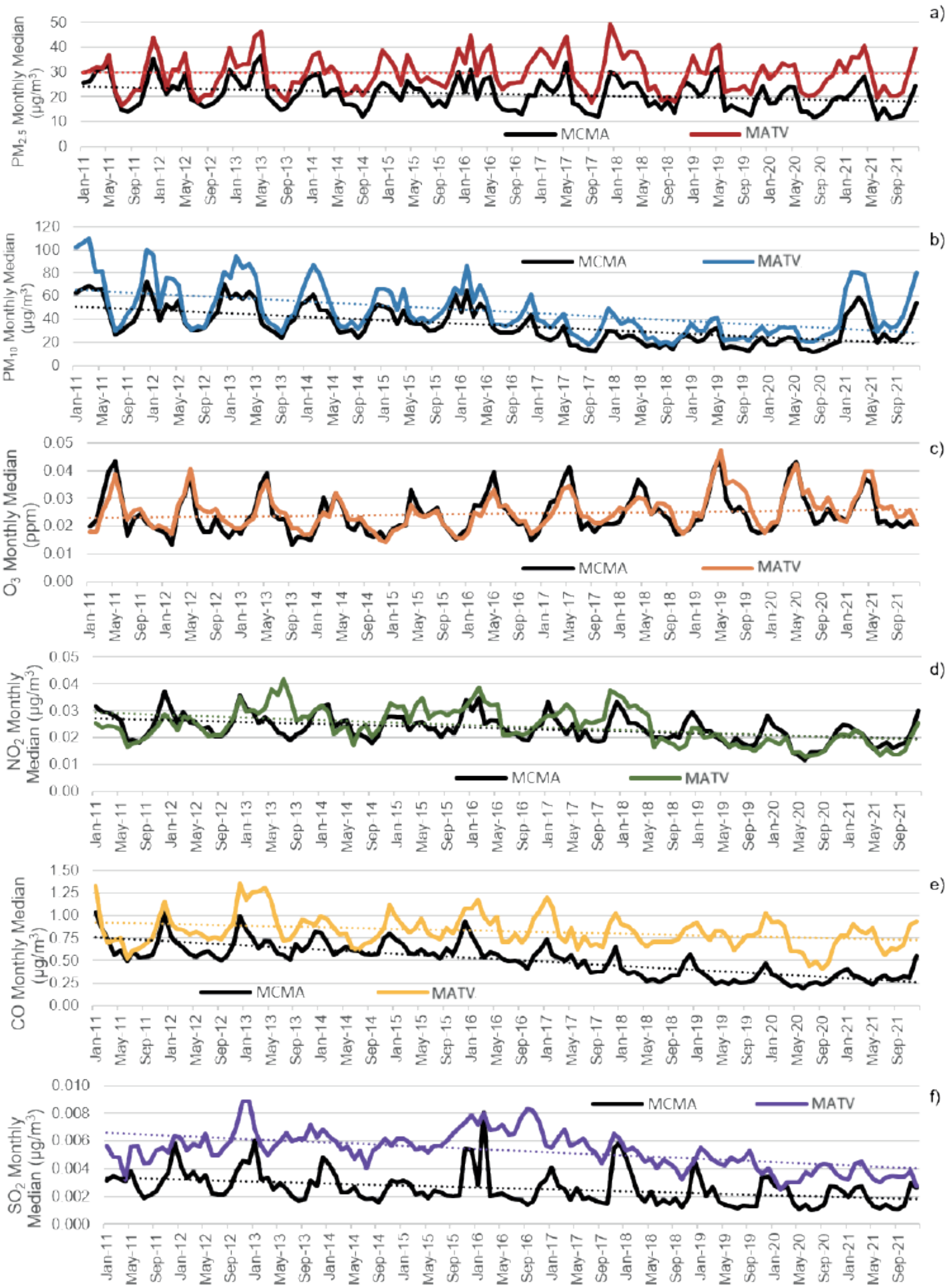

Fig. 3. Time series of the monthly medians of the ACP from Jan 2011 to Dec 2021 of the MATV and MCMA. Dashed lines represent the trend for each time series.

$PM_{2.5}$, PM_{10} and O_3 showed similar tendencies among cities Fig. 3, this can be associated to the exportation of air pollution between cities but mostly from MCMA to MATV, Hernández-Moreno et al., (2023) demonstrated that the MCMA exports a large quantities of $PM_{2.5}$ to the surrounding metropolitan areas, even at a degree of equivalence of 100% of its local emissions [42].The MATV tendency of $PM_{2.5}$ has remained relatively constant along the 10 year period, 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. 4f).

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, weekly driving restriction strategies and improvements in public transportation infrastructure [43]. Currently, MATV does not have a mass transportation system, neither 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.

$PM_{2.5}$ 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.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 $PM_{2.5}$. Compared to previous years (2015-2017), the estimated attributable proportion is lower as $PM_{2.5}$ concentrations also decreased [44]. 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 [45]. 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 [46].

INPUT DATA	MATV*		Mexico City** 2019
	2018	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 2019**
	2018	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.

Table 2. AirQ+ input data and model results

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 population of the State of Mexico City is six times greater than that of the four MATV municipalities considered, hence the number of natural deaths associated to $PM_{2.5}$ exposure is estimated in proportion to the amount of exposed population. In contrast, in terms of the estimated mortality proportion values, Mexico City has about half of the value of MATV, owing to the 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 mortality 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. The studies considered for the comparison used AirQ+ for the mortality proportion estimations.

	MATV 2019	Mexico City 2019	Keran, Iran 2017 [47]	Mukono, Uganda 2020 [48]	Konya, Turkey 2017 [49]
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)

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

The annual $PM_{2.5}$ concentrations of the five compared cities are all far above the WHO annual AQG for $PM_{2.5}$ of 5 $\mu g/m^3$ [50]. 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 [48]. While in the case of Konya, it is a more urban environment with high traffic density and industrial emissions [49], the mortality proportion is quite 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 in cities as a challenge for public health since urbanization is one of the major threats to health in the twenty-first century [51].

COVID-19 lockdown impact assessment

The analysis of the impact of the COVID-19 total confinement that occurred in MATV from March 29 to May 28, 2020 on the concentrations of the ACP is presented in Fig. 6. Kruskal-Wallis test results showed significant differences between the pre, during and post lockdown periods, ($p < 0.05$).

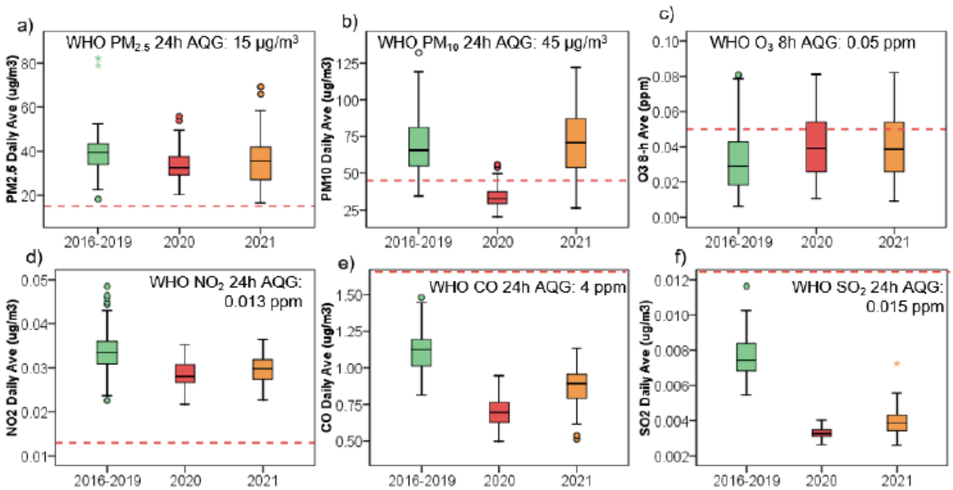

Fig. 4. Comparison of daily averages of the MATV ACP concentrations during the complete lockdown period (red boxes) from March 23rd to May 28th, 2020, in comparison to a four-year reference (2016-2019) of data during the same days (green boxes) and after the complete lockdown "new normality" (orange boxes) during the same days in 2021.

As shown in Fig 6, 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, as shown in Fig. 6c. 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 (Fig. 4f). PM_{10} detriment is related to reductions in industrial activity (Fig. 4b). $PM_{2.5}$ reduction can be associated to lower mobile and industrial emissions, although $PM_{2.5}$ secondary formation continued (Fig. 4a). NO_2 and CO reductions are mainly related to lower mobile emissions (Fig. 4d and 4e).

Since O_3 is a secondary pollutant, the increase in O_3 median 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 [52]. On this matter, in MATV the NO_2 concentrations were reduced and, despite of the confinement, the VOC emissions continued, since domestic activities such as cooking and water heating continued as well as the industries considered priority continued to operate, both factors would explain the increase in O_3 concentrations during the lockdown period. By 2021, all the ACP median concentrations grew respect to the 2020 complete lockdown period, 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 [53]. They found 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.

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 surveillance. The MATV case study provides context for understanding the 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.

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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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ETHICAL CONSIDERATIONS

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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