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A Spatio-Temporal Behavior of $PM_{2.5}$ and PM_{10} on Changes of Their Concentration Levels in the Metropolitan Area of Lima

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ABSTRACT

This work aimed to analyze the temporal behavior of the concentration profiles of $PM_{2.5}$ (period 2014-2023) and PM_{10} (period 2010-2023) collected in five districts of the metropolitan area of Lima (MAL). The year 2016 and 2021 showed the highest annual averages for $PM_{2.5}$ while PM_{10} reported higher concentrations in 2013, 2016, and 2021 for most stations. For $PM_{2.5}$ higher peaks were recorded between May and September and lower peaks between January and March. For PM_{10}, higher peaks were found in March-May and August-October, and lower peaks were observed between January and June. Daily minimum and maximum values of $PM_{2.5}$ ranged between 3.74 and 148 $\mu g/m^3$, while PM_{10} ranged from 7.16 to 579 $\mu g/m^3$, respectively. For hourly variations were observed peaks that occur between 6:00 and 10:00 a.m. and between 6:00 p.m. and 11:00 p.m. for both PMs. The information obtained will help to identify episodes of air pollution, pollution sources, monitor climate change, and can be used to alert communities and take immediate action.

1. INTRODUCTION

Air pollution by particulate matter (PM) is a current problem in worldwide. PM is a complex mixture of solids and aerosols containing metals and metalloids, carbonaceous species (elemental carbon and organic carbon), and ionic species [1]. The PM is classified according to their aerodynamic diameter in coarse or "inhalable" particles (PM_{10}, ≤ 10 µm (microns) in diameter) and fine or "respirable" particles ($PM_{2.5}$, ≤ 2.5 µm (microns) in diameter) [2]. PM10 and $PM_{2.5}$ are widely monitored because their short or large exposure time can have adverse health impacts and environmental effects (visibility impairment, environmental damage, and materials damage) [3]. Exposure to PM_{10} particles can lead to reduced lung function, increased hospitalization and emergency visits, reduced life expectancy, and worsening of asthma and other respiratory diseases, among others [4]. Exposure to $PM_{2.5}$ is more dangerous due to its ability to penetrate directly into the bloodstream, causing a decrease in lung function, exacerbated asthma, intensification of symptoms of diseases related to the circulatory, cardiovascular, and respiratory systems, and even promotes cancer (lung, throat and laryngeal) [5]. For instance, Vu et al. [6] reported 103,974 cases of asthma during 2010-2016 across 39 districts in Lima associated with exposure to $PM_{2.5}$.

The World Health Organization (WHO) reported that 99% of the world population still breathes air that exceeds air quality limits based on particulate matter, putting its health at risk [7]. Besides, a 2022 update of the WHO´s ambient air quality database (PM_{10} and $PM_{2.5}$) revealed that more than 6000 cities in 117 countries, all showing unhealthy levels of fine particles [8]. WHO established air quality limits that $PM_{2.5}$ should not exceed 5 $\mu g/m^3$ annual mean, or 15 $\mu g/m^3$ 24-hour mean, while PM_{10} should not exceed 15 $\mu g/m_3$ annual mean, or 45 µg/m3 24-hour mean [9]. Likewise, the Peruvian air quality standards (ECA), state maximum values for PM_{10} and $PM_{2.5}$ of 25 $\mu g/m^3$ and 50 $\mu g/m^3$ annual mean [10]. The worst air pollution generated by PM is usually reported in big cities, which originates mainly from anthropogenic activities related to fossil fuel combustion that are used by the vehicular fleet [11]. Besides, in urban areas, sources of PM are usually related to emissions from residential biomass combustion, road transport, vehicle traffic, industrial activities, and fossil fuel combustion [12].

In Peru, MAL is the largest metropolitan area of this country, the fourth largest in Latin America, and it is positioned among the thirty largest in the world. Besides, it is home to the largest population (around 11.3 million inhabitants for 2024), showing an increase of 1.41% related to 2023. Besides, the MAL faces significant challenges related to air pollution, particularly concerning to particulate matter ($PM_{2.5}$ and PM_{10}) such as traffic congestion (large number of vehicles, many of which are older models), industrial activities (many parts of lima are close to industrial areas such as manufacturing, construction, and other), topography (Lima is situated in a coastal desert region with surrounding mountains, thus its topography can trap pollutants, preventing their dispersion and leading to higher concentrations of PM) and climate (the area's relatively dry climate and limited rainfall), informal sector and dust sources (unregulated urban development, construction dust), burning of waste, lack of effective public policies (regulatory gaps, monitoring challenges), and public health impacts.

Likewise, the Urban Transport Authority of Lima and Callao (ATU) revealed that the vehicular fleet is responsible for 58% of air pollution in the MAL [13]. The presence of PM in the MAL may also be related to the construction of Metro Lima, that started in 2014 and was planned to finish in 2019, however, the slow advance and problems between the Peruvian state and the concessionaire and the traffic chaos originated by the enclosures of avenues are the main reason for the delays so far [14]. These challenges are interrelated and require a coordinated approach to effectively address the issue of particulate matter pollution in Lima.

Several studies have reported levels of PM_{10} and $PM_{2.5}$ in different cities around the world [15-17]. The metropolitan area of Lima is not the exception [18, 19]. Likewise, exposure to PM (PM_{10} and $PM_{2.5}$) and other toxic elements were reported previously in the different districts of the MAL [20-22].

Thus, this work aimed to analyze the temporal behavior of the concentration profiles of the annual, monthly, daily, and hourly average values of $PM_{2.5}$ and PM_{10} as well as the variabilities in the metropolitan area of Lima (MAL). This was done by using data provided by the SENAMHI of $PM_{2.5}$ (period 2014-2023) and PM_{10} (period 2010-2023) from five monitoring stations installed around the MAL. This information obtained will serve to make important social decisions.

2. MATERIALS AND METHODS

2.1 Study area

The metropolitan area of Lima (AML) or Metropolitan Lima (12º00'49" S and 76º51'18" W) is made up of a total of 50 districts belonging to the Province of Lima and the Constitutional Province of Callao. It is the largest, most extensive, and most populated urban area in Peru and one of the five largest megacities in Latin America, with a territorial extension of 2683 km^2 and an estimated population of 11.3 million inhabitants (population density of Lima 3620 inhabitants/km^2 and Callao 8050 inhabitants/km^2) in 2023 [23]. According to the environmental quality bulletin of the Urban Transport Authority (ATU), the AML owns 68.6% (more than 2 million vehicles) of the light and heavy vehicle fleet in Peru [24], which run mainly on petroleum, its derivatives and natural gas liquids such as diesel (about 46% of total liquid fuel consumption), LPG (24%) and gasoline/diesel (20%) [25]. Fixed sources of air pollution in AML include chemical, metallurgical, steel, textile, non-metallic mining, and paper and printing industries. The climate of the AML is subtropical, with an average annual temperature of 19°C, relative humidity of 80% and with approximate rainfall of 10 mm per year, and cloudy skies almost all year.

2.2 PM_{10} and $PM_{2.5}$ air quality data

The AML has a network of real-time air quality monitoring stations installed in 10 districts: Ate Vitarte (ATE), Huachipa (HUA), San Juan de Lurigancho (SJL), Santa Anita (STA), Puente Piedra (PP), San Borja (SBJ), Campo de Marte (CM), Carabayllo (CRB), Villa María del Triunfo (VMT), and San Martin de Porres (SMP) which are in charge of the National Meteorology and Hydrology Service (SEHAMHI). These stations are installed in urban environments and report the concentrations of PM_{10}, $PM_{2.5}$, O_3, and NO_2 every hour. $PM_{2.5}$ data (period 2014-2023) and PM10 data (2010-2023) from five monitoring stations (SBJ, STA, VMT, SJL, and CRB) were provided by SENAMHI (Figure 1 and Table 1). PM_{10} and $PM_{2.5}$ monitoring equipment were purchased in 2010 and 2014, respectively. Thus, PM_{10} monitoring began in 2010, while $PM_{2.5}$ monitoring began in 2014. The five stations selected in this work were because have sufficient data compared to the other monitoring stations that have a fairly large number of missing data.

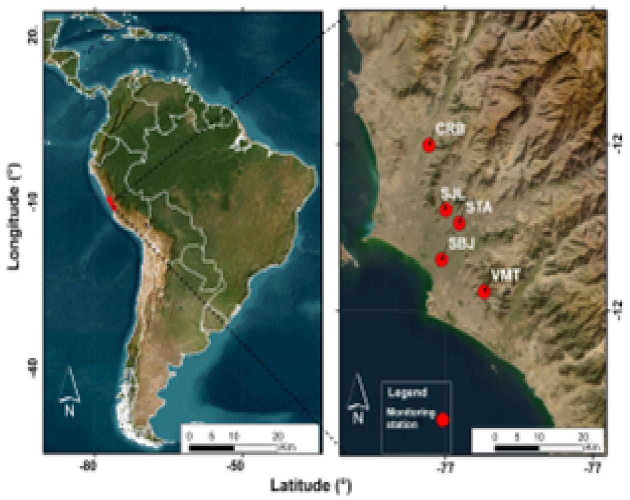

Figure 1. Map of localization of AML and the monitoring stations network

Table 1. Localization of air quality monitoring station from the SENAMHI

Monitoring Station	Latitude and Longitude	Population	Superficial Area (km^2)	Elevation (m.a.s.l.)
San Borja (SBJ)	12º6´31.1''S, 77º0'27.9''W	133328	11.5	128
Carabayllo (CRB)	11º54´7.9''S, 77º2'1.1''W	426895	384.89	179
San Juan de Lurigancho (SJL)	12º1'8.0''S, 76º59'57.4''W	1240489	131.25	240
Santa Anita (STA)	12º2´35.9''S, 76º58'17.0''W	232739	10.69	253
Villa María del Triunfo (VMT)	12º9´59.0''S, 77º55'12.0''	459010	70.57	292

2.3 Statistical analysis

The $PM_{2.5}$ and PM_{10} data provided by SENAMHI were sorted in MS Excel by station and year. After this, all data was entered into the free software CRAN R version 4.2.1 [26]. Trend analyses (hourly, daily, monthly, and yearly) on PM_{10} (2010-2023) and $PM_{2.5}$ (2014-2023) concentrations of each monitoring station and MAL were performed using the openair [27], ggplot2 [28] packages, and TheilSen function of the open air package. The R statistical software provides a wide variety of statistical and graphical techniques, providing facilities for data manipulation, calculation and graphical display. The historical trends on the monitoring stations for PM_{10} and $PM_{2.5}$ were estimated through the TheilSen method [29], which calculates slopes between all pairs of points, and the median of the slopes is selected [30]. This method is the most popular nonparametric technique for estimating a linear trend, with advantages like, most notably its ability to yield accurate confidence intervals, and its resistance to outliers.

3. RESULTS AND DISCUSSIONS

3.1 Annual variation of $PM_{2.5}$ and PM_{10} by monitoring station

The annual average concentrations based on daily data of each monitoring station for $PM_{2.5}$ inside the metropolitan area of Lima are shown in Figure 2. The results show that the daily minimum and maximum values of $PM_{2.5}$ ranged between 3.74 and 148 μg/m^3 at the SJL and CRB stations, respectively. The annual averages of $PM_{2.5}$ throughout the monitoring period were higher in 2016 and 2022. For 2016, higher averages values were observed in SJL (32.6 ± 11.5 μg/m^3) and STA (32.7 ± 10.8 μg/m^3), and in 2022 the higher averages values were observed in SJL (41.2 ± 14.9 μg/m^3) and CRB (38.2 ± 14.6 μg/m^3). The lower averages values were recorded in 2020 with minimums in SBJ (14.9 ± 4.3 μg/m^3) and CRB (18.8 ± 6.3 μg/m^3). Similar to our results, $PM_{2.5}$ concentrations in the city of Tabriz city (Iran) ranged from 25.7 μg/m^3 to 38.6 μg/m^3. This city is characterized by having commercial and trading centers, lack of green space, and high traffic volume, which environment is like the MAL.

Compared to the European Union (EU) quality standards (red line) and Peru´s Environmental Quality standards (ECA) (blue line) for $PM_{2.5}$ (25 μg/m^3), 2016 and 2022 were the years with the highest limit value violations, with 774 and 1262 exceedances respectively. From the stations, the STA station, SJL, and CRB were the ones that registered the highest infractions, the lowest exceedances were recorded in SBJ, with a total of 346 days of infraction in the entire monitoring period, in the same way, the lowest average annular $PM_{2.5}$ were recorded compared to the other stations that ranged from 14 ± 3.3 μg/m^3 (2019) to 26.4 ± 11 μg/m^3 (2021). The station with the highest number of violations during the entire study period was SJL with 1933 days exceeding the limit value, whose averages ranged from 22.5 ± 8.6 μg/m^3 (2023) to 41.2 ± 14.9 μg/m^3 (2022).

In the case of the average annual concentrations based on daily data of each PM_{10} monitoring station (Figure 3). The SBJ station showed the lowest daily average PM_{10} values for most years (except 2020 to 2023), varying from 7.16 to 177 μg/m^3, while the VMT station showed the highest PM_{10} values varying from 14.7 to 579 μg/m^3 for most years (except 2019, 2022, and 2023). The highest average annual peak of PM_{10} was found in 2015 (138 ± 59.0 μg/m^3) at the VMT station, while the lowest average annual was reported in 2023 (34.3 ± 10.4 μg/m^3) at the STA monitoring station. In addition, it is observed that in the years 2020 and 2021, there is a reduction in the concentration of PM_{10} compared to previous years. This reduction is likely related to the COVID-19 pandemic, which is based on several scientific articles [31-33].

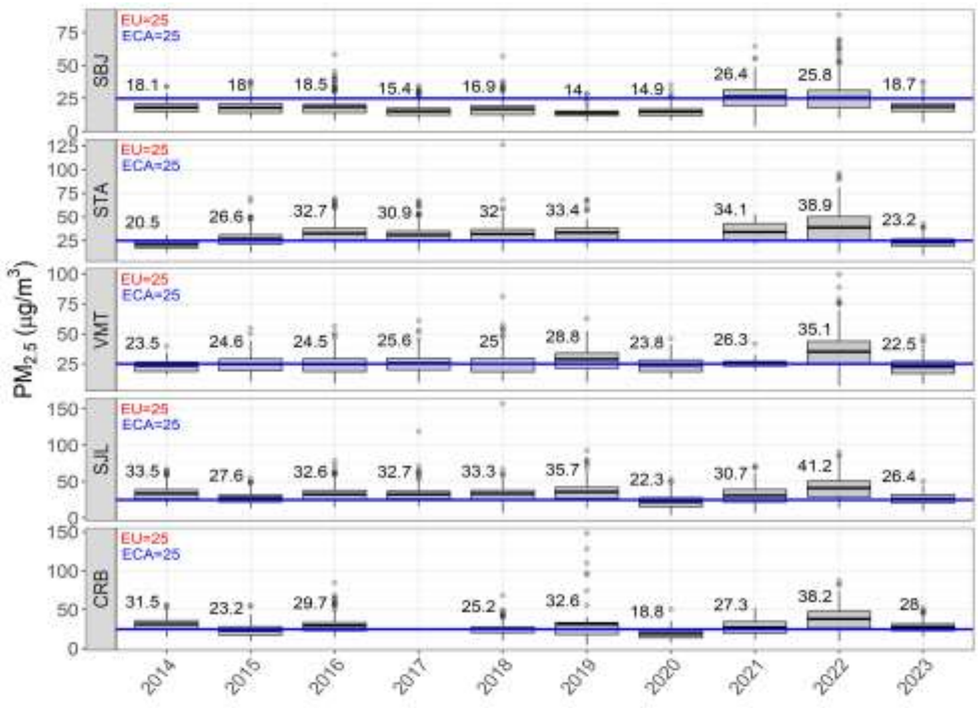

Figure 2. Annual average and distributions of $PM_{2.5}$ based on daily data per monitoring station in the metropolitan area of Lima during the period 2014-2023. Redline = EU limit value (25 μg/m^3), Blue line = ECA limit (25 μg/m^3)

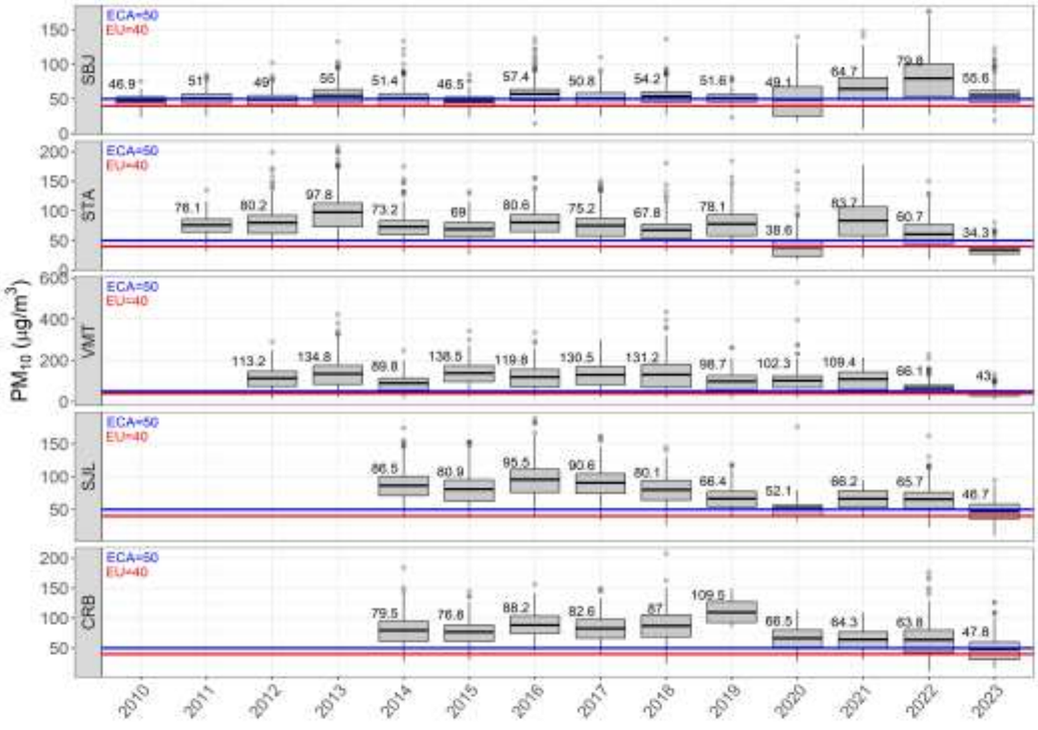

Figure 3. Annual average and distributions of PM_{10} per monitoring station in the metropolitan area of Lima during the period 2010-2023. Redline = EU limit value (40 µg/m^3), blue line = ECA limit value (50 µg/m^3)

The annual average of PM_{10} for each monitoring station considering all years has the following order: VMT (106 ± 28 µg/m^3) > CRB (76.7 ± 16.3 µg/m^3) > SJL (73.1 ± 15.4 µg/m^3) > STA (70.4 ± 17.0 µg/m^3) > SBJ (54.5 ± 8.4 µg/m^3). In this case, VMT is home to the cement industry, which probably influences the presence of particulate matter [34]. Likewise, the Environmental Assessment and Control Agency (OEFA) reported fifty critical points of accumulation of solid waste distributed in different areas of the district. In contrast, the lowest PM_{10} concentrations found in SBJ may be attributed to that the Municipality of San Borja in 2017, ratified its participation in the Global Covenant of Mayors for Climate and Energy, committing to implement policies and take measures to reduce greenhouse gas emissions and particulate matter [35]. Rainfall is an important factor for reducing air pollution [36]. Lima is characterized by its arid and mild conditions, which are primarily influenced by its subtropical desert climate, geographical location, topography, and the presence of the cold Humboldt Current (HC) off the coast. Its subtropical desert climate results in low precipitation levels and high levels of sunshine throughout the year. The HC brings cold waters and cool air to the region, which contributes to keeping mild temperatures and low moisture content in the air, leading to arid conditions. Likewise, Lima is located in a region situated between the Pacific Ocean and the Andes Mountains where subtropical high-pressure systems dominate, which leads to stable atmospheric conditions, inhibiting cloud formation and precipitation. Thus, as rainfall is extremely rare in Lima, the pollution of particulate matter is possibly not reduced compared to other regions that have the presence of precipitation.

Compared to the annual limit value of the EU (40 µg/m^3), 2017 and 2022 were the years with the highest violations of the limit value, with 1335 and 1253 exceedances respectively, with the VMT stations (309) and CRB (304) registering the highest violations in 2017, for 2022 they were SBJ (281) and SJL (281). The lowest exceedances in PM_{10} were recorded in SBJ, where the lowest mean annual ranged from 46.5 ± 10.9 µg/m^3 (2015) to 79.8 ± 33.2 µg/m^3 (2022). The highest infractions were observed in STA, followed by VMT with 2624 and 2347 days exceeding the European standard during the entire monitoring period. The year with the lowest number of violations was 2010 when only the SBJ station was in operation where 37 violations were registered, in 2011 PM10 monitoring began in STA, 2012 in VMT, and 2014 in SJL and CRB.

3.2 Average annual of $PM_{2.5}$ and PM_{10} for the metropolitan area of Lima

There is a variable trend in the annual average of $PM_{2.5}$ in the metropolitan area of Lima and observed maximum peaks in 2016, 2019, and 2022 and decreases in average values for 2015, 2020, and 2023. In 2022, the highest average value and the highest number of violations of the limit values of the EU and Peruvian ECA per year were recorded (Figure 4). The difference between the average and the annual median of $PM_{2.5}$ was increased from 2014 to 2023, indicating the increase in days with violations of the limit values, 2023 shows decreases.

Similarly, for PM_{10}, there is a variable trend of the annual average with peaks in 2013, 2018, and 2021 and decreases in 2014, 2019, and 2023. In 2010, there were higher average values and violations of the limit values of the EU and the annual Peruvian ECA (Figure 5). Solís et al. [37] reported annual exceedances of the daily WHO guidelines for $PM_{2.5}$ and PM_{10} in 77% and 57%, respectively in Coyhaique city (Patagonia Chile) in the period of 2014-2020. The difference between the average and the annual median of PM_{10} increased from 2014 to 2023, indicating an increase in days with violations of the limit values.

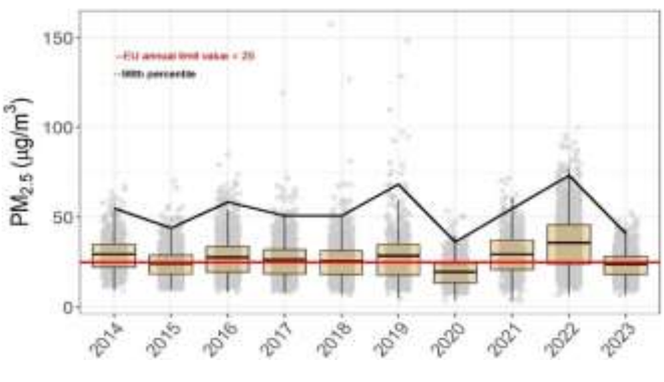

Figure 4. Average annual variation and distribution of $PM_{2.5}$ (2014-2023) inside the metropolitan area of Lima

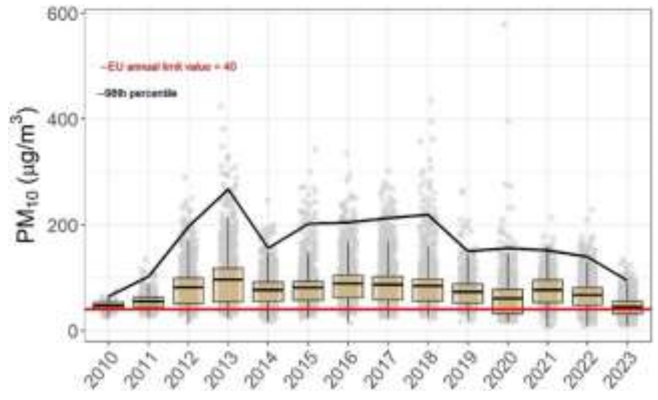

Figure 5. Average annual variation and distribution of PM_{10} (2010-2023) inside the metropolitan area of Lima

Regarding the annual variation of $PM_{2.5}$ and PM_{10} in the metropolitan area of Lima, a variable trend was found in the average values throughout the years of study. In both cases, peaks were recorded in certain years followed by declines in others. The year 2022 stood out for having the highest average value and the highest number of violations of the EU limit values for both particle sizes. In addition, a gradual increase in the difference between the average and the annual median of $PM_{2.5}$ and PM_{10} was observed, suggesting an increase in the number of days with violations of the limit values throughout the period analyzed. For $PM_{2.5}$ the SJL station stood out as the one that registered the highest number of violations during the entire study period, in the case of PM_{10} it was observed that the STA station had the highest number of violations during the entire study period. It should be mentioned that for both particle sizes, SBJ recorded the lowest infractions during the entire study period.

The annual variation of $PM_{2.5}$ and PM_{10} in Lima, Peru, reflects a complex interplay between various variables, including human activities, and meteorological and geographic conditions. Maximum peaks in certain years suggest the influence of temporal factors as the location of AML such as its topography, climate, and its proximity to the Pacific Ocean and because it is surrounded by the Peruvian Andes, which act as barriers that protect it from humid winds [38], e.g., the years 2016 and 2022 had the highest average values and the highest number of violations of EU limit values for both particle sizes. This could be related to an increase in industrial activity, garbage, an increase in vehicular traffic during those periods, and the last years the construction of Line 2 of the Lima Metro. Newer vehicles emit less air pollution than older vehicles [39]. Thus, higher PM concentrations may be related a many old cars that circulate (around 18 years) in the MAL without inspection and informally, which are responsible for tailpipe pollution because these produce higher amounts of lung-damaging particulate pollution compared to modern automobiles. The second largest source (26%) of PM emissions is related to the cement and lime industries [40]. Another big problem that increases pollution inside the AML is attributed to garbage, because Lima produces around 23,000 tons per day, and besides has 1400 garbage dumps where almost 90% of the garbage generated daily is not recycled and processed [41].

3.3 Temporal behavior of $PM_{2.5}$ and PM_{10} at each monitoring stations

Figure 6 shows the temporal variability of $PM_{2.5}$ month and weekday data (top), and hourly, m(bottom) by monitoring stations within the metropolitan area of Lima.

In the case of the behavior of the daily averages within the weekly cycle for $PM_{2.5}$, the amplitude of variation between the days of the week (2 and 5 µg/m^3) is not statistically significant between the average concentrations on different days of the week ($p > 0.05$). These results coincide with those recorded by Silva et al. [42] who attribute those found results to the permanence of $PM_{2.5}$ for longer times due to its small size and small mass. Hourly variations for $PM_{2.5}$ in the stations under study show that maximum concentrations occur at a peak generally between 6:00 and 10:00 a.m. and a second peak between 6:00 p.m. and 11:00 p.m. At these times, there is usually more vehicle traffic because most of them leave for work or school, which would explain the higher peaks of particulate matter. Average hourly maximums are observed at stations SJL (10:00, 44 µg/m^3), STA (9:00, 43 µg/m^3), CRB (11:00, 39 µg/m^3), followed by VMT (10:00, 36 µg/m^3) and SBJ (10:00, 24 µg/m^3). The records are similar to those reported by Silva et al. [42], who give the transport of passengers in the metropolis at peak traffic hours. Therefore, the broadcasts occur at these times. In the case of the average monthly variability of $PM_{2.5}$, the maximum concentrations observed for $PM_{2.5}$ per station, from highest to lowest, are SJL (39 µg/m^3), STA (36 µg/m^3), CRB (32 µg/m^3), VMT (32 µg/m^3) and SBJ (24 µg/m^3). Peak concentrations are generally evident between May and September. Minimum $PM_{2.5}$ concentrations vary from season to season between 14 and 22 µg/m^3, with absolute minimums generally observed between January and March. The amplitude of variability (expressed as the difference between the maximum and minimum monthly concentrations) is in the range of 10 to 15 µg/m^3, depending on the season. Significant differences were observed between the maximum and minimum values at 95% confidence (p-value < 0.05).

The temporal variability of PM_{10} month and weekday data (top) and hourly, m(bottom) by monitoring stations within the metropolitan area of Lima are presented in Figure 7. In the case of the behavior of the daily averages within the weekly cycle for PM_{10}, the amplitude of variation between the days of the week ranged between 5 and 16 µg/m^3, which shows statistically significant differences between the average concentrations for Sundays ($p < 0.05$).

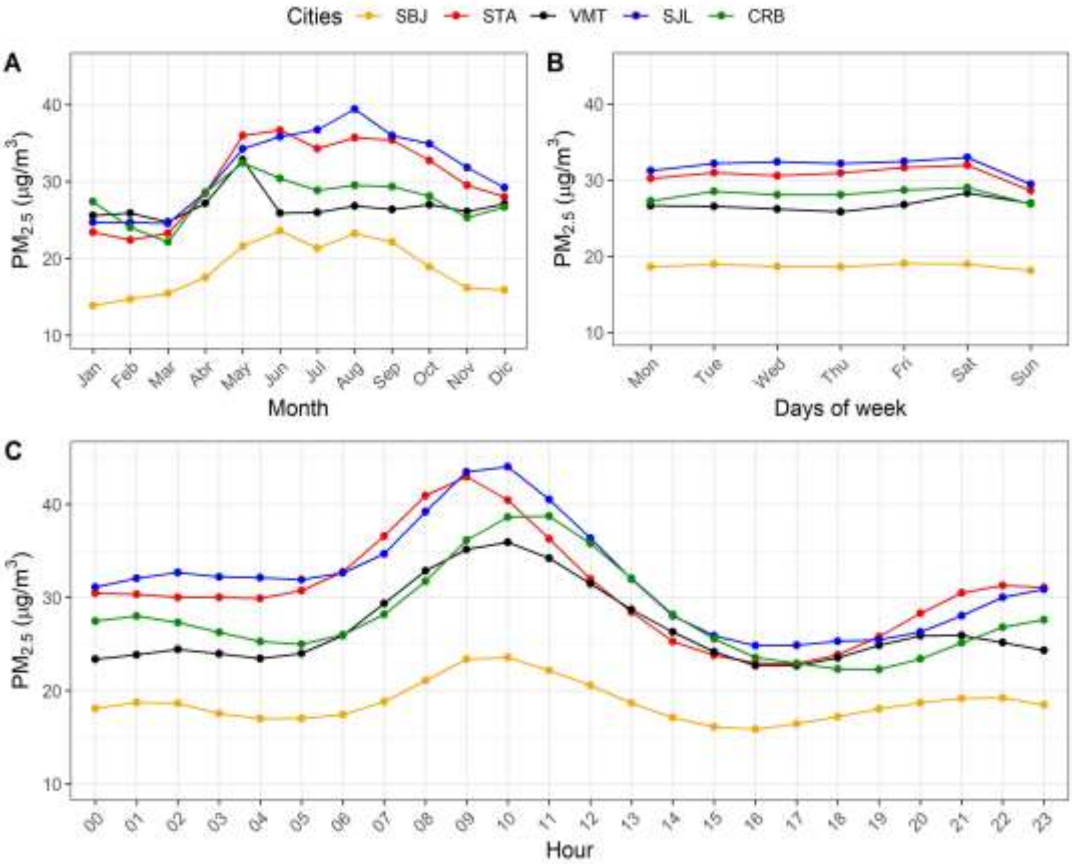

Figure 6. Temporal variability of $PM_{2.5}$ (2014-2023) concentrations: the top plots show the month (A) and days weekday (B) concentration levels of $PM_{2.5}$ by monitoring stations within the metropolitan area of Lima. The bottom plot shows the hourly concentration levels of $PM_{2.5}$ by monitoring stations within the metropolitan area of Lima (C)

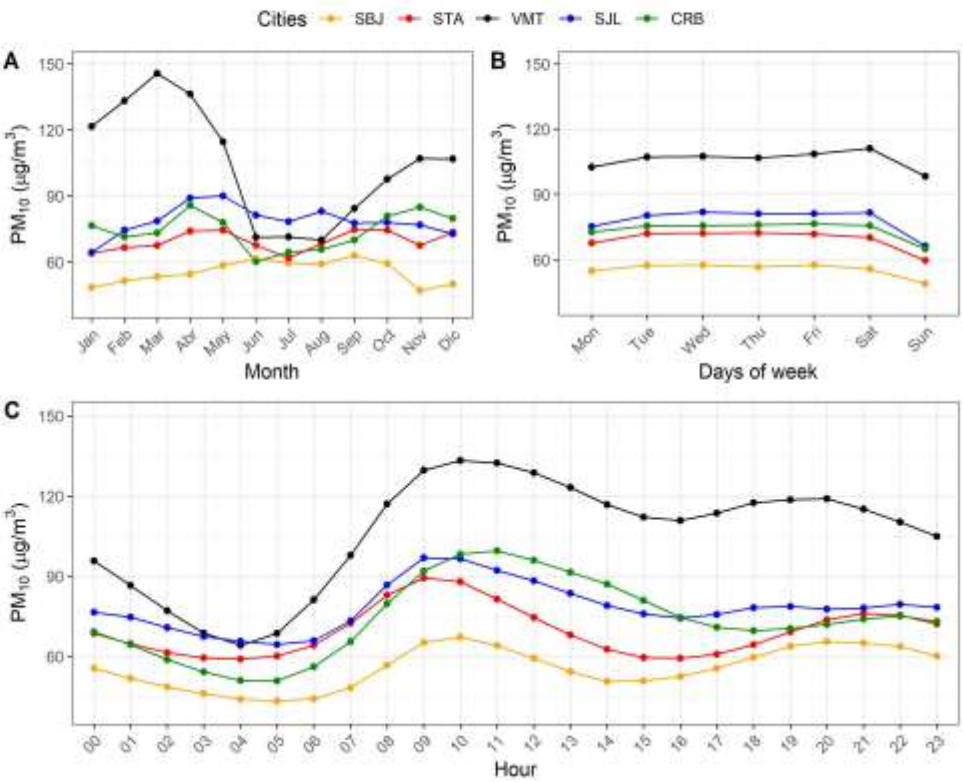

Figure 7. Temporal variability of PM_{10} (2010-2023) concentrations: the top plots show the month (A) and days weekday (B) concentration levels of PM_{10} by monitoring stations within the metropolitan area of Lima. The bottom plot shows the hourly concentration levels of PM_{10} by monitoring stations within the metropolitan area of Lima (C)

Hourly variations show that peak concentrations occur at a peak usually between 6:00 and 10:00 a.m. and a second peak between 6:00 p.m. and 11:00 p.m. The hourly average maximum is observed at the VMT station (10:00, 132 μg/m^3) followed by CRB (11:00, 100 μg/m^3), SJL (9:00, 98 μg/m^3), STA (10:00, 88 μg/m^3) and SBJ (10:00, 66 μg/m^3). The records are similar to those reported by Silva et al. [42] who reported also highest PM_{10} concentrations in peak hours (peak hours), which is characteristic when there is a heavy vehicular traffic. Cipoli et al. [43] indicate that during nocturnal campaign, the main contributions to the PM_{10} concentrations are related to biomass burning, followed by traffic, dust, secondary inorganic aerosol and sea salt. Thus, high concentrations of PM_{10} found could be related to the burning of biomass, traffic in a smaller proportion and sea salt, because AML is bordered by the Pacific Ocean.

For weekdays it is observed that PM_{10} concentrations have a similar behavior from Sunday to Saturday, and a reduction on Sunday for all monitoring stations. In urban areas, vehicular traffic usually decreases because a large part of the population prefers to be at home and others to travel to the interior of the country. Therefore, this reduction observed could be attributed to a lower number of vehicles circulating in the urban area, specifically on Sunday days. Likewise, these results coincide with those recorded by Silva et al. [42], who indicate that the variability on Sundays is related to a decrease in traffic flow and consequently the emissions of pollutants are reduced. Likewise, Vinasco and Nastar [44] reported PM_{10} increasing from Monday to Saturday when traffic flow in intense and decreased on Sunday in Cali Colombia when traffic flow decreased notably. These results are also comparable to those previously reported in Lima [45] where PM_{10} concentrations decreased only on Sunday for most months.

In the case of the average monthly variability of PM_{10}, the maximum concentrations observed for PM_{10} per station, from highest to lowest, are VMT (148 μg/m^3), SJL (90 μg/m^3), CRB (85 μg/m^3), STA (76 μg/m^3) and SBJ (62 μg/m^3). Peak concentrations are generally evident between March-May and August-October. Minimum PM_{10} concentrations ranged from 46 to 70 μg/m^3, with absolute minimums generally observed between January and June. Similar trend was reported previously by Encalada-Malca et al. [45] in the MAL for the period 2017-2018.

The amplitude of variability (expressed as the difference between the maximum and minimum monthly concentrations) is in the range of 11 to 65 μg/m^3, depending on the season. Significant differences were observed between the maximum and minimum values at 95% confidence (p-value < 0.05).

Regarding the monthly, daily, and hourly temporal behavior, significant variability is observed in $PM_{2.5}$ and PM_{10} concentrations throughout the day and year. Daily patterns show peaks during peak human activity hours, especially related to vehicular traffic and industrial emissions. In addition, peak concentrations tend to occur during peak industrial activity and traffic months, while peak concentrations are recorded during off-peak months. These results confirm that there were no effective policies and strategies to reduce air pollution during the study period. Thus, the importance of implementation of effective control policies to improve ambient air quality of the metropolitan area of Lima is vital.

Figure 8 shows the variability of mean annual $PM_{2.5}$ concentrations. The solid red line shows the estimate of the trend, and the dashed red lines show the 95% confidence intervals for the trend based on resampling methods. The results of the analysis show non-significant trends in $PM_{2.5}$ ($p > 0.05$) in all stations, which confirms a permanent potential risk in the inhabitants almost constant in all the stations evaluated.

In the case of PM_{10} concentration variability (Figure 9). The solid red line shows the estimate of the trend, and the dashed red lines show the 95% confidence intervals. The results of the analysis show significant negative trends of PM_{10} ($p < 0.001$) at the stations of SJL (-5.15), VMT (-4.36), CRB (-3.15) and STA (-2.67) places where there is a tendency to decrease. In the case of SBJ, it did not show a significant trend, so PM_{10} values have an almost constant behavior.

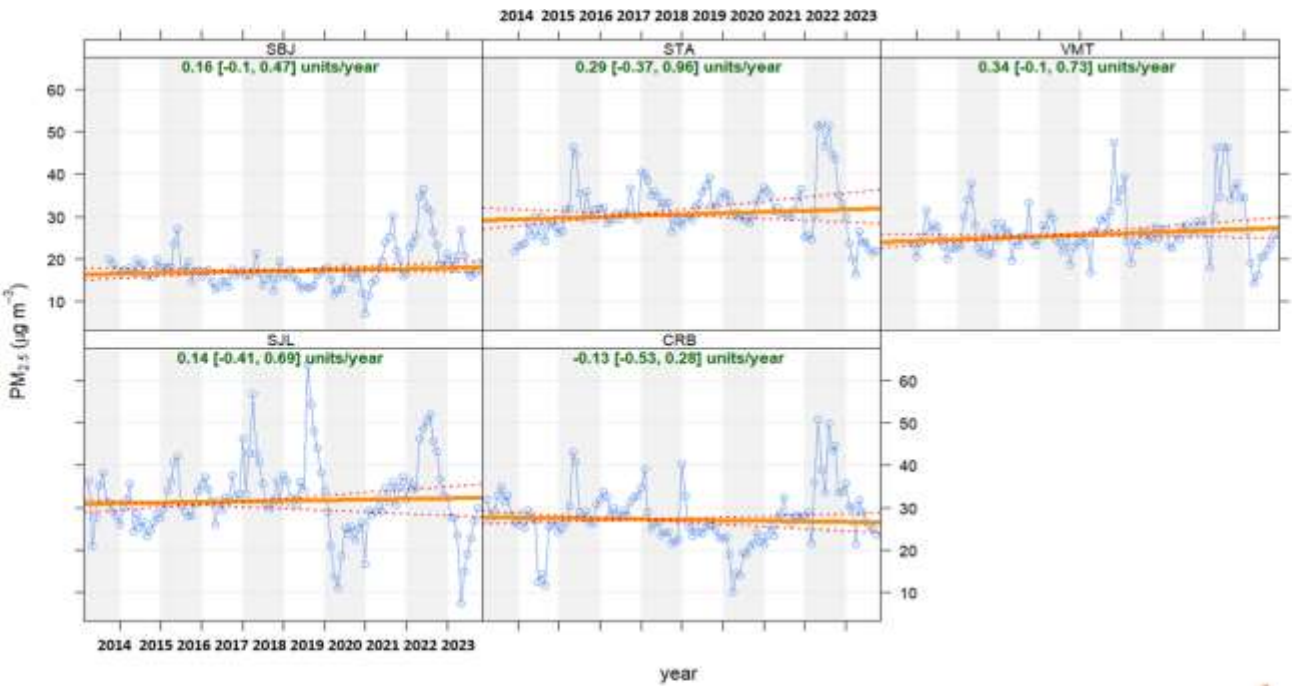

Figure 8. Trends in annual $PM_{2.5}$ concentrations (2014-2023) by monitoring stations in the Lima metropolitan area

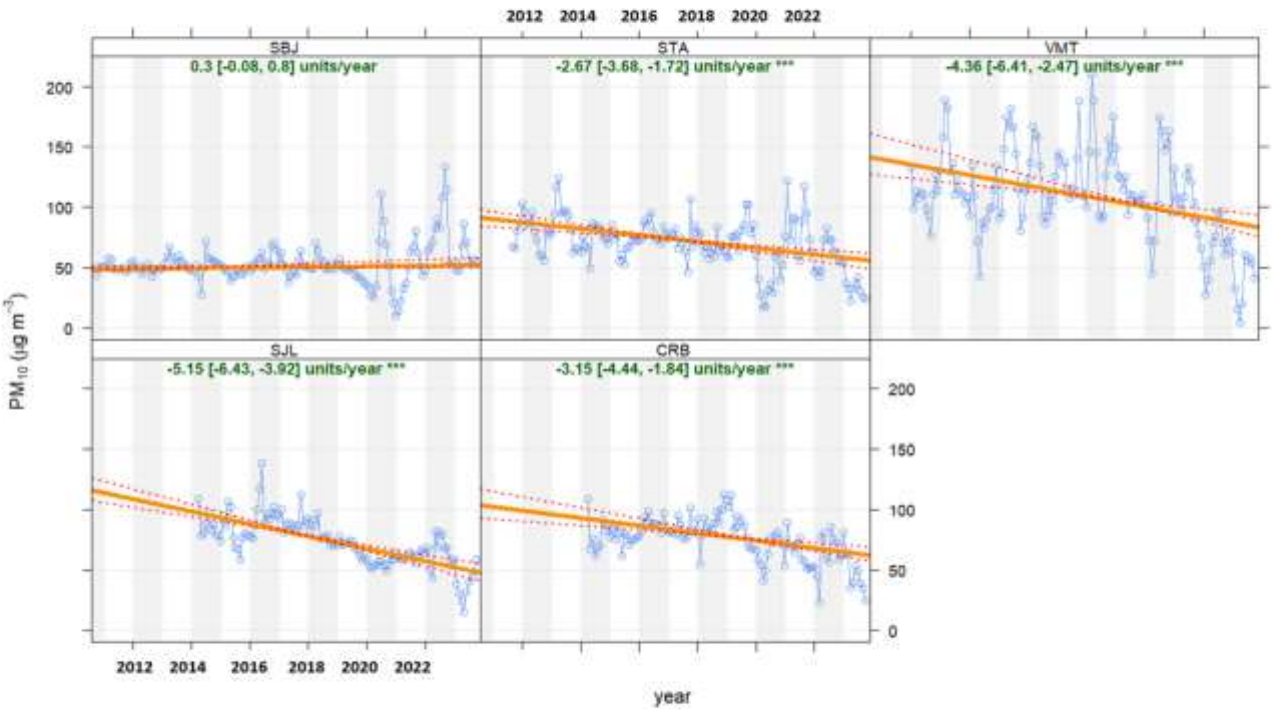

Figure 9. Trends in annual PM_{10} concentrations (2010-2023) by monitoring stations in the Lima metropolitan area

This suggests that pollution control actions may be having positive effects in some areas in PM_{10} but it is urgent to implement strategies and control in the case of $PM_{2.5}$, which has more detrimental health effects and remains in the atmosphere for a longer time. The limitation of the study is that not all the stations were operating simultaneously in all years, there are periods without data due to calibration and maintenance of the same. Despite this limitation, the results contribute to a better understanding of the behavior of $PM_{2.5}$ and PM_{10} in the city of Lima. The population hopes that when the construction of the Lima metro is completed, it will be able to reduce traffic congestion, decrease air pollution, and improve the quality of life for Lima´s residents. The results found will allow valuable information to be able to implement policies and take measures to reduce (or limit when relevant) the emission of particulate matter and prepare for the impacts of climate change, seeking to increase access to sustainable energy.

4. CONCLUSIONS

The results of this study showed that although there was no clear and significant trend for $PM_{2.5}$ and PM_{10} concentrations between 2010 to 2023, the annual trend of PM_{10} had increased from 2010 to 2013, and after a similar trend for the following years (except 2020). The annual mean of the $PM_{2.5}$ concentrations was almost constant, except with and decrease in 2020 and an increase in 2022. The years 2016 and 2022 stand out for having the highest annual averages of $PM_{2.5}$ and PM_{10}, as well as the highest number of violations of the limits established by EU and the Environmental Quality Standard from Peru. Monitoring stations, especially SJL, STA, and CRB, recorded the highest violations, while SBJ showed the lowest annual averages and exceedances throughout the period.

With respect to the trends with weekdays (annual, monthly, daily and hourly) of both PM, it has been concluded that the problem has been compounded due to the lack of or ineffective environmental regulations, lack of suitable public transportation, older vehicles, increasing personal vehicles, inadequate street spacing and insufficient parking facilities.

Therefore, the implementation of control policies and strategies such as the development of public transportation systems, land use integration, use of clean energy, and dismantles of worn-out taxi and bus fleet may be useful to prevent and reduce air pollution in the MAL.

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REFERENCES

[1] Zhang, G., Ding, C., Jiang, X., Pan, G., Wei, X., Sun, Y. (2020). Chemical compositions and sources contribution of atmospheric particles at a typical steel industrial urban site. Scientific Reports, 10(1): 7654. https://doi.org/10.1038/s41598-020-64519-x

[2] EPA. (2011). Particulate Matter Emissions. Washington, USA. https://www.epa.gov/pm-pollution.

[3] Saju, J.A., Bari, Q.H., Mohiuddin, K.A., Strezov, V. (2023). Measurement of ambient particulate matter (PM1. 0, PM2. 5 and PM10) in Khulna City of Bangladesh and their implications for human health. Environmental Systems Research, 12(1): 42. https://doi.org/10.1186/s40068-023-00327-2

[4] Han, C.H., Pak, H., Lee, J.M., Chung, J.H. (2022). Short-term effects of exposure to particulate matter on hospital admissions for asthma and chronic obstructive pulmonary disease. Medicine, 101(35): e30165. https://doi.org/10.1097/MD.0000000000030165

[5] Xing, Y.F., Xu, Y.H., Shi, M.H., Lian, Y.X. (2016). The impact of PM2. 5 on the human respiratory system. Journal of Thoracic Disease, 8(1): E69. https://doi.org/10.3978/j.issn.2072-1439.2016.01.19
[6] Vu, B.N., Tapia, V., Ebelt, S., Gonzales, G.F., Liu, Y., Steenland, K. (2021). The association between asthma emergency department visits and satellite-derived PM2. 5 in Lima, Peru. Environmental Research, 199: 111226. https://doi.org/10.1016/j.envres.2021.111226
[7] WHO billions of people still breathe unhealthy air: New WHO data. https://www.who.int/news/item/04-04-2022-billions-of-people-still-breathe-unhealthy-air-new-who-data.
[8] WHO World Health Organization. http://www.who.int/news-room/headlines/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action.
[9] WHO. What are the WHO air quality guidelines? https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines.
[10] MINAM. (2017). Aprueban Estandares de Calidad Ambiental (ECA) Para Aire y Establecen Disposiciones Complementarias. https://sinia.minam.gob.pe/sites/default/files/sinia/archivos/public/docs/ds-003-2017-minam.pdf.
[11] Maciejczyk, P., Chen, L.C., Thurston, G. (2021). The role of fossil fuel combustion metals in PM2. 5 air pollution health associations. Atmosphere, 12(9): 1086. https://doi.org/10.3390/atmos12091086
[12] Karagulian, F., Belis, C.A., Dora, C.F.C., Prüss-Ustün, A.M., Bonjour, S., Adair-Rohani, H., Amann, M. (2015). Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. Atmospheric Environment, 120: 475-483. https://doi.org/10.1016/j.atmosenv.2015.08.087
[13] El Peruano MTC: Parque automotor causa 58% de contaminación en aire de lima y callao. https://www.elperuano.pe/noticia/220890-mtc-parque-automotor-causa-58-de-contaminacion-en-aire-de-lima-y-callao.
[14] Martinez, M.J. (2024). Critical evaluation of transit policies in Lima, Peru; resilience of rail rapid transit (Metro) in a developing country. Green Energy and Intelligent Transportation, 100172. https://doi.org/10.1016/j.geits.2024.100172
[15] Pereira, G.M., Oraggio, B., Teinilä, K., et al. (2019). A comparative chemical study of PM10 in three Latin American cities: Lima, Medellín, and Sao Paulo. Air Quality, Atmosphere & Health, 12: 1141-1152. https://doi.org/10.1007/s11869-019-00735-3
[16] Kassomenos, P.A., Vardoulakis, S., Chaloulakou, A., Paschalidou, A.K., Grivas, G., Borge, R., Lumbreras, J. (2014). Study of PM10 and PM2.5 levels in three European cities: Analysis of intra and inter urban variations. Atmospheric Environment, 87: 153-163. https://doi.org/10.1016/j.atmosenv.2014.01.004
[17] Sloss, L.L., Smith, I.M. (2000). PM10 and PM2. 5: An international perspective. Fuel Processing Technology, 65: 127-141. https://doi.org/10.1016/S0378-3820(99)00081-8
[18] Gonzales, G.M.I., Quincho, J.P.R., Torres, R.J.C., Alvan, C.A.U. (2020). Chemical characteristics and identification of PM10 sources in two Lima districts, Peru. Dyna, 87(215): 57-65. https://doi.org/10.15446/dyna.v87n215.83688
[19] Sánchez-Ccoyllo, O.R., Llacza, A., Ayma-Choque, E., Alonso, M., Castesana, P., Andrade, M.D.F. (2022). Evaluating the impact of vehicular aerosol emissions on particulate matter (PM2.5) formation using modeling study. Atmosphere, 13(11): 1816. https://doi.org/10.3390/atmos13111816
[20] Tapia, V., Steenland, K., Vu, B., Liu, Y., Vásquez, V., Gonzales, G.F. (2020). PM 2.5 exposure on daily cardio-respiratory mortality in Lima, Peru, from 2010 to 2016. Environmental Health, 19: 63. https://doi.org/10.1186/s12940-020-00618-6
[21] Vu, B. N., Sánchez, O., Bi, J., et al. (2019). Developing an advanced PM2.5 exposure model in Lima, Peru. Remote Sensing, 11(6): 641. https://doi.org/10.3390/rs11060641
[22] Vasquez-Apestegui, B.V., Parras-Garrido, E., Tapia, V., Paz-Aparicio, V.M., Rojas, J.P., Sanchez-Ccoyllo, O.R., Gonzales, G.F. (2021). Association between air pollution in Lima and the high incidence of COVID-19: Findings from a post hoc analysis. BMC Public Health, 21(1): 1161. https://doi.org/10.1186/s12889-021-11232-7
[23] INEI población peruana alcanzó los 33 millones 726 mil personas en el año 2023. https://m.inei.gob.pe/prensa/noticias/poblacion-peruana-alcanzo-los-33-millones-726-mil-personas-en-el-ano-2023-14470/.
[24] MTC parque automotor nacional estimado por clase vehicular, según departamento: 2011-2022. https://www.gob.pe/institucion/mtc/informes-publicaciones/344892-estadistica-servicios-de-transporte-terrestre-por-carretera-parque-automotor.
[25] ¡Estás en Gob.pe!. (2022). Informe de lanzamiento del Estudio de Mercado sobre Combustibles Líquidos y Gas Licuado de Petróleo en el Perú. https://www.gob.pe/institucion/indecopi/informes-publicaciones/5476531-informe-de-lanzamiento-del-estudio-de-mercado-sobre-combustibles-liquidos-y-gas-licuado-de-petroleo-en-el-peru.
[26] R Team Core A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. (2019). https://www.r-project.org/.
[27] Carslaw, D. (2019). The openair manual open-source tools for analysing air pollution data. University of York and Ricardo Energy & Environment.
[28] Wickham, H., Chang, W., Henry, L., et al. (2023). ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics. https://ggplot2.tidyverse.org/reference/ggplot2-package.html.
[29] Theil, H. (1950). A rank-invariant method of linear and polynomial regression analysis. Indagationes Mathematicae, 12(85): 173.
[30] Carslaw, D., Ropkins, K. (2015). Tools for the Analysis of Air Pollution Data. Openair.
[31] Dantas, G., Siciliano, B., França, B.B., da Silva, C.M., Arbilla, G. (2020). The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. Science of the Total Environment, 729: 139085. https://doi.org/10.1016/j.scitotenv.2020.139085
[32] Toro, R., Catalán, F., Urdanivia, F.R., et al. (2021). Air pollution and COVID-19 lockdown in a large South American city: Santiago Metropolitan Area, Chile. Urban Climate, 36: 100803.

https://doi.org/10.1016/j.uclim.2021.100803
[33] Rojas, J.P., Urdanivia, F.R., Garay, R.A., et al. (2021). Effects of COVID-19 pandemic control measures on air pollution in Lima metropolitan area, Peru in South America. Air Quality, Atmosphere & Health, 14, 925-933. https://doi.org/10.1007/s11869-021-00990-3
[34] MINAM ministro del ambiente inspecciona puntos de alta contaminación en villa maría del triunfo. https://www.gob.pe/institucion/minam/noticias/630537-ministro-del-ambiente-inspecciona-puntos-de-alta-contaminacion-en-villa-maria-del-triunfo.
[35] MuniSanBorja. (2017). Municipalidad Distrital de San Borja, Lima, Perú: Medidas de Mitigación y Adaptación Al Cambio Climatico. https://www.ciudad.org.pe/wp-content/uploads/2020/11/FICHA-TECNICA-MUNICIPALIDAD-DISTRITAL-DE-SAN-BORJA.pdf.
[36] Zheng, Z., Xu, G., Li, Q., Chen, C., Li, J. (2019). Effect of precipitation on reducing atmospheric pollutant over Beijing. Atmospheric Pollution Research, 10(5): 1443-1453. https://doi.org/10.1016/j.apr.2019.04.001
[37] Solís, R., Toro, R., Gomez, L., et al. (2022). Long-term airborne particle pollution assessment in the city of Coyhaique, Patagonia, Chile. Urban Climate, 43: 101144. https://doi.org/10.1016/j.uclim.2022.101144
[38] Reátegui-Romero, W., Zaldivar-Alvarez, W.F., Pacsi-Valdivia, S., Sánchez-Ccoyllo, O.R., García-Rivero, A. E., Moya-Alvarez, A. (2021). Behavior of the average concentrations as well as their PM10 and PM2.5 variability in the metropolitan area of Lima, Peru: Case study February and July 2016. International Journal of Environmental Science and Development, 12(7): 204-213. https://doi.org/10.18178/ijesd.2021.12.7.1341
[39] Jacobsen, M.R., Sallee, J.M., Shapiro, J.S., Van Benthem, A.A. (2023). Regulating untaxable externalities: Are vehicle air pollution standards effective and efficient? The Quarterly Journal of Economics, 138(3): 1907-1976. https://doi.org/10.1093/qje/qjad016
[40] ICF Pollution. https://dicf.unepgrid.ch/peru/pollution#:~:text=Another major pressure on air,as cement and lime factories.
[41] WWF almost 90% of the garbage generated daily is not recycled. https://www.wwf.org.pe/en/?328834/Almost-90-of-the-garbage-generated-daily-is-not-recycled.
[42] Silva, J., Rojas, J., Norabuena, M., Molina, C., Toro, R. A., Leiva-Guzmán, M.A. (2017). Particulate matter levels in a South American megacity: The metropolitan area of Lima-Callao, Peru. Environmental Monitoring and Assessment, 189: 635. https://doi.org/10.1007/s10661-017-6327-2
[43] Cipoli, Y.A., Furst, L., Feliciano, M., Alves, C. (2023). Respiratory deposition dose of PM2.5 and PM10 during night and day periods at an urban environment. Air Quality Atmosphere and Health, 16: 2269-2283. https://doi.org/10.1007/s11869-023-01405-1
[44] Vinasco, J.P.S., Nastar, T.D.R.C. (2013). Variación espacial y temporal de concentraciones de PM10 en el área urbana de Santiago de Cali, Colombia. Ingeniería de Recursos Naturales y del Ambiente, (12): 129-141.
[45] Encalada-Malca, A.A., Cochachi-Bustamante, J.D., Rodrigues, P.C., Salas, R., López-Gonzales, J.L. (2021). A spatio-temporal visualization approach of pm10 concentration data in metropolitan Lima. Atmosphere, 12(5): 609. https://doi.org/10.3390/atmos12050609