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# Temporal Trend of $PM_{10}$ and the Associated Risk to Human Health in the Lima Metropolitan Area

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## ABSTRACT

Based on the monthly average of $PM_{10}$ and the 90th percentile of $PM_{10}$ concentration, respectively, the study's goal was to assess the risk to human health posed by $PM_{10}$ exposure for residents of the Metropolitan Area of Lima (MAL), Peru, in both the best-case and worst-case scenarios. The National Meteorology and Hydrology Service (SENAMHI) published hourly $PM_{10}$ concentrations for five monitoring stations from 2010 to 2023. The air quality index (AQI) was used to evaluate the quality of the air. Since there is no toxicity value (TVs) for $PM_{10}$, the yearly limit value set by the World Health Organization (WHO, 15 µg/m$^3$) and the European Union (EU, 40 µg/m$^3$) was used to generate the hazard quotient (HQ) to assess the danger to human health. The average annual $PM_{10}$ concentration was higher than the annual limit set by the EU and WHO, ranging from 45.1 µg/m$^3$ to 96.1 µg/m$^3$. According to the AQI, Lima's air quality is categorized as moderate to unhealthy, with most days having dangerous levels. While WHO AQG indicated a potential chronic non-carcinogenic health risk in most months of the year, the worst-case scenario indicated a non-carcinogenic risk for the majority of the period. In the best-case scenario and worst-case scenario based on the EU, both showed higher potential chronic non-cancer risk in the summer and spring months.

## 1. INTRODUCTION

Air pollution is a hidden issue that affects everyone negatively [1]. Particulate matter (PM) is one of the air pollutants constituted by a complex mixture of dry solid fragments and liquid aerosols released from natural and anthropogenic sources [2]. The PM can be locally generated or transported by long distances. Its chemical composition, shape, and size distribution vary greatly in function of its origin and transformation processes in the atmosphere [3]. The PM is divided into two categories based on their aerodynamic diameter: coarse particles ($PM_{10}$, ≤ 10 µm (microns) in diameter) and tiny particles ($PM_{2.5}$, ≤ 2.5 (microns) µm in diameter), which may contain inorganic and organic compounds, trace metals, elemental carbon, and other compounds such as black carbon, ammonia, dust [4]. Because both PMs can have detrimental effects on human health (worse respiratory and lung diseases) and the environment (affect ecosystems negatively altering plant growth and yield, reducing visibility, and causing environmental and material problems), they are closely monitored [5, 6]. $PM_{10}$ particles indicate a large variety of substances including carbonaceous compounds (elemental and organic carbon), water-soluble compounds (anions and cations species), and metals and metalloids [7]. According to scientific literature, $PM_{10}$ particles have been linked to respiratory problems, including tissue damage, lung inflammation, worsening asthma, an increase in chronic obstructive pulmonary disease, breathing difficulties, a reduction in life expectancy, and an increase in hospitalizations, cardiovascular problems, which raise the risk of heart attacks and high blood pressure, as well as other problems, such as cancer and early mortality. Similarly, it has been claimed that $PM_{10}$ in the ground or water can modify the quality of the water, harm crops and plants, alter the balance of nutrients, and cause acid rain [8, 9].

According to WHO, nearly all people on the planet (99%) breathe air that is harmful and violates WHO standards, endangering their health [10]. An update from WHO revealed that air quality monitoring is being carried out in more than 6000 cities out of 117 countries, however, people living in these cities still breathe unhealthy levels of fine PM, with people living in low- and middle-income countries being exposed to higher concentrations [11]. $PM_{2.5}$ should not exceed 5 µg/m$^3$ annual mean, or 15 µg/m$^3$ 24-hour mean, according to WHO air quality regulations, and $PM^{10}$ should not exceed 15 µg/m$^3$ annual mean, or 45 µg/m$^3$ 24-hour mean [12]. Both rural and urban areas typically report PM-generated air pollution, which is mostly caused by human activities including inefficient combustion of fuels (petroleum, coal, wood, kerosene, crop residues, charcoal), road transport, construction dust, industries, and other activities [13-15]. The Lima Metropolitan Area (MAL) is the biggest metropolitan area in Peru, as well as the fourth largest in Latin America and one of the top 30 worldwide.

Additionally, it has the greatest population (about 11.3 million in 2024, up 1.41% from 2023), the most vehicle feet, and a wide range of businesses (such as those in the food, textile, timber, and chemical industries) situated inside the MAL. Air pollution in the MAL is a significant environmental and public health challenge, primarily due to vehicle emissions, industrial activities, and inadequate waste management. The Urban Transport Authority of Lima and Callao (ATU), indicates that 58% of MAL's air pollution is caused by the vehicle fleet, while 85% of public transportation runs on diesel, with only a small percentage on electricity and natural gas. A substantial proportion of air pollution in Lima is attributed to transportation, particularly older (more than 20 years) non-compliant vehicles and traffic congestion [16]. Lima is an industrial zone that releases harmful pollutants for example nitrogen oxides and sulfur oxide which were exacerbated by the rapid urbanization. Likewise, Also, since Lima does not have waste disposal systems, much of it is incinerated. Faced with all this information, the population is the most affected because daily it is exposed to different contaminations and concentrations.

Several studies have reported levels of $PM_{10}$ in cities around the world [17, 18]. Human health risks related to $PM_{10}$ exposure and its toxic elements also were carried out in several cities [19-21]. Most of these studies revealed problems with high PM concentrations as well as health impacts, therefore studies related to air pollution exposure are key to assessing human health risk and thus implement to control and mitigate urban air pollution.

Therefore, the purpose of this study was to evaluate the health risks related to $PM_{10}$ for the inhabitants of one of Peru's largest agglomerations. To determine the seasons when air quality became a problem for the local population, the AQI was used in the urban agglomeration of the MAL to examine the temporal fluctuation of the $PM_{10}$ pollution level from 2010 to 2023.

The EU and WHO guidelines were used to estimate the health risk assessment (HRA), which will provide local governments with data on how well air quality control is working. The findings might help policymakers create and implement better policies and plans to enhance air quality and lessen its negative health consequences.

## 2. MATERIALS AND METHODS

### 2.1 Study area

The study was conducted in the MAL or Metropolitan Lima (75º30'18" S, 77º53'02" W) which is a conurbation constituted by the districts of the Peruvian provinces of Callao and Lima. The AML is the largest metropolitan area and most populated urban area in Peru, and it is located inland from the Pacific Ocean covering a surface total of 2683 km$^2$ and a population estimated at 11.3 million inhabitants (population density of Lima 3620 inhabitants/km$^2$ and Callao 8050 inhabitants/km$^2$) in 2023 [22]. It is the fourth largest city in Latin America and among the thirty largest in the world [22]. The ATU environmental quality bulletin states that the AML owns 68.6% (more than 2 million) of Peru's fleet of light and heavy vehicles [23], which runs mainly on diesel (around 46%), LPG (24%), and gasoline (20%) of the total consumption of fuels [24]. Within the AML several fixed sources include a variety of industries such as textiles, services, pharmaceuticals, manufactures, machinery, mining and refining of minerals, steel, non-metallic mining, paper, petroleum extraction, and refining, among other industries, which probably contribute to the PM emissions. Due to Lima's equatorial location, a year-round mild climate is facilitated by the cool offshore Humboldt current. The winter months of May through November have average temperatures of 16-18°C, while the summer months of December through April. Besides, presents an average of relative humidity of 80%, and 10 mm of average annual precipitation, and usually the sky is cloudy all year.

### 2.2 $PM_{10}$ air quality data

The SENAMHI of Peru carries out air quality monitoring in the AML through a Network of automatic air quality monitoring stations which are installed in urban areas inside ten districts: Ate Vitarte (ATE), Campo de Marte (CM), Carabayllo (CRB), Huachipa (HUA), San Juan de Lurigancho (SJL), Santa Anita (STA), San Borja (SBJ), Villa María del Triunfo (VMT), San Martin de Porres (SMP), and Puente Piedra (PP). These stations provide information validated from hourly data on $PM_{10}$ and $PM_{2.5}$. For this investigation, $PM_{10}$ data (period 2010-2023) from five monitoring stations (SBJ, STA, VMT, SJL, and CRB) was required from the SENAMHI (Figure 1 and Table 1). $PM_{10}$ data were collected with the automatic Micro Oscillatory Monitor TEOM 1405 Ambient Air Monitor from THERMO SCIENTIFIC, Brazil, which takes continuous direct mass measurements of particulates utilizing a tapered element oscillating microbalance.

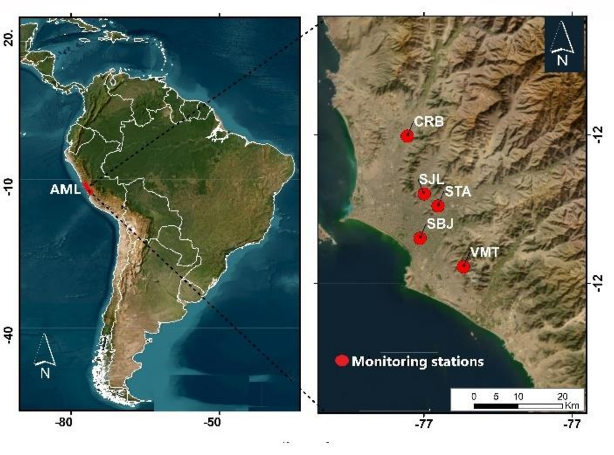


**Figure 1.** Localization of the MAL and the monitoring stations network [25]

**Table 1.** Localization and brief description of air quality monitoring station from the SENAMHI

| Monitoring Station | Brief Description | Latitude and Longitude | Population [15] | Superficial Area ($km^2$) | Elevation m.a.s.l |
|---|---|---|---|---|---|
| CRB | Located in the northernmost part, It is one of the oldest districts in Lima, with its foundation dating back to colonial times, and it has since evolved into a diverse and growing urban area. | 11º54'7.9" S, 77º2'1.1" W | 426895 | 384.89 | 179 |
| VMT | Located in the southern part, It is known for its diverse communities, economic activity, and cultural vibrancy, though it faces challenges related to urban growth and infrastructure | 12º9'59.0" S, 77º55'12.0" W | 459010 | 70.57 | 292 |
| SJL | Located in the eastern part, is one of the largest and most populous districts and plays a significant role in the social and urban landscape | 12º1'8.0" S, 76º59'57.4" W | 1240489 | 131.25 | 240 |
| STA | Located in the eastern part, Known for its mix of residential and commercial activity, it is a vibrant and growing urban area that serves as a critical node for commerce and transportation | 12º2'35.9" S, 76º58'17.0" W | 232739 | 10.69 | 253 |
| SBJ | Located in the central part of Lima, it is known for its residential neighborhoods, green spaces, and modern infrastructure, and is recognized for its focus on urban planning, safety, and environmental initiatives. | 12º6'31.1" S, 77º0'27.9" W | 133328 | 11.5 | 128 |

### 2.3 AQI

An indicator that offers pertinent data on the air quality of a particular location is the AQI. Since only one monitoring station is representative and would not adequately reflect the variations of $PM_{10}$ within the AML, it was used in this study to analyze the monthly variability and identify multi-year trends using the five monitoring stations installed in the AML. Normally, it is used to gather data on the daily air quality of each monitoring station. Therefore, the daily AQI was computed using Eq. (1) and the daily limit value of the EU (40 μg/$m^3$) as well as the mean $PM_{10}$ concentration of each monitoring station [26].

$$AQI = \frac{PM_{10}\ concentration}{threshold\ concentration} \times 100 \tag{1}$$

They are categorized as good (0-50), moderate (51-100), hazardous to health for sensitive populations (101-150), damaging to health (151-200), highly harmful to health (201-300), and dangerous (more than 300) using the six AQI scales, which range from 0 to 500. Air pollution and health hazards are indicated by AQI readings greater than 100, whereas values below 100 are regarded as adequate [27].

### 2.4 Human HRA

The HQ is a commonly used metric in risk assessment to evaluate the potential health risk posed by exposure to a particular substance. This assessment makes it possible to calculate and estimate the hazard or risk that a place (residence, work area, or site) represents to human health [28]. Thus, the risk of $PM_{10}$ exposure to human health was estimated using Eq. (2).

$$HQ = EC/TV \tag{2}$$

Using Eq. (3), the exposure concentration of $PM_{10}$ (μg/$m^3$) is determined [29]. Since there was no toxicity estimate for $PM_{10}$ in the literature, TV used the WHO AQG of 20 μg/$m^3$ ($HQ_2$) and the EU yearly limit value of 40 μg/$m^3$ ($HQ_1$). Using the EU and WHO limits as TVs for $PM_{10}$ in risk assessments is a justified approach in the absence of specific local or regulatory TVs.

$$EC = (CA \times ET \times EF \times ED)/AT \tag{3}$$

where, $ED$ is the duration of exposure (year), $ET$ is the exposure time (hours/day), $EF$ is the exposure frequency (days/year), and $AT$ is the average time calculated by multiplying ED × 365 days/year × 24 hours/day, and $CA$ is the monthly average concentration of $PM_{10}$ for the best-case scenario and the monthly 90 quartiles for the worst-case scenario. The residents' exposure was calculated using the following values: EF was 350 days per year, ED was 30 years for adults, and ET was 24 hours per day [29].

However, using EU and WHO limits as TVs in risk assessments offers practicality in the absence of specific local thresholds but introduces several limitations that can influence the precision and applicability of the assessment, potentially impacting public health decision-making.

All harmful health outcomes other than cancer brought on by exposure are referred to as non-carcinogenic risks. For headquarters, the security reference level is 1. Accordingly, if HQ > 1, exposure to $PM_{10}$ may result in long-term non-carcinogenic effects; if HQ < 1, there is no noncarcinogenic danger [30].

### 2.5 Statistical analysis

The $PM_{10}$ values obtained for the period 2010-2023 from each monitoring station were treated independently and jointly (representing the AML) to find their basic statistics (minimum, maximum, average, standard deviation, percentiles (10, 50, and 90), and number of days that exceeded the established limits). Likewise, the temporal evolution of the pollutant inside the MAL was plotted considering each monitoring station. All statistical and graphical treatments were carried out in the free software R studio, version 4.2.6 [31] using the openair [32] and ggplot2 [33] packages.

## 3. RESULTS AND DISCUSSIONS

### 3.1 Air quality

Based on the daily readings from every monitoring station, the descriptive statistics for $PM_{10}$ for the years 2010–2023 are shown in Table 2. Except for 2010 (46.9 μg/m$^3$) and 2023 (45.1 μg/m$^3$), the majority of years had $PM_{10}$ concentrations above the EU's 40 μg/m$^3$ limit and the Environmental Quality Standards (ECA - 50 μg/m$^3$) of Peruvian regulations. The annual average of $PM_{10}$ concentrations ranged from 45.1 μg/m$^3$ (2023) to 96.1 μg/m$^3$ (2013). The minimum $PM_{10}$ values were 23.7 μg/m$^3$ in the year 2010, while the maximum value was 579 μg/m$^3$ in 2020. The years with more daily violations were 2022 (n=1049), followed by 2017 (n=920), 2015 (n=900), 2016 (n=888), 2018 (n=811), and 2014 (n=727). This finding indicates that during this period (2014 to 2018) Lima faced a variety of modifications in transport and urbanization probably. Few violations observed in 2010, 2011, and 2023 (data until March) could be related to the little data that was collected, such as the missing data in some monitoring stations. Likewise, it was found that the average annual concentration of $PM_{10}$ in all years exceeded the AQS established by the WHO (20 μg/m$^3$). Similar results were previously reported in 2018 for $PM_{10}$ in the MAL [34]. Likewise, Peláez 2020 [35] reported that Lima among other megacities during the period of monitoring (2010-2017) exceeds the WHO air quality guidelines for $PM_{10}$. These findings corroborate what was reported in this work.

The annual maximum value was recorded in 2020 (579 μg/m$^3$), while the annual minimum value was found in 2010 (75.6 μg/m$^3$). The maximum annual values showed a temporal behavior with three periods of higher peaks in 2013 (423 μg/m$^3$), 2018 (435 μg/m$^3$), and 2020 (579 μg/m$^3$). In addition, a similar behavior is observed for most daily measurements whose values were greater than 50 μg/m$^3$ and in the 10th, 50th, and 90th percentiles with differences in the years with the highest peak, with 2022 presenting the highest number of infractions (1049 days exceeded the EU limits) and 2013 with the highest 90th percentile. One possible explanation for this discrepancy is that not every station operated consistently throughout the years.

In the year with the highest violation of annual $PM_{10}$ limits, 281 occurred in SJL and SBJ followed by VMT with 252. 2010 was the year with the fewest infractions, with just the SBJ station operating and 37 infractions reported. The increase in breaches from 2010 to 2017 can be explained by the start of PM10 monitoring in STA in 2011, VMT in 2012, and SJL and CRB in 2014.

The annual change in $PM_{10}$ within the Lima metropolitan region from 2010 to 2023 is shown in Figure 2. Figure 2 shows an average annual increase in $PM_{10}$ from 2010 to 2013, a decrease in 2014, and a further increase from 2014 to 2018. In 2019 and 2020 there was a consecutive reduction in $PM_{10}$, which is probably related to the COVID-2019 pandemic restrictions, and an increase in 2021, which could be explained by the lifting of pandemic restrictions. In addition, it is observed that most of the $PM_{10}$ values measured daily are above the median (with greater emphasis in the years 2013 and 2018) and that in all years the annual limit established by the EU, WHO, and ECA limits were exceeded. For instance, there was an increase until 2013 (19.6), a decline in 2014, an increase until 2018 (10), and a further decrease until 2023 in the difference between the average and the annual median of PM10. For 2023, the reduction may be related to the fact that only have data from the first four months, which would not be representative.

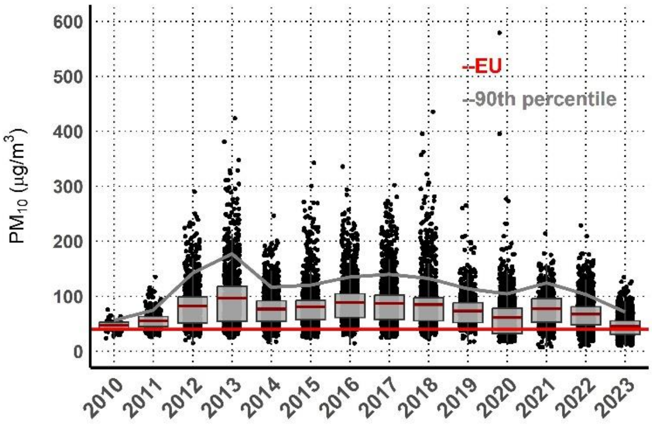


**Figure 2.** Changes in $PM_{10}$ levels annually throughout the MAL from 2010 to 2023. The black line represents the 90th percentile, while the red line represents the EU threshold limit value of 40 μg/m$^3$

**Table 2.** Statistics descriptive of the annual $PM_{10}$ (2010-2023) concentrations (μg/m$^3$) measured in the MAL

| Year | N | Mean ± CI (S.D.) | [Min, Max] | 10th Percentile | 50th Percentile | 90th Percentile | Day with $PM_{10}$ > 40 μg/m$^3$ |
|---|---|---|---|---|---|---|---|
| 2010 | 87 | 46.9 (9.38) | [23.7, 75.6] | 35.1 | 47.9 | 56.2 | 37 |
| 2011 | 396 | 55.0 (15.8) | [25.9, 135] | 37.9 | 51.4 | 74.7 | 212 |
| 2012 | 879 | 81.6 (42.2) | [14.7, 290] | 41.1 | 69.9 | 142.2 | 455 |
| 2013 | 905 | 96.1 (58.4) | [24.4, 423] | 43.5 | 76.5 | 177.2 | 415 |
| 2014 | 1191 | 76.5 (31.0) | [16.7, 246] | 42.6 | 71.7 | 116.6 | 727 |
| 2015 | 1364 | 80.9 (37.3) | [24.1, 342] | 46.3 | 73.7 | 120.1 | 900 |
| 2016 | 1477 | 88.5 (38.8) | [14.5, 336] | 49.6 | 80.4 | 135.1 | 888 |
| 2017 | 1564 | 86.6 (41.9) | [24.6, 302] | 44.1 | 77.4 | 139.9 | 920 |
| 2018 | 1351 | 84.7 (45.5) | [22.2, 435] | 45.3 | 74.7 | 132.4 | 811 |
| 2019 | 664 | 73.3 (31.3) | [17.2, 265] | 43.7 | 64.7 | 113.5 | 421 |
| 2020 | 1007 | 61.0 (40.4) | [17.0, 579] | 23.2 | 53.7 | 104.4 | 429 |
| 2021 | 505 | 76.9 (32.1) | [7.16, 214] | 41.9 | 72.1 | 124.4 | 290 |
| 2022 | 1744 | 67.2 (27.7) | [8.40, 229] | 36.3 | 63.7 | 103.2 | 1049 |
| 2023 | 1166 | 45.1 (19.3) | [9.81, 134] | 24.3 | 41.7 | 71.3 | 375 |

S.D.= standard deviation

Figure 3 displays the average of the AQI, the 90th percentile of the AQI, the temporal variation of the PM10 concentration, and the 90th percentile of the $PM_{10}$ in the MAL from 2010 to 2023.

Monthly $PM_{10}$ concentrations (Figure 2A) were highest in March (131±78.7 μg/m$^3$) and April (136±73.6 μg/m$^3$) of 2013, with the lowest recorded in August (39.8±11.5 μg/m$^3$) and October (43±14.8 μg/m$^3$) of 2023. The peak values were recorded in two periods: 1) February-April and 2) September-November, with a similar behavior in all stations, except VMT where the highest values were recorded in February-April. In general, monthly concentrations of $PM_{10}$ were higher in summer-autumn and spring seasons, manifesting their permanence in the air. This may be due to the influence of traffic, changes in weather patterns, and intensification of the industry as in the summer and winter months the values decrease [36].

These displayed comparable patterns across years for the 98th percentile of monthly PM10 (Figure 2B). The highest values were measured between March (318 μg/m$^3$) and April (326 μg/m$^3$) of 2013. The average monthly AQI (Figure 2C) ranged from 57.1 (October 2023) to 273 (April 2013), indicating that air quality in Lima is classified from moderate to unhealthy. However, the 98th percentile (Figure 2D) ranged from 73.5 (October 2023) to 418 (April 2013), indicating that there are mostly days with hazardous air quality for more vulnerable population groups.

These findings suggest that air pollution in Lima is still a serious issue, even with the improvements made in air quality control. Similarly, the stations displayed poorer air quality, most likely due to their proximity to hills and busy roadways, such as the primary highway. Furthermore, the unpaved roadways around it could contribute to the rising PM levels.

This finding contrasts with those reported by Valdivia [37], Silva et al. [38], Tapia et al. [39], and Delgado-Villanueva and Aguirre-Loayza [40].

The moderate to dangerous air quality is largely attributed to the vehicle fleet, and the use of fossil fuels such as oil, diesel, gasoline, LPG, and CNG. In addition, increased industrial activity during certain periods can contribute significantly to PM emissions [17, 41] as seasonal changes in weather patterns can influence the dispersion and accumulation of air pollutants [37]. Months with higher values, such as March and April 2013, may be associated with a combination of factors, including intensified human activity and unfavorable weather conditions.

The results of the analysis indicate a worrying air quality situation in Lima concerning the EU, with $PM_{10}$ concentrations consistently above established limits, worrying pollution peaks, and a temporal distribution that highlights the influence of multiple factors on air quality in the region. Given that Lima is regarded as one of the most polluted cities in Latin America in terms of PM10, these findings highlight the urgency with which the city's air pollution needs to be addressed and reduced [42].

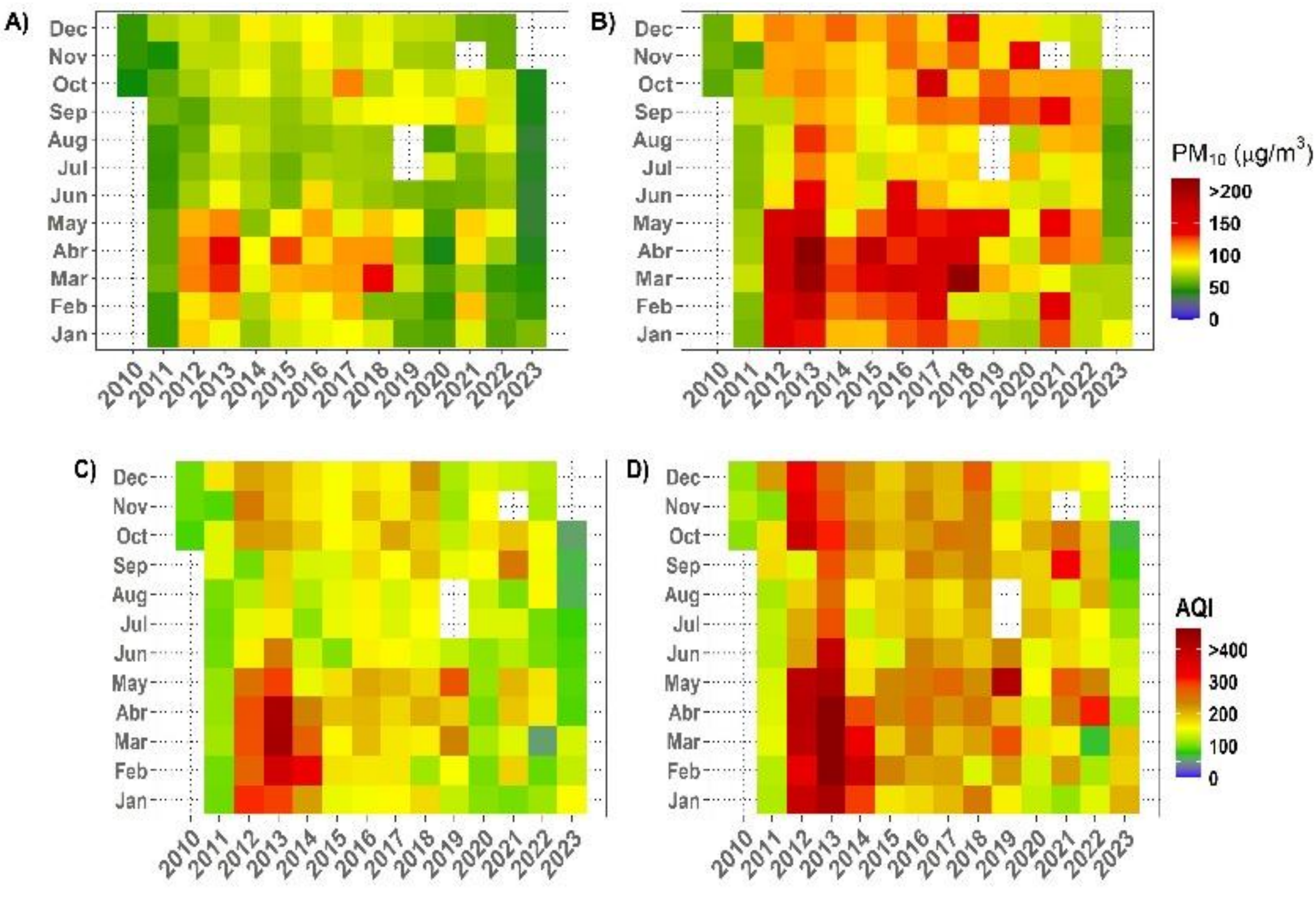


**Figure 3.** Changes in the MAL from 2010 to 2023 in terms of (A) average $PM_{10}$ concentration, (B) 90th percentile of $PM_{10}$ (μg/m$^3$) concentration, (C) average of AQI, and (D) 90th percentile of AQI

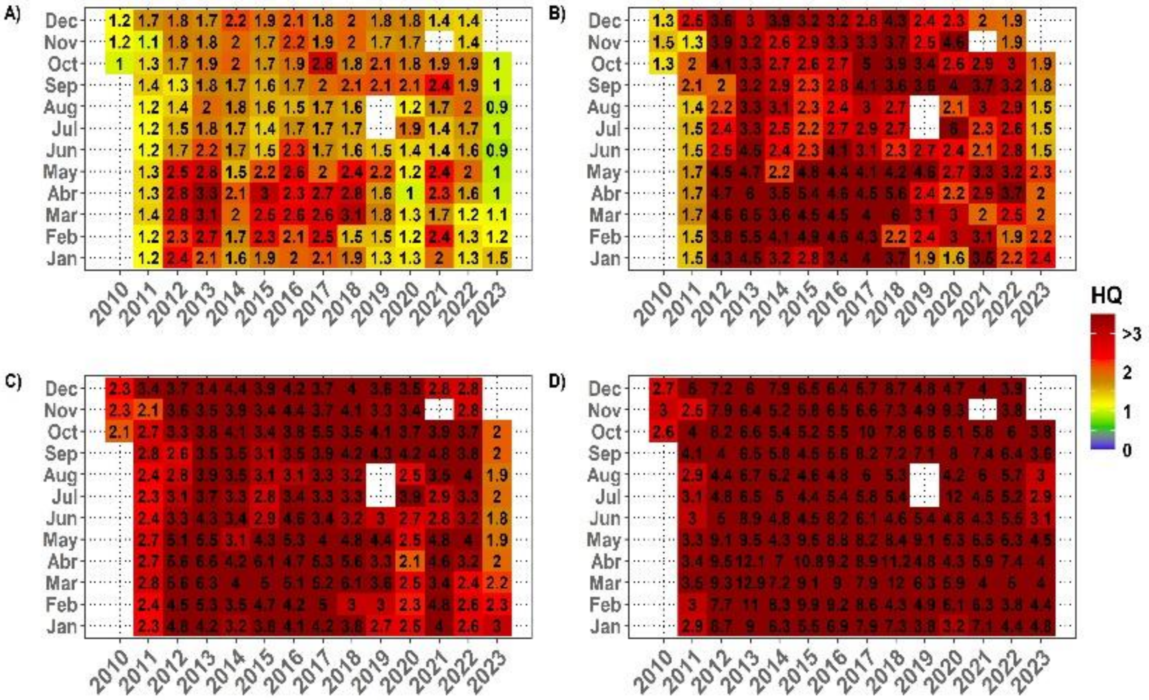

**Figure 4.** HQ variation over time in the MAL from 2010 to 2023 was calculated using EU limit values for best-case (A) and worst-case (B) scenarios, and WHO air quality guidelines for best-case (C) and worst-case (D) scenarios

### 3.2 Human HRA

The monthly average $PM_{10}$ concentration for the study periods was used to calculate exposure concentrations (ECs), which ranged from 40.8 μg/m$^3$ (October 2023) to 131.2 μg/m$^3$ (April 2013). The monthly concentration of the 98th percentile was used to calculate ECs, which ranged from 63.6 μg/m$^3$ (October 2023) to 200.4 μg/m$^3$ (April 2013). According to these findings, exposure concentrations increased during the spring and summer.

In every year under study, the chronic non-carcinogenic $HQ_1$ ranged from 0.9 to 3.3, depending on the EU limit value acquired for the optimal residential environment. Similarly, $HQ_1$ levels were greater (1.3–6.5) in the worst-case scenario, and monthly peaks with values over the safety benchmark were discovered every year. The best-case (Figure 4A) and worst-case (Figure 4B) monthly variations of $HQ_1$ indicate a higher potential chronic non-cancer risk during the summer and spring. In the worst-case scenario, the non-carcinogenic health risk was discovered, and in the best-case scenario, it was detected from the beginning of the monitoring, which was conducted more thoroughly until 2017. Every year was found in both exposure scenarios, indicating ongoing exposure and risk to Lima residents' health.

In every year examined, the chronic non-carcinogenic $HQ_2$ computed using the WHO AQG acquired for the best-case scenario varied between 1.8 and 6.6 (Figure 4C), suggesting a possible chronic non-carcinogenic health risk in the majority of the year's months, in contrast, the worst-case scenario's $HQ_2$ values were higher, ranging from 2.6 to 12.9 (Figure 4D), above the safety standard in every month and exhibiting consistent behavior and suggesting a non-carcinogenic risk for the majority of the time.

Figure 5 shows the variations between the best and worst scenarios for the city of Lima's air quality monitoring stations' assessments of human health hazards from 2014 to 2023. Since $HQ_1$ values are greater in VMT and SJL, all monitoring stations are over the threshold, suggesting a possible threat to public health. In the instance of $HQ_2$, VMT and SJL stations pose a greater health risk. In the worst-case scenario, a similar pattern is seen for both $HQ_1$ and $HQ_2$, with all seasons above 1, suggesting a lasting possible non-carcinogenic danger in the population.

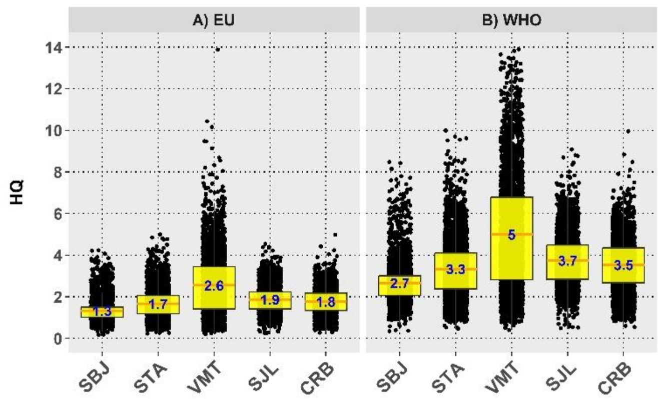


**Figure 5.** HQ variation across air quality monitoring sites in the MAL from 2010 to 2023, calculated using EU limit values (A) and WHO air quality recommendations (B)

The VMT and SJL stations are part of the southern cone and northern cone of Lima respectively. These urban areas have a high population density, diversity of activities (industrial, vehicle fleet), and lack of green areas, which in combination with meteorological factors would be causing the highest health risk recorded in the entire study period. A similar situation was reported in previous years by Carranza et al. [43].

Despite being within Peruvian regulatory requirements, the high HQ values indicate that environmental $PM_{10}$ levels are likely to cause a variety of chronic diseases, indicating that the city of Lima has ongoing health hazards associated with air pollution exposure. These results complement what has already been reported [44-46].

It highlights the need to review and potentially readjust Peruvian legislative thresholds to ensure adequate protection of public health against exposure to air pollutants as mentioned by Ordoñez-Aquino and Gonzales [47]. In addition, they underscore the importance of implementing preventive and mitigation measures to reduce the risks associated with air pollution, even when levels appear to be within acceptable limits.

The study's weaknesses are due to its only focus on $PM_{10}$ and failure to account for concurrent exposure to other air contaminants. Furthermore, assumptions about the timing, frequency, and duration of exposure were used to calculate the non-carcinogenic health risk; these assumptions are not unique to the group under study and do not take individual behavioral differences into account. Additionally, it was believed that the average daily $PM_{10}$ concentrations recorded by air quality monitoring sites were typical of the city as a whole. Notwithstanding these drawbacks, the findings advance knowledge of the possible health hazards associated with $PM_{10}$ exposure in cities and offer practical data to support the various accountable parties' air quality management in Lima.

The urgency of taking concrete and effective measures to address air pollution in Lima and protect the health of its inhabitants is emphasized. In addition, it is important to continuously review and update environmental regulations to ensure the safety and well-being of the population.

## 4. CONCLUSIONS

There is evidence of a persistent problem with air quality in the city of Lima throughout the period studied from 2010-2023. Average annual $PM_{10}$ concentrations were consistently above the limits set by EU legislation and Peruvian regulations, as well as WHO-AQG. The population of Lima is exposed to dangerously high levels of particle pollutants in the air, which can have long-term repercussions on public health, as indicated by these high $PM_{10}$ concentrations. Thus, the levels of $PM_{10}$ to which the population of the MAL is exposed indicate that the risks to human health are permanent, which highlights the need to review and potentially adjust legislative thresholds to ensure adequate protection of public health. In addition, it underlines the importance of implementing preventive and mitigation measures to reduce the risks associated with air pollution, even when levels appear to be within acceptable limits.


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