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Health Risk of Particulate Matter in Canoas and Paulínia for the Population Aged 30 to 59 Years

Risco à Saúde Associado ao Material Particulado em Canoas e Paulínia na População de 30 a 59 Anos

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ABSTRACT

Particulate matter, such as PM_{10}, poses a threat to health and the environment. This study assessed the health impacts associated with the average annual PM concentrations in Canoas, Rio Grande do Sul, and Paulínia, São Paulo, from 2010 to 2019, comparing them to World Health Organization (WHO) guidelines. Air pollution is a global concern due to its association with respiratory diseases. Computational tools such as AirQ+ and Openair (R programming language) are essential for linking health and pollution data. The analyses showed a decrease in PM_{10} concentrations over time according to the Theil-Sen test. In Canoas, a significant reduction (p-value < 0.01) of 2.18 $\mu g.m^{-3}$ per year was observed, while in Paulínia a reduction of 0.35 $\mu g.m^{-3}$ per year was not significant (p-value > 0.10) and still remained above the 15 $\mu g.m^{-3}$ recommended by the WHO. The relative risk calculation estimated that with this reduction,$4,367$ and $2,351$ health events could have been avoided in Canoas and Paulínia, respectively. These data highlight the need for policies to improve air quality and protect public health.

keywords air pollution, mortality, AirQ+, PM_{10}

RESUMO

O material particulado, como o MP_{10}, representa uma ameaça à saúde e ao meio ambiente. Este estudo avaliou os impactos na saúde relacionados às concentrações anuais médias de PM em Canoas, Rio Grande do Sul, e em Paulínia, São Paulo, entre 2010 e 2019, comparando com as recomendações da Organização Mundial da Saúde (WHO). A poluição do ar é globalmente preocupante devido à associação com doenças respiratórias. Ferramentas computacionais como o AirQ+ e o *Openair* (*software* R) são essenciais para relacionar dados de saúde e poluição. As análises mostraram uma queda nas concentrações de MP_{10} ao longo dos anos, conforme o teste *Theil-Sen*. Em Canoas, observou-se uma redução significativa (p-valor $< 0{,}01$) de 2.18 $\mu g.m^{-3}$ ao ano, enquanto em Paulínia a redução de 0.35 $\mu g.m^{-3}$ ao ano não foi significativa (p-valor $> 0{,}10$) e ainda permaneceu acima dos 15 $\mu g.m^{-3}$ recomendados pela WHO. O cálculo do risco relativo estimou que, com essa redução, 4.367 e 2.351 eventos de saúde poderiam ter sido evitados em Canoas e Paulínia, respectivamente. Esses dados ressaltam a necessidade de políticas que melhorem a qualidade do ar e protejam a saúde pública.

palavras-chave poluição atmosférica, mortalidade, AirQ+, MP_{10}

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Introduction

The rapid progress of industrialization coupled with the overexploitation of natural resources has led to a significant increase in air pollution, which, in turn, can cause respiratory and cardiovascular diseases, lung cancer, and even premature deaths. In addition, air pollution ranks sixth among the leading causes of reduced life expectancy and is the main source of environmental damage (Corá et al., 2020). If air pollution is not controlled by 2050, it will be the major cause of death worldwide. Some locations experience a higher incidence of disease due to intense human activity (Gou et al., 2024).

Several studies have been conducted to assess the health status resulting from exposure to air pollution. According to the World Health Statistics report released by the World Health Organization (WHO), air pollution caused approximately 6.7 million deaths globally in 2019 (World Health Organization [WHO], 2023), and a study by the Pan American Health Organization (PAHO) reported that 51,000 deaths every year are attributed to outdoor air pollution in Brazil (Vormittag et al., 2021).

In this context, particulate matter (PM) is a mixture of solid and liquid phases suspended in the atmosphere, divided into fractions based on the aerodynamic diameter (d_a) of the particle. Two well-known fractions are $PM_{2.5}$, or fine particulate matter ($d_a \leq 2.5\,\mu m$), and PM_{10} ($d_a \leq 10\,\mu m$), considered coarse particulate matter (Conselho Nacional do Meio Ambiente [CONAMA], 2024; Seinfeld & Pandis, 2006). $PM_{2.5}$ originates from anthropogenic activities, such as vehicle emissions, industrial processes, and biomass burning, as well as natural sources, such as wildfires and volcanic eruptions. PM_{10} originates from natural sources, such as soil particle resuspension, geological processes, and soil erosion, as well as local sources (Marín et al., 2025). Therefore, it is important to use the maximum PM concentration limits as a guide.

In Brazil, air quality standards were defined in CONAMA 3/1990, which was later amended by CONAMA 491/2018 (within the period of this study, from 2010 to 2019). It establishes the maximum limit of 40 $\mu g.m^{-3}$ for the annual average concentration of PM_{10} and a 24-hour average of 120 $\mu g.m^{-3}$ to protect the health of the population (Conselho Nacional do Meio Ambiente [CONAMA], 2018; Wikuats, 2023). CONAMA 506/2024 is currently in force (CONAMA, 2024), following the recommendations of the WHO (World Health Organization [WHO], 2021), but with intermediate stages.

In the State of São Paulo (SP), State Decree 59113/2013 had already established even stricter intermediate limits and final standards, with progressively lower values for PM_{10}, aligned with the recommendations of the WHO and promoting the gradual improvement of air quality (São Paulo, 2013). The final standard for PM_{10} is 50 $\mu g.m^{-3}$ (24-hour average) and 20 $\mu g.m^{-3}$ (annual average). In the state of Rio Grande do Sul (RS), the same national standards defined by CONAMA are adopted, without specific state limits, according to reports from the *Fundação Estadual de Proteção Ambiental Henrique Roessler* (FEPAM) (Fundação Estadual de Proteção Ambiental [FEPAM], 2024), which use the values established in federal resolutions for monitoring and assessing air quality in the state.

The limits recognize the impacts of PM on public health and highlight the need for policies and actions to control atmospheric emissions. To define a more restrictive value, the WHO recommends 15 $\mu g.m^{-3}$ as the annual average concentration of PM_{10} (WHO, 2021). This value can help public administration and monitoring agencies in preventing adverse effects on human health in municipalities and states (Tavella et al., 2024; Wang et al., 2019).

In India, PM values exceeded the limits defined in local legislation and the guidelines recommended by the WHO. A study conducted by Manojkumar and Srimuruganandam (2021), in India, concluded that cities with high PM concentrations lead to more hospitalizations and higher mortality rates. In Iran, a 10-year study by Raji et al. (2020) demonstrated that adults and the elderly are more likely to be hospitalized due to respiratory causes after short-term exposure to air pollutants. Moreover, given that air pollutants contribute, to mortality from various diseases, especially cardiovascular and respiratory diseases, preventive measures are required to contain sources of emission (Sokoty et al., 2020). In Brazil, studies report similar concerns regarding the effects of air pollution associated with prolonged exposure and mortality (Corá et al., 2020; Gouveia & Junger, 2018; Gouveia et al., 2017).

In 2016, the WHO Regional Office for Europe implemented the AirQ+ tool for statistical analyses to estimate the health impact of air pollutant concentrations, including the ability to calculate reductions in life expectancy. AirQ+ provides two main types of estimates: one for short-term exposure and the other for long-term exposure (Arregocés et al., 2023; Sharma et al., 2024).

Using data on pollutant concentrations, total population, population at risk, and incidence per 100,000 inhabitants, the program calculates the fraction and number of cases of diseases and deaths attributable to air pollution exposure, allowing the development of studies that assess the impacts of air quality on the health of exposed population (Amini et al., 2024; Wikuats et al., 2023). The use of the recommended concentration standard is suggested as a guideline.

Studies conducted in countries such as Brazil, Greece, Kuwait, Iran, and South Korea have used this tool to quantify health risks (Al-Hemoud et al., 2018; Gholampour et al., 2014; Gonçalves, et al., 2024; Jeong, 2013; Moustris et al., 2017).

Therefore, understanding and evaluating the behavior of air pollutants and their different sources of emission remains a challenge for researchers. Large-scale datasets are available from air quality monitoring systems, requiring computational tools to help evaluate these data. The Openair package of R programming language, was developed to analyze air quality monitoring information related to atmospheric pollutants and meteorological variables (Carslaw & Ropkins, 2012).

In a study conducted in the city of Yasuj, Iran, Fallahizadeh et al. (2021) demonstrated that meteorological factors, such as decreased rainfall and dust storms, contributed to increased PM_{10} concentrations, with a direct impact on the health of the population. In Brazil, Almeida et al. (2019) used the Openair package to assess air quality in two metropolitan areas of Rio de Janeiro, one characterized by industrial activity and an urban area. This study highlighted the importance of using statistical software in data processing, emphasizing the results of atmospheric air quality monitoring stations.

Given the issue described before, this study assessed two medium-sized municipalities located in different regions of Brazil: Canoas in the state of Rio Grande do Sul and Paulínia in the state of São Paulo, both with active oil refineries. These cities were selected because of the presence of these industrial plants, which significantly influence air quality (Tavella et al., 2025) and, consequently, population health. In Paulínia, the refinery is responsible for approximately 96% of the greenhouse gas emissions of the municipality, making it one of the most polluted cities in the state of São Paulo (Instituto de Pesquisa Econômica Aplicada [IPEA], 2022). Problems related to PM have already been reported (Nogarotto et al., 2020) and population health data have been collected (Fernandes et al., 2020) in the city.

Considering the above, this study aimed to assess the impact of air pollution on human health by estimating the mortality from respiratory diseases and causes related to PM_{10} exposure in the cities of Paulínia, São Paulo, and Canoas, Rio Grande do Sul. Individuals aged 30 to 59 years were assessed, using hospitalization data from 2010 to 2019. In addition, the average trends of PM_{10} concentrations were estimated over this period. This age group for the analysis of PM_{10} impacts was selected because it represents the economically active population, frequently exposed to environmental and occupational factors that enhance the effects of PM. Bennett et al. (2018) showed that adults in this age group are at significant risk of lung function decline due to prolonged exposure to PM_{10} and present a higher prevalence of chronic respiratory diseases. The literature also recommends standardizing age groups in epidemiological studies to allow for more accurate comparisons and analyses of the effects of pollutants (WHO, 2021).

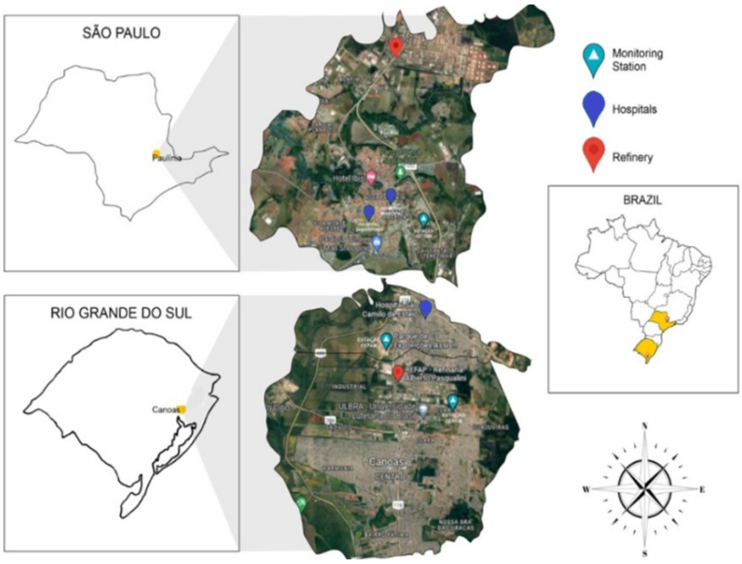
Material and methods

Study sites

The study site covers the municipalities of Canoas (Rio Grande do Sul), in the South region, and Paulínia (São Paulo), located in the Southeast region, see Figure 1. These municipalities have similar population densities and offer systems with real-time air quality monitoring data.

Canoas, situated in the central area of Porto Alegre Metropolitan Area. It has 323,827 inhabitants, 11,658 active companies, a fleet of 206,250 vehicles, and an area of approximately 131 km^2 (Instituto Brasileiro de Geografia e Estatística [IBGE], 2022. It is located at latitude $29°55'12''S$ and longitude $51°10'48''W$, eight meters above sea level. Canoas is located near one of the largest petrochemical companies in Rio Grande do Sul, the Refinaria Alberto Pasqualini (REFAP), which occupies 5.8 km^2 and processes 32,000 m^3 petroleum/day (Petrobrás, 2021). The municipality has a high population density, with around 2,470 inhabitants per km^2 and an intense industrial activity, including metalworking, gas, electrical, furniture, and fertilizer plants. Another important factor is the influence of vehicle emissions, as it is located near the BR-116 highway, one of the main highways in the area, with a high flow of light and heavy vehicles.

Figure 1 - Geographical location of the municipalities of Canoas (Rio Grande do Sul) and Paulínia (São Paulo), Brazil.



It is considered one of the urban and industrial hubs of the South region of Brazil, which reinforces the importance of the municipality for studies assessing the impacts of anthropogenic emissions on air quality (Alves et al., 2020; Ceratti et al., 2021).

Paulínia is located in Campinas Metropolitan Area, in the northwest of the state of São Paulo, with a territory of around 138 km^2 and an estimated population of 114,508 people (IBGE, 2022). It is located at latitude $22°45'39''\mathrm{S}$ and longitude $47°09'15''\mathrm{W}$, $588\,\mathrm{m}$ above sea level. The largest petrochemical complex in Latin America is located there, which includes an oil refinery, Refinaria Planalto de Paulínia (REPLAN), which has about 20% of the production of petroleum products in Brazil (Petrobrás, 2025). Also, it is influenced by the metropolitan area of Campinas and its vehicle fleet of 76,832 vehicles (IBGE, 2022; Nogarotto et al., 2020).

According to an Air Quality report issued by the *Companhia Ambiental do Estado de São Paulo* (CETESB), the city has two air quality monitoring stations, the oldest of which has operated since 2000 and the other since March 2018, both located in different districts of the municipality (Companhia Ambiental do Estado de São Paulo [CETESB], 2021; Miranda, et al., 2015).

In terms of the Köppen climate classification both Canoas and Paulínia have a *Cfa* climate, which is a humid subtropical climate with hot summers and evenly distributed rainfall throughout the year. Canoas has an average annual temperature of $19.6\ °\mathrm{C}$ and precipitation of about $1.580\,\mathrm{mm}$, also with rainfall evenly distributed throughout the year. Paulínia, on the other hand, has average summer temperatures above $22\ °\mathrm{C}$, with an average annual precipitation of about $1.478\,\mathrm{mm}$. Although both cities have the same climate classification, there are significant differences in their local meteorological conditions, such as temperature range and annual precipitation, which can influence the dispersion of atmospheric pollutants (Climate-Data, 2025).

Canoas and Paulínia were selected particularly due to the presence of major oil refineries, such as REFAP and REPLAN, respectively, as well as other industrial plants. These industrial hubs are significant sources of emissions of atmospheric pollutants, including PM, allowing assessments of the impact of oil refining activities on air quality in medium-sized urban centers, which, in turn, help expand the understanding of local effects of pollutant emissions and how they affect human health (Tavella et al., 2025).

Data acquisition and treatment

Data on the average annual PM_{10} concentration for Canoas were obtained from the Air Quality Monitoring Network of the *Fundação Estadual de Proteção Ambiental Henrique Luís Roessler* (FEPAM), located at Rua Viana Moog, 101, at latitude $-29.88°$ and longitude $-51.14°$. For Paulínia, data were obtained from the CETESB QUALAR System, from the Automatic Network station located at Praça Oadil Pietrobom, s/nº, Vila Bressani, at $29°55'$ S - $51°10'$ W. The study used PM_{10} concentration data from 2010 to 2019 for both municipalities.

Mortality and hospitalization data were also used in this study. They were obtained from the Department of Informatics of the Brazilian Unified Health System (DATASUS) system, and the ICD-10 (International Classification of Diseases) Chapter X, Diseases of the respiratory system (age group 30 to 59 years) was selected. These data are specific for hospitalizations in public hospitals, data from the private health system are not considered. Based on the number of hospital admissions, the incidence rate for the specific population in each municipality was calculated for each year, using a factor of 100,000 inhabitants, given by equation (1):

$$\text{Incidence} = \frac{\text{number of hospital admissions}}{\text{specific population}} \times n. \quad (1)$$

To assess the impact of air pollution, the following data were used in AirQ+:

(i) air pollutant data;

(ii) incidence per 100,000 inhabitants;

(iii) hospital admissions and deaths.

The AirQ+ model correlates air quality data, such as the various ranges of average annual concentrations, with epidemiological parameters. These parameters can include relative risk (RR), incidence, and the estimated number of cases attributable to a certain level of exposure (Gonçalves, et al., 2024).

However, the tool has some limitations, as it does not consider situations of simultaneous exposure to multiple pollutants or scenarios with different sources of contamination. It also uses environmental data as an indirect way to estimate population exposure, which can cause uncertainty. Another important point is that estimates related to morbidity have a low level of precision. This is because it is difficult to establish a direct and reliable correlation between hospital admission data and the adverse effects on population health caused by pollution (World Health Organization [WHO], 2016).

Relative risk (RR) represents the likelihood of disease occurrence due to exposure to the pollutant (Khaniabadi, Fanelli, et al., 2017; Khaniabadi, Goudarzi, et al., 2017). It is the main output of the tool, and relates the effects of PM_{10} concentrations on population health. Based on the RR, the impact fraction can be determined, indicating the percentage of all deaths that can be attributed to exposure to the pollutant (Ostro, 2004; Sharma et al., 2024).

AirQ+ has two calculation lines, one for short-term exposure and one for long-term exposure. Our study was based on the short-term exposure calculation. The RR calculation requires the coefficient β (Ostro, 2004), which assesses the impact of air pollutants on human health, along with mortality and life expectancy of the population, according to equation (2):

$$RR = \exp\left[\beta \cdot (X - X_0)\right], \quad (2)$$

where X is the average annual concentration of PM_{10}; X_0 is the cutoff concentration (using the value recommended by the WHO of 15 µgm^{-3}); β is the the risk coefficient for PM_{10} ($\beta = 0.0008$, with a lower limit of 0.0006 and an upper limit of 0.0010, default values of the tool), considering a 95% confidence interval (CI), as recommended by Ostro (2004), and Wikuats et al. (2023).

The analysis of PM_{10} concentration data was performed using the `Openair` package available in R 4.1.0 (R Core Team, 2023). This package facilitates the evaluation of a larger amount of data correlating air pollutants, topography, and meteorological information.

The `TheilSen` function in the *Openair* package was used as it estimates trends for pollutant concentrations over the selected period, with a 95% confidence interval (Carslaw & Ropkins, 2012). According to Carslaw (2015) and Carslaw and Ropkins (2012), this function is used to analyze the annual trend of increasing or decreasing air pollutant concentrations, correlating them with the seasons. The advantages of using the `TheilSen` function include its ability to resist outliers and heteroscedasticity, and it is a nonparametric method, that is, it makes no assumptions about data distribution and dispersion (Ancelet et al., 2015; Mateus & Gioda, 2017).

For PM_{10}, the annual average concentrations of each municipality in the study sites were compared with the air quality values recommended by the WHO (2021), considering the number of times these values were exceeded.

Results and discussion

Table 1 shows the epidemiological data (hospital admissions, incidence, and deaths) and the annual average concentrations of PM_{10} for Canoas and Paulínia, for the age group of 30 to 59 years old. These data were used as input in AirQ+ to estimate the impact of PM exposure on the health of local populations, allowing an assessment of the potential reduction in the number of cases and deaths with improved air quality.

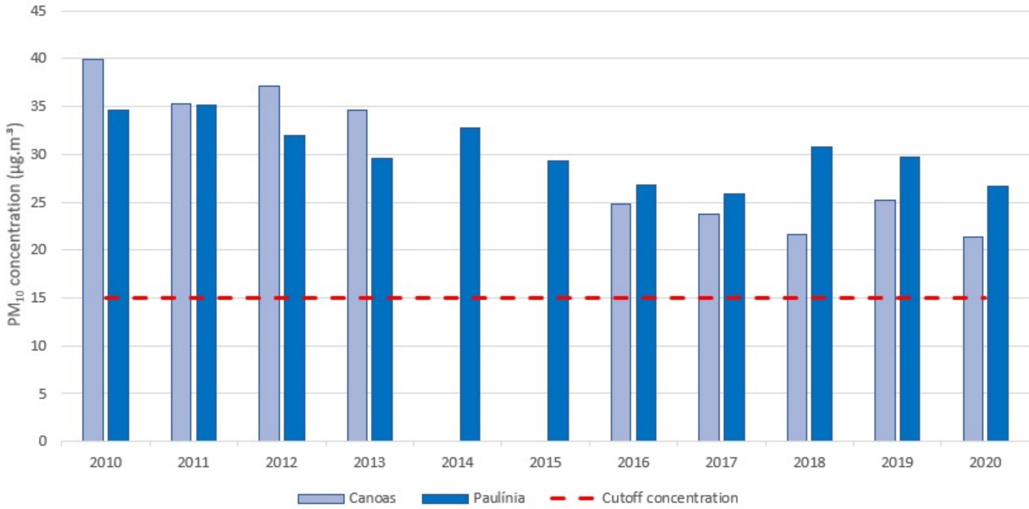
Table 1 - Input data used in AirQ+ referring to the municipalities of Canoas and Paulínia for the age group of 30 to 59 years old, with their respective missing data (%) from 2010 to 2019.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Canoas										
Hospital admissions	581	635	633	662	667	612	594	531	469	408
Incidence	435.9	471.5	465.2	481.6	480.9	438.0	422.9	376.4	331.5	287.7
Deaths	51	51	65	69	86	79	68	56	56	55
Average conc. ($\mu g.m^{-3}$)	39.9	35.2	37.1	34.6	22.0	19.0	24.8	23.7	21.6	25.2
Missing data (%)	3.88	7.92	3.73	38.30	**99.31**	**86.16**	11.13	5.54	2.76	31.64
Paulínia										
Hospital admissions	81	104	89	125	109	75	88	86	77	85
Incidence	288.3	281.5	231.6	313.4	263.7	175.4	191.0	188.6	164.0	176.2
Deaths	7	7	7	3	5	7	2	12	3	8
Average conc. ($\mu g.m^{-3}$)	34.5	35.1	31.9	29.5	32.7	29.3	26.8	25.8	30.8	29.7
Missing data (%)	0.73	1.31	4.12	3.57	6.00	1.26	2.40	3.60	6.00	2.04

Table 1 also shows a compilation of missing data from the QUALAR database of CETESB, organized by year. A higher level of missing data is seen in Canoas in 2014 and 2015, when compared to other years, which may explain the low concentrations of PM_{10} observed for these years. Therefore, for Canoas, these years were not considered in the analysis of this study.

Figure 2 shows the average annual concentration of PM_{10} in Paulínia and Canoas from 2010 to 2019, compared with the WHO (2021) guideline value of 15 $\mu g.m^{-3}$. A reduction in average annual concentrations is observed, although the values are still well above this reference during the study period (2010 to 2019).

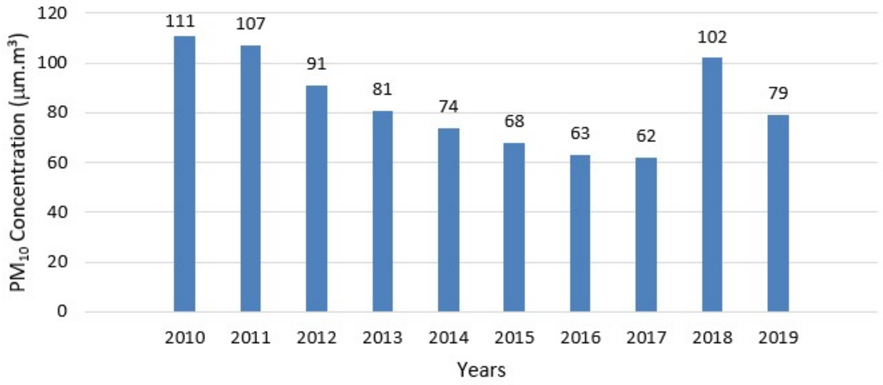
Figure 2 - Average annual concentration of PM_{10} (2010 to 2019) in Canoas and Paulínia.



High PM_{10} concentrations were observed in 2010 and 2011, as illustrated in Figure 2. The annual report, "Winter Operation and Air Quality," by CETESB (2012) states that the winter of 2011 and the previous year had low humidity, which hinders the dispersion of pollutants.

Figure 3 shows the maximum annual concentrations in Paulínia from 2010 to 2019, during the winter period between May and September.

Figure 3 - Maximum daily concentrations of PM_{10} ($\mu g.m^{-3}$) in winter (May to September) from 2010 to 2019 in Paulínia.

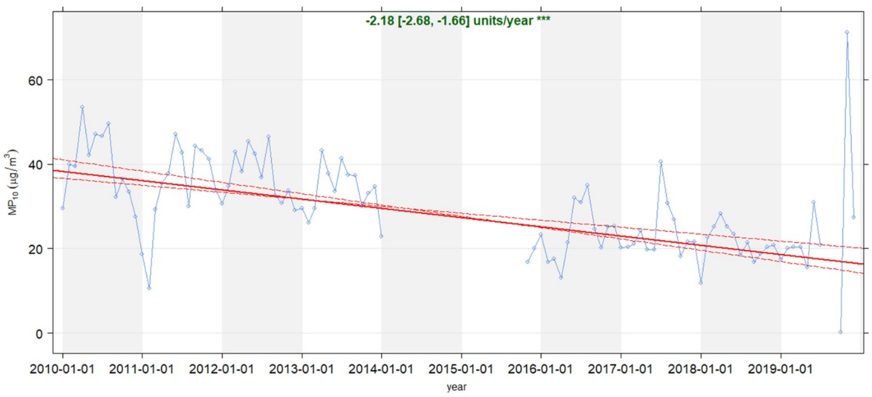


The data, Figure 3, indicated maximum daily concentrations of 111 and 107 $\mu g.m^{-3}$ in 2010 and 2011, respectively. The characteristics of this season were mainly influenced by La Niña (Andreão et al., 2018), which is a phenomenon characterized by the predominance of hot air masses in South America, covering several areas of the state of São Paulo, including the northwest area where Paulínia is located. August was the month with no precipitation in 2010, with relative humidity around or below 20% (CETESB, 2021). In Canoas, in 2010 and 2011, high annual average concentrations of PM_{10} were also observed. Between 2013 and 2017, the lack of data may have resulted in low concentration values. However, it was not possible to perform the same analysis for Canoas due to the lack of data available for the winter in the area during the study period.

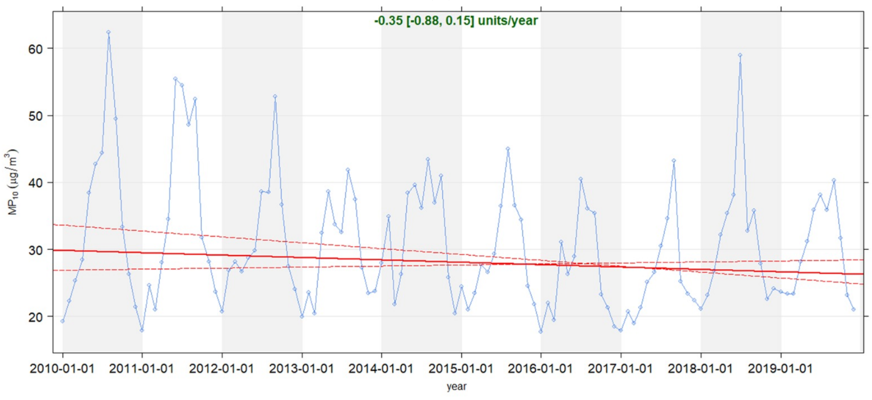
Figure 4 illustrates the trend analysis of average monthly concentrations of PM_{10} in Canoas and Paulínia from 2010 to 2019, where the solid red line represents the trend estimate with 95% confidence intervals (dashed red lines) obtained through bootstrap resampling methods. Asterisks (**) denote a significant trend at the 0.001 level, while the absence of a symbol indicates no statistically significant trend.

Figure 4 - Trend analysis of monthly PM_{10} concentrations in: (a) Canoas, and (b) Paulínia.

(a)



(b)



A downward trend in concentration was observed over the years. In Canoas, Figure 4(a), a significant decrease of 2.18 $\mu g.m^{-3}$ per year was reported (p-value < 0.01). However, in Paulínia, Figure 4(b), a decrease of 0.35 $\mu g.m^{-3}$ per year was reported (p-value > 0.10).

A study conducted by Marinho et al. (2022) in Paulínia analyzed an 18-year historical series of data and found a reduction in PM_{10} concentrations. The decrease was 2.41% per year in winter and 0.95% per year in summer. Another study conducted in Portugal by Gama et al. (2018) indicated that, during dry periods, average air pollutant concentrations increased significantly due to the resuspension of soil particles and the incidence of fires, with data collected over 10 years.

Relative risk

Table 2 shows the relative risk (RR), given in equation(2), expressed as the probability ratio indicating how different levels of air pollutant concentrations affected hospitalizations in Canoas and Paulínia during the period 2010 to 2019.

Table 2 - Relative risk (RR) to the population aged 30 to 59 years exposed to PM_{10} concentrations in Canoas and Paulínia based on β values.

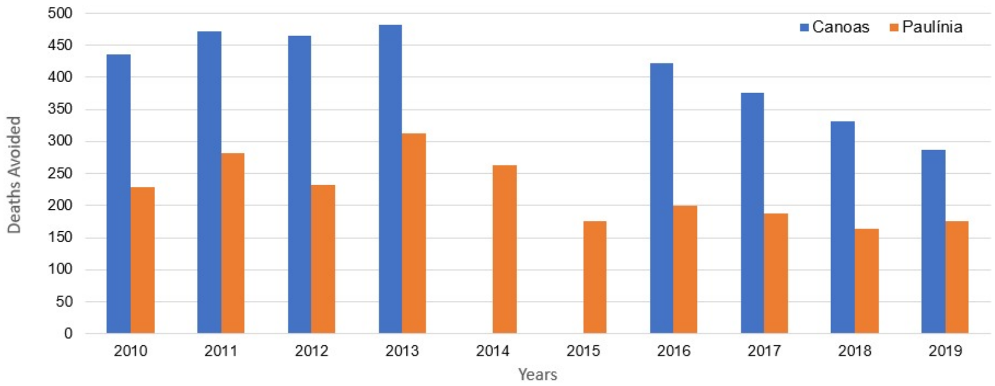
Year	RR ($\beta = 0.0006$)	RR ($\beta = 0.0008$)	RR ($\beta = 0.0010$)
		Canoas	
2010	1.0151	1.0194	1.0253
2011	1.0122	1.0163	1.0205
2012	1.0134	1.0179	1.0224
2013	1.0118	1.0158	1.0198
2014	–	–	–
2015	–	–	–
2016	1.0059	1.0079	1.0099
2017	1.0053	1.0070	1.0088
2018	1.0040	1.0067	1.0094
2019	1.0022	1.0042	1.0103
		Paulínia	
2010	1.0118	1.0158	1.0198
2011	1.0122	**1.0163**	1.0204
2012	1.0088	1.0131	1.0171
2013	1.0117	1.0170	1.0247
2014	1.0080	1.0117	1.0145
2015	1.0090	1.0127	1.0164
2016	1.0045	1.0067	1.0090
2017	1.0065	1.0087	1.0120
2018	1.0061	**1.0087**	1.0159
2019	1.0089	1.0119	1.0148

Note that, as shown in Table 2, both municipalities presented *RR* values above 1, indicating a positive association between exposure to PM10 and hospital admissions due to this exposure (Corá et al., 2020; Pope et al., 2002). Canoas showed a reduction of about 1.40% from 2010 to 2019, and Paulínia, 0.39%. In Canoas, *RR* values ranged from 1.0050 to 1.0190, while in Paulínia, the highest RR was 1.0163 in 2011 and the lowest 1.0087 in 2017. *RR* values greater than 1 (considering confidence intervals) indicate that PM_{10} exposure increases the risk of hospitalization, meaning that the likelihood of a health event is higher among exposed individuals than among unexposed individuals (Lund et al., 2016). In Paulínia, the *RR* of 1.0163 in 2011 corresponds to a 1.63% increase in the risk of respiratory diseases for exposure to 25.8 $\mu g.m^{-3}$ of PM_{10} compared with 15 $\mu g.m^{-3}$, as recommended by the WHO.

Thus, an increase of about 10 $\mu g.m^{-3}$ in PM_{10} represents a significant public health impact, especially in frequent exposures and large populations.

If PM_{10} concentrations had followed the WHO recommendation of 15 $\mu g.m^{-3}$, a total of 4,367 deaths in Canoas and 2,351 in Paulínia, see Figure 5, could have been avoided in the 9-year study period (2010 to 2019), representing about 0.5% to 0.3% of deaths in Canoas and Paulínia, respectively, which could have been lower every year. In comparison to Spain, if pollutants could be kept within the safe limits established by the WHO for human health, the number of deaths could be reduced by 0.5% to 7% every year (Rovira et al., 2020). In addition, according to the study by Abdolahnejad et al. (2017), a 10 $\mu g.m^{-3}$ increase in PM_{10} concentration can lead to a 6% increase in the mortality rate.

Figure 5 - Deaths that could be avoided per 100,000 inhabitants aged 30 to 59 years exposed to PM_{10} concentrations in Canoas and Paulínia.



Comparative assessment of PM_{10} impacts

Comparative studies reveal the impact of PM_{10} pollution on the total number of deaths attributed to it in Brazilian municipalities and other cities in Iran, Table 3.

Table 3 - Comparison of total deaths attributable to PM_{10} in Canoas, Paulínia, and other cities based on different studies.

Study site	Period	Deaths due to PM_{10}	Total deaths	Reference
		Brazil		
Paulínia	2010–2019	2,222	222.2	Authors of this study
Canoas	2010–2019	4,912	419.2	Authors of this study
Florianópolis	2018–2020	52.5	17.5	Martins et al. (2025)
Ribeirão Preto	2017–2021	100	20.0	Gonçalves, et al., (2024)
		Iran		
Tehran	2008–2010	2,194	731.3	Gharehchahi et al. (2013)
Tabriz	09/2012–05/2013	363	544.5	Gholampour et al. (2014)
Khorramabad	2014	320	32.0	Nourmoradi et al. (2015)

The analysis over different periods, Table 3, highlights the urgent need for action to monitor and improve air quality globally. While comparison with data from other studies is important for contextualizing the results, it is essential to emphasize that the geographic and meteorological characteristics, as well as the different sources of emission in each location, directly influence the concentrations of air pollutants and, consequently, the results obtained. Therefore, these specificities must be considered in the analysis and interpretation of the results (Gonçalves, et al., 2022).

To date, there are no records of previous studies using AirQ+ to estimate the health risks associated with air pollution in the cities of Paulínia and Canoas, making this analysis the first in this context. Wikuats et al. (2023) conducted a health impact assessment in the city of São Paulo (about 120 km from Paulínia) to investigate the negative impacts of air pollution on the health of the population using the same program to analyze avoided deaths. These data, compared with our study, provide a comprehensive view of the consequences of PM_{10} exposure in different geographic, social, and economic contexts, reinforcing the importance of developing public policies to protect human health.

Reducing air pollutant concentrations is a way to ensure safe limits for human health, thus reducing mortality rates and the negative impacts on the quality of life of the population (Pope et al., 2002).

Martins et al. (2025) used the APHEKOM model to assess the risk of exposure to $PM_{2.5}$ and PM_{10} in the city of Florianópolis. A reduction in PM_{10} concentrations to the levels recommended by the WHO could avoid about 29 hospital admissions due to respiratory diseases and 12 due to cardiovascular causes, resulting in annual savings of over US$ 313,000 for the public health system.

Due to data availability, this study considered only PM_{10} concentrations. The selection of this pollutant, which focuses on respiratory diseases (ICD-10 Chapter X), is supported by scientific studies. For example, in Visby, Sweden, Tornevi et al. (2022) analyzed the short-term associations between PM_{10} concentrations and the daily number of visits in hospitals and primary care facilities due to acute respiratory problems from 2013 to 2019. The authors observed that increases in PM_{10} concentration levels were directly associated with an increase in respiratory diseases, particularly among children, where asthma-related medical appointments increased 5% for each 10 $\mu g.m^{-3}$ increase of PM_{10}. The study used PM_{10} exclusively as an environmental parameter, demonstrating that even in scenarios with different particle compositions, the adverse effects on respiratory health are significant and measurable. Therefore, the use of PM_{10} as the sole pollutant in this study is methodologically justified and is supported by recent international studies (Sasmita et al., 2022).

Although PM_{10} is a relevant indicator for respiratory health, the model applied in this study using AirQ+ has certain limitations, as it does not account for various other factors that may affect the relationship between air pollution and hospitalization or mortality rates. Such factors may include body mass index, lifestyle characteristics (such as smoking and alcohol consumption), engagement in physical activities, educational attainment, income, and medical background as previously reported by Wikuats et al. (2023) and Martins et al. (2025).

Conclusions

Air pollution has a global impact on the quality of life of population, so assessing the behavior of air pollutants over time is extremely important. Therefore, the use of statistical tools and models to evaluate long-term air quality data series helps understand the spatial and temporal nature of air pollutants.

In our study, the PM_{10} values recommended by the WHO (2021) were exceeded in both Canoas and Paulínia from 2010 to 2019. Also, a downward trend in PM_{10} concentrations was observed using the TheilSen function. The trend assessment of monthly average PM_{10} concentrations was significant in Canoas, but not significant in Paulínia.

The incidence of respiratory diseases showed a correlation with PM_{10} concentrations, which impacted the mortality rate. The incidence was 4,367 in Canoas and 2,351 in Paulínia. The *RR* was above 1 in both municipalities, with the largest variations of 1.019 and 1.016 in Canoas and Paulínia, respectively. These population and health data were extracted from a comprehensive nationwide data source. Therefore, this relative information may be influenced by air quality data and response patterns to air pollutant concentrations.

It should be noted that this study did not consider other factors that can influence pollution levels, such as meteorological variables, economic activities, wild fires, among others. We considered only PM_{10} concentrations and incidence to calculate the relative risk. Also, hospital admission data are related to public hospitals and do not include the private healthcare network.

In this study, the impact of air quality was focused exclusively on PM_{10}. However, for more accurate and comprehensive analyses of the correlation between air pollutant concentrations and epidemiological studies, it would be more efficient to include different pollutants such as fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3) (Zhang et al., 2021).

Finally, AirQ+ is an essential tool for monitoring and, if necessary, control measures to reduce air pollution levels, according to the recommendations of the WHO, in order to achieve the targets established in the 2030 Agenda for Sustainable Development (Sustainable Development Goals – SDGs), especially those related to promoting good health and well-being (SDG 3) and improving air quality in cities (SDG 11). These measures could have significantly reduced the number of deaths over the study period in both municipalities, which emphasizes the need for public policies that minimize and reduce the impact of air quality degradation on the quality of life of the population.

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Author Contributions

B. C. R. Pinto: data curation, formal analysis, funding acquisition, investigation, visualization, writing – original draft preparation; **J. M. P. Americo**: data curation, formal analysis, funding acquisition; **D. C. Nogorotto**: formal analysis, software, validation; **D. M. M. Osório**: methodology, validation; **S. A. Pozza**: conceptualization, funding acquisition, project administration, resources, supervision, validation, writing – review & editing.

Conflicts of Interest

The authors declare no conflict of interest.

References

Abdolahnejad, A., Jafari, N., Mohammadi, A., Miri, M., Hajizadeh, Y., & Nikoonahad, A. (2017). Cardiovascular, respiratory, and total mortality ascribed to PM_{10} and $PM_{2.5}$ exposure in Isfahan, Iran. *Journal of Education and Health Promotion*, *6*(1), 1–6. https://pubmed.ncbi.nlm.nih.gov/29296610/

Al-Hemoud, A., Gasana, J., Al-Dabbous, A., A. N. anad Al-Shatti, & Al-Khayat, A. (2018). Disability adjusted life years (DALYs) in terms of years of life lost (YLL) due to premature adult mortalities and postneonatal infant mortalities attributed to $PM_{2.5}$ and PM_{10} exposures in Kuwait. *International Journal of Environmental Research and Public Health*, *15*(11), 2609. https://doi.org/10.3390/ijerph15112609

Almeida, R. P. S., Souza, T. C., Souza, S. L. Q., Martins, E. M., & Corrêa, S. M. (2019). Comparação da Qualidade do Ar em Localidades Industrial e Urbana. *Revista Internacional de Ciências*, *9*(3), 47–62. https://doi.org/10.12957/ric.2019.42897

Alves, D. D., Riegel, R. P., Klauck, C. R., Ceratti, A. M., Hansen, J., Cansi, L. M., Pozza, S. A., de Quevedo, D. M., & Osório, D. M. M. (2020). Source apportionment of metallic elements in urban atmospheric particulate matter and assessment of its water-soluble fraction toxicity. *Environmental Science and Pollution Research*, *27*, 12202–12214. https://doi.org/10.1007/s11356-020-07791-8

Amini, H., Yousefian, F., Faridi, S., Andersen, Z. J., Calès, E., Castro, A., Cervantes-Martínez, K., Cole-Hunter, T., Correia, M., Dragić, N., Evangelopoulos, D., Gapp, C., Hassanvand, M. S., Kim, I., Le Tertre, A., Medina, S., Miller, B., Montero, S., Requia, W. J., … Mudu, P. (2024). Two decades of air pollution health risk assessment: Insights from the use of WHO's AirQ and AirQ+ tools. *Public Health Reviews*, *45*, 1600699. https://doi.org/10.3389/phrs.2024.1606969

Ancelet, T., Davy, P. K., & Trompetter, W. J. (2015). Particulate matter sources and long-term trends in a small New Zealand City. *Atmospheric Pollution Research*, *6*(6), 1105–1112. https://doi.org/10.1016/j.apr.2015.06.008

Andreão, W. L., Albuquerque, T., & Kumar, P. (2018). Excess deaths associated with fine particulate matter in Brazilian cities. *Atmospheric Environment*, *194*, 71–81. https://doi.org/10.1016/j.atmosenv.2018.09.034

Arregocés, H. A., Rojano, R., & Restrepo, G. (2023). Health risk assessment for particulate matter: application of AirQ+ model in the northern Caribbean region of Colombia. *Air Quality, Atmosphere and Health*, *16*(5), 897–912. https://doi.org/10.1007/s11869-023-01304-5

Bennett, J. E., Kontis, V., Mathers, C. D., Guillot, M., Rehm, J., Chalkidou, K., & Ezzati, M. (2018). NCD Countdown 2030: worldwide trends in non-communicable disease mortality and progress towards Sustainable Development Goal target 3.4. *The Lancet*, *392*(10152), 1072–1088. https://doi.org/10.1016/S0140-6736(18)31992-5

Carslaw, D. C. (2015). *The openair manual: open-source tools for analysing air pollution data. Manual for version 1.1-4*. King's College London.

Carslaw, D. C., & Ropkins, K. (2012). Openair — An R package for air quality data analysis. *Environmental Modelling & Software*, *27-28*, 52–61. https://doi.org/https://doi.org/10.1016/j.envsoft.2011.09.008

Ceratti, A. M., da Costa, G. M., Alves, D. D., Cansi, L. M., Hansen, J., Brochier, F., de Quevedo, D. M., & Osorio, D. M. M. (2021). Polycyclic aromatic hydrocarbons (PAH) in atmospheric particles ($PM_{2.5}$ and $PM_{2.5-10}$): Integrated evaluation of the environmental scenario in urban areas. *Water, Air, and Soil Pollution*, *232*(1), 6. https://doi.org/10.1007/s11270-020-04967-3

Climate-Data. (2025). *Climate: Brazil*. https://en.climate-data.org/south-america/brazil-114/

Companhia Ambiental do Estado de São Paulo. (2012). *Operação Inverno 2011: qualidade do ar*. CETESB. https://repositorio.cetesb.sp.gov.br/items/b5208dbf-165c-43e1-9b78-8e8fb7c5d777/full

Companhia Ambiental do Estado de São Paulo. (2021). *Endereços das Estações das Redes de Monitoramento da Qualidade do Ar*. CETESB. https://repositorio.cetesb.sp.gov.br/bitstreams/0c6fbd73-84c0-4d90-88bb-81dd15fac677/download

Conselho Nacional do Meio Ambiente. (2018). *Resolução Conama n° 491/2018*. Dispõe sobre padrões de qualidade do ar. Conama. https://www.legisweb.com.br/legislacao/?id=369516

Conselho Nacional do Meio Ambiente. (2024). *Resolução Conama n° 506, de 5 de julho de 2024*. Estabelece padrões nacionais de qualidade do ar e fornece diretrizes para sua aplicação. Conama.

Corá, B., Leirião, L., & Miraglia, S. (2020). Impacto da poluição do ar na saúde pública em municípios de alta industrialização do estado de São Paulo. *Brazilian Journal of Environmental Sciences*, *55*(4), 498–509. https://doi.org/10.5327/Z2176-947820200671

Fallahizadeh, S., Kermani, M., Esrafili, A., Asadgol, Z., & Gholami, M. (2021). The effects of meteorological parameters on PM_{10}: Health impacts assessment using AirQ+ model and prediction by an artificial neural network (ANN). *Urban Climate*, *38*, 100905. https://doi.org/10.1016/j.uclim.2021.100905

Fernandes, M. A. O., Andreão, W. L., Maciel, F. M., & Albuquerque, T. T. A. (2020). Avoiding hospital admissions for respiratory system diseases by complying to the final Brazilian air quality standard: An estimate for Brazilian southeast capitals. *Environmental Science and Pollution Research*, *27*, 35889–35907. https://doi.org/10.1007/s11356-020-07772-x

Fundação Estadual de Proteção Ambiental. (2024). *Monitoramento da Qualidade do Ar*. https://www.fepam.rs.gov.br/monitoramento-da-qualidade-do-ar

Gama, C., Monteiro, A., Pio, C., Miranda, A., Baldasano, J., & Tchepel, O. (2018). Temporal patterns and trends of particulate matter over Portugal: a long-term analysis of background concentrations. *Air Quality, Atmosphere & Health*, *11*, 390–407. https://doi.org/10.1007/s11869-018-0546-8

Gharehchahi, E., Mahvi, A. H., Amini, H., Nabizadeh, R., Akhlaghi, A. A., & Shamsipour, M. (2013). Health impact assessment of air pollution in Shiraz, Iran: A two-part study. *Journal of Environmental Health Science and Engineering*, *11*(11), 1–8. https://doi.org/10.1186/2052-336X-11-11

Gholampour, A., Nabizadehr, N. S., Yunesianm, T. H., Rastkari, N., Nazmara, S., Faridi, S., & Mahvi, A. H. (2014). Exposure and health impacts of outdoor particulate matter in two urban and industrialized areas of Tabriz, Iran. *Journal of Environmental Health Science and Engineering*, *12*(27), 1–10. https://doi.org/10.1186/2052-336X-12-27

Gonçalves, P. B., Eulalio, J. C. D., Rufino, R. C., Nogarotto, D. C., & Pozza, S. A. (2024). Incidência de doenças respiratórias pela exposição ao material particulado atmosférico em três municípios de médio porte. *Cadernos Técnicos de Engenharia Sanitária e Ambiental*, *4*(1), 3–12. https://doi.org/10.5327/276455760401001

Gonçalves, P. B., Nogarotto, D. C., Canteras, F. B., & Pozza, S. A. (2022). The relationship between the number of COVID-19 cases, meteorological variables, and particulate matter concentration in a medium-sized Brazilian city. *Brazilian Journal of Environmental Sciences*, *57*(1), 167–178. https://doi.org/10.5327/Z217694781300

Gou, A., Zhu, X., Ding, X., Wang, J., Gou, C., Tan, Q., & Lv, X. (2024). Spatial association between chronic respiratory disease mortality rates and industrial manufacturing enterprises: A case study of Chongqing, China. *Sustainable Cities and Society*, *113*, 105720. https://doi.org/10.1016/j.scs.2024.105720

Gouveia, N., Corrallo, F. P., Ponce de Leon, A. C., Junger, W., & Freitas, C. U. (2017). Poluição do ar e hospitalizações na maior metrópole brasileira. *Revista de Saúde Pública*, *51*, 117. https://doi.org/10.11606/s1518-8787.2017051000223

Gouveia, N., & Junger, W. L. (2018). Effects of air pollution on infant and children respiratory mortality in four large Latin-American cities. *Environmental Pollution*, *232*, 385–391. https://doi.org/10.1016/j.envpol.2017.08.125

Instituto Brasileiro de Geografia e Estatística. (2022). *Cidades e Estados do Brasil*. IBGE. https://cidades.ibge.gov.br/

Instituto de Pesquisa Econômica Aplicada. (2022). *Atlas da vulnerabilidade socioambiental: impactos das mudanças climáticas na saúde humana nas cidades brasileiras*. Brasília: Ipea. https://www.ipea.gov.br

Jeong, S. J. (2013). The Impact of Air Pollution on Human Health in Suwon City. *Asian Journal of Atmospheric Environment*, *7*(4), 227–233. https://doi.org/10.5572/ajae.2013.7.4.227

Khaniabadi, Y. O., Fanelli, R., De Marco, A., Daryanoosh, S. M., Kloog, I., Hopke, P. K., Conti, G. O., Ferrante, M., & Mohammadi, M. J. (2017). Hospital admissions in Iran for cardiovascular and respiratory diseases attributed to the middle eastern dust storms. *Environmental Science and Pollution Research*, *24*, 16860–16868. https://doi.org/10.1007/s11356-017-9298-5

Khaniabadi, Y. O., Goudarzi, G., Daryanoosh, S. M., Borgini, A., Tittarelli, A., & De Marco, A. (2017). Exposure to PM_{10}, NO_2, and O_3 and impacts on human health. *Environmental Science and Pollution Research*, *24*, 2781–2789. https://doi.org/10.1007/s11356-016-8038-6

Lund, J. L., Richardson, D. B., & Stürmer, T. (2016). The active comparator, new user study design in pharmacoepidemiology: historical foundations and contemporary application. *Current Epidemiology Reports*, *3*(4), 297–305. https://doi.org/10.1007/s40471-015-0053-5

Manojkumar, N., & Srimuruganandam, B. (2021). Health effects of particulate matter in major Indian cities. *International Journal of Environmental Health Research*, *31*(3), 258–270. https://doi.org/10.1080/09603123.2019.1651257

Marín, D., Herrera, V., Piñeros-Jiménez, J. G., Rojas Sánchez, O. A., Mangones, S. C., Rojas, Y., Cáceres, J., Agudelo-Castañeda, D. M., Rojas, N. Y., Belalcazar-Ceron, L. C., Ochoa Villegas, J., Montes Mejía, M. L., Lopera-Velasquez, V. M., Castillo-Navarro, S. M., Torres-Prieto, A., Baumgartner, J., & Rodríguez-Villamizar, L. A. (2025). Longterm exposure to $PM_{2.5}$ and cardiorespiratory mortality: An ecological smallarea study in five cities in Colombia. *Cadernos de Saúde Pública*, *41*(4), e00071024. https://doi.org/10.1590/0102-311XEN071024

Marinho, L. V., Nogarotto, D. C., & Pozza, S. A. (2022). Análise de tendência de concentração de material particulado atmosférico e efetividade de políticas públicas. *Holos Environment*, *22*(2), 78–93. https://doi.org/10.14295/holos.v22i2.12470

Martins, E. H., Eicardi, M. S., Nogarotto, D. C., & Pozza, S. A. (2025). Health and economic benefits of lowering particulate matter (PM) levels: Scenarios for a southern Brazilian metropolis. *Aerosol Science and Engineering*, *5*, 91–112. https://doi.org/10.1007/s41810-024-00239-3

Mateus, V. L., & Gioda, A. (2017). A candidate framework for $PM_{2.5}$ source identification in highly industrialized urban-coastal areas. *Atmospheric Environment*, *164*, 147–164. https://doi.org/10.1016/j.atmosenv.2017.05.025

Miranda, A., Silveira, C., Ferreira, J., Monteiro, A., Lopes, D., Relvas, H., Borrego, C., & Roebeling, P. (2015). Current air quality plans in europe designed to support air quality management policies. *Atmospheric Pollution Research*, *6*(3), 434–443. https://doi.org/10.5094/APR.2015.048

Moustris, K. P., Ntourou, K., & Nastos, P. T. (2017). Estimation of particulate matter impact on human health within the urban environment of Athens City, Greece. *Urban Science*, *1*(1), 6. https://doi.org/10.3390/urbansci1010006

Nogarotto, D., Lima, M., & Pozza, S. (2020). Análise de componentes principais para verificar relação entre variáveis meteorológicas e a concentração de PM_{10}. *Holos*, *36*(1), 1–17. https://doi.org/10.15628/holos.2020.8649

Nourmoradi, H., Goudarzi, G., Daryanoosh, S. M., Omidi-Khaniabadi, F., Jourvand, M., & Omidi-Khaniabadi, Y. a. (2015). Health impacts of particulate matter in air using airq model in khorramabad city, iran. *Journal of Basic Research in Medical Sciences*, *2*(2). http://jbrms.medilam.ac.ir/article-1-157-en.html

Organization, W. .-. W. H. (2021). A call for standardised age-disaggregated health data. *Bulletin of the World Health Organization*, *99*(1), 3–3A.

Ostro, B. (2004). *Outdoor air pollution: assessing the environmental burden of disease at national and local levels*. Organização Mundial da Saúde, Occupational and Environmental Health Team. https://apps.who.int/iris/handle/10665/42909

Petrobrás. (2021). *Petróleo Brasileiro S.A.* https://www.petrobras.com.br

Petrobrás. (2025). *Refinaria de Paulínia*. https://petrobras.com.br/quem-somos/refinaria-de-paulinia

Pope, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA*, *287*(9), 1132–1141. https://doi.org/10.1001/jama.287.9.1132

R Core Team. (2023). *The R Project for Statistical Computing*. https://www.r-project.org/

Raji, H., Riahi, A., Borsi, S. H., Masoumi, K., Khanjani, N., AhmadiAngali, K., Goudarzi, G., & Dastoorpoor, M. (2020). Acute Effects of Air Pollution on Hospital Admissions for Asthma, COPD, and Bronchiectasis in Ahvaz, Iran. *International Journal of Chronic Obstructive Pulmonary Disease*, *15*, 501–514. https://doi.org/10.2147/COPD.S231317

Rovira, J., Domingo, J. L., & Schuhmacher, M. (2020). Air quality, health impacts and burden of disease due to air pollution (PM_{10}, $PM_{2.5}$, NO_2 and O_3): Application of AirQ+ model to the Camp de Tarragona County (Catalonia, Spain). *Science of The Total Environment*, *703*, 135538. https://doi.org/10.1016/j.scitotenv.2019.135538

São Paulo. Governo do Estado. (2013). *Decreto nº 59.113, de 23 de abril de 2013.* Estabelece novos padrões de qualidade do ar e dá providências correlatas. https://www.al.sp.gov.br/repositorio/legislacao/decreto/2013/decreto-59113-23.04.2013.html

Sasmita, S., Kumar, D. B., & Priyadharshini, B. (2022). Assessment of sources and health impacts of PM_{10} in an urban environment over eastern coastal plain of India. *Environmental Challenges*, *7*, 100457. https://doi.org/10.1016/j.envc.2022.100457

Seinfeld, J. H., & Pandis, S. N. (2006). *Chemistry and physics of air pollution: From air pollution to climate change* (2nd ed.). Scientific Research An Academic Publisher. https://doi.org/10.4236/ahs.2015.44023

Sharma, S., Singhal, A., Venkatramanan, V., Verma, P., & Pandey, M. (2024). Variability in air quality, ozone formation potential by VOCs, and associated air pollution attributable health risks for Delhi's inhabitants. *Environmental Science: Atmospheres*, *4*(8), 897–910. https://doi.org/10.1039/d4ea00064a

Sokoty, L., Kermani, M., Janani, L., Dowlati, M., Hassanlouei, B., & Rimaz, S. (2020). Estimation of cardiovascular and respiratory diseases attributed to PM_{10} using AirQ model in Urmia during 2011-2017. *Medical Journal of The Islamic Republic of Iran*, *34*, 60. https://doi.org/10.47176/mjiri.34.60

Tavella, R. A., de Moura, F. R., Miraglia, S. G. E. K., & Silva, F. M. R., Jr. (2024). A New Dawn for Air Quality in Brazil. *The Lancet Planetary Health*, *8*(10), e717–e718. https://doi.org/10.1016/S2542-5196(24)00203-1

Tavella, R. A., Silva, F. M. R., Jr., Santos, M. A., Miraglia, S. G. E. K., & Pereira, R. D., Filho. (2025). A Review of Air Pollution from Petroleum Refining and Petrochemical Industrial Complexes: Sources, Key Pollutants, Health Impacts, and Challenges. *ChemEngineering*, *9*(1), 13. https://doi.org/10.3390/chemengineering9010013

Tornevi, A., Olstrup, H., & Forsberg, B. (2022). Short-term associations between PM_{10} and respiratory health effects in Visby, Sweden. *Toxics*, *10*(6), 333. https://doi.org/10.3390/toxics10060333

Vormittag, E. M. P. A., Cirqueira, S. S. R., Wicher, N. H., & Saldiva, P. H. N. (2021). Análise do monitoramento da qualidade do ar no Brasil. *Estudos Avançados*, *35*(102), 7–30. https://doi.org/10.1590/s0103-4014.2021.35102.002

Wang, W., Liu, C., Ying, Z., Lei, X., Wang, C., Huo, J., Zhao, Q., Zhang, Y., Duan, Y., Chen, R., Fu, Q., Zhang, H., & Kan, H. (2019). Particulate air pollution and ischemic stroke hospitalization: how the associations vary by constituents in Shanghai, China. *Journal of Environmental Health Science and Engineering*, *695*, 1–8. https://doi.org/10.1016/j.scitotenv.2019.133780

Wikuats, C. F. H., Nogueira, T., Squizzato, R., Freitas, E. D., & Andrade, M. F. (2023). Health Risk Assessment of Exposure to Air Pollutants Exceeding the New WHO Air Quality Guidelines (AQGs) in São Paulo, Brazil. *International Journal of Environmental Research and Public Health*, *20*(9), 5707. https://doi.org/10.3390/ijerph20095707

World Health Organization. (2016). *AirQ+: Main Features.* World Health Organization. https://www.who.int/europe/publications/i/item/WHO-EURO-2016-4104-43863-61761

World Health Organization. (2021). *WHO global air quality Guidelines.* World Health Organization. https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y

World Health Organization. (2023). *Global Health Statistics: Health Monitoring for the SDGs, Sustainable Development Goals.* World Health Organization. https://www.who.int/publications/i/item/9789240074323

Zhang, X., Fung, J. C. H., Lau, A. K. H., Hossain, M. S., Louie, P. K. K., & Huang, W. (2021). Air quality and synergistic health effects of ozone and nitrogen oxides in response to China's integrated air quality control policies during 2015–2019. *Chemosphere*, *268*, 129385. https://doi.org/10.1016/j.chemosphere.2020.129385