

Impact of PM_{2.5} Air Pollution on Mortality from Circulatory System Diseases in the Neighborhoods of the City of Rio de Janeiro (2000-2019)

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Abstract

Background: Air pollution by fine particulate matter with an aerodynamic diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}) is the main environmental risk factor associated with diseases of the circulatory system (DCS), ischemic heart disease (IHD), and cerebrovascular diseases (CBVD).

Objective: To estimate mortality rates from DCS, IHD, and CBVD (2000-2019) among residents of the 164 neighborhoods of Rio de Janeiro, according to PM_{2.5} levels.

Methods: This retrospective ecological study used georeferenced satellite data classified into three PM_{2.5} levels and mortality records from the Department of Information and Informatics of the Unified Health System for DCS, IHD, and CBVD among individuals of both sexes aged ≥ 20 years from 2000 to 2019. Age-adjusted mortality rates per 1,000 inhabitants were calculated, and comparative statistical analyses were performed by sex, PM_{2.5} level, and age group (5% significance).

Results: Approximately 91% of the 4.7 million residents (≥ 20 years) live in areas with high or extreme PM_{2.5} pollution. Deaths occurred up to 3.4 years earlier among men living in highly polluted areas compared with those in moderately polluted areas. The highest DCS mortality rates were observed in neighborhoods with high and extreme pollution (female = 3.9 ± 1.7 ; 95% CI = 3.5-4.2; male = 4.6 ± 2.1 ; 95% CI = 4.1-4.9), particularly in individuals aged ≥ 70 years. Significant associations were found between mortality rates and pollution levels for DCS ($p = 0.019$), IHD ($p = 0.025$), and CBVD ($p = 0.002$) in the 50-69-year age group when comparing moderately and extremely polluted areas. Intermediate/high social vulnerability was identified in 71% of neighborhoods, with an increasing socioenvironmental gradient linking higher vulnerability to higher PM_{2.5} concentrations ($R = 0.354$; $p = 0.001$).

Conclusion: Mean PM_{2.5} concentrations in the neighborhoods of Rio de Janeiro exceeded the World Health Organization's recommended standard by a factor of four. Mortality from DCS is significantly higher and occurs earlier in areas with high or extreme levels of pollution.

Keywords: Mortality; Cardiovascular Diseases; Air Pollution; Geographic Mapping.

Introduction

Diseases of the circulatory system (DCS), which include ischemic heart disease (IHD) and cerebrovascular diseases (CBVD), are the leading cause of global mortality, accounting for 34% of all deaths in 2019. Together, IHD and CBVD represented 85% of deaths from DCS, with three-quarters of these fatalities occurring in low- and middle-income countries.¹

The incidence of DCS increases with age and is influenced by classical risk factors, such as hypertension, smoking, diet, and physical inactivity as well as emerging factors like air pollution and social inequalities, which accelerate the age at death.²

Air pollution is an urgent global public health challenge. In 2021, the Global Burden of Disease attributed 8.1 million deaths to air pollution, ranking it as the second leading risk factor for mortality and the first for disability-adjusted life years (235.9 million), surpassed only by hypertension.³⁻⁵

In Brazil, the annual mean concentration of fine particulate matter with an aerodynamic diameter $\leq 2.5 \mu\text{m}$ (PM_{2.5}) reaches $12 \mu\text{g}/\text{m}^3$, exceeding by 140% the limit recommended by the World Health Organization (WHO) ($5.0 \mu\text{g}/\text{m}^3$), which warns that no level of exposure is considered safe. IHD and CBVD account for the highest percentage of deaths attributable to PM_{2.5}.^{4,6}

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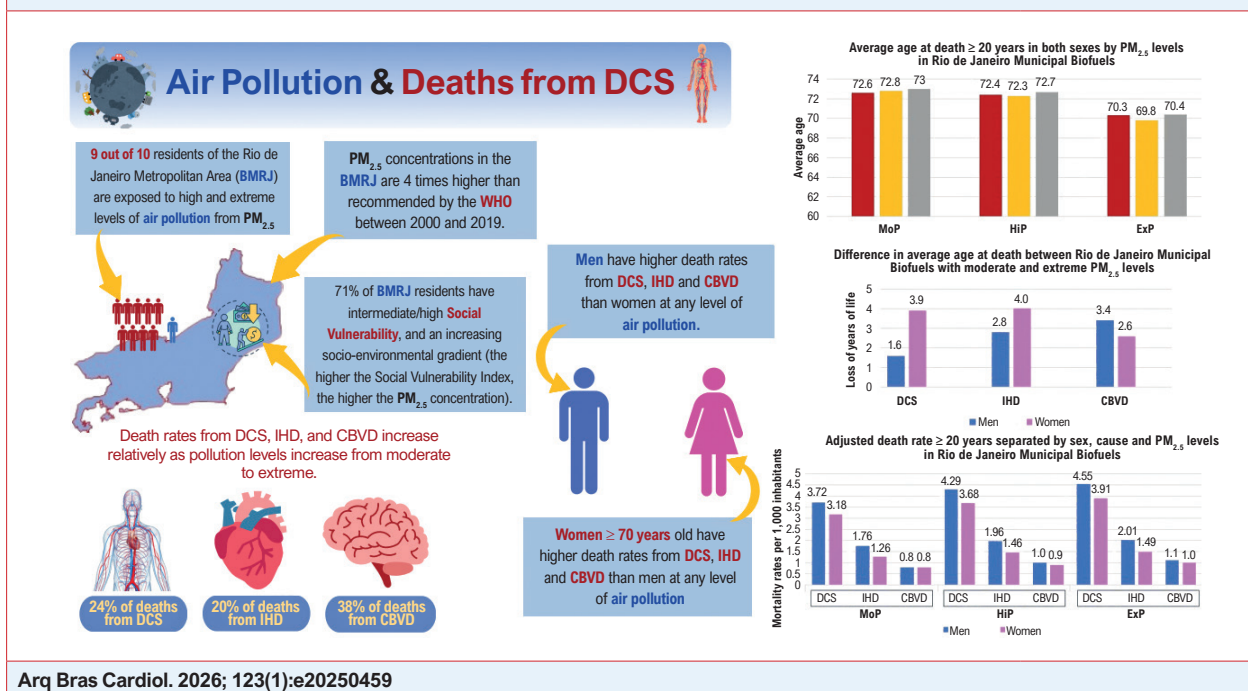
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Central Illustration: Impact of PM_{2.5} Air Pollution on Mortality from Circulatory System Diseases in the Neighborhoods of the City of Rio de Janeiro (2000-2019)

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Air pollution levels in neighborhoods of the municipality of Rio de Janeiro, mortality rates from DCS, IHD e CBVD (per 1,000 inhabitants) in individuals ≥ 20 years, precocity of deaths and Social Vulnerability Index, 2000-2019. DCS: diseases of the circulatory system; IHD: ischemic heart disease; CBVD: cerebrovascular diseases; PM_{2.5}: fine particulate matter ≤ 2.5 µm; ExP: extreme pollution; HiP: high pollution; MoP: moderate pollution.

Satellite-based remote monitoring has been used for air-pollution surveillance, providing broad geographic coverage and long temporal series, making it particularly valuable for studies on health outcomes.⁷

Despite consistent evidence linking air pollution to cardiovascular health, important gaps remain in the literature, especially at finer spatial scales, such as neighborhood-level analyses. No studies to date have specified mortality rates from DCS, IHD, and CBVD across different PM_{2.5} levels in the 164 neighborhoods of Rio de Janeiro. Therefore, this study investigates the association between mortality rates from DCS, IHD, and CBVD among individuals aged ≥ 20 years, according to satellite-estimated PM_{2.5} levels in the 164 neighborhoods of the city of Rio de Janeiro, from 2000 to 2019.

Methods

Study design

This ecological study employed space-time series with a retrospective cohort design, using mortality and air-pollution databases from the neighborhoods of Rio de Janeiro. The analytical approach covered the period from 2000 to 2019.

Data sources: air pollution and mortality

The air pollutant analyzed was PM_{2.5}, measured in µg/m³. Data were obtained from the Atmospheric Composition Group, derived from satellite-based remote sensing. Annual mean PM_{2.5} concentrations for the 164 neighborhoods were used for the period 2000–2019.

The 164 neighborhoods were categorized into three strata based on PM_{2.5} concentration levels over the 20-year period. Stratification followed the final standard proposed by the Brazilian National Environmental Council, which considers annual PM_{2.5} concentrations up to 10 µg/m³ as “safe.” For exposure assessment, strata were defined as follows: moderate pollution (MoP), with annual concentrations ≤ 12.5 µg/m³; high pollution (HiP), with concentrations of 12.6–15.0 µg/m³; and extreme pollution (ExP), with concentrations > 15.1 µg/m³. Based on this classification, 107 neighborhoods were assigned to ExP, 43 to HiP, and 14 to MoP.

For socioeconomic analyses, the social vulnerability index (SVI) for 2010 was used for all 164 neighborhoods, provided by the Brazilian Institute for Applied Economic Research.

Mortality data for DCS, IHD, and CBVD (lines A, B, C, and D and underlying cause of death) were obtained from the Mortality Information System, linked to the Department of Information and Informatics of the Unified Health System. Records included individuals of both sexes, aged ≥ 20 years,

residing in the 164 neighborhoods monitored for $PM_{2.5}$ from 2000 to 2019. Neighborhoods with missing data and deaths with invalid cause-of-death codes were excluded.

Diagnostic coding followed the International Classification of Diseases, 10th revision: DCS (I00-I99), IHD (I20-I25, I50), and CBVD (I60-I69). Mortality analysis proceeded in three filtering steps: selection by municipality code for Rio de Janeiro, by neighborhood code, and by cause of death (DCS, IHD, CBVD).

This study was approved by an ethics review board (CAAE 72977223.1.0000.8044).

Statistical analysis

The three $PM_{2.5}$ concentration strata for the 164 neighborhoods were described in terms of annual mean, maximum, minimum, and dispersion over the 20-year period. Annual means and overall mean $PM_{2.5}$ concentrations for all neighborhoods were calculated. Pearson correlation was applied between mean $PM_{2.5}$ and SVI, and SVI was also stratified according to $PM_{2.5}$ levels.

Age-adjusted mortality rates per 1,000 inhabitants per neighborhood were calculated for deaths from DCS, IHD, and CBVD among individuals aged ≥ 20 years (2000-2019). Adjustment was obtained by weighting crude mortality rates in each age group (20-49, 50-69, and ≥ 70 years) by the respective population percentage, followed by summation.

Annual age-adjusted mortality rates for DCS, IHD, and CBVD (≥ 20 years) were analyzed across 20 years according to $PM_{2.5}$ levels, sex, and age groups. Population estimates by neighborhood for 2010-2019 were derived through linear interpolation based on the 2000 and 2010 censuses.

Normality of continuous variables was assessed using the Shapiro-Wilk test. For comparisons of mean age and adjusted mortality rates between sexes (parametric data), Student's *t*-test for independent samples was applied. The significance level was set at 5%. Analysis of adjusted mortality types and rates by age group and $PM_{2.5}$ strata employed one-way ANOVA with Tukey's post hoc test.

Statistical analyses, figures, and maps were produced using RStudio (version 4.3.2) and the QGIS Geographic Information System (version 3.44.0).

Results

Demographic data and $PM_{2.5}$ concentrations

Of the 164 neighborhoods of Rio de Janeiro analyzed, 14 were classified as MoP, with a mean $PM_{2.5}$ concentration of $11.6 \pm 0.6 \mu\text{g}/\text{m}^3$; 43 as HiP, with $14.2 \pm 0.6 \mu\text{g}/\text{m}^3$; and 107 as ExP, with $16.7 \pm 0.7 \mu\text{g}/\text{m}^3$. No neighborhood exhibited an annual mean $PM_{2.5}$ concentration below $10.0 \mu\text{g}/\text{m}^3$.

The mean annual population was 4.7 million inhabitants, with residents living in ExP areas being seven times more numerous than those in MoP areas. Population distribution by pollution stratum was as follows: MoP (14 neighborhoods, 8.6% of neighborhoods and 8.6% of the population), HiP (43 neighborhoods, 26.2% of

neighborhoods and 31.1% of the population), and ExP (107 neighborhoods, 65.2% of neighborhoods and 60.3% of the population). Mean annual population density per neighborhood varied among the strata.

Across the 20-year follow-up period, $PM_{2.5}$ concentrations increased in all strata: 10.5% in MoP, 5% in HiP, and 9% in ExP, with annual means ranging from $9.6 \mu\text{g}/\text{m}^3$ (2001) to $23.0 \mu\text{g}/\text{m}^3$ (2009).

Mean SVI values showed a rising gradient: neighborhoods classified as MoP had an SVI of 0.16, whereas HiP and ExP exhibited higher values (0.21 and 0.28, respectively). A socioenvironmental gradient was observed, in which higher social vulnerability was associated with higher $PM_{2.5}$ concentrations ($R = 0.354$; $p = 0.001$).

Geographic distribution of pollution strata ($PM_{2.5}$) in the neighborhoods of the city of Rio de Janeiro

Figure 1 shows the spatial distribution of the 164 neighborhoods of Rio de Janeiro according to the strata of annual mean $PM_{2.5}$ concentration. Most neighborhoods (65%) were classified as ExP, 26% as HiP, and 9% as MoP.

Throughout the 20-year period analyzed, the entire estimated mean annual population (4,699,224 inhabitants) was exposed to unhealthy levels of $PM_{2.5}$. Of this total, 60.3% (2,831,761 inhabitants) resided in areas classified as ExP; when HiP neighborhoods are included, this percentage reaches 91% of the population exposed to critical levels of air pollution (Central Illustration).

Figure 1 shows that neighborhoods classified as MoP are geographically surrounded by HiP and ExP areas. The lowest $PM_{2.5}$ concentrations were observed in the central zone (Alto da Boa Vista, Grajaú, Tijuca, Cosme Velho, and Laranjeiras) and in part of the southern zone (São Conrado, Gávea, and Jardim Botânico). In contrast, neighborhoods such as Urca, Ipanema, Lagoa, and Leblon were classified under HiP.

Deaths from cardiovascular diseases

Over the 20-year period, DCS accounted for 37.1% of all deaths, totaling 983,692 individuals aged ≥ 20 years. Among these causes, IHD represented 15.9% of proportional mortality, exceeding CBVD, which accounted for 9.7% (Table 2).

In neighborhoods classified as ExP, the mean age at death from cardiovascular causes was lower in both sexes when compared with MoP areas. Among men, the differences (ExP – MoP) were –1.6 years for DCS, –2.8 years for IHD, and –3.4 years for CBVD. Among women, the differences were –3.9 years for DCS, –4.0 years for IHD, and –2.6 years for CBVD, suggesting a sex-specific impact of pollution on age at death (Central Illustration). Deaths from IHD occurred earlier than those from CBVD within the same $PM_{2.5}$ stratum (Table 2).

Analysis of age at death according to sex, cause, and $PM_{2.5}$ stratum showed statistically significant differences between men and women for all DCS causes and pollution levels, except for CBVD in MoP neighborhoods. Male deaths were consistently earlier than female deaths, with larger differences for IHD (6.5 years) and smaller ones for CBVD (3.1 years).

Age-adjusted mortality rates per 1,000 inhabitants (≥ 20 years, both sexes) for DCS, IHD, and CBVD were consistently lower in neighborhoods classified as MoP

compared with those classified as HiP and ExP (Table 3). A relative increase in mortality rates from MoP to ExP was observed: 24% for DCS, 20% for IHD, and 38% for CBVD

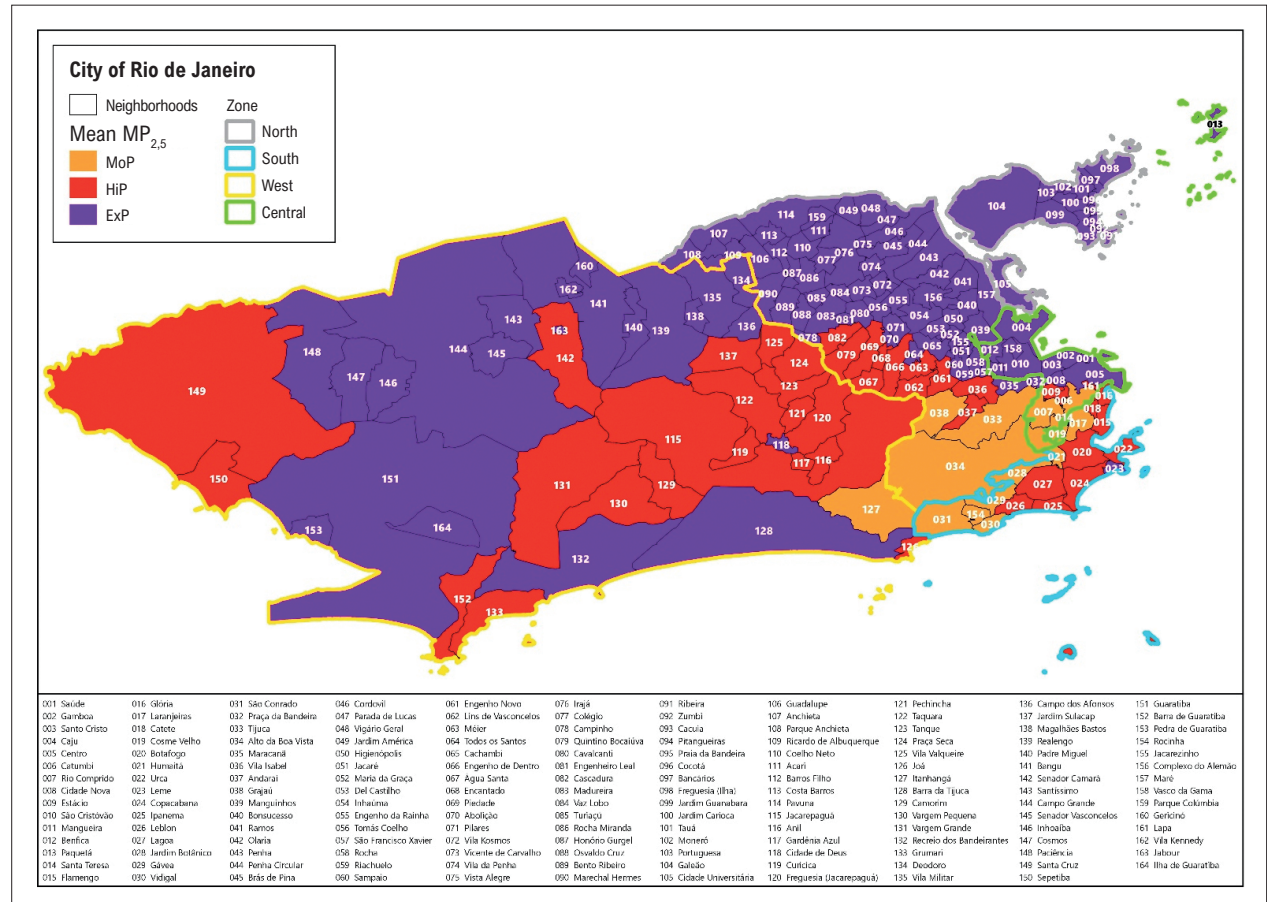


Figure 1 – Spatial distribution of annual mean $PM_{2.5}$ concentration strata in the neighborhoods of the city of Rio de Janeiro, 2000-2019. Source: <https://sites.wustl.edu/acag/datasets/surface-pm2-5/#V4.GL.03>.

Table 1 – Resident population (≥ 20 years) according to $PM_{2.5}$ concentration strata in the neighborhoods of the city of Rio de Janeiro, 2000-2019

$PM_{2.5}$ stratum	No. of neighborhoods*	Mean SVI	Annual mean population (95% CI)**	Minimum population***	Maximum population***	Total population****
MoP ($\leq 12.5 \mu\text{g}/\text{m}^3$)	14	0.16	28,858 (10,093-47,623)	532	132,537	404,009
HiP ($12.6\text{--}15.0 \mu\text{g}/\text{m}^3$)	43	0.21	34,034 (24,237-43,830)	96	140,714	1,463,454
ExP ($\geq 15.1 \mu\text{g}/\text{m}^3$)	107	0.28	26,465 (20,217-32,713)	863	231,797	2,831,761

ExP: extreme pollution; HiP: high pollution; MoP: moderate pollution; $PM_{2.5}$: fine particulate matter $\leq 2.5 \mu\text{m}$; SVI: social vulnerability index. *Number of neighborhoods in the city of Rio de Janeiro. **Annual mean resident population ≥ 20 years in each $PM_{2.5}$ stratum, with 95% CI. ***Minimum and maximum population: lowest and highest annual mean number of residents ≥ 20 years per neighborhood in each stratum. ****Total population: sum of annual mean population values for neighborhoods composing each $PM_{2.5}$ stratum. Source: Mortality Information System/Department of Information and Informatics of the Unified Health System.

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Table 2 – Deaths from DCS, IHD, and CBVD (age ≥ 20 years) according to PM_{2.5} concentration strata, sex, proportional mortality, and mean age at death in the neighborhoods of the city of Rio de Janeiro, 2000-2019

Cause of death	PM _{2.5} Level	Neighborhoods per PM _{2.5} stratum (n)*	No. of deaths (total M + F)	Proportional mortality (total M + F)**	Mean age at death (total M + F) ± SD***	Mean age at death (F) ± SD (95% CI)****	Mean age at death (M) ± SD (95% CI)†	Age difference (F – M)‡	p-value§
DCS	MoP	14	32.540	0.364	72.6 ± 5.4	75.9 ± 5.5 (72.8-79.1)	69.8 ± 4.7 (67.1-72.6)	6.1	0.002
	HiP	43	115.708	0.373	72.4 ± 4.0	75.6 ± 4.2 (74.3-76.9)	69.9 ± 3.5 (68.8-71.0)	5.7	< 0.001
	ExP	107	216.946	0.370	70.3 ± 3.2	72.0 ± 10.4 (70.0-74.0)	68.2 ± 2.7 (67.6-68.7)	3.8	< 0.001
IHD	MoP	14	14.676	0.161	72.8 ± 5.1	76.5 ± 5.2 (73.5-79.5)	70.0 ± 4.4 (67.4-72.5)	6.5	0.002
	HiP	43	51.057	0.163	72.3 ± 4.1	74.1 ± 12.2 (70.3-77.8)	69.7 ± 3.7 (68.6-70.9)	4.4	< 0.001
	ExP	107	91.025	0.157	69.8 ± 7.5	72.5 ± 10.5 (70.5-74.5)	67.2 ± 7.1 (65.9-68.6)	5.3	< 0.001
CBVD	MoP	14	7.473	0.086	73.0 ± 5.0	74.4 ± 5.5 (71.3-77.5)	71.3 ± 4.4 (68.7-73.8)	3.1	0.125
	HiP	43	28.944	0.092	72.7 ± 4.0	75.2 ± 4.0 (74.0-76.5)	70.8 ± 4.0 (69.5-72.0)	4.4	< 0.001
	ExP	107	59.210	0.100	70.4 ± 7.5	71.8 ± 10.5 (69.8-73.8)	67.9 ± 9.7 (66.0-69.8)	3.9	< 0.001

CBVD: cerebrovascular diseases; DCS: diseases of the circulatory system; ExP: extreme pollution; F: female; HiP: high pollution; IHD: ischemic heart disease; M: male; MoP: moderate pollution; PM_{2.5}: fine particulate matter ≤ 2.5 µm; SD: standard deviation. No. of deaths: total number of deaths from DCS, IHD, and CBVD over 20 years. *Number of neighborhoods of the municipality of Rio de Janeiro in each PM_{2.5} stratum. **Proportional mortality: proportion of deaths from DCS, IHD, and CBVD relative to all-cause deaths over 20 years (cause-specific deaths/total deaths in the period). ***Mean age at death for each specific cause and pollution stratum, both sexes combined, with SD. ****Mean age at death for F per cause and PM_{2.5} stratum, with SD and 95% CI. †Mean age at death for M per cause and PM_{2.5} stratum, with SD and 95% CI. ‡Difference between mean age at death for women and men (F – M). §p-value from comparison of mean age at death between sexes (significance considered at p ≤ 0.05).

(Central Illustration).

The largest absolute differences between sexes in DCS mortality rates were found in ExP neighborhoods (0.7 deaths per 1,000 inhabitants). Men had higher mortality rates for DCS and IHD. For CBVD, however, rates were similar between sexes, especially in MoP neighborhoods. Statistical analysis confirmed significant sex differences in mortality rates for DCS and IHD, but not for CBVD (Table 3).

ANOVA followed by post hoc testing did not identify a statistically significant effect of PM_{2.5} strata on mortality rates from DCS (p = 0.072) or IHD (p = 0.144). However, a significant effect was found for CBVD (p = 0.027), specifically between neighborhoods classified as MoP and ExP (post hoc p = 0.039) (Table 3).

Table 4 presents age-adjusted mortality rates per 1,000 inhabitants (≥ 20 years), stratified by age group and sex, demonstrating a progressive increase in rates with advancing age

across all causes, PM_{2.5} strata, and both sexes, with a transition from lower values among women to higher values among men.

Significant sex differences were identified, particularly in the 20-49 and 50-69 age groups, with consistently higher rates among men. This disparity was most pronounced in MoP for the 50-69 age group, in which the male mortality rate represented a 165% increase relative to the female rate (female rate = 0.68). In contrast, among individuals aged ≥ 70 years, female mortality rates were higher or similar to male rates for all causes and PM_{2.5} strata.

Mortality rates from IHD were lower among women, but the sex difference increased with rising PM_{2.5} levels. For CBVD, although male rates in the 50-69 age group were lower than female rates, this relationship was reversed in the remaining age groups, with higher magnitude among men.

Statistical inference using ANOVA followed by post hoc testing did not show a significant effect of PM_{2.5} levels on mortality rates

Table 3 – Age-adjusted mortality rates (DCS, IHD, and CBVD) according to PM_{2.5} concentration strata and sex in the neighborhoods of the city of Rio de Janeiro, 2000-2019

Cause of death	PM _{2.5} level	Neighborhoods per PM _{2.5} stratum (n)*	Mean Total mortality rate (F + M) per 1.000 inhabitants $\pm$ SD**	F mortality rate per 1.000 inhabitants***	M mortality rate per 1.000 inhabitants****	Absolute sex difference (F – M) [†]	Relative percentage difference (M – F)/F (%) [‡]	p-value [§]
DCS	MoP	14	3.4 $\pm$ 0.6	3.2 $\pm$ 0.6 (2.8-3.5)	3.7 $\pm$ 0.6 (3.3-4.1)	0.5	15.6	0.044
	HiP	43	4.0 $\pm$ 1.8	3.7 $\pm$ 1.6 (3.1-4.2)	4.3 $\pm$ 1.9 (3.6-4.8)	0.6	16.2	0.033
	ExP	107	4.2 $\pm$ 1.8	3.9 $\pm$ 1.7 (3.5-4.2)	4.6 $\pm$ 2.1 (4.1-4.9)	0.7	17.9	0.004
IHD	MoP	14	1.5 $\pm$ 0.2	1.3 $\pm$ 0.2 (1.1-1.4)	1.8 $\pm$ 0.3 (1.5-1.9)	0.5	38.5	< 0.001
	HiP	43	1.7 $\pm$ 0.9	1.5 $\pm$ 0.8 (1.2-1.7)	2.0 $\pm$ 0.8 (1.6-2.2)	0.5	33.3	< 0.001
	ExP	107	1.8 $\pm$ 0.8	1.5 $\pm$ 0.6 (1.3-1.6)	2.0 $\pm$ 0.9 (1.8-2.1)	0.5	33.3	< 0.001
CBVD	MoP	14	0.8 $\pm$ 0.2	0.8 $\pm$ 0.2 (0.6-0.9)	0.8 $\pm$ 0.2 (0.6-0.9)	0.0	0.0	0.874
	HiP	43	1.0 $\pm$ 0.5	0.9 $\pm$ 0.5 (0.8-1.1)	1.0 $\pm$ 0.6 (0.8-1.1)	0.1	11.1	0.694
	ExP	107	1.1 $\pm$ 0.5	1.0 $\pm$ 0.5 (0.9-1.1)	1.1 $\pm$ 0.5 (1.0-1.2)	0.1	10.0	0.215

CBVD: cerebrovascular diseases; DCS: diseases of the circulatory system; ExP: extreme pollution; F: female; HiP: high pollution; IHD: ischemic heart disease; M: male; MoP: moderate pollution; PM_{2.5}: fine particulate matter $\leq 2.5 \mu\text{m}$; SD: standard deviation. *Number of neighborhoods in each PM_{2.5} stratum. **Annual mean age-adjusted mortality rate per 1,000 inhabitants (F + M) over 20 years. The adjusted rate is calculated from the crude rate (total number of deaths ≥ 20 years from each specific cause in the neighborhood/population ≥ 20 years) $\times 1,000$, weighted by the age distribution, with neighborhoods grouped by PM_{2.5} stratum. ***Annual mean age-adjusted mortality rate for F over 20 years. ****Annual mean age-adjusted mortality rate for M over 20 years. [†]Absolute difference between F and M mortality rates (F – M). [‡]Relative percentage difference between sexes [(M – F) / F], expressed as %. [§]p-value from the statistical comparison of age-adjusted mortality rates between sexes (significance level $p \leq 0.05$).

in the 20-49 or ≥ 70 age groups. However, statistically significant effects were observed for DCS ($p = 0.019$), IHD ($p = 0.025$), and CBVD ($p = 0.002$) in the 50-69 age group when comparing neighborhoods classified as MoP and ExP.

Figure 2 shows that age-adjusted mortality rates for DCS, IHD, and CBVD among individuals aged ≥ 20 years displayed a continuous downward trend from 2000 to 2019, regardless of PM_{2.5} stratum. Neighborhoods classified as MoP consistently recorded the lowest annual mortality rates for all three causes throughout the 20-year period. In contrast, the HiP and ExP strata alternated in presenting the highest annual rates, indicating temporal variation in the magnitude of mortality associated with higher pollution levels.

Figure 3 presents the spatial distribution of mean mortality rates from DCS, IHD, and CBVD (2000-2019) across the 164 neighborhoods of the city of Rio de Janeiro. The lowest rates were concentrated predominantly in the South Zone and parts of the West Zone (Botafogo, Copacabana, Ipanema, Lagoa, Leblon, Barra da Tijuca). In contrast, neighborhoods such as Vidigal and Rocinha, located within the same region, displayed intermediate values. The highest rates were observed in the West Zone (Santa Cruz, Campo Grande) and the North Zone (Bonsucesso, Ramos, Penha, Manguinhos, Benfica, and São Cristóvão), revealing a heterogeneous spatial pattern characterized by pronounced intra-urban inequality.

Discussion

Although air pollution is a widespread problem, its toxicity varies by location, making analyses at the neighborhood micro-area level essential for the city of Rio de Janeiro. In this study, we investigated the relationship between air pollution and mortality from DCS in an adult population of 4,699,224 individuals over a 20-year period.⁸⁻¹⁰

Mean PM_{2.5} concentrations across the 164 neighborhoods analyzed far exceeded the WHO-recommended limit ($5 \mu\text{g}/\text{m}^3$). Approximately 91% of the population resided in areas classified as HiP or ExP, exposed to levels up to four times higher than international standards. Even in neighborhoods classified as MoP, concentrations exceeded twice the safe limit, demonstrating severe violations and the need for urgent interventions. The highest concentrations occurred in dense urban areas (Vigário Geral and Caju: $17.3\text{-}21.2 \mu\text{g}/\text{m}^3$), whereas the lowest were observed in more remote regions, such as Guaratiba, and in South Zone neighborhoods, revealing socio-spatial inequities in pollutant distribution.^{8,11}

The spatial distribution of air pollution followed a progressive gradient (MoP–HiP–ExP), increasing from coastal areas toward inland regions, influenced by local topographic and climatic characteristics. Areas with greater vegetation cover and lower vehicle flow, such as the Tijuca Forest and Jardim Botânico, showed lower concentrations,^{8,9} whereas densely populated

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Table 4 – Mortality rates per 1,000 inhabitants for DCS, IHD, and CBVD according to PM_{2.5} strata, age group, and sex, with absolute and relative differences between sexes and statistical inference, neighborhoods of the city of Rio de Janeiro, 2000-2019

Cause of death	PM _{2.5} level	Neighborhoods (n)	Age group (years)	Mortality rate per 1.000 inhabitants (F + M) ± SD*	F mortality rate per 1.000 inhabitants ± SD (95% CI)**	M mortality rate per 1.000 inhabitants ± SD (95% CI)***	Absolute difference (F – M)****	Relative difference (%) F†	Relative difference (%) M‡	p-value (sex)§	p-value (PM _{2.5} strata)§
DCS	PoM	14	20-49	0.26 ± 0.1	0.22 ± 0.1 (0.3-0.4)	0.33 ± 0.1 (0.3-0.4)	-0.11	—	—	0.005	0.121
		14	50-69	0.95 ± 0.3	0.68 ± 0.2 (0.5-0.8)	1.29 ± 0.3 (1.0-1.5)	-0.61	—	—	< 0.001	0.017
		14	≥ 70	2.37 ± 1.0	2.53 ± 1.1 (1.9-3.2)	2.20 ± 0.9 (1.6-2.7)	0.33	—	—	0.396	0.392
	PoA	43	20-49	0.29 ± 0.2	0.22 ± 0.1 (0.2-0.3)	0.37 ± 0.2 (0.3-0.4)	-0.15	0	12.1	0.001	—
		43	50-69	1.21 ± 0.5	0.88 ± 0.5 (0.7-1.0)	1.53 ± 0.6 (1.3-1.7)	-0.65	29.4	18.6	< 0.001	—
		43	≥ 70	2.50 ± 0.9	2.68 ± 0.1 (2.3-2.9)	2.35 ± 0.8 (2.1-2.6)	0.33	5.9	6.8	0.053	—
	PoE	107	20-49	0.34 ± 0.2	0.26 ± 0.2 (0.2-0.3)	0.39 ± 0.2 (0.3-0.4)	-0.13	18.1	18.1	< 0.001	—
		107	50-69	1.36 ± 0.7	1.03 ± 0.5 (0.9-1.1)	1.80 ± 0.9 (1.6-1.9)	-0.77	51.4	39.5	< 0.001	—
		107	≥ 70	2.40 ± 1.2	2.55 ± 1.3 (2.3-2.8)	2.22 ± 1.2 (1.9-2.5)	0.33	0.8	0.9	0.028	—
	PoM	14	20-49	0.09 ± 0.0	0.04 ± 0.1 (0.0-0.1)	0.14 ± 0.1 (0.1-0.2)	-0.10	—	—	0.002	0.320
		14	50-69	0.43 ± 0.1	0.28 ± 0.1 (0.2-0.3)	0.64 ± 0.2 (0.5-0.7)	-0.36	—	—	< 0.001	0.019
		14	≥ 70	1.04 ± 0.4	1.05 ± 0.4 (0.7-1.3)	1.06 ± 0.4 (0.7-1.3)	-0.01	—	—	0.960	0.278
IHD	PoA	43	20-49	0.11 ± 0.1	0.06 ± 0.1 (0.0-0.1)	0.13 ± 0.1 (0.1-0.2)	-0.07	50.0	-7.1	< 0.001	—
		43	50-69	0.54 ± 0.2	0.38 ± 0.2 (0.3-0.4)	0.77 ± 0.3 (0.6-0.9)	-0.39	35.7	20.3	< 0.001	—
		43	≥ 70	1.06 ± 0.4	1.07 ± 0.4 (0.9-1.2)	1.06 ± 0.5 (0.9-1.2)	0.01	1.9	0.0	0.843	—
	PoE	107	20-49	0.13 ± 0.1	0.07 ± 0.1 (0.0-0.07)	0.16 ± 0.1 (0.1-0.2)	-0.09	75.0	14.2	< 0.001	—
		107	50-69	0.61 ± 0.3	0.41 ± 0.2 (0.3-0.4)	0.84 ± 0.4 (0.7-0.9)	-0.43	45.4	32.8	< 0.001	—
		107	≥ 70	1.00 ± 0.5	1.01 ± 0.5 (0.9-1.1)	1.00 ± 0.6 (0.8-1.0)	0.01	-3.8	-5.6	0.362	—

		14	20-49	0.06 ± 0.0	0.06 ± 0.1 (0.0-0.1)	0.03 ± 0.0 (0.0-0.1)	0.03	—	—	0.111	0.717
	PoM	14	50-69	0.19 ± 0.1	0.17 ± 0.1 (0.1-0.2)	0.26 ± 0.1 (0.1-0.3)	-0.09	—	—	0.064	< 0.001
		14	≥ 70	0.57 ± 0.2	0.61 ± 0.2 (0.4-0.7)	0.50 ± 0.1 (0.4-0.6)	0.11	—	—	0.210	0.825
		43	20-49	0.07 ± 0.0	0.07 ± 0.1 (0.1-1.0)	0.06 ± 0.1 (0.0-0.1)	0.01	16.6	100	0.986	—
CBVD	PoA	43	50-69	0.27 ± 0.1	0.20 ± 0.1 (0.1-0.2)	0.33 ± 0.2 (0.2-0.3)	-0.13	17.6	26.9	< 0.001	—
		43	≥ 70	0.63 ± 0.2	0.71 ± 0.3 (0.6-0.8)	0.56 ± 0.2 (0.5-0.6)	0.15	16.4	12	0.004	—
		107	20-49	0.07 ± 0.1	0.07 ± 0.1 (0.0-0.1)	0.07 ± 0.1 (0.1-0.1)	0	16.7	133	0.582	—
	PoE	107	50-69	0.35 ± 0.2	0.27 ± 0.2 (0.2-0.3)	0.43 ± 0.3 (0.3-0.4)	-0.16	58.8	65.3	< 0.001	—
		107	≥ 70	0.65 ± 0.3	0.71 ± 0.4 (0.6-0.1)	0.59 ± 0.3 (0.5-0.6)	0.12	16.40	18.00	0.004	—

CBVD: cerebrovascular diseases; DCS: diseases of the circulatory system; ExP: extreme pollution; F: female; HiP: high pollution; IHD: ischemic heart disease; M: male; MoP: moderate pollution; $PM_{2.5}$: fine particulate matter $\leq 2.5 \mu m$; SD: standard deviation. *Age-adjusted mortality rate ≥ 20 years per 1,000 inhabitants, considering both sexes (M + F). **Age-adjusted mortality rate per 1,000 inhabitants for F, with SD and 95% CI. ***Age-adjusted mortality rate per 1,000 inhabitants for M, with SD and 95% CI. ****Absolute difference between the age-adjusted mortality rates of females and males (F – M); negative values indicate a lower female rate, and positive values indicate a higher female rate. [†]Relative percentage difference in mortality rates per 1,000 inhabitants for F, within the same age group and cause, across $PM_{2.5}$ strata. [‡]Relative percentage difference in mortality rates per 1,000 inhabitants for M, within the same age group and cause, across $PM_{2.5}$ strata. [§]p-value (sexes): statistical significance of differences in mortality rates between sexes, by age group and $PM_{2.5}$ stratum (Student's t test for independent samples); p-value ($PM_{2.5}$ strata): statistical significance of differences in mortality rates across $PM_{2.5}$ strata (MoP vs. HiP and MoP vs. ExP), both sexes, by age group and cause of death (ANOVA with Tukey post-hoc test).

coastal areas (Copacabana, Ipanema-Leblon, Urca, Flamengo-Botafofo, and Barra da Tijuca), despite their ventilation, were mostly classified as HiP. Figure 1 illustrates that neighborhoods classified as MoP are surrounded by HiP areas, maintaining relative distance from ExP zones.

Mean age at death from DCS, IHD, and CBVD was lower in ExP neighborhoods compared with MoP neighborhoods for both sexes. This age reduction was particularly marked in male CBVD deaths (–3.4 years) and female IHD deaths (–4.0 years), suggesting differential effects of pollution according to sex and cause of death. Overall, men experienced earlier deaths than women for DCS across $PM_{2.5}$ strata (except for CBVD in MoP), with the greatest difference observed for IHD (6.5 years) and the smallest for CBVD (3.1 years).

$PM_{2.5}$ pollution is associated with cardiovascular mortality and may reduce healthy life expectancy. The findings indicate an increase in DCS deaths (particularly IHD, predominantly among men) as $PM_{2.5}$ concentrations rise. Age-adjusted mortality rates

(≥ 20 years) increased with age but remained consistently lower in MoP neighborhoods than in ExP areas.¹²⁻¹⁴

Mortality rates were higher among men, especially in the 50-69 age group and in ExP areas. However, among individuals aged ≥ 70 years, the influence of pollution on mortality appeared less linear, possibly due to a greater presence of multiple comorbidities.¹⁵ The sex gap was most evident for IHD (female < male), and this disparity increased with higher $PM_{2.5}$ levels in the 50-69 age group.^{16,17}

Although mortality rates were lower in MoP neighborhoods, we observed substantial reductions over the study period in deaths from DCS (43%), IHD (32%), and CBVD (110%). However, high pollution levels may limit further gains in healthy life expectancy.¹⁸

Figure 3 illustrates that the lowest mortality rates from DCS, IHD, and CBVD were concentrated in neighborhoods with better socioeconomic indicators and living conditions (Flamengo, Ipanema, Jardim Botânico, Lagoa). Conversely, high

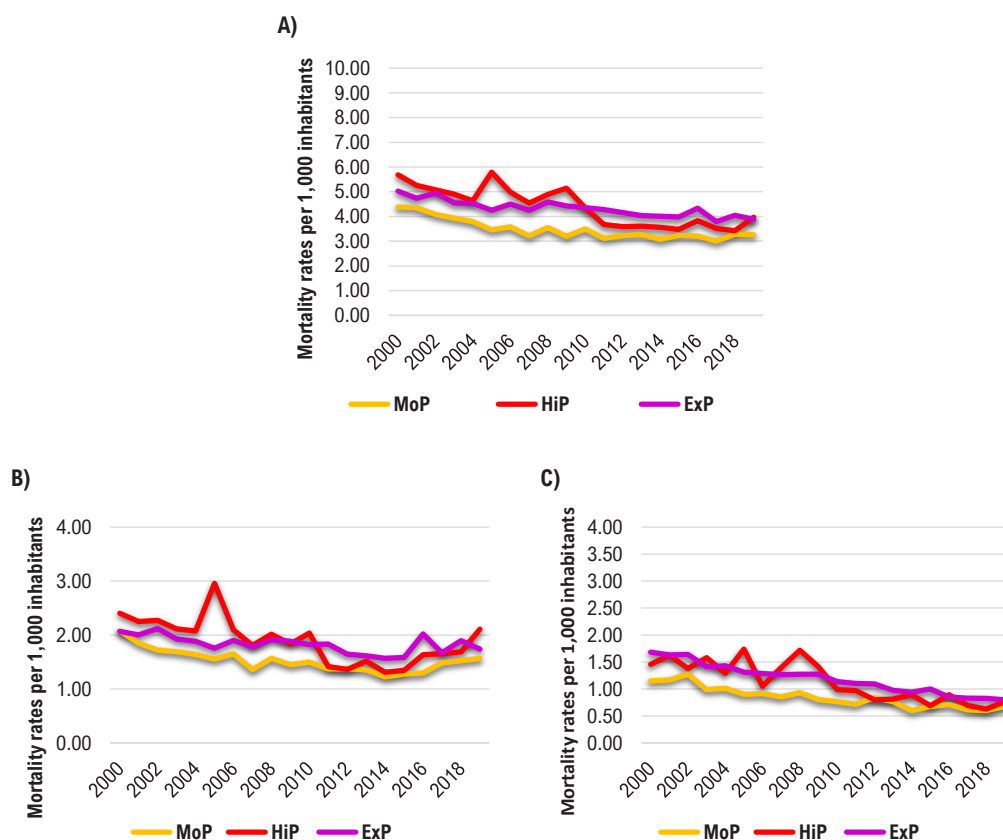


Figure 2 – Age-adjusted mortality rates per 1,000 inhabitants (≥ 20 years) according to $PM_{2.5}$ strata in the neighborhoods of the city of Rio de Janeiro, 2000-2019. A) Age-adjusted mortality rates from diseases of the circulatory system. B) Age-adjusted mortality rates from ischemic heart disease. C) Age-adjusted mortality rates from cerebrovascular diseases.

or intermediate rates predominated in peripheral areas with high population density and inadequate housing conditions (Santa Cruz, Padre Miguel, Ramos, Olaria).^{18,19} Intermediate or high social vulnerability, identified in 71% of neighborhoods, correlated positively with higher $PM_{2.5}$ concentrations and mortality rates, forming a clear socio-environmental inequity gradient.

Reducing air pollution in the neighborhoods of Rio de Janeiro could positively impact DCS mortality, contributing to gains in healthy life expectancy.^{19,20} Ecological studies integrating air pollution and georeferenced mortality data face challenges related to the city's complex urban and topographic morphology. Although this study did not include meteorological variables such as humidity, temperature, or precipitation, these factors may be incorporated in future analyses. Mortality data may present limitations, such as underreporting, ill-defined causes, or garbage codes; however, such limitations do not invalidate the results presented.

Although fundamental, $PM_{2.5}$ exposure alone does not fully explain differences in DCS mortality, given the multifactorial nature of these diseases, which include additional unmeasured risk factors (obesity,

smoking, physical inactivity, and hypertension). Therefore, interpretation of the findings must consider this multicausality.

Conclusion

$PM_{2.5}$ pollution in the neighborhoods of the city of Rio de Janeiro exceeds WHO-recommended standards by up to fourfold, reflecting shortcomings in public policy implementation and disproportionately affecting populations in situations of greater vulnerability. Residents of high and extreme pollution areas experience earlier deaths and higher mortality rates from DCS, IHD, and CBVD, particularly among men.

Despite the overall declining trend in DCS mortality, air pollution remains associated with premature deaths, with major social and economic repercussions. The right to a healthy environment has been systematically neglected for millions of residents, especially those living under adverse socioeconomic conditions.

Author Contributions

Conception and design of the research: Moura PH, Salis LHA, Maia LFPG, Silva NAS; Acquisition of data: Godoy PH, Santos RL; Analysis and interpretation of the data: Carvalho LDG, Paez MS, Alves MB, Silva NAS; Statistical analysis: Moura PH,

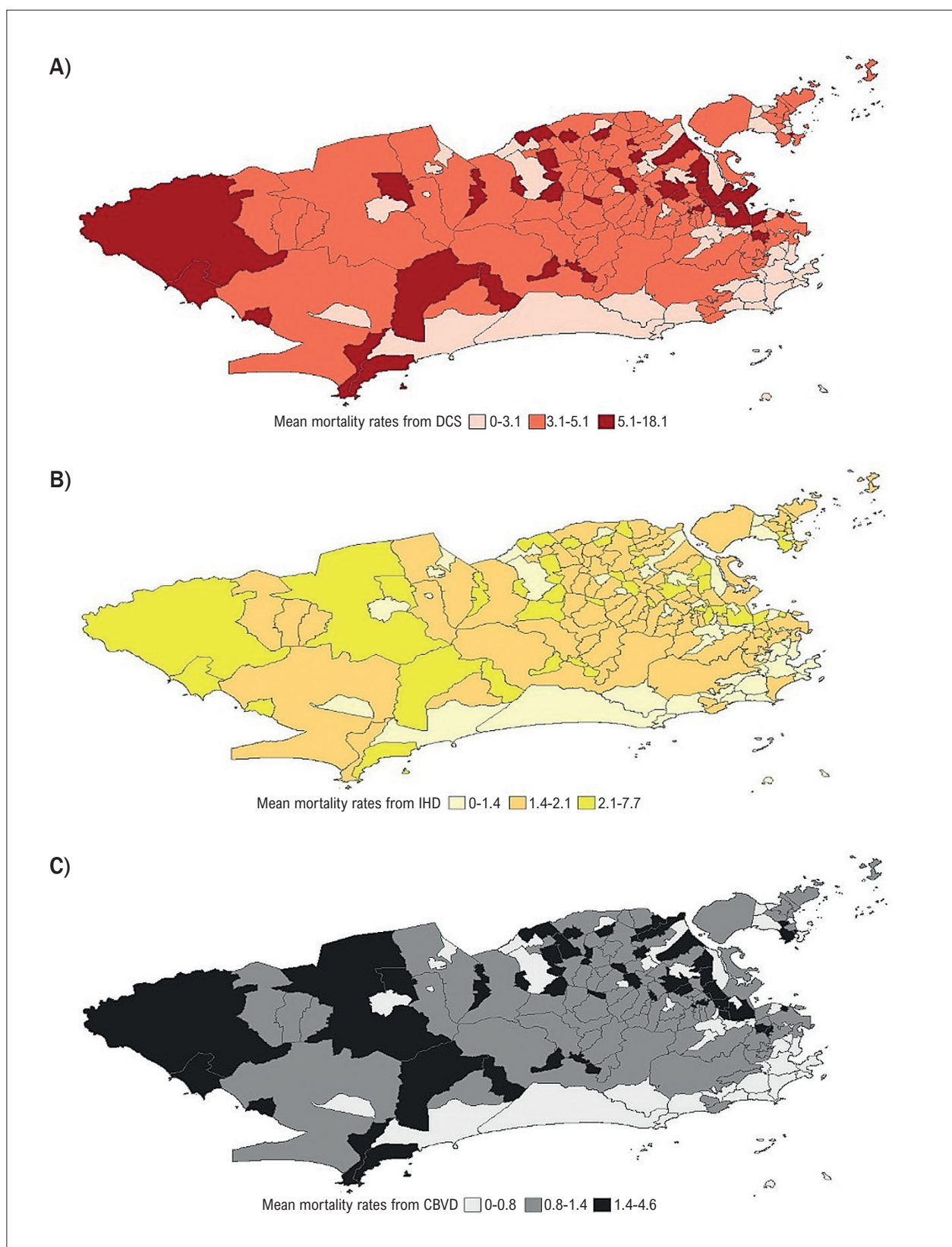


Figure 3 – Georeferenced mean mortality rates per 1,000 inhabitants (≥ 20 years), stratified by cause, across the 164 neighborhoods of the city of Rio de Janeiro over 20 years. A) Mean age-adjusted mortality rate from diseases of the circulatory system (DCS). B) Mean age-adjusted mortality rate from ischemic heart disease (IHD). C) Mean age-adjusted mortality rate from cerebrovascular diseases (CBVD).

Carvalho LDG, Paez MS, Alves MB; Writing of the manuscript: Moura PH, Godoy PH, Salis LHA, Maia LFG; Critical revision of the manuscript for content: Santos RL, Silva NAS.

Potential conflict of interest

No potential conflict of interest relevant to this article was reported.

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Study association

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Ethics approval and consent to participate

This study was approved by the Ethics Committee of the Associação de Ensino Superior de Nova Iguaçu under the protocol number 6.294.723. All the procedures in this study were in accordance with the 1975 Helsinki Declaration, updated in 2013.

Use of Artificial Intelligence

The authors did not use any artificial intelligence tools in the development of this work.

Data Availability Statement

The underlying content of the research text is contained within the manuscript.

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