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RESEARCH ARTICLE

Health impact assessment of air pollution in an area of the largest coal mine in Brazil

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Abstract

Coal exploration and burning activities are among the activities with the greatest potential to cause atmospheric pollution due to the combustion process of this mineral and the consequent release of particles that, in significant quantities, can pose a potential health risk, mainly respiratory and cardiovascular diseases. The Candiota region, in the extreme south of Brazil, concentrates 40% of the national reserves of mineral coal, and its burning is capable of releasing air pollutants, including particulate matter (PM). Some environmental and epidemiological studies have been carried out in the region, but so far, there is no investigation to estimate the impact of PM on health outcomes. The current study aimed to estimate the mortality attributed to the PM, as well as the benefits in health indicators associated with the reduction of air pollution to the limits set forth in local legislation and the WHO. Daily data on PM levels collected from an air quality monitoring station over a year were used, as well as population data and health indicators from 7 cities influenced by mining activities, such as total mortality and cardiovascular diseases and hospitalizations for cardiac and respiratory problems. In a scenario where PM levels are within legal limits, a percentage greater than 11% of cardiovascular deaths was attributed to pollution by $PM_{2.5}$, and the reduction in PM_{10} and $PM_{2.5}$ levels may be responsible for the increase in the expectation of life in up to 17 months and monetary gains of more than $ 24 million, due to the reduction in hospitalizations and mortality. Studies of this nature should be important tools made available to decision-makers, with a view to improving environmental laws and a consequent improvement in the quality of life and health indicators of the population.

Keywords Candiota · Particulate matter · Health services

Introduction

The World Health Organization (WHO) estimates that approximately seven million deaths worldwide are due to air pollution and that nine out of ten people breathe polluted air (WHO 2021). Poor air quality is one of the most important environmental factors in many major cities in the world, as it can cause a wide range of acute and chronic diseases, including impaired lung function and systemic inflammation (EPA, 2021; Gao et al. 2020), different types of cancers (EPA, 2021; Hwang et al. 2020, Turner et al. 2020), cardiac ischemia (Kim et al. 2021), chronic obstructive pulmonary disease, myocardial infarction, and stroke (Chen et al. 2020; Lee et al. 2018; Niu et al. 2021).

Air pollution is composed of a mixture of gases and particles, among which we highlight the gases ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and particulate matter (PM) (CONAMA 2018). PM is a complex mixture of solid and liquid particles suspended in the air, of natural or anthropogenic origin, which have a chemical composition of inorganic (sulfates, nitrates, ammonium, sodium, potassium, calcium, magnesium, and chloride) and organic ions (hydrocarbons of various chemical classes) in addition to metals such as cadmium, copper, nickel vanadium, and zinc (Cheung et al. 2013; Guo et al. 2020). PM is classified according to its diameter in PM_{10}

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inhalable particles with aerodynamic diameter less than 10 μm and $PM_{2.5}$ultra-fine inhalable particles with aerodynamic diameter less than 2.5 μm (USEPA 2021).

Since 2013, the International Agency for Research on Cancer (IARC) has included atmospheric particulate matter within the group of carcinogenic substances (IARC, 2021). In general, studies point to negative health effects due to exposure to $PM_{2.5}$ and PM_{10}, (Alemayehu et al. 2020; Liu et al. 2021), as a higher risk of cardiac arrhythmia, stroke, acute myocardial infarction, lung disease, asthma, and cancer (Hayes et al. 2019; Qibin et al. 2020; Chen et al., 2021).

A meta-analysis carried out with 19 cohort studies pointed out that the 10 $\mu g/m^3$ increase in $PM_{2.5}$ levels is responsible for the 6 to 11% increase in lung cancer mortality (Cui et al. 2015). However, such studies are still expensive and difficult to implement, and methodologies of lower cost and complexity, as mathematical models validated by international agencies, are highlighted and can help in predicting health impacts.

The methodology called "health impact assessment" has been widely used to estimate the relationship between the levels of air pollutants and health outcomes, such as mortality and hospital admissions (WHO 2015). Studies around the world have used this methodology and revealed that scenarios with decreased levels of air pollutants are able to reduce mortality, hospitalizations, and economic costs and increase the life expectancy of the population (Naddafi et al. 2012, Abe & Miraglia 2016, Bayat et al. 2019).

In the extreme south of Brazil, the Candiota region has been the subject of environmental health studies because it is an important area for exploration and burning of coal. The Candiota mine concentrates 40% of the national reserves of mineral coal (ANEEL 2008), which is the raw material for a coal-fired power plant with a capacity greater than 700 MW. In the region, numerous epidemiological studies have pointed out negative effects resulting from human exposure to the activities of coal mining and its pollutants (Pinto et al. 2017, Da Silva Júnior et al. 2018, Dos Santos et al. 2018, Bigliardi et al. 2021). However, there are no data on the mortality attributed to air pollution in the region, nor are there studies that estimate the health benefits related to the reduction of air pollution in the region. The evaluation of this scenario is useful, since PM_{10} and $PM_{2.5}$ concentrations may be elevated in coal burning area (Aneja et al. 2012, Roy et al. 2019).

Thus, the present study aimed to assess the health impact of air pollution in the largest coal mining region in the country, based on the estimation of deaths attributable to PM_{10} and $PM_{2.5}$, as well as the potential benefits on mortality, hospital admissions, life expectancy and economic costs in two simulated scenarios to improve the levels of these pollutants.

Material and methods

Study area

The study was conducted with data from 7 municipalities in a coal mining and burning region in Rio Grande do Sul, Brazil (Figure 1). The municipality of Candiota, home to coal mining activities, has approximately 8,771 inhabitants and is located approximately 420 km from the state capital, Porto Alegre. Also included were 6 municipalities that are considered to be influenced by coal activities: Bagé has approximately 117 thousand inhabitants and 64.9 km away from Candiota, Pinheiro Machado 12,780 inhabitants and 46.4 km away from Candiota, Herval 6,753 inhabitants and with 93.9 km distance from Candiota, Hulha Negra 6,043 inhabitants and 39.6 km in relation to Candiota, Aceguá 4,394 inhabitants and 120km distance from Candiota, finally Pedras Altas 2,212 inhabitants and 20.35km distance from Candiota (Brazil, 2010), totaling an impacted population of 157,953 thousand inhabitants. The economy of these locations is based on agriculture and the extraction and industrial exploitation of minerals.

Environmental data

PM_{10} levels were estimated using a high volume (HV) sampler installed at a monitoring station in the municipality of Candiota managed by the coal-fired power plant. The study considered the PM_{10} measurements of the Candiota station as the average for the entire study area and used the daily values between January 1, 2013, and December 31, 2013. The PM_{10} quantification was performed by b-ray attenuation mass monitor (BAM-1020 model), manufactured by Met One Instruments Inc.

As there is no monitoring of $PM_{2.5}$ levels from monitoring stations in the region, $PM_{2.5}$ values were estimated from the ratio obtained in a study in the region conducted by satellite data and which indicates that the ratio between $PM_{2.5}/PM_{10}$ is 0.67 (Da Silva Júnior et al. 2020).

Population and health data

The demographic and health data of the municipalities were collected through the database of the Unified Health System (DATASUS) in 2013 (DATASUS 2021). Data on morbidity and mortality rates from cardiovascular and respiratory diseases, mortality from non-external causes, and total population mortality were extracted.

Health impact assessment

The health impact assessment was carried out according to the methodology of Pascal et al. (2013). Health benefits were evaluated by simulating two scenarios for each pollutant:

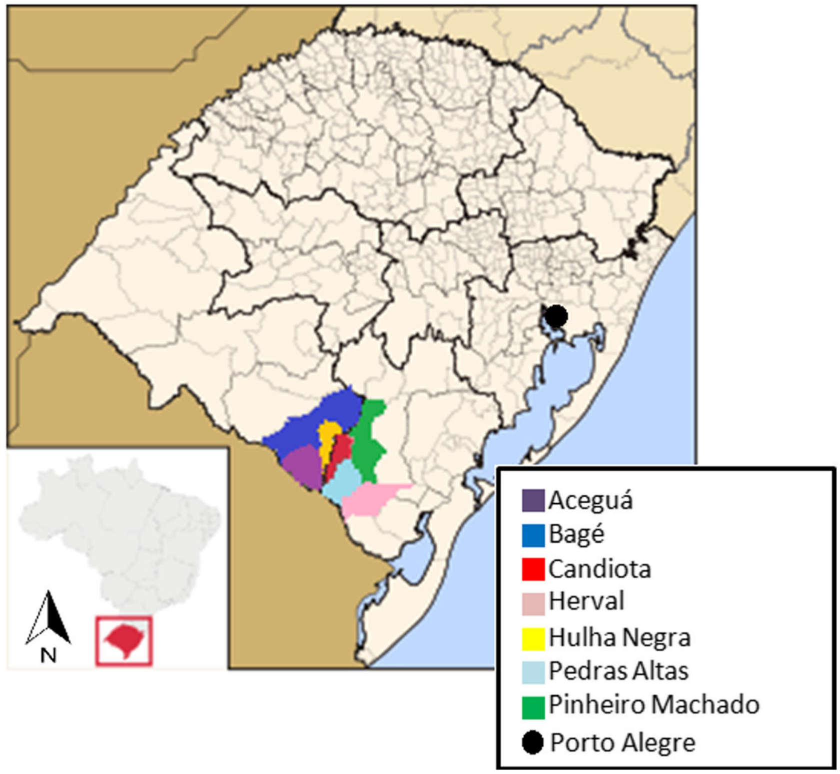

Fig. 1 Map of the study region (Pinto et al. 2017)

decrease in average values by 5 μg/m^3 for $PM_{2.5}$ and for PM_{10} and scenarios in which the levels of the two pollutants would be within the limit imposed by the WHO (WHO 2005): to 10 μg/m^3 for $PM_{2.5}$ and 20 μg/m^3 for PM_{10}.

For short-term exposure to PM_{10}, the health impact assessment was carried out using the following equation:

$$\Delta y = y_0\left(1 - e^{-\beta\Delta x}\right) \quad (1)$$

where:

- Δy is the decrease in health outcome associated with decrease in concentrations of pollutants, in annual number of deaths or hospitalizations.
- $y0$ is the baseline health outcome, in annual number of deaths or hospitalizations.
- β is the concentration response function coefficient.
- Δx is the decrease in the concentration of the pollutant in a given scenario, in μg/m^3.

Regarding the exposure to long-term health effects of $PM_{2.5}$, we applied the standard summary life table methodology, as described by Pascal et al. (2013) calculated from the following equation:

$$nD_{m^{impacted}} = nD_{x.e^{\beta\Delta}x} \quad (2)$$

where:

- nDm is the total number of deaths in the age group starting at age "*n*" for "*m*" years.
- nDx is the number of deaths over a 5-year interval (starting at the age of 30 to the class of 85 or older).

The function was applied to groups of 5 years old from 30 years old, using the same β value for all age groups, in order to calculate the average potential gain in life expectancy. The results were expressed in number of deaths avoided and as gains in life expectancy in individuals over 30 years old. The annual survival burden, expressed as the total number of years of life that could have been gained, was calculated as the product of the average life expectancy at 30 years of age by the estimated number of the population at 30 years of age.

All health impact assessment calculations were performed on the Microsoft Excel® spreadsheet developed by the Aphekom project, available at http://aphekom.org/web/aphekom.org/. All detailed equations are provided in these tools.

Deaths attributed to air pollution

The estimate of deaths related to air pollution was carried out according to Ostro (2004). The $PM_{2.5}$ data were used to measure cardiovascular mortality, using the annual mean of $PM_{2.5}$ (17.8 μg/m^3) and the background value of 7.5 μg/m^3(Pope et al. 1995). To estimate deaths from non-external causes, the annual average of PM_{10} (26.7 μg / m3) was used, and the background value used was 10 μg/m^3(Ostro et al. 2004)

To estimate cardiovascular mortality and total mortality from non-external causes attributed to pollution, the following equations were used:

$$RR = [(X+1)/Xo+1]^{\beta 1} \tag{3}$$

$$RR = \exp[\beta 2(X - Xo)] \tag{4}$$

$$N_{assigned} = [(RR-1)/RR] \times N_{total} \tag{5}$$

where:

- *RR* = relative risk.
- *X* = average annual concentration of $PM_{2.5}$(cardiovascular) or PM_{10} (total for non-external causes).
- *Xo* = basal concentration of PM2.5 (cardiovascular) or PM10 (total for non-external causes).
- *β1* = concentration response function coefficient = 0.155515.
- *β2* = concentration response function coefficient = 0.0008.
- $N_{assigned}$ = number of cardiovascular deaths or total from non-external causes assigned to PM2.5 or PM10, respectively/
- N_{total} = total number of cardiovascular deaths or total from non-external causes.

Economic evaluation on morbidity

The economic evaluation of expenses for hospitalizations due to respiratory and circulatory problems was calculated based on the average cost per day and the average hospital stay (Abe & Miraglia 2016). Data on hospitalization costs and average number of hospitalization days in the cities studied were obtained through the DATASUS database, referring to the year 2013.

The morbidity assessment was estimated according to Equation (6):

$$Ch = Vi \times Nd \times Nc \tag{6}$$

where:

- *Ch* = cost of hospitalization.
- *Vi* = unit value of a daily admission.
- *Nd* = average number of days of hospitalization due to a certain disease.
- *Nc* = number of cases due to a specific disease.

Economic assessment of mortality > 30 years

The economic evaluation of mortality for > 30 years was estimated according to Corá et al. (2005) using Equation 7:

$$Cm = Vd \times VSL \tag{7}$$

where:

- *Cm* = health cost of mortality for people over 30 years old.
- *Vd* = deaths associated with air pollution.
- *VSL* = value of a statistical life, attributed to Bickel and Friedrich (2005), a value of € 1,000,000 and converted into reais. The following conversion was considered: 1 euro is equivalent to 6.80 Brazilian reais.

Results

The daily averages and the annual average of the PM_{10} and $PM_{2.5}$ are shown in Figure 2. The PM_{10} had an annual average of 26.7 μg/m^3 (min, 5 μg/m^3; max, 116 μg/m^3), while the $PM_{2.5}$ had an estimated annual average of 17.8 μg/m^3 (min, 3.35 μg/m^3; max, 77.2 μg/m^3).

The estimate of deaths attributed to air pollution, as well as the annual number of hospitalizations (respiratory and cardiovascular) and total and non-external causes mortality in the study region (sum of the 7 cities in the year 2013), is shown in the Table 1. Among respiratory hospitalizations, we observed that individuals over the age of 65 represent 28.9% of cases. Of deaths from air pollution, mortality from non-external causes represented 10.3 cases while cardiovascular mortality from 47.8 cases, equivalent to 0.8 and 11.6% of total deaths, respectively.

Table 2 shows the potential benefits in reducing $PM_{2.5}$ in the study region, simulating two possible scenarios: reduction of 5 μg/m^3 in the annual average to PM_{10} and $PM_{2.5}$ and reduction until legal limits (10 μg/m^3 to $PM_{2.5}$ and 20 μg/m^3 to PM_{10}). With a reduction of 5 μg/m^3 of $PM_{2.5}$, there would be 12 annual deaths avoided and 7 annual cardiovascular deaths avoided. Still, this is a gain of 10.8 months of life expectancy. Already simulating the scenario with a decrease to 10 μg/m^3 of $PM_{2.5}$ (OMS and Brazilian limit), 18 deaths due to total mortality and 11 cardiovascular would be avoided. The gain in life expectancy would be almost a year and a half (17.5 months). In these scenarios, the reduction in expenses with total mortality would be 26,674,656,2 dollars (reduction of 5 μg/m^3) and 41,509,031,4 dollars (reduction to 10 μg/m^3).

The potential health benefits of reducing PM_{10} levels by 5 μg/m^3 would be 16 hospitalizations (11 respiratory and 5 cardiovascular) and 3.7 deaths from avoided non-external causes.

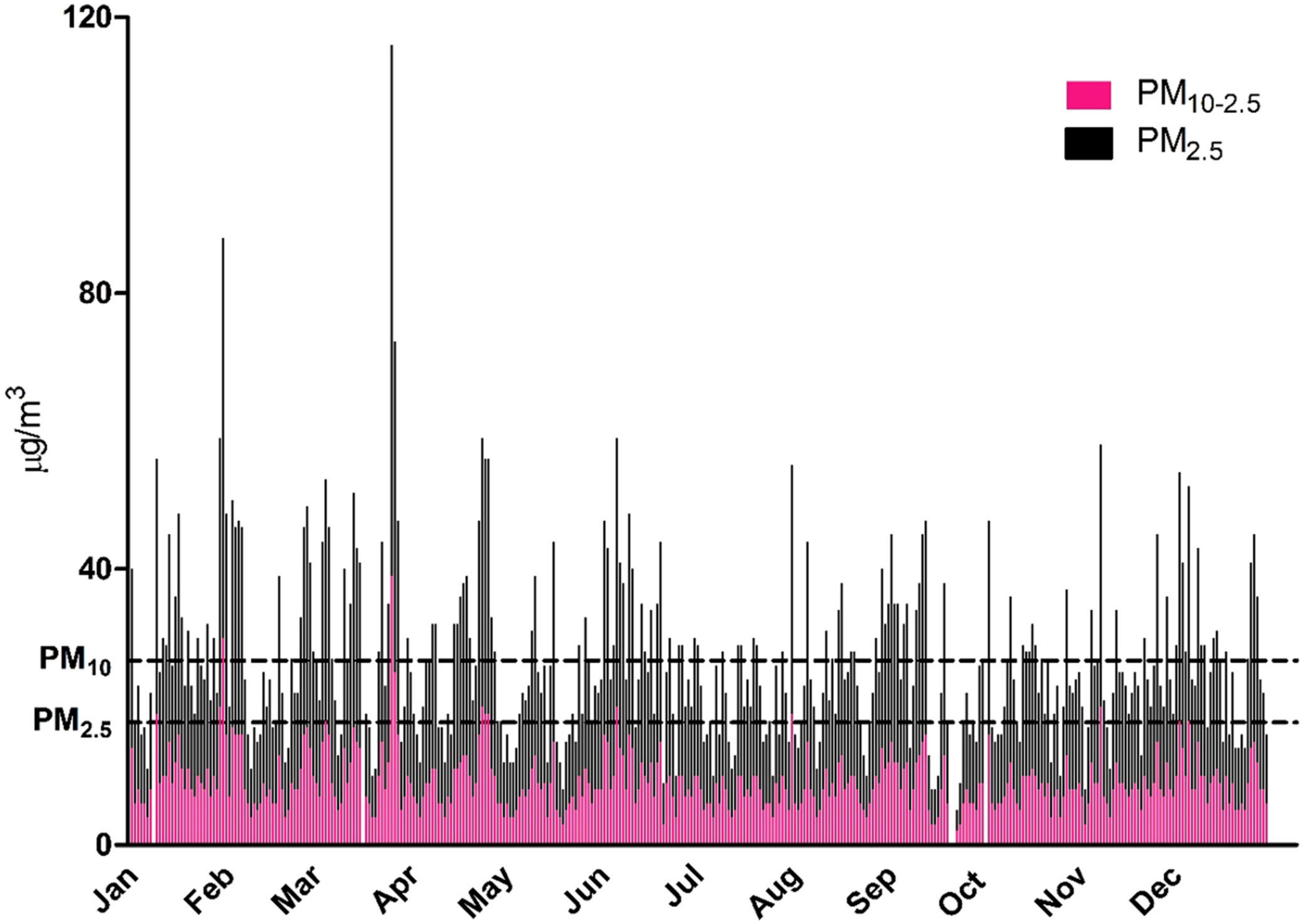

Fig. 2 Daily averages of PM10-2.5 (pink) and PM2.5 (black) and the respective annual averages (—)

In relation to economic benefits, the reduction in spending on respiratory hospitalizations would be $2,272,446, cardiac hospitalizations $2,121,746 and with mortality $5,035,521,854. In a scenario of a decrease to 20 $\mu g/m^3$ of PM_{10}, the potential health benefits would be 21 hospitalizations (14 respiratory and 7 cardiac) and 5 deaths from prevented non-external causes. These health benefits would represent savings of $5,903,032 dollars in hospitalizations (respiratory and cardiac) and $6,668,664,076 million dollars in mortality from non-external causes (Table 3).

Table 1 Annual average of respiratory and cardiac hospitalizations and total mortality, due to non-external and cardiac causes in 2013 in the coal region, Brazil

Health outcomes	ICD10 International Classification of Diseases and Health-Related Problems	Age	Annual average	Deaths attributed to air pollution	Percentage of deaths from air pollution	Annual average per 100,000 inhabitants
Total mortality	A00-Y98	> 30	1,254	-	-	774.9
Cardiovascular mortality	I00-I99	> 30	412	47.6	11,6	254.6
Mortality from non-external causes	A00-R99	All ages	1,232	10.3	0,8	761.4
Cardiac hospitalizations	I00-I52	All ages	1,922	-	-	1187.8
Respiratory hospitalizations	J00-J99	All ages	1,944	-	-	1201.4
Respiratory hospitalizations	J00-J99	15–64	444	-	-	274.4
Respiratory hospitalizations	J00-J99	> 65	561			346.7

Table 2 Potential health benefits of reducing daily $PM_{2.5}$ levels in hospitalizations and mortality from non-external causes and cardiovascular mortality, in the coal region, Brazil (2013)

	Annual number of deaths avoided	Annual number of deaths averted per 100,000 population	Life expectancy gain (months)	Life years gain	Monetary gains US$
Decrease of 5 μg/m^3 of $PM_{2.5}$					
Total mortality	12.0	13.4	10.8	2136.3	26,674,656,2
Cardiovascular mortality	7.6	8.5	-	-	-
Decrease to 10 μg/m^3 of $PM_{2.5}$					
Total mortality	18.7	21.1	17.2	3400.6	41,509,031,4
Cardiovascular mortality	11.8	13.2	-	-	-

Discussion

The findings of the present study estimated that a percentage greater than 11% of deaths from cardiovascular diseases among those over 30 years of age are attributable to pollution by $PM_{2.5}$ and almost 1% of total deaths from non-external causes for all ages associated with the levels of PM_{10} in the region. The study also showed the health benefits associated with the reduction of PM levels, in terms of reducing deaths, hospitalizations, and economic costs, in addition to increasing life expectancy in the study region. This scenario of potential benefits is extremely relevant in the study region, since according to data from the Ministry of Health (DATASUS 2021), the highest mortality rates are related to cardiovascular diseases, tumors, and diseases of the respiratory tract, which are closely related in relation to air pollution.

A study based on data from 185 countries estimated that exposure to $PM_{2.5}$ is responsible for the reduction of the global life expectancy in approximately 1 year and that the reduction of 10 μg/m^3 in the levels of this pollutant would be responsible for the increase of 0.6 years of life in global life expectancy, having an impact equivalent to the eradication of cases of lung and breast cancers (Apte et al. 2018). In the context of Latin American countries, the impacts of air pollution on health services are still poorly understood. In the case of Brazil, less than 2% of cities have air quality monitoring stations (Réquia et al. 2015), restricting studies that estimate the impacts on the population's health to large national metropolises (Abe & Miraglia 2016, Leão et al. 2021).

In addition to the large metropolises, Brazil has regions with high levels of air pollution related to other sources, such as fires (Marlier et al. 2020) and activities for the extraction and use of ores (Da Silva Júnior et al. 2020). The country has one of the largest reserves of mineral coal in the world, and the region of the present study concentrates 40% of all national reserves (ANEEL 2008). In other regions of the world, some studies in coal mining areas have already shown the impact of air pollution on health indicators and the benefits associated with reducing pollutant levels, especially PM (Mokhtar et al. 2014, Chio et al. 2019).

The potential health benefits associated with the reduction in the levels of pollution of PM_{10} and $PM_{2.5}$ in the present study are fundamental to show the government and society that the adoption of stricter air pollution control policies can have social and economic impacts, improving the quality of life and the economy at the local level. Brazil belatedly adopted the levels stipulated by the WHO (WHO 2006)

Table 3 Potential health benefits of reducing daily PM_{10} levels in hospitalizations and mortality from non-external causes and cardiovascular mortality, in the coal region, Brazil (2013)

	Annual number of deaths avoided	Annual number of deaths avoided per 100,000 inhabitants	Monetary gains US$
Decrease of 5 μg/m^3 of PM_{10}			
Total mortality from non-external causes	3.7	2.27	5,035,521,854
Respiratory hospitalizations	11.0	6.79	2,272,446
Cardiac hospitalizations	5.7	3.55	2,121,746
Decrease to 20 μg/m^3 of PM_{10}			
Total mortality from non-external causes	4.9	3.05	6,668,664,076
Respiratory hospitalizations	14.7	9.11	3,036,814
Cardiac hospitalizations	7.7	4.76	2,866,218

through CONAMA Resolution 491 (CONAMA 2018). The previous legislation (CONAMA 1990), besides admitting daily limits of PM_{10} three times higher than the WHO limits, did not contemplate $PM_{2.5}$.

The data in the present study refer to values prior to the implementation of the new national legislation that imposes stricter limits on air pollutants, and future studies should investigate the impact of the new legislation on the levels of the pollutants and on the potential health benefits. Government actions in proposing stricter environmental laws combined with the commitment of different industrial sectors can be effective in reducing air pollution and its consequent health benefits. In the sense, a study conducted in the North American state of North Carolina (NC), from the establishment of an environmental law stricter than the rules imposed by the federal government in 2002, followed the levels of sulfur dioxide (SO_2) and associated sulfate to $PM_{2.5}$ between 2002 and 2012 and revealed significant reductions in the levels of these two pollutants (−20.3%/year for SO_2 and −8.7%/year for sulfate associated with $PM_{2.5}$), especially in the region that concentrates 9 of the 14 largest coal-fired power plants in the NC. This reduction in air pollution resulted in 1700 deaths avoided in 2012 (Li & Gibson 2014).

Discussions about the damage of air pollution to health need to go beyond the limits of the environmental sphere and become a recurring theme in the daily lives of doctors and other health professionals (Iriti et al. 2020), since exposure to air pollutants kills more people worldwide each year than diseases such as HIV/AIDS, malaria, and tuberculosis (Landrigan 2017) and is responsible for 19% of all deaths from cardiovascular disease, 24% of deaths from heart ischemia, 21% of deaths from stroke, and 23% of lung cancer deaths (Wang et al., 2016). These concerns should be further reinforced in areas of socioeconomic vulnerability and inequality, since the severity of the health effects resulting from air pollution seems to have relationship with economic indicators (Lipfert 2004) and development (Mannucci & Franchini 2017).

Numerous studies carried out in the region show negative outcomes in this population (Pinto et al. 2017, Dos Santos et al. 2018, Dos Santos et al. 2021a, Bigliardi et al. 2021, Dupont-Soares et al. 2021), which is exposed to environmental pollutants and is socioeconomically vulnerable. Other studies have been concerned with estimating the environmental risk of exposure to pollutants present in different compartments in the region (Bonifácio et al. 2021, Dos Santos et al. 2021b, Müller et al. 2021), revealing a scenario of exposure to pollutants across different pollutants and environmental compartments.

The current study scales the deaths attributed to air pollution, as well as the potential benefits of reducing PM_{10} and $PM_{2.5}$ levels. These unprecedented findings may serve as subsidies for health surveillance and for new epidemiological studies, since there is a forecast for the creation of new coal-fired power plants in the region. The health and economic benefits need to be taken into account when planning future actions in the region. A study carried out in Northeast Brazil estimated that the restriction of PM_{10} emission standards generates economic gains related to health benefits that exceed by more than 60 times the costs of controlling air pollutant emissions in new coal-fired power plants (Howard et al. 2019).

Conclusion

In Brazil, mainly in the extreme south, where there are large reserves of coal, coal-fired power plants are likely to continue to play an important role, as they are the basis of the economy for countless poor municipalities. However, the current study showed that air pollution has an important contribution to preventable deaths. Approximately 11% of deaths from cardiovascular problems are attributable to the levels of $PM_{2.5}$, and the reduction in the levels of PM_{10} and $PM_{2.5}$ can bring benefits in health indicators and associated cost reductions. These new findings are important instruments available to decision-makers, with a view to improving environmental legislation and in the planning of new enterprises.

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Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contribution LCH, JOP, and VSG were responsible for writing the article and analyzing and interpreting the data. ASB and PRRMB were responsible for extracting the data from the databases and preparing the spreadsheets. MS, PA, and ALMB helped to formulate the key research question and to correct the text. FMRSJ was the advisor and responsible for the research.

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Declarations

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Competing interests The authors declare no competing interests.

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