

Environment

Temporal analysis of the impact of air quality on the relative risk of mortality in the population of the Southern region of Brazil

Análise temporal no impacto da qualidade do ar no risco relativo de mortalidade na população da região Sul do Brasil

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ABSTRACT

Calculations to estimate the Relative Risk (RR) of air pollution on the exposed population are essential to create strategies for reducing deaths. This study aimed to perform a temporal analysis of atmospheric pollutants and mortality indicators, assessing the influence of air quality on RR in the Região Metropolitana de Porto Alegre (RMPA), Brazil. The ecological study was conducted between 2007 and 2021, using air quality data from FEPAM (State Environmental Protection Foundation) and health data from DATASUS (Department of Informatics of the Brazilian Unified Health System). The mortality rates considered were: respiratory mortality in children under 5 years, all-cause mortality in all ages (PM₁₀, short-term), and cardiopulmonary mortality in adults aged 30–59 years (PM_{2.5}, long-term). These data were incorporated into AirQ+ through β coefficients, allowing the estimation of RR. Results indicated that pollution levels were above the WHO recommendations. The RR ranged from 1.00 for respiratory and all-cause mortality to 5.51 for cardiopulmonary mortality, with 217,311 deaths attributable to the particulate matter. Limitations include the dependence on secondary databases, the use of international coefficients, and restricted monitoring coverage. Local data gaps may compromise the results and reinforce the need to strengthen monitoring and studies to estimate the impacts of pollution.

Keywords: Air pollution; Risk assessment; Health impact; Particulate matter; AirQ+

RESUMO

Cálculos para estimar o Risco Relativo (RR) da poluição do ar sobre a população exposta são essenciais para criar estratégias de redução de mortes. Este estudo teve como objetivo realizar uma análise temporal dos poluentes atmosféricos e dos indicadores de mortalidade, avaliando a influência da qualidade do ar no RR na Região Metropolitana de Porto Alegre (RMPA), Brasil. O estudo ecológico ocorreu entre 2007 e

2021, com dados de qualidade do ar obtidos da FEPAM e de saúde do DATASUS. As taxas de mortalidade consideradas foram: mortalidade respiratória em crianças menores de 5 anos, mortalidade por todas as causas em todas as idades (MP 10, curto prazo) e mortalidade cardiopulmonar em adultos de 30–59 anos (MP2.5, longo prazo). Essas informações foram incorporadas ao AirQ+ por meio dos coeficientes β , possibilitando estimar RR. Os resultados indicaram que os níveis de poluição estiveram acima das recomendações da OMS. O RR variou de 1,00 para mortalidade respiratória e por todas as causas até 5,51 para mortalidade cardiopulmonar, com 217.311 mortes atribuíveis ao material particulado. As limitações incluem a dependência de bancos de dados, uso de coeficientes internacionais e cobertura restrita de monitoramento. Lacunas de dados locais podem comprometer os resultados e reforçam a necessidade de fortalecer o monitoramento e os estudos para estimar os impactos da poluição.

Palavras-chave: Poluição do ar; Avaliação de risco; Impacto na saúde; Material particulado; AirQ+

1 INTRODUCTION

Air pollution is responsible for several adverse effects on the health of the population. It is estimated that pollution is responsible for millions of deaths each year. However, there For instance, in Salvador have been some improvements in air quality, but unfortunately the number of deaths related to poor air quality has not decreased since the 1990s. According to the World Health Organization (WHO), air pollution is considered the greatest environmental threat to human health. Epidemiological studies in developing countries, such as Brazil, show that high concentrations of pollutants are responsible for adverse effects on the health of the exposed population (WHO, 2021). In 2015 alone, air pollution in Brazil was responsible for 52.300 deaths (Cohen et al., 2017).

Air pollutants come mainly from anthropogenic sources. Emissions from motor vehicle traffic contribute to the increase in the concentration of atmospheric pollutants, especially in low- and middle-income countries (Atuyambe et al., 2024). Air pollution related to exposure to particulate matter smaller than $2.5 \mu\text{m}$ (PM2.5) is associated with an increase in deaths; a study made in India and China shows that this pollutant is capable of increasing mortality from cardiovascular diseases, especially in the elderly (Zhang et al., 2024). Another study carried out in several countries revealed that PM2.5 was responsible for 4.2 million deaths in 2015, representing 7.6% of global deaths (Cohen et al., 2017). In Kazakhstan, air pollution is responsible for more than

10.000 premature deaths annually. This research indicates that it is necessary to adopt measures to reduce air pollutant concentrations to improve the population's quality of life (Kanat et al., 2024). In Spain, an increase in hospital admissions for cardiovascular diseases was found as pollutants increased. The annual values established by the WHO were not exceeded. However, there were negative health effects due to air pollution (Rodríguez et al., 2022). In Nepal, it was observed that there was a substantial premature mortality rate due to high levels of PM_{2.5} (Dhital et al., 2024). In Brazil, a study showed that there was a 2.93% increase in deaths from respiratory diseases for every 10 µg/m³ increase in the concentration of the pollutant PM_{2.5}. This research demonstrates that atmospheric pollutants are capable of increasing the risk of cardiorespiratory mortality in exposed individuals (Requia et al., 2024).

Poor urban air quality is related to greater morbidity and premature mortality (Silveira et al., 2024). The indicator used to assess the relation between environmental exposure to a pollutant and the probability of an adverse event occurring in a population exposed to this pollutant is called Relative Risk (RR). This relation considers a reference group for each 10 µg/m³ increase in the annual concentration of the selected pollutant. Values greater than 1 indicate that the exposure is associated with a higher risk of an adverse event occurring, while a relative risk less than 1 indicates that the exposure is associated with a lower risk of the event (WHO, 2019).

The RR related to mortality due to PM exposure has been a target of research. Several studies demonstrate the applicability of the AirQ+ software for calculating the RR. The program makes several estimates, including preventable deaths due to exposure to air pollutants, the portion of the population at risk, among other metrics (Arregocés et al., 2023; Kahraman & Sivri, 2022; Leili et al., 2023; Miri et al., 2017; Nikoonahad et al., 2017; Nishikawa et al., 2023; Ostro, 2004; Pala et al., 2021; Sicard et al., 2019). Mortality due to population exposure to air pollutants, such as PM, has been observed in some studies carried out in Iran, Turkey, Colombia, Japan, Brazil, and some European countries (Arregocés et al., 2023; Kahraman &

Sivri, 2022; Leili et al., 2023; Miri et al., 2017; Nikoonahad et al., 2017; Nishikawa et al., 2023; Requia et al., 2024; Sicard et al., 2019).

In the Metropolitan Region of Porto Alegre (RMPA), an area with more than 4 million inhabitants, urban growth, heavy traffic, and the presence of industrial and petrochemical complexes significantly contribute to pollutant emissions (FEPAM, 2022). Despite this critical profile, there are few local studies addressing the association between air pollution and mortality, especially using risk metrics such as RR. This lack of evidence highlights the importance of generating regional data to support public health policies and environmental management.

Therefore, the aim of this study was to perform a temporal analysis of atmospheric pollutants and mortality indicators, and to analyze the influence of air quality on the relative risk (RR) associated with population mortality due to air pollution in the RMPA, Rio Grande do Sul, Brazil.

2 METHODS

This is an ecological study with descriptive and analytical components, presenting a quantitative approach to the data collected in the period from 2007 to 2021. This period was selected due to the availability of air quality data from the State Environmental Protection Foundation (FEPAM). This database is in the public domain and can be accessed on the following website: www.fepam.rs.gov.br

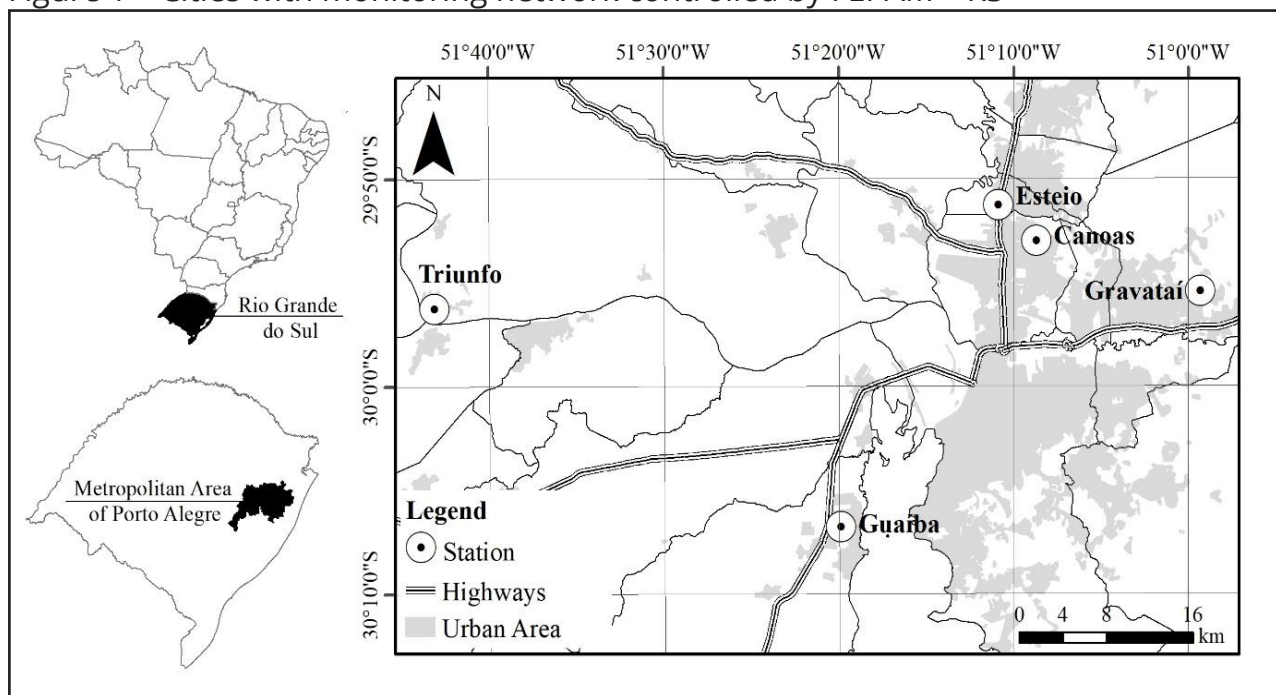
2.1 Environmental air quality database

For the air quality analysis, the database of FEPAM for the cities of Esteio, Guaíba, Gravataí, Canoas and Triunfo, located in the state of Rio Grande do Sul (RS), was used. Only these stations are in operation in the RMPA. These municipalities were selected because they host the only active monitoring stations in the region and are strategically located near major urban centers, industrial areas, and petrochemical complexes, thus representing the most critical sources of emissions in the RMPA. The air quality

parameters evaluated were the annual average of particulate matter smaller than 10 μm (PM10) and PM2.5. To estimate PM2.5, a conversion factor based on the annual average of PM10 was used; this conversion factor was 0.5, according to the study by Ostro (2004). For the RMPA as a whole, the concentrations from each monitoring station were aggregated using arithmetic mean values, providing a regional estimate representative of population exposure.

Figure 1 shows the cities that have Air Quality Monitoring Station (EMQA) which will be used in this research. Each station covers a radius of 3 km, except for the Triunfo station, which covers a radius of 10 km.

Figure 1 – Cities with monitoring network controlled by FEPAM – RS



Source: Prepared by the authors (2024)

2.2 Health Database

The object of study was the mortality data of the following age groups from both genders, being 30-59 years for cardiopulmonary mortality, under 5 years for respiratory mortality, and all ages for mortalities from all causes. These data were

made available by the platform of the Department of Informatics of the Brazilian Unified Health System (DATASUS), being freely accessible on the following website: <https://datasus.saude.gov.br/informacoes-de-saude-tabnet/>. The causes of death were selected according to the study by Ostro (2004), being cardiovascular mortality in adults associated with long-term exposure to PM_{2.5}, all-cause mortality for all ages associated with short-term exposure to PM₁₀, and infant mortality from respiratory diseases associated with exposure to PM₁₀. For classification, the following ICD-10 codes were applied: J00–J99 for respiratory diseases and I00–I99 for cardiovascular and cardiopulmonary diseases. Given this specific population, it is possible to determine a β coefficient for each associated disease and its corresponding age group (Table 1). This coefficient is extremely important for calculating RR in the software (Ostro, 2004). A log-linear model was applied, $RR = \exp(\beta \Delta C)$, where $\Delta C = C - C_0$. Concentration–response functions reported per 10 $\mu\text{g}/\text{m}^3$ were expressed as RR_{10} , with $\beta_{10} = \ln(RR_{10})$, and the relative risk estimated as $RR = RR_{10}^{\Delta C/10}$. When necessary, coefficients were converted to the per 1 $\mu\text{g}/\text{m}^3$ scale ($\beta_1 = \beta_{10}/10$). In this study, $C_0 = 5 \mu\text{g}/\text{m}^3$ was adapted to PM_{2.5}, in line with the WHO Air Quality Guidelines (2021).

Table 1 – Data and risk functions recommended for calculating relative risk according to the study by Ostro (2004)

Causes of mortality	Type of exhibition	Pollutant	Suggested Coefficient β	Age group (years)
All-cause mortality	Short term	PM ₁₀	0.0008 (0.0006 – 0.0010)	All ages
Respiratory mortality	Short term	PM ₁₀	0.00166 (0.00034 – 0.0030)	< 5
Cardiopulmonary mortality	Long term	PM _{2.5}	0.15515* (0.0562 – 0.2541)	30 – 59

Source: Adapted from Ostro (2004)

* β was expressed per 1 $\mu\text{g}/\text{m}^3$

Note: PM₁₀: particulate matter smaller than 10 μm ; PM_{2.5}: particulate matter smaller than 2.5 μm .

2.3 Data analysis

The model proposed by the WHO, called AirQ +, was used to assess health risks due to air pollution. This software performs calculations that allow the quantification of the effects of exposure to air pollution on health, including estimates of reduced life expectancy (WHO, 2019). The program is available online, as well as all manuals for its use.

This program makes it possible to calculate the impact assessment based on data provided by the user, such as the total population of the city, specific population of each age group, related disease, annual values of the pollutant evaluated (PM10 and PM2.5) and finally, the corresponding β coefficients. The value established as the recommended limit value for each pollutant followed the WHO recommendations, with an annual limit value of 15 $\mu\text{g}/\text{m}^3$ for PM10 and a limit value of 5 $\mu\text{g}/\text{m}^3$ for PM2.5, considering a 95% confidence interval (OSTRO, 2004; WHO, 2021).

The AirQ+ program generated the results of the RR calculation, as well as the number of preventable premature deaths due to exposure to air pollutants. Another metric obtained through the AirQ+ program is the Estimated Number of Attributable Cases (ENAC), which estimates the incidence of cases of a given disease related to air pollution in a specific population. The Estimated Attributable Proportion (EAP) was obtained directly in AirQ+, based on the relative risk (RR) and the prevalence of exposure in the studied population. This metric represents the fraction of cases that can be attributed to exposure to air pollutants within the population at risk. The calculation is performed according to the following formula: $\text{EAP} = (\text{RR} - 1) / \text{RR} \times 100\%$, where RR is the relative risk associated with exposure to a given pollutant. Values greater than zero indicate the proportion of adverse health outcomes that may be attributed to exposure (WHO, 2019).

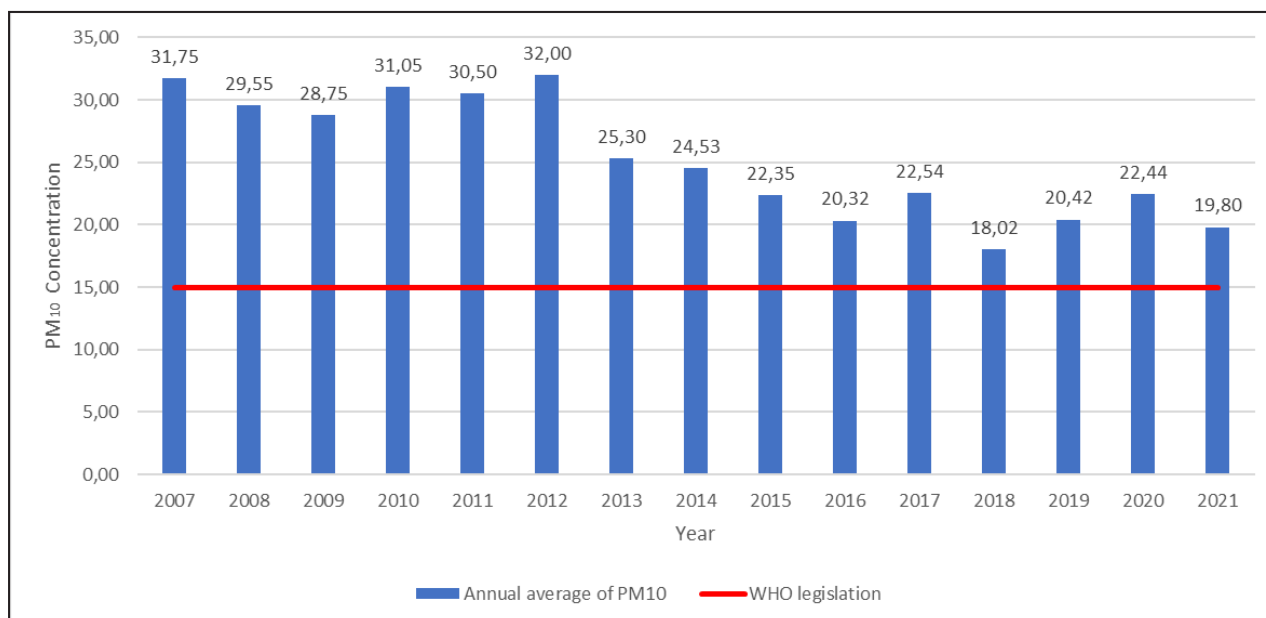
For data analysis, an exploratory analysis of the studied variables was performed and, subsequently, a temporal trend analysis was performed between the environmental and health variables, using the linear regression method. The variables used in the study were arithmetic mean, standard deviation, coefficient of variation,

maximum and minimum values, accepting a significance level of $p \leq 0.05$, with a 95% confidence interval. These analyses were conducted using Excel software.

3 RESULTS

The results of this study demonstrate that in relation to air quality, PM levels exceeded the values established as safe for human health, according to the WHO in all annual averages. For the pollutant PM₁₀, the highest annual average was 32 $\mu\text{g}/\text{m}^3$ in 2012, exceeding the limit of 15 $\mu\text{g}/\text{m}^3$ established by the WHO. In 2018, PM₁₀ presented the lowest annual average of 18.02 $\mu\text{g}/\text{m}^3$, however, even though it presented the lowest value in this year evaluated, this data is above the values established as safe for human health (Graph 1).

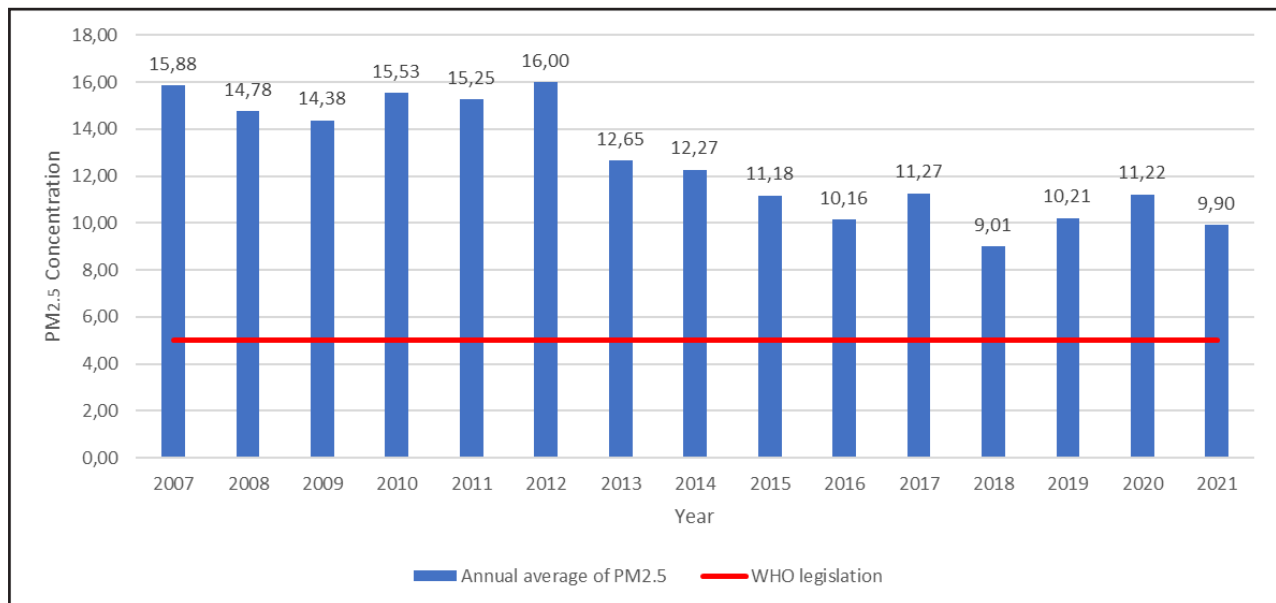
Graph 1 – Annual concentrations of particulate matter smaller than 10 μm in the metropolitan region of Porto Alegre



Source: WHO, 2021. Prepared by the authors (2024)

For the pollutant PM_{2.5}, the highest value was 16 $\mu\text{g}/\text{m}^3$ in 2012, and the lowest value was 9.01 $\mu\text{g}/\text{m}^3$ in 2018 for the annual average. It can be seen that this pollutant exceeded the limits of 5 $\mu\text{g}/\text{m}^3$ in all years evaluated (Graph 2).

Graph 2 – Annual concentrations of particulate matter smaller than 2.5 μm in the metropolitan region of Porto Alegre



Source: WHO, 2021. Prepared by the authors (2024)

The AirQ+ program was developed to analyze the effects of air quality in urban areas on human health. Table 2 shows that the EAP results varied from 2.74% to 0.5% in the RMPA, considering respiratory mortality in individuals under 5 years of age due to short-term exposure to the pollutant PM10. This result indicates that up to 2.74% of deaths from respiratory diseases in 2007 may have been due to high levels of PM10 in the region analyzed.

The ENAC indicator, in this case being the respiratory mortality due to short-term exposure to the pollutant PM10 in individuals under 5 years old, varied from 484 to 14 cases between the years evaluated. In 2012 alone, the program estimated that 484 deaths due to respiratory events in children under 5 years could have been avoided in the RMPA. The RR varied between 1.00 and 1.02, that is, for each increase of 10 $\mu\text{g}/\text{m}^3$ of PM10 in the average annual concentration, these exposed individuals have twice the risk of respiratory mortality, compared to unexposed individuals.

Table 2 shows the population at risk assessed by the AirQ+ program according to the number of inhabitants who fit into the age group analyzed. The population under 5 years old varied between 286.671 and 264.146 children.

Table 2 – Impact Assessment of the Metropolitan Region of Porto Alegre (RMPA) for respiratory mortality for short-term exposure to 10 µm Particulate Matter (PM10)

Year	2007	2008	2009	2010	2011	2012	2013	2014
Variable								
EAP (%)	2,74%	2,39%	2,26%	2,63%	2,54%	2,78%	1,7%	1,57%
ENAC	14	246	262	309	261	484	179	159
Population at Risk	286.671	279.878	273.516	266.871	263.393	264.146	266.803	270.304
Relative Risk (RR)	1,02	1,02	1,02	1,02	1,02	1,02	1,01	1,01
PM ₁₀ (µg/m ³)	31,75	29,55	28,75	31,05	30,5	32	25,3	24,53

Year	2015	2016	2017	2018	2019	2020	2021
Variable							
EAP (%)	1,21%	0,88%	1,24%	0,5%	0,9%	1,23%	0,79%
ENAC	120	89	117	43	78	49	44
Population at Risk	275.786	280.269	282.284	283.685	283.964	282.507	280.797
Relative Risk (RR)	1,01	1,00	1,01	1,00	1,00	1,01	1,00
PM ₁₀ (µg/m ³)	22,35	20,32	22,54	18,02	20,42	22,44	19,8

Note: EAP: Estimated Attributable Proportion. ENAC.: Estimated Number of Attributable Cases.

Source: Prepared by the authors (2024)

Table 3 shows the following results for mortality from all causes due to short-term exposure to PM10. For the EAP metric, this variable was between 1.35% and 0.24% in the RMPA. This result shows that up to 1.35% of deaths from all causes in 2012 may be due to high levels of PM10 in the region analyzed.

The indicator of ENAC, considering mortality from all causes due to short-term exposure to the pollutant PM10, varied from 3.688 and 257 cases for the years evaluated in the RMPA. The program estimated that 3.688 deaths could have been avoided in 2012. The RR varied between 1.00 and 1.01, that is, for each increase of 10 µg/m³ of PM10 in the average annual concentration, these exposed individuals have twice the risk to mortality in general, compared to unexposed individuals.

Table 3 shows the population at risk assessed by the AirQ+ program according to the number of inhabitants; for mortality from all causes, all age groups were included, with the population at risk being the entire resident population during the

period evaluated; this population varied between 4.362.711 and 4.037.023 people. It was observed that the population of the RMPA has been growing over the years.

Table 3 – Impact Assessment of the Porto Alegre Metropolitan Region (RMPA) for all-cause mortality for short-term exposure to 10 µm Particulate Matter (PM₁₀)

Year Variable	2007	2008	2009	2010	2011
EAP (%)	1,33%	1,16%	1,09%	1,28%	1,23%
ENAC	257	3.012	2.951	3.480	3.263
Population at Risk	4.037.023	4.056.314	4.076.453	4.095.488	4.118.984
Relative Risk (RR)	1,01	1,01	1,01	1,01	1,01
PM ₁₀ (µg/m ³)	31,75	29,55	28,75	31,05	30,5
Year Variable	2012	2013	2014	2015	2016
EAP (%)	1,35%	0,82%	0,76%	0,59%	0,42%
ENAC	3.688	2.278	2.178	1.672	1.188
Population at Risk	4.143.751	4.168.958	4.194.764	4.221.868	4.248.101
Relative Risk (RR)	1,01	1,00	1,01	1,01	1,00
PM ₁₀ (µg/m ³)	32	25,3	24,53	22,35	20,32
Year Variable	2017	2018	2019	2020	2021
EAP (%)	0,6%	0,24%	0,43%	0,59%	0,38%
ENAC	1.654	647	1.218	1.474	968
Population at Risk	4.272.432	4.296.349	4.319.425	4.341.574	4.362.711
Relative Risk (RR)	1,00	1,00	1,00	1,00	1,00
PM ₁₀ (µg/m ³)	22,54	18,02	20,42	22,44	19,8

Note: EAP: Estimated Attributable Proportion. ENAC: Estimated Number of Attributable Cases.

Source: Prepared by the authors (2024)

Table 4 shows the following results for cardiopulmonary mortality in individuals aged 30 to 59 years old due to long-term exposure to PM_{2.5}. For the EAP metric, this variable was between 81.85% and 46.32% in the region analyzed. This result represents that up to 81.85% of deaths from cardiopulmonary diseases in 2012 may be due to high levels of PM_{2.5} in the RMPA.

In the ENAC indicator, considering cardiopulmonary mortality in people aged 30 to 59 years old due to long-term exposure to the pollutant PM_{2.5}, the years

evaluated presented a variation of 24.892 and 1.361 in the RMPA. The program estimated that 24.892 deaths could have been avoided in the region during 2018. The RR varied between 5.51 and 1.86, that is, for each increase of 10 $\mu\text{g}/\text{m}^3$ of PM_{2.5} in the average annual concentration, these exposed individuals in the age group of 30 to 59 years have approximately 5 times the risk of cardiopulmonary mortality, compared to unexposed individuals.

Table 4 shows the population at risk assessed by the AirQ+ program according to the number of inhabitants; for cardiopulmonary mortality, this population varied between 1.790.166 and 1.600.766 people.

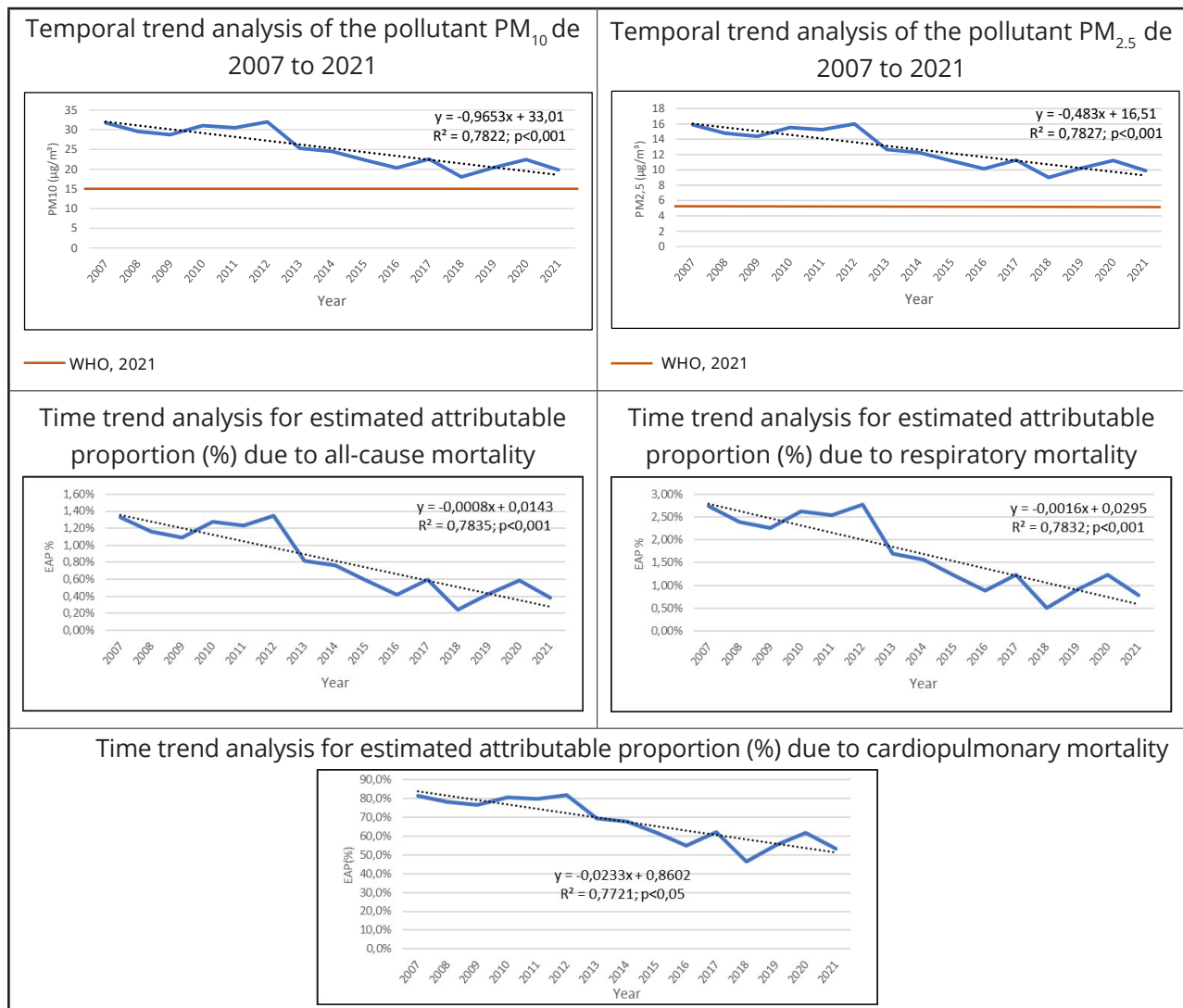
Table 4 – Impact Assessment of the Porto Alegre Metropolitan Region (RMPA) for cardiopulmonary mortality for long-term exposure to 2.5 μm Particulate Matter (PM_{2.5})

Year	2007	2008	2009	2010	2011
Variable					
EAP (%)	81,51%	78,07%	76,67%	80,47%	79,61%
ENAC	1.378	17.315	17.795	1.361	16.940
Population at Risk	1.600.766	1.620.757	1.641.221	1.662.024	1.681.053
Relative Risk (RR)	5,40	4,56	4,28	5,12	4,90
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	15,88	14,78	14,38	15,53	15,25
Year	2012	2013	2014	2015	2016
Variable					
EAP (%)	81,85%	69,48%	67,62%	61,67%	55,08%
ENAC	16.697	14.569	14.473	12.160	10.502
Population at Risk	1.700.381	1.719.413	1.736.932	1.752.271	1.762.722
Relative Risk (RR)	5,51	3,27	3,08	2,60	2,22
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	16	12,65	12,27	11,18	10,16
Year	2017	2018	2019	2020	2021
Variable					
EAP (%)	62,2%	46,32%	55,44%	61,9%	53,24%
ENAC	11.087	24.892	9.617	8.929	7.214
Population at Risk	1.770.892	1.777.177	1.782.296	1.786.560	1.790.166
Relative Risk (RR)	2,64	1,86	2,24	2,62	2,13
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	11,27	9,01	10,21	11,22	9,9

Note: EAP: Estimated Attributable Proportion. ENAC: Estimated Number of Attributable Cases.

Source: Prepared by the authors (2024)

Figure 2 – Time trend analysis of the variables Particulate Matter 10 µm (PM10), Particulate Matter 2.5 µm (PM2.5) and Estimated Attributable Proportion (%)



Source: Prepared by the authors (2024)

Note: PM10: Particulate Matter 10 µm. PM2.5: Particulate Matter 2.5 µm. EAP (%): Estimated Attributable Proportion (%).

When adding the ENAC numbers for respiratory mortality, all-cause mortality and cardiopulmonary mortality of all the years evaluated (2007 to 2021), the total number of 217.311 deaths attributable to exposure to PM was obtained. A time trend analysis was performed, where it was possible to identify a significant decreasing trend ($p < 0.001$) for the pollutants PM10 and PM2.5. The same decreasing trend ($p < 0.001$) was also found for the EAP variable over the time studied for respiratory mortality and all-cause

mortality due to short-term exposure to PM₁₀. Regarding long-term exposure to PM_{2.5} for cardiopulmonary mortality, this trend ($p < 0.001$) was observed in the EAP variable over the time studied as well. Figure 2 demonstrates this finding.

4 DISCUSSION

The annual concentrations of PM₁₀ in the RMPA exceeded the values previously established as safe for human health according to the WHO guideline in all years evaluated, from 2007 to 2021. In the present study, the highest annual average for the pollutant PM₁₀ was 32 $\mu\text{g}/\text{m}^3$ in 2012, exceeding the limit of 15 $\mu\text{g}/\text{m}^3$ established by legislation. A study carried out in Iran found an annual average concentration of PM₁₀ of 97 $\mu\text{g}/\text{m}^3$, a value much higher than that recommended by the WHO. The maximum value found for PM₁₀ was 731 $\mu\text{g}/\text{m}^3$, this value was found in the summer season of the Iranian region (Miri et al., 2017). Data found in the city of Zahedan, located in Iran, showed that PM₁₀ levels were 7.3 times above the limits established by the WHO guideline (Leili et al., 2023). In the research by Nikoonahad et al. (2017), it was found that the average annual concentration of PM₁₀ was approximately 5.6 to 88 times above the WHO limits in 2012 and 2013. For the year 2014, the annual average of PM₁₀ was 3.35 and 22 times higher than the WHO guideline (Nikoonahad et al., 2017).

The values found in this study for the pollutant PM_{2.5} were above the values established by the guidelines in all years evaluated. In this study, the highest value of 16 $\mu\text{g}/\text{m}^3$ was found in 2012. A survey carried out in Turkey showed levels of PM_{2.5} higher than those suggested by the WHO during the years evaluated (Kahraman & Sivri, 2022). A study carried out in Italy, France, and Iran revealed that concentrations of PM_{2.5} and PM₁₀ were above the WHO guideline values (Sicard et al., 2019). A study in Nepal shows that more than 39,000 deaths due to the pollutant PM_{2.5} could be avoided if this pollutant remained within the values suggested by the WHO (Dhital et al., 2024). In Uganda, PM_{2.5} values were found to be approximately 8 times higher

than the WHO recommendation for 2021, reaching an annual average of 38.8 $\mu\text{g}/\text{m}^3$ (Atuyambe et al., 2024). A study carried out in Iran showed that PM_{2.5} values were approximately 2 to 4 times higher compared to the values suggested by the WHO (Kazemi et al., 2024). Another study carried out in Iran revealed an annual concentration of 16.39 $\mu\text{g}/\text{m}^3$, a finding that corroborates with the results found in this study (Safari et al., 2022). In the years 2003 to 2017, a study carried out in Brazil indicated an average annual PM_{2.5} value of 10.35 $\mu\text{g}/\text{m}^3$, which is above the values suggested by the WHO in the AQG 2021 (Requia et al., 2024).

According to the European Environment Agency (EEA), 96% of the population of the European Union was exposed to high levels of inhalable particles in 2020. This exposure was responsible for 238,000 premature deaths in the European region. In addition, pollution caused several causes of morbidity, impacting quality of life and increasing costs related to health care (European Environment Agency, 2022). For 2021, there was an increase to 253.000 deaths attributable to exposure to PM_{2.5} in the European Union. If pollutants remained within WHO standards, this would significantly reduce the number of deaths. However, it is worth noting that there is no pre-established concentration of pollutants considered safe for human health, that is, without impacts on the population (European Environment Agency, 2023). The diseases that demonstrate the most impacts resulting from exposure to PM_{2.5} causing morbidity and mortality are Ischemic Heart Disease (IHD), stroke, diabetes mellitus, Chronic Obstructive Pulmonary Disease (COPD), lung cancer and asthma (European Environment Agency, 2023).

This study used the AirQ+ software to assess short and long-term exposure to the pollutant PM in the population residing in the RMPA during the years 2007 to 2021. It can be seen that there were impacts resulting from the pollutant in this population. For respiratory mortality in children under 5 years of age due to short-term exposure to PM₁₀, the highest value for the estimated attributable proportion was 2.74%. For the estimated number of attributable cases, the highest value was 484 cases. The RR ranged from 1.00 to 1.02 for the group evaluated.

For the indicator of all-cause mortality due to short-term exposure to PM₁₀, the estimated attributable proportion reached 1.35%. For the indicator of the estimated number of attributable cases, the highest value was 3.688 cases, which could have been avoided in just a single year. In this group, the RR ranged from 1.00 to 1.01.

Another group analyzed was the group of cardiopulmonary mortality in individuals aged 30 to 59 years due to long-term exposure to PM_{2.5}. The results show that the estimated attributable proportion was up to 81.85%. Additionally, the indicator of the estimated number of attributable cases reached 24.892 in just one year in the RMPA. The RR ranged from 5.51 to 1.86 for the population analyzed.

Ostro's research (2004) showed that the negative effects of pollution will manifest primarily in elderly individuals with previous cardiovascular and respiratory diseases, as well as in children, who are the main risk group. There is a strong association between air pollution and mortality, especially mortality from cardiovascular and respiratory diseases. Higher mortality rates were found in regions that presented a higher concentration of PM in the atmosphere (Ostro, 2004).

In Uganda, there were 7.257 deaths attributable to long-term exposure to PM_{2.5} during the 4 years of the study. In the impact assessment, deaths attributable to air pollution ranged between 17% and 19% in the city evaluated. Furthermore, the authors emphasized that this has a serious impact on the health of the population, especially on the most vulnerable population such as children, the elderly, and people with chronic diseases (Atuyambe et al., 2024).

A study carried out in nine cities in three European countries showed that environmental exposure to pollutants PM_{2.5}, PM₁₀, and O₃ increased hospital admissions and mortality in the regions studied. The RR values of this study were between 1.00 and 1.07. Exposure to air pollution was responsible for approximately 8.200 deaths from all causes, 2.400 deaths from cardiovascular diseases, 540 deaths from respiratory diseases, and 220 deaths from COPD in this European region. The

program estimated that 3.795 deaths could have been avoided if pollutants had stayed within the limits set by the WHO (Sicard et al., 2019).

A study carried out in Colombia evaluated the impact of exposure to PM_{2.5} on mortality from various diseases. The results of the study demonstrate that the estimated proportions attributed to mortality due to prolonged exposure to PM_{2.5} were approximately 11.6% deaths for acute lower respiratory diseases in children under 4 years, 16.1% for COPD, 26.6% for IHD, 9.1% for lung cancer and 18.9% for stroke in adults over 18 years of age (Arregocés et al., 2023). This same research estimated that 738 deaths are related to air pollution annually. The RR values were 1.00 for respiratory and cardiovascular mortality, and 1.11 for mortality due to lung cancer (Arregocés et al., 2023).

The study by Miri et al. (2017) demonstrated an estimated attributable proportion of 4.98% for total mortality, 7.3% for cardiovascular mortality, and 10.21% for respiratory mortality. The RR found in the Iranian research was 1.00 for total mortality and cardiovascular mortality, and 1.01 for respiratory mortality due to short-term exposure to the pollutant PM₁₀ (Miri et al., 2017).

In Turkey, the maximum estimated attributable proportion found was 26.32% for all-cause mortality due to exposure to PM_{2.5} in individuals over 30 years of age. The estimated number of attributable cases reached 6.719 in just one city in Turkey evaluated in 2017. In the same year, in the cities evaluated in this study, the number of cases attributable to exposure to PM_{2.5} was 13.853 (Kahraman & Sivri, 2022). In another study carried out in Turkey in 2018, it was found that the estimated number of attributable cases was 44.617 people, due to long-term exposure to PM_{2.5} in the region (Pala et al., 2021).

In Iran, a study carried out in the city of Zahedan showed an estimated attributable proportion of 8.03% for mortality from cardiovascular diseases, 11.2% for respiratory mortality, and 5.5% for total mortality (95% CI) (Leili et al., 2023).

In a study in the city of Ilam, located in Iran, the estimated attributable proportion for total mortality, respiratory mortality, and cardiovascular mortality in the year 2012-

2013 was 5%, 10.8%, and 7.7% respectively. This was the year with the highest values found in the study. These data describe the short-term impacts caused by exposure to the pollutant PM10 (Nikoonahad et al., 2017).

This study demonstrates a decreasing trend in PM10 and PM2.5 pollutants over the years, as well as the EAP % of deaths evaluated. A temporal analysis was carried out between 1977 and 2015 in Japan, and a decreasing trend was found in some atmospheric pollutants, including PM10, in addition to a decrease in mortality from cardiovascular diseases due to this pollutant. However, the study found a reduction in the RR related to short-term exposure to PM10 and cardiovascular diseases (Nishikawa et al., 2023). In Portugal, a significant decline in PM2.5 was observed in the temporal analysis from 2010 to 2019, except for the years 2015 and 2017. As expected, the EAP% due to exposure to PM2.5 followed the same temporal trend in the same period of the study (Brito et al., 2022). A study made in several countries, including Brazil, revealed that PM2.5 levels have been decreasing slightly in Brazil from 1990 to 2015 (Cohen et al., 2017). In contrast, a study in Nepal shows an increasing trend in the cardiorespiratory deaths due to exposure to PM2.5, as well as in the mortality rate over the decades (Dhital et al., 2024). These findings suggest that when there is a higher concentration of the pollutant PM in the atmosphere, there is a greater tendency related to deaths. Furthermore, the southern region analyzed in Brazil shows a decrease in the annual concentrations of the pollutants evaluated. According to the European Environment Agency (EEA), air pollution is decreasing, especially PM2.5, which has seen a 41% reduction in atmospheric concentration. According to EEA Executive Director Leena Ylä-Mononen, the implementation of clean air public policies, which encourage the use of public transports and legislation reviewing, have a positive impact on air quality (European Environment Agency, 2024). Globally, there is a major effort to reduce the concentration of air pollutants, in addition to more restrictive guidelines, such as those issued by the WHO in 2021, which are driving the updating of national legislation. Working from home, a current reality, ends up reducing the need to use motor vehicles,

leading to a reduction in the emission of air pollutants. More aware citizens, more restrictive guidelines and legislation are necessary measures to further reduce air pollution. I believe we are on the path to soon being able to breathe cleaner air.

High concentrations of PM in the atmosphere are responsible for several adverse effects on the health of the exposed population (Kazemi et al., 2024). Moreover, air pollution is responsible for several deaths. In this context, the lack of adequate monitoring of these pollutants becomes a problem. It is necessary to reduce the concentrations of atmospheric pollutants, thus reducing premature mortality by exposure to these particles in the general population, increasing the life expectancy (Pala et al., 2021). It is a fact that morbidity and mortality could decrease if pollutants were considerably reduced. AirQ+ is a tool that helps in the development of public policies in favor of the population. Besides, this program also collaborates in the implementation of the 2030 agenda (Brito et al., 2022).

When comparing the results of this study with local evidence, it becomes clear that the PM_{2.5}/PM₁₀ ratio varies considerably according to region, season, and emission sources. For instance, in Salvador, an average value of 0.52 has been used to estimate PM_{2.5} from PM₁₀ measurements (Jacobson et al., 2024), whereas in the state of São Paulo, typical values range between 0.33 and 0.47 (Franzin et al., 2020). In Recife, the restrictions imposed during the COVID-19 pandemic temporarily reduced this ratio to approximately 0.48, increasing again to 0.56 after the relaxation of measures (Tavella et al., 2024). Conversely, in southern regions such as Rio Grande, higher ratios were observed during autumn and winter, indicating a greater contribution of fine particles in colder seasons (Silveira et al., 2025). These findings highlight that the estimation of the fine particulate fraction should take into account regional and seasonal characteristics, as well as recent shifts in emission patterns.

The air quality guidelines proposed by the WHO were updated in 2021, being the first update since 2005. This update brought more restrictive levels of each pollutant. In 2022, the European Union brought a zero-pollution action plan, where

the objective is to reduce premature deaths due to exposure to air pollution. This plan aims to reduce deaths due to PM_{2.5} by 55% compared to 2005, by the year 2030 (European Environment Agency, 2023).

5 CONCLUSIONS

This research shows that, in all years evaluated, the concentrations of PM₁₀ and PM_{2.5} were above the values suggested by the WHO in 2021. In addition, the population residing in the study area has a higher risk of death due to exposure to these air pollutants. However, when the temporal analysis was carried out, it became clear that the pollutants reduced over the years, but even with the decrease in pollution, the death risk remains five times higher. The estimated attributable proportion of deaths in percentage follows the decline in air pollutants, which demonstrates that air pollutants and deaths are related.

Considering the results expressed by the AirQ+ software, it can be concluded that this model proposed by the WHO is a useful tool for public health, elucidating effects resulting from exposure to air pollutants. In addition, it is possible to prepare reports and indicators related to mortality attributable to air pollutants, facilitating the elucidation of potential effects on the exposed population and the development of strategies to mitigate these effects.

Despite its limitations, the study shows that average concentrations of PM₁₀ and PM_{2.5} remained above the levels recommended for most of the analyzed period, indicating a significant public health impact. Although a decreasing trend was observed, it was not sufficient to reach safe levels. Therefore, local actions are recommended, including the expansion of air quality monitoring networks, the strengthening of environmental and industrial regulations, and the implementation of measures aimed at mitigating the effects of air pollution, especially among vulnerable populations.

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